# Design and construction preferences for connections in the precast concrete industry of South Africa

Louwrens Hubert Mostert

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Supervisor: Prof JA Wium

Department of Civil Engineering

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# DECLARATION

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# ABSTRACT

Precast concrete has been used for decades in the construction industry, locally as well as internationally. Rapid urban development and the need for shorter construction periods for building and infrastructure projects have however encouraged more use of precast concrete construction. The improved speed of construction, high quality and less labour requirements that precast offers makes it an effective type of construction method for modern development. The utilization of various precast concrete systems has been frequently used in the international construction industry, making it a very popular construction method.

It was however found that one of the major drawbacks or concerns with the use of precast concrete is the connections between the precast elements. In-situ construction does not have this problem, because it is designed to a monolithic structure or building. It was identified that if the connections in precast buildings or structures are designed or constructed in an insufficient way, it can lead to severe structural problems and even failure. This highlights the importance the design and construction of precast concrete connections have on the overall stability, strength and robustness of the structure. Precast concrete buildings are not merely separate precast elements, connected together to eventually form the same principals of in-situ construction. Precast concrete and connection design is considered to be a specialist field and requires the sufficient expertise and knowledge to understand the structural system and all its different aspects.

The precast connection's function is not merely to transfer loads, but also to develop continuity and ensure monolithic behaviour of the entire precast concrete structure (Englekirk 2003). The most important or desirable structural functions of precast connections are; (i) direct transfer of loads (load paths and flow or forces), (ii) develop structural continuity and integrity, (iii) distribution of concentrated loads, (iv) allow for movements and unintended restraints and lastly to (v) ensure efficient rigidity and robustness for the connection. It can be seen that there is many factors that contribute to the overall design and construction phases of precast concrete connections.

The aim of this study is to identify and investigate aspects that influence the design and construction of precast concrete connections. This study will mainly focus on precast concrete and precast connection preferences of participants in the South African construction industry. During this study, industry participants (contractors and consultants) were asked to identify certain aspects and concerns associated with precast concrete and precast connection construction. These answers were used to develop guidelines and preferences that can be used by industry participants to improvise and effectively manage the precast construction, mainly focussing on the connections between the precast elements.

# OPSOMMING

Voorafvervaardigde beton word al vir dekades gebruik in die konstruksiebedryf, plaaslik sowel as internasionaal. Vinnige stedelike ontwikkeling en die behoefte vir korter konstruksie tydperke vir die struktuur en infrastruktuur projekte het egter die gebruik en implementasie van voorafvervaardigde beton konstruksie laat toeneem. Die verbeterde spoed van die konstruksie proses, 'n hoë gehalte produk en minder arbeid vereistes wat voorafvervaardiging bied maak dit dus 'n effektiewe tipe konstruksie metode vir moderne ontwikkelings. Die benutting van verskeie voorafvervaardigde beton sisteme en elemente word reeds herhaaldelik gebruik in die internasionale konstruksiebedryf, wat dit vervolglik ŉ baie populêre en effektiewe sisteem maak.

Dit is egter bevind dat een van die groot struikelblokke of probleme met die gebruik van voorafvervaardigde beton is die verbindings tussen die voorafvervaardigde elemente. In-situ beton konstruksie het dus nie hierdie probleem nie, want dit word ontwerp om 'n monolitiese beton struktuur of gebou te vorm. Dit was immers geïdentifiseer dat as die verbindings in ŉ voorafvervaardigde gebou of struktuur, ontwerp word deur ŉ ontoereikende manier, dit kan lei tot ernstige strukturele probleme en selfs strukturele faling. Dit beklemtoon dus die belangrikheid wat die ontwerp en konstruksie proses van voorafvervaardigde beton verbindings het op die algehele stabiliteit, sterkte en robuustheid van die struktuur. Voorafvervaardigde beton geboue en strukture kan nie slegs beskou word as aparte voorafvervaardigde elemente wat met mekaar verbind word om eventueel dieselfde beginsels van in-situ konstruksie te vorm nie. Voorafvervaardigde beton en verbinding ontwerp word beskou as 'n spesialis veld en vereis dat die ontwerper die nodige kundigheid en kennis van die strukturele stelsel en al sy verskillende aspekte verstaan.

Voorafvervaardigde beton verbindings se funksie is nie net om toegepaste kragte oor te dra nie, maar ook om strukturele kontinuïteit te ontwikkel en te verseker dat monolitiese gedrag gehandhaaf word vir die hele voorafvervaardigde beton struktuur (Englekirk 2003). Die mees belangrike strukturele funksies van voorafvervaardigde beton verbindings sluit die volgende in; (i) verseker direkte oordrag van toegepaste kragte (vloei van kragte), (ii) ontwikkeling van strukturele kontinuïteit en integriteit, (iii) die verspreiding van puntbelastings, (iv) moet voorsiening maak vir die bewegings in die voorafvervaardigde element en konneksie self en laastens (v) verskaf doeltreffende rigiditeit en robuustheid vir die konneksie sone. Dus kan daar afgelei word dat daar baie faktore is wat bydra tot die algehele ontwerp en konstruksie fases van voorafvervaardigde beton verbindings.

Die doel van hierdie studie is om aspekte te identifiseer en te ondersoek wat die ontwerp en konstruksie van aspekte beton verbindings wel beïnvloed. Die studie sal hoofsaaklik fokus op voorafvervaardigde beton en verbindings voorkeure van persone in die Suid-Afrikaanse konstruksiebedryf. Tydens die studie was persone in die industrie (kontrakteurs en konsultante) ook gevra om sekere aspekte en kwellings wat verband hou met voorafvervaardigde beton asook die

verbindings te identifiseer. Die antwoorde wat verkry was uit die industrie deelnemers kan toepaslik gebruik om word riglyne en voorkeure op te stel wat vervolglik gebruik en toegepas kan word in die konstruksie bedryf van Suid Afrika. Die riglyne kan effektief gebruik word om voorafvervaardigde beton asook die verbindings te verbeter en persone in die konstruksie bedryf in te lig oor voorkeure en toepassings van hierdie metode.

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# ABBREVIATIONS AND DESCRIPTIONS

- **Precast –** Prefabricated concrete elements that are usually manufactured off-site.
- **In-situ –** Structural concrete elements that are constructed on site.
- **Hybrid concrete –** Mixture between the use of precast and in-situ.
- **STM –** Strut and Tie Method
- **SABS –** South African Bureau of Standards
- **ACI –** American Concrete Institute
- **BS & EN–** British Standards of Eurocode
- **IBC –** International Building Code
- **CMA –** Concrete Manufacturers Association
- **PCI –** Precast Concrete Institute
- **SCC –** Self Compacting Concrete
- **UHPC –** Ultra High Performance Concrete
- **UHPFRC -** Ultra High Performance Fibre Reinforced Concrete

# CHAPTER 1 - INTRODUCTION

## 1.1 Introduction

The topic of this thesis is to investigate the design and construction of precast concrete connections that are typically found in precast or hybrid concrete buildings. The aim is to prepare design and construction preferences and guidelines to facilitate the utilization of precast concrete in the civil engineering industry of South Africa.

Figure 1.2 shows a general overview of factors to be considered when choosing between precast and in-situ construction. This study focuses on precast connections and relevant information on this topic. The other topics listed in Figure 1.2 are topics that are considered as studies on their own and do not form part of this report's objectives and aims.

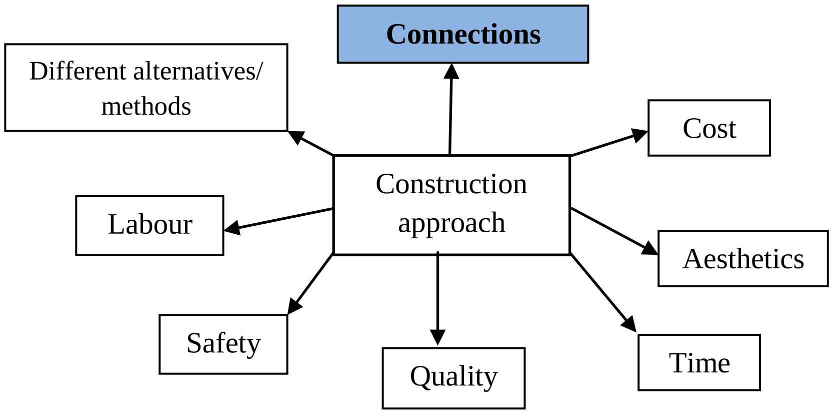



**Figure 1.1 – Aspects to consider when choosing a construction method**

## 1.2 Background

Precast concrete is considered to be a feasible method of construction, and the use of precast concrete has been gaining popularity as an alternative construction method as opposed to the more popular in-situ construction method (Irish Precast Concrete Association (IPCA) 2007). Its applications and variety have gained much interest worldwide as well as in the local construction industry of South Africa. It has been found that the application of precast concrete has been limited in the local civil engineering and building industry. The exact factors that contribute to this lack of application have not yet been fully established and part of this thesis is to investigate and determine the reasons contributing to this phenomenon.

When considering the various factors that contribute to the insufficient application of precast concrete in the construction industry of South Africa, one of the main concerns that were identified are the connections between the precast elements. The connections between the precast concrete elements have been labelled as one of the most significant factors to consider when successfully designing and constructing a precast or hybrid concrete building (Elliot 2002). This study aims to investigate different aspects and considerations that contribute to the design and construction of various precast concrete connections, typically found in a precast or hybrid concrete frame building. The main factors that contribute to successful precast concrete connection design and construction were identified by (Björn 2006) as:

- The need for overall structural integrity and continuity,
- Creating a monolithic precast or hybrid concrete structure,
- Applying the most effective connection method for the specific connection zone,
- Force transfer between precast concrete elements, and
- The connections should be able to withstand seismic actions

It is very important that the design and construction of precast concrete connections adhere to all the above listed aspects. If the connection fails to comply with the identified parameters, it may lead to insufficient design, structural damage, connection failure and even structural failure. This highlights the fact that the connections in a precast or hybrid concrete building should be noted as one of, if not the most important aspects to consider during the design and construction phases. This thesis formulates guidelines or preferences for the use and implementation of precast concrete elements, focussing on the connections between the precast elements. The study and contents of the study focuses on the South African construction industry, but may implement some international uses and applications of precast concrete connections. With information gathered from literature, interviews, design codes, surveys and experts' opinion, applicable guidelines and preferences for successfully utilizing and optimising the use of precast concrete in the South African construction industry will be formulated.

## 1.3 Aim

The lack of knowledge and implementation of precast concrete elements during the construction of concrete structures often leads to the delivery of non-optimal building structures. It was identified by Kurt Billig in 1955 already, that the design and construction of joints and connections are one of the most important aspects of precast concrete construction. Joints and connections provide strength/robustness and transmit forces between the structural components.

**1.** The main aim of this study is to provide guidelines and to identify preferences for civil contractors and designers in the construction industry of South Africa, underlining the importance of precast concrete connections.

- The study addresses some of the typical problems and difficulties found during the design and the construction phases of precast structures and buildings, mainly focussing on the connections between precast concrete members.
- During this report different connection zones typically found in a precast or hybrid concrete building are identified and several connection types are listed and discussed for every connection type that was initially identified.
- Typical buildings or frames that are primarily constructed from precast concrete are also discussed and typical connections used in these frames or building types are identified.

**2.** The study aims to identify some of the basic considerations and preferences when designing and constructing connections found in typical precast or hybrid concrete frame buildings.

- This report formulates and lists applicable precast connection design philosophies obtained from literature. Basic considerations and design forces typically found in precast connection areas are identified and listed in the report.
- Design codes provide design regulations and guidelines for precast concrete as well as connections between precast elements. During this study the local concrete design code, the SABS 0100-1 (2000 Edition) is investigated and compared to international codes, including ACI 318-2008 and EN 1992-1-1:2004. This comparison aims to identify certain shortages or advantages that can be found in the current SABS 0100-1 (2000 Edition) design code.

**3.** The study formulates concluding preferences that can be implemented as development tools and guidelines to facilitate the use of precast concrete construction in the South African industry. The study uses surveys to obtain valuable design and construction preferences for precast concrete and precast connections from industry participants in the South African construction industry.

- The surveys were used to obtain information from contractors and consultants in the South African construction industry and use the survey results to facilitate guidelines and preferences for precast concrete and precast connections.

**4.** During this study some connection enhancement methods are investigated and discussed. The connection enhancement methods may evidently be implemented to address some of the problems or obstacles that were identified in the study.

The conclusions that are drawn from this study aim to assist those in the local engineering and construction industry by providing them with information and preferences for designing and constructing precast concrete elements and primarily the connections between the precast elements.

## 1.4 Research objectives

The main objective of the study is to facilitate the use of precast concrete in the engineering industry of South Africa by providing guidelines and information on local preferences for design and construction of the connections between precast concrete elements. Some of the main objectives for this study include the following:

- Identify the different precast concrete elements that are typically found in a precast or hybrid concrete frame building;
- Identify and list the different connection zones found in a typical precast or hybrid concrete frame building;
- Make a list obtained from literature to identify different popular connection types, typically found in the different connection zones that will be listed;
- Develop criteria that summarises the types of connections along with some difficulties or advantages to the use of that specific connection;
- Identify the design considerations and typical forces present when designing precast concrete connections and also provide design guidelines and preferences;
- Investigate the local design code for the design of precast concrete connections by comparing the local design code, the SABS 0100-1 (2000 Edition) to international design codes including the ACI 318:2008, and the BS & EN 1992-1-1:2004;
- Propose alternative precast concrete connection and enhancement methods that may address some of the problems found from either literature or information obtained from questionnaires;

## 1.5 Scope and Limitations

A scope for this study is required to set boundaries. The boundaries of this study include the following:

- The focus point of this study is connections between precast concrete elements. However, there is a large amount of precast concrete elements available in the market. For the purpose of the study it will be limited to connections between precast elements typically found in precast or hybrid concrete frame buildings.
- For the purpose of the study no physical tests will be done on the different types of connections that were listed,
- This study is also limited in only providing design and construction preferences and will evidently not focus on the mathematical design of connections.

- The results that were obtained from the surveys will be analysed and given as qualitative data. (No quantitative data or tests were done on the specific connection types.)
- For the purpose of the study the connections will be limited to connection zones typically found between foundational footings, columns, beams and floor slabs (typical precast elements for a concrete frame building).
- This study will also focus on the construction industry of South Africa; there will however be some listed precast connections that originated from other countries.
- No software programmes that are used in the industry for designing precast concrete connections have been implemented for this study.
- All assumptions made during this study will be stated and explained through the course of the report.

## 1.6 Research Methodology

The methodology for this study is as follows:

**Step 1: Establish a scope of different connection types that will be investigated and frequently used throughout the study.**

Typical types of precast concrete elements found in a precast or hybrid concrete building are briefly discussed in the literature study in Chapter 2. Different types of connection zones found in a typical precast or hybrid concrete frame building were also identified and listed. For every type of connection zone that were identified during the literature study, three or more specific connection types are identified and listed. For the purpose of the study, only the most popular and frequently used connections in the local and international precast industry were identified and listed. A brief discussion of each connection type is included in the literature review and at the end of Chapter 2 some positive and negative aspects of connection under consideration will be given. Furthermore, different types of precast structures and precast building systems are identified and discussed in Annexure A of the report. The design and construction of the different precast systems given in Annexure A includes various types of connections that have previously been listed in Chapter 2.

**Step 2: Quantify and identify relevant factors that influence the design and construction of precast concrete connections in the South African engineering industry, obtained from contractors and consultants in the South African engineering industry.**

To understand and discuss some of the required design and construction preferences for connections in precast construction, information from participants (contractors and consultants) in the South African construction industry was required. It was decided to set up a survey (use questionnaires as the survey tool), and eventually two separate questionnaires were set up for both consultants and contractors in the industry. The questionnaires are handed out to selected participants from various construction and consulting engineering companies in the South African industry. The questionnaires includes typical questions concerning the design and construction of precast concrete buildings and also includes concerns for precast connections found in precast or hybrid concrete frame buildings. The questionnaires can be used to obtain valuable information, opinions and preferences from participants that have previous experience with precast concrete and precast connection types. The results obtained from the two different groups that participated in the survey (consultants and contractors), are compared to each other to see whether these groups agree or disagree on certain aspects of precast concrete and precast connection design and construction. The content of the questionnaires are discussed and compared to the information found from previous literature and other findings.

**Step 3: Investigate different design aspects and design codes that include design guidelines and rules for precast concrete connections.**

When designing and constructing a precast or hybrid concrete structure there are many factors and considerations that should be taken into account. Some basic design considerations and typical design forces of precast concrete connections are identified during the results obtained from the questionnaires, and are included in Chapter 3 of the report. Chapter 3 includes important considerations such as: the design philosophy of precast concrete connections, force transfer and force connection behaviour and briefly discusses the development of the strut-and-tie method that is frequently being used in the precast concrete construction industry.

Structural rules and design guidelines are often specified in design codes and standards. Designers or consulting engineers use design codes and standards as rules and guidelines to help design and construct precast concrete buildings and structures. If the design codes are insufficient and do not provide the engineer with acceptable design rules and guidelines, it may limit the designer's ability and expertise. Chapter 5 will include typical design codes used for precast concrete design and construction in South Africa (SABS design code). The SABS 0100-1(2000 Edition), specifically the clause concerning precast concrete connections are investigated and compared to international design codes, including the ACI 318:2008 and EN 1992-1-1:2004. This was done to see whether there is a lack of rules and guidelines concerning the design and construction of precast concrete buildings and precast concrete connections in the current precast concrete design code of South Africa.

**Step 4: Identify basic considerations when designing and constructing precast concrete buildings, most importantly the connections between the precast concrete elements.**

The influence of seismic activity on the design and construction of precast concrete buildings, especially the connections between the precast elements is another important factor that should be taken into account. It was however found that seismic considerations is a specialist field and should be conducted as a study on its own. Chapter 4 identifies different design forces and factors that should be incorporated in both the design and construction of precast concrete connections. From this chapter, some relevant preferences and guidelines may be obtained and the importance of the connections to the entire precast structure can be emphasized.

Precast connection enhancement methods and solutions that have been developed and implemented for the use in precast concrete connections are investigated and have been included in Chapter 7 of the report. The development of different alternatives for precast concrete connections may be implemented to solve some of the problems and difficulties that were identified and listed from literature or the information gathered from the questionnaires. Finally some conclusions and recommendations drawn from this study are included in Chapter 8 of the report. The figure shown in section 1.7 provides a graphical illustration of the methodology followed during the study.

## 1.7 Graphical presentation of this study

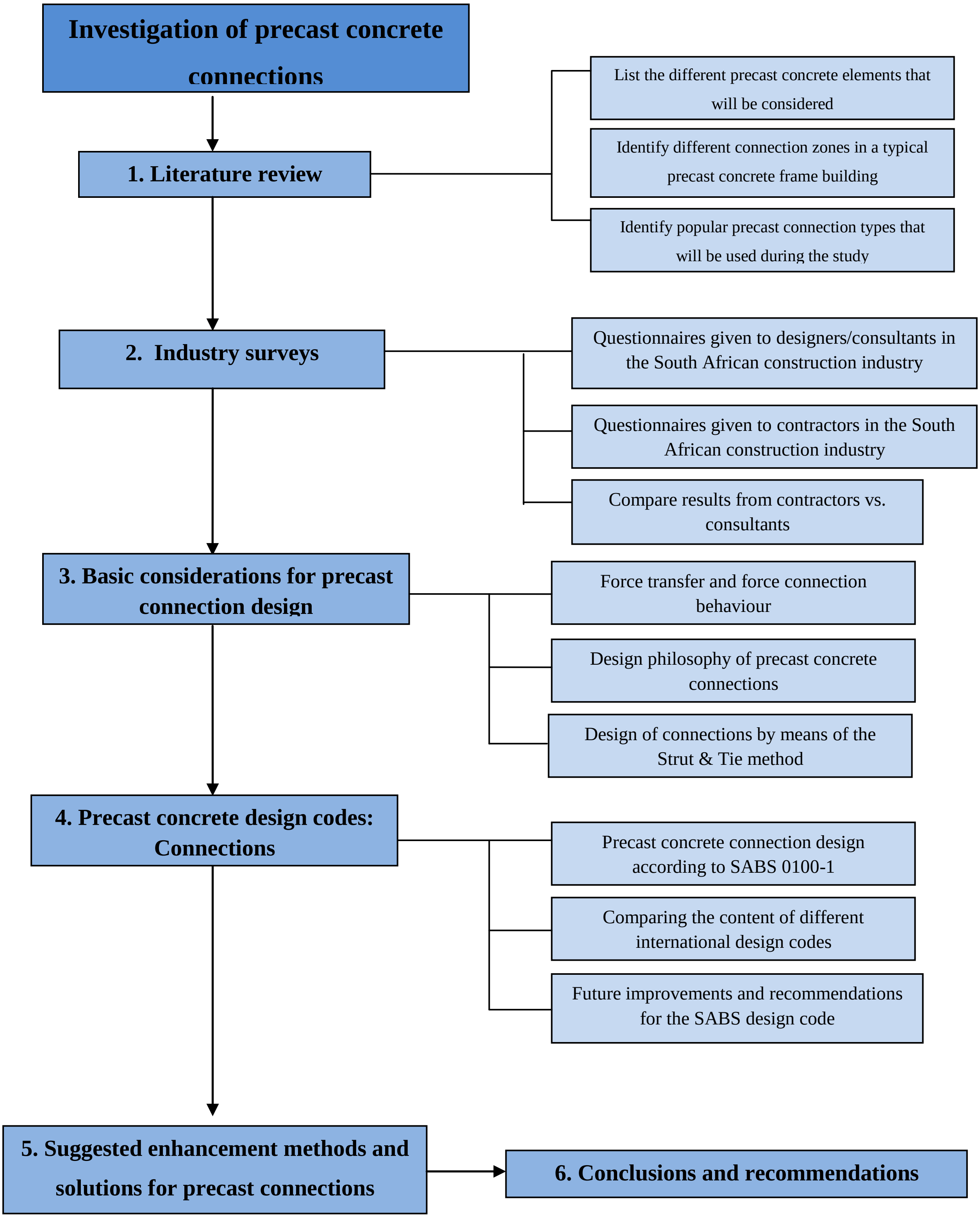



**Figure 1.1 – Graphical layout of thesis**

# CHAPTER 2 - LITERATURE STUDY

The literature study includes information about precast concrete elements as well as precast concrete connections. The chapter elaborates on different connection zones and connection types typically found in precast or hybrid concrete frame buildings. A short summary of this chapter is illustrated in the following figure:

**2.1- The development of precast concrete**

**2.2 – Different prefabricated concrete elements**

**2.3 – Basic description and consideration of structural connections**

**2.4 - Different connections found in typical precast concrete**

**2.5 – Various precast concrete structural systems**

**Figure 2.1- Chapter Layout**

## 2.1- Historical development of precast concrete

Precast concrete have been developing from ancient Rome and have come to wide use in the civil engineering and building industry. Modern uses of pre-cast technology include a variety of architectural and structural applications featuring parts of or an entire building system. Precast concrete construction has thus been in use since the early 20th century, coming into wide use during the 1960's. The versatility and compatibility of precast concrete makes it ideal for many structural applications. (Task Group 6:2: A.Van Acker et al 2010)

The most general description for precast concrete is given by (Menegotto 2010), as the following:

> ***Precast concrete consists of concrete (a mixture of cement, water, aggregates and admixtures) that is cast into a specific shape at a location other than its in-service position. The concrete is placed into formwork or a mould, typically made from wood or steel, and cured before being stripped from the form. These components are then transported to the construction site for erection into place and eventually connecting the different parts of the structure or building.***

The precast concrete elements can also be produced on site, this is usually when the precast factory is too far from the site, the elements are too large for transport or tilt-up precast concrete elements will be used. Tilt-up elements are also cast on site in moulds and eventually tilted and fitted into position.

Precast concrete systems usually enable fast and effective completion of many different types of buildings and various concrete structures (Alfred A. Yee 2001). There is a general misconception of precast technology only as a mere translation of cast in-situ into a number of precast elements that are assembled on the site in such a manner that the initial cast in-situ concept is obtained (FIB - Féd. Int. du Béton 2002). This misconception may occur due to lack of understanding of the design and rules associated with precast concrete design and construction. According to (Menegotto 2006), "Effective design and construction is achieved through the use of suitable connections to cater for all service, environmental and ultimate load conditions". Connecting the precast concrete elements is not just a matter of fixing the elements to each other, but should be done in a way to ensure structural integrity and overall continuity of the structure as a whole.

Therefore, in the initial design of a concrete building, the first requirement should consist of identifying whether the project or parts of the project are suitable for construction by using precast concrete elements in the most applicable areas. The use and application of precast concrete does however include numerous advantages, and according to (Tzikou 2011) some of these advantages may include the following aspects:

- Good durability and smooth finishing,
- Efficient and safe erection speed,
- High quality control due to controlled environment during manufacturing,
- Less labour required on site to install precast elements, and
- Prestressing is easily done which can reduce the size and number of the structural members.

There are also some shortcomings or disadvantages that may occur when making use of precast concrete elements and according to (Tzikou 2011), some of the disadvantages may include the following:

- Members may become very heavy if they're too big,
- Camber in beams and slabs may occur,
- Very small margin for error, small tolerances is allowed,
- Connections may be difficult to design and construct, and
- The need for repetition of forms will affect the building design.

The listed disadvantages may have an effect on design and construction of precast structures, but due to the several advantages that precast offer and the various applications that this method proposes, makes it an economic and effective method of construction (Task Group 6:2: A.Van Acker et al 2010). From the list of disadvantages given above, it was noted that the connections between the precast elements can be a big concern. The study will address the concerns associated with the design and construction of precast concrete connections.

## 2.2 - Development of prefabricated concrete elements

Precast concrete elements are usually cast in a factory, removed from site, transported and erected or constructed on site. These precast elements can consist of either standard or non-standard designs, depending on the structure that will be built. The standard precast elements are usually available from stock from the precast manufacturer (e.g. slabs, beams, columns etc.) with available standard dimensions. The use of non-standard size elements is usually specified by the architect or engineer and may include a specific shape or size that complements the designed structure or building. The designed concrete building can be subdivided into different precast concrete elements either consisting of standard or non-standard dimensions. The elements that are typically found in a frame of the precast concrete building can be listed as the following:

- Columns
- Beams
- Floor slabs
- Foundations

In some cases other prefabricated concrete elements such as wall panels, stair cases, precast shafts, foundational units etc. can be identified, but for the purpose of this study, only the connections between the above mentioned precast elements will be investigated and discussed.

### *2.2.1 – Prefabricated columns*

Columns usually have standardized cross-sections including shapes such as: square, rectangular, circular and in some extreme cases also oval. The precast concrete columns may be manufactured to various standard dimensions but can also be customized to the client's specific recommendations.

The height of the columns is usually determined by the design specifications set by the architectural or engineering considerations of the structure or building. This will also depend on the availability of transport of the columns in the surrounding area. The precast columns may be continuous throughout the full height of the building or it can be single storey columns that are spliced if the length of the column becomes too long. (Van Acker 1996).

Precast concrete columns are usually connected to the foundational footing by means of: steel base plates, projecting steel bars, tying of reinforcement or by means of pocket foundations (concrete filled foundations). Columns may also have built in structural inserts or corbels. These corbels are used at floor levels to provide support for the beams that will span across and connect to the columns. The position of the corbels may vary to effectively provide support or connections at varying levels of the structure. Figure 2.2 shows a typical presentation of a precast column corbel. (Elliot 2002)

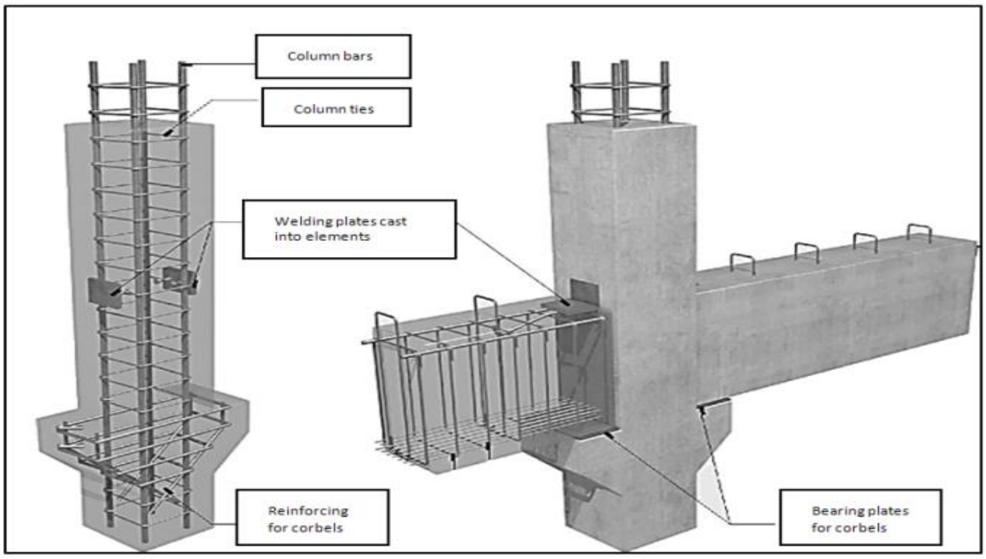



**Figure 2.2 - Column corbel (European Commission - Joint research centre 2012)**

## *2.2.2 – Prefabricated beams*

Precast concrete beams used in a frame structure are designed to resist certain loadings and support conditions. A precast column's main purpose is to transfer vertical loads, where as a precast beam's function is to transfer vertical loads, horizontally in the structure. The type of load applied to the precast beam will affect the kind of connection that is required at the end of the beam. (Elliot 2002)

Beams, the same as columns, can come in different cross sectional areas and shapes. These beams can differ from inverted T-shaped beam that can be used as a support on either sides of the beam or an L-shaped beam that can be used as support only on the one side. Three types of precast beams that are frequently used in the precast industry include:

- Inverted T - beams,
- L-beams,
- Rectangular beams

The shapes and sections of precast beams vary to lend support on different levels as required, a wide variety of sections is however available on the market depending on the type of precast structure or building that will be built.

## *2.2.3 – Prefabricated floor slabs*

Floor systems provide a very important role in the lateral resistance of a building. By providing diaphragm action, the floor slabs transfer lateral loads to the internal load resisting elements (e.g. shear walls). Of all the structural elements, the precast floor system is the system that is most often used in design and construction of structural systems and buildings.

The main reason why precast floors are more frequently used than any other precast system is the fact that precast floors offers many advantages over cast in-situ floors. Advantages mainly include the absence of scaffolding, shorter construction time, smooth finishing, high mechanical durability and it can be used for longer spans (Van Acker 1996).

According to (Van Acker 1996), a large variety of precast floor systems are available on the market, with five main types which can be distinguished as follows:

- Hollow core floors
- Rib and block floor slabs
- Coffer floor slabs
- Composite floor-plate floors
- Composite beam-block floors

According to the Concrete Manufacturers Association (Concrete Manufacturers Association (CMA) 2002) some of the main structural requirements of floor slabs include: (i) length of load bearing area, (ii) transverse load distribution of concentrated loadings and (iii) distribution of horizontal action by in-plane diagram action. The Concrete Manufacturers Association (CMA) also created the following criteria for choosing an appropriate type of flooring system for a precast or hybrid concrete structure:

- The self-weight of the structure,
- The applied load and span length of the slab,
- The fire resistance of the structure,
- Sound insulation,
- The overall appearance,
- The required flexibility in the design concept

Precast floor slabs can be fully precast or either partially precast. Fully precast floor slabs are cast at the plant and transported and erected on site, where partially precast floors are composed from both cast in-situ and precast parts. The variety of fully precast floor slabs and partially precast floor slabs is illustrated in Table 2.1. (Task Group 6:2: A.Van Acker et al 2010)

**Table 2.1 - Types of precast floor systems**

| Fully precast floor slabs | Partially precast floor slabs |
|---|---|
| Hollow-core slab systems | Composite floor-plate floors |
| Reinforced hollow-core slabs | Semi-precast floor panel |
| Pre-stressed slip formed hollow core slabs | Semi-precast double T-shaped floor units |
| - | Rib-and-block floors |

According to Jaco Karstens (2014), the South-African building industry is frequently tending to make use of hollowcore floor slabs in low rise concrete buildings such as schools, flat blocks, hotels residences, multi-storey houses etc. This trend is thought to follow throughout the whole of South Africa due to the list of benefits that the hollow core slabs provide to consultants as well as contractors.

## 2.3 - Basic description and consideration of structural connections

A structural connection normally consists of several components. The structural behaviour and the performance of the connection depend on the interaction between these components (Elliot 2002). Typical components that are usually found in these connections can be identified as joints with joint fills, tie bars, anchor bars as well as other modern designed coupling devices. There is however a difference between joints and connections, the difference between them will be discussed in the following paragraph.

### 2.3.1 - Joints and Connections

It is very important to distinguish between joints and connections in the precast construction industry, especially when the connections between the precast elements are considered. A joint can typically be described as an interface between two elements in a structure where the forces can be transferred whereas a connection can be described as an assembly of two or more elements that is designed to resist the applied forces. (Björn 2006)

Unlike cast in-situ concrete work, the design philosophy for precast connections concerns both the structural requirements and the chosen method of construction. In many instances the working practices in the factory also strongly influences the connection design (FIB - Féd. Int. du Béton 2002). The structural connection interacts closely with the adjacent structural elements, and the design as well as the detailing of the connection is influenced by the design and detailing of the adjacent elements.

The connections between the precast concrete elements are in close contact with the adjacent elements of the structure, thus the design and detailing of the connections are influenced by the design and detailing of the adjacent elements. The connection must be designed so that the flow of the forces, found in the connection is logical, but also that the forces can be transferred to the overall load bearing elements of the structure (Task Group 6:2: A.Van Acker et al 2010). Figure 2.3 illustrates typical joints that can be found in a precast concrete connection zone.

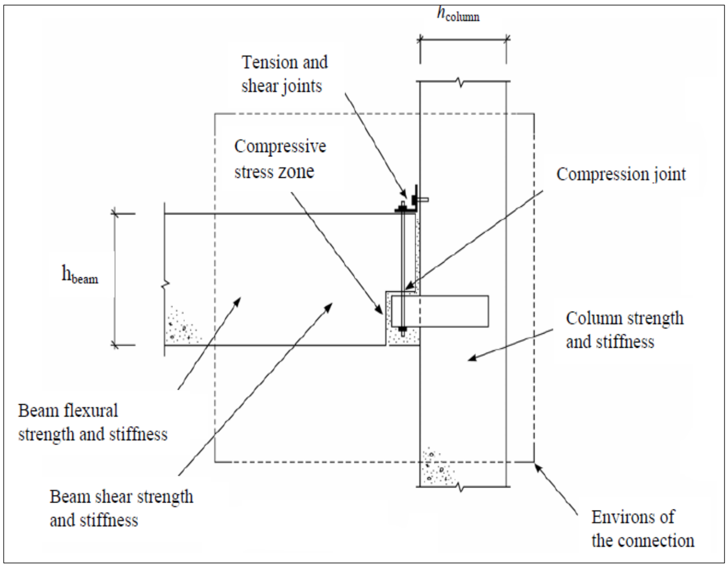



**Figure 2.3 - Illustration of a connection and joints (Task Group 6:2: A.Van Acker et al 2010)**

The materials that are used for the connections must be durable for the entire working life of the concrete structure. The connections must also be protected against all chemical or physical influences and must be fire resistant as steel loses its strength under heat exposure. Simply supported connection types are sometimes supported by means of load bearing pads. It is thus important that the bearing pads supporting the elements have the appropriate capacity in accordance with the design of the connection (Task Group 6:2: A.Van Acker et al 2010).

Structural connections are among the most essential parts in prefabrication (Elliot 2002). Effective connections are the key to successful precast concrete systems. They must meet a full variety of all above mentioned aspects as well as design and performance requirements, manufacturing, assemblage, serviceability and resistance. A thorough understanding of the basic mechanisms and the role of the connections within the overall structural system forms the basis of a conceptual precast concrete design. Designers should understand how the connections are part of the system and should be aware of the flow of forces, as well as of the deformations, throughout the whole structure and the connections itself (Elliot 2002).

## 2.4 - Connections found in typical precast buildings

It is thought to be a general misconception to distinguish precast concrete technology only as a simple translation of a cast in-situ structure into a number of precast concrete elements, which have to be assembled on site in such a manner that the initial cast in-situ concept is obtained (Elliot 2002). This misconception can be described due to a lack of understanding of the design guidelines, philosophy and the special characteristics and rules associated with precast concrete design and construction. It is found that in the precast concrete industry there are numerous types of connections that occur in different connection zones in a precast structure or building.

### 2.4.1 – Design and construction considerations for precast connections

According to (Task Group 6:2: A.Van Acker et al 2010) and (FIB - Féd. Int. du Béton 2002), the following significant considerations for the design and construction of precast concrete were identified:

(1) - **Standardisation**: A standardised connection system will always be beneficial. Structural connections are supposed to transfer forces, and the magnitude of these forces will vary from connection to connection. Therefore it is preferred to try and standardize a light, medium and heavy-duty type element of the same principal solution, but each with a different capacity for force transfer. This makes it easy for the designer to choose a standard solution (saves time and eliminates possibilities of errors in the calculation), and creates repetition for the labourers (possibility of less mistakes).

(2) – **Simplicity**: Simplicity is important to achieve for a connection detail that is inexpensive and least likely to be used incorrectly. Consequently all connection arrangements should aim to consist of as few as possible different pieces that need to be assembled.

(3) - **Tensile capacity**: If a connection is required to have a tensile force capacity, then consequently all the embedded units must have sufficient anchorage, and friction can never be part of the developed force transfer mechanism. The connection between anchored units must also have a tensile force capacity.

(4) – **Ductility**: Connections should preferably behave in a ductile manner. Ductility can be defined as the ability to have large plastic deformations before it fails. In concrete members with moment-resisting connections, the flexural tension is normally resisted by steel components, either by reinforcing bars or structural steel members.

(5) – **Movements**: Connections should not restrain the required movements that are necessary for the structure. Necessary movements will in most cases be the deformation of beams and slabs due to loads and/or pre-stressing forces, shrinkage and also creep.

(6) – **Durability**: Evidence of poor durability usually appears as corrosion of exposed steel details, or by cracking and spalling of concrete as a result of corrosion of the reinforcement bars. Connections subjected to corrosion must have steel details adequately covered with concrete, or should be corrosion protected e.g. galvanised steel.

(7) - **Fire resistance**: Many precast concrete connection details are not vulnerable to fire, and require no special treatment. Connection where weakening by fire would jeopardize the structure's stability should be protected to give the same resistance as the structural frame.

(8) – **Aesthetics**: It must be kept in mind that aesthetics play a very important role in a structure. Any structural connection that will not be hidden can either be emphasized or become part of the architecture of the structure.

## 2.4.2 – Identified connection types

The red circles in Figure 2.4 show a variety of connection types that occurs in typical precast concrete frame buildings. The connections zones that have been identified for the use during this entire study will include the following:

- Foundation-to-column connections,
- Column-to-column connections,
- Column-to-beam connections,
- Connections between floor slabs, and
- Beam-to-slab connection

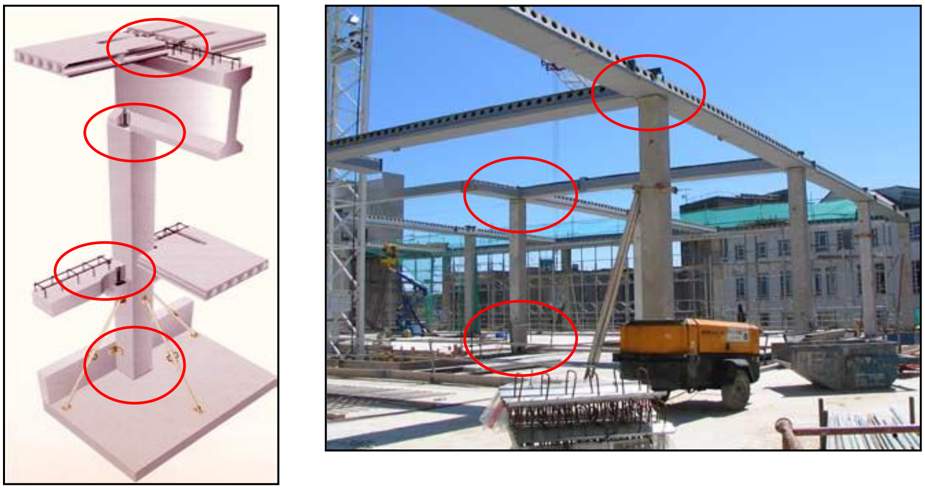


**Figure 2.4 - Typical connections found in precast structures (Walraven 2013)**

Figure 2.5 shows the different kind of connection zones found between precast elements typically found in a precast concrete frame building. The different precast concrete elements include: footings, columns, beams, floor slabs as well as wall panels in some cases. From Figure 2.5, it can be seen that there are more than one method to connect these precast elements to one another. The prescribed connection method usually depends on the type of precast structure or building that will be built, the implied restrictions and also the design aspects of the structure itself.

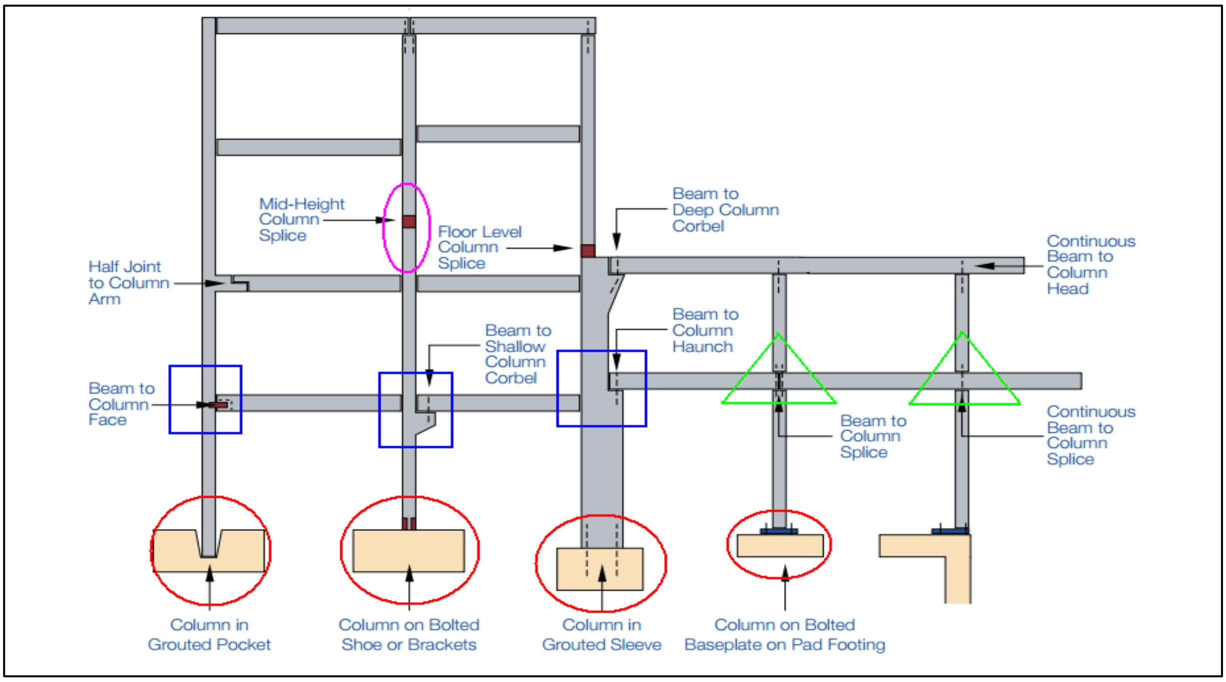



**Figure 2.5 - Different connections found in a precast concrete structure (Irish Precast Concrete Association (IPCA) 2007)**

The connections in Figure 2.5 marked with a red circle present typical foundation-to-column connection types. The connections marked with a blue block shows different variations of column-to-beam connections. The connections marked with a green triangle present an internal connection between precast columns and beams. This connection can either be located where the beam is continuous (green triangle on right hand side) or located where the column is continuous (green triangle on left hand side). Lastly Figure 2.5 shows alternative ways of forming column-to-column connections (marked with purple oval ring in Figure 2.5).

Figure 2.6 provides a list of the different identified zones where precast connections are typically located in a precast or hybrid concrete frame building. In Figure 2.6, the different connection types that are most frequently used in the local and international precast construction industry are listed. In the following part of the report, a typical illustration of all the mentioned connection types will be given as well as a brief description of each of the connections. This will assist as a guide to identify what types of precast connections are available in the market and may assist contractors and designers to help choose the most appropriate connection for the identified connection zones.

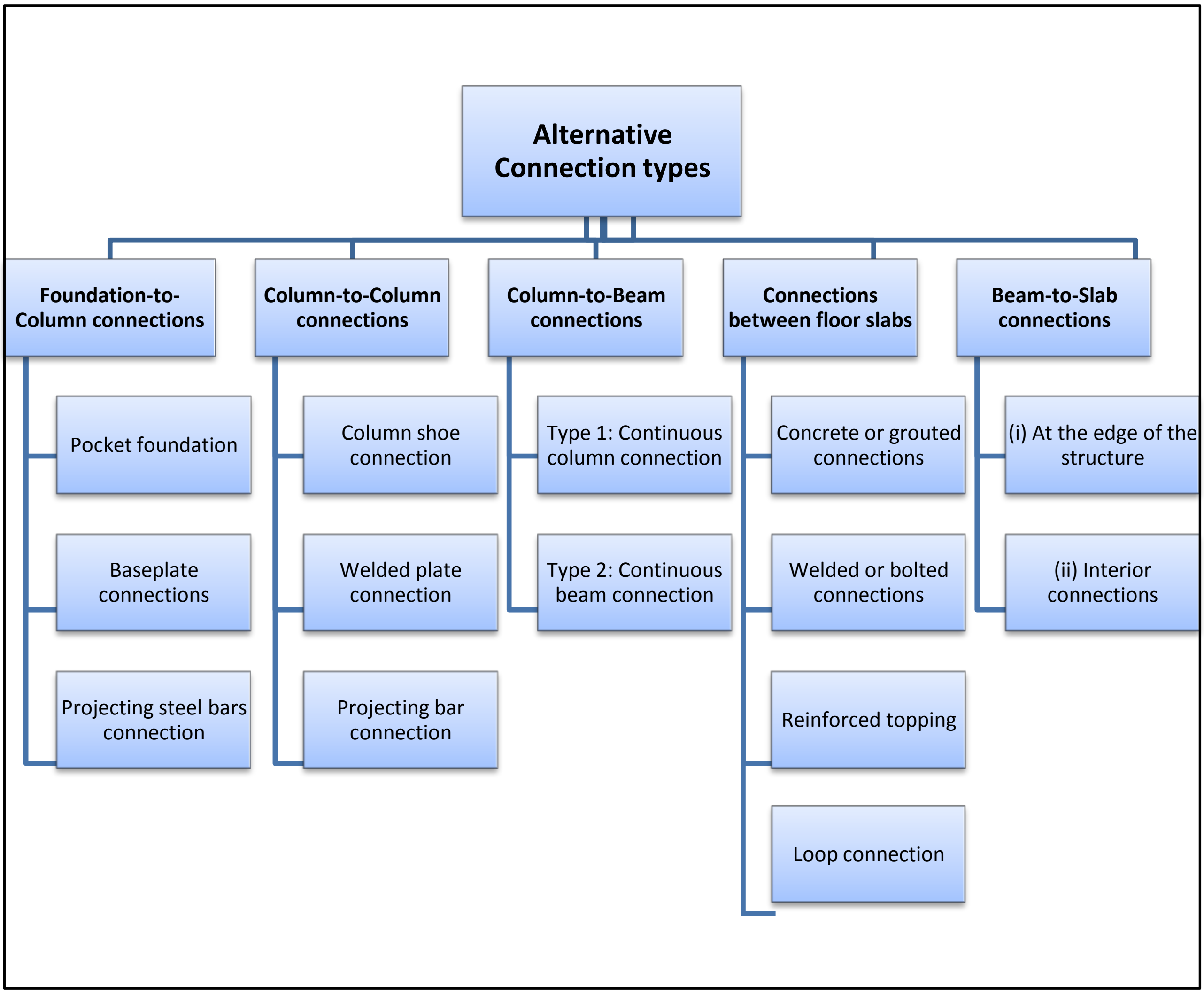



**Figure 2.6 - List of connections that will be discussed**

During the discussion of the connections listed in Figure 2.6, the following should be kept in mind:

- An image of the connection type will be provided,
- An overview as well as positive and negative aspects of the connection type will be given,
- At the end of each connection type, brief conclusions will be discussed,
- At the end of this chapter, summary tables including all the connection types will be given and positive and negative aspects of the specific connection type will be provided.

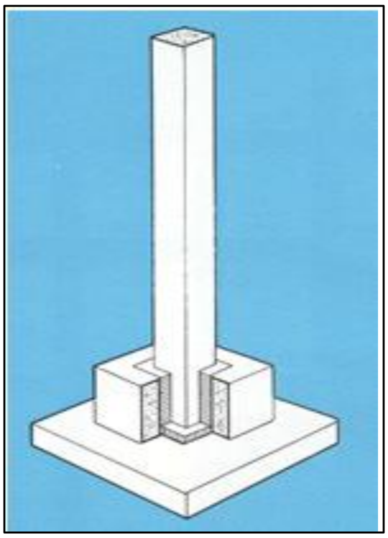
## 2.4.3 - Foundation-to-column connections

The foundation-to-column connections are typically found where a column is to be connected to the foundation of the structure. The three foundation-to-column connections that were identified during the study are:

- Pocket foundation,
- Baseplate connection,
- Projecting steel bar connection

The structural boundary conditions and also the height of the concrete structure will have a major influence on the ultimate choice of selecting one of the foundation-to-column connection types mentioned above. The following part of the section will provide a brief description and will also include general design concerns of the connection under consideration.

### *2.4.3.1 - Pocket foundation*

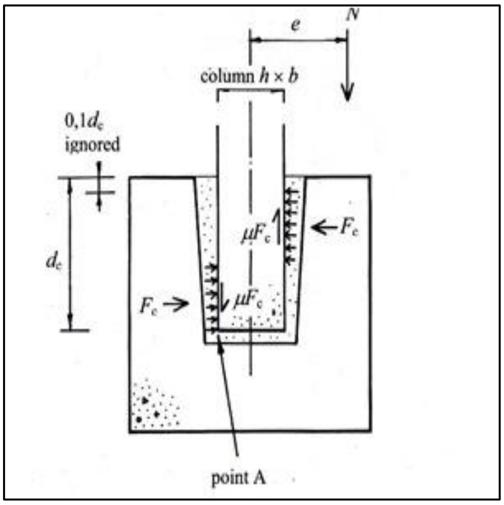


According to (Tovey, A.K. and Elliot, K.S., 1992), some of the characteristics that are commonly associated with precast pocket foundations include the following:

- It is a moment resisting foundation,
- It has minimum tolerance issues, and
- The foundation work should be deeper for the precast pocket to be installed

**Figure 2.7 - Example of a pocket foundation (Walraven 2013)**

From figure 2.7 it can be seen that the connection is fixed at the bottom of the pocket. This ensures stability in the structure and reduces the bracing that are normally required. The column should be embedded into the foundation by at least a distance of 1.5 times the dimension of the column (Tovey, A.K. and Elliot, K.S., 1992). The general problem with the pocket foundation is that if the size of the column becomes too large and it then becomes uneconomical and inefficient to use. Figure 2.8 shows the forces and moments typically acting on the column as well as the pocket of the foundation. The reinforcement in the column and the foundation itself should be able to resist all the forces and moments acting on this connection.




The erection of this connection is less complex, and special attention must be given during the erection period to ensure that the column is perpendicular with the foundation before casting the infill void of the pocket. The casting of the pocket's void must also be strictly monitored to ensure that it is fully compacted and the excess air voids have been removed to avoid these air voids causing a defect in the connection as well as the overall structure. (Tovey, A.K. and Elliot, K.S., 1992)

**Figure 2.8 - Forces working in on the pocket foundation (Menegotto 2006)**

### *2.4.3.2 - Baseplate connection*

The baseplate connection is used as an alternative method and is closely related to connections often used in steel frames. It was found that this connection type is the least troublesome of the 3 foundation-to-column connections being addressed here.

The baseplate connection is used mainly because it provides instant stability to the column and structure itself. The size of the baseplate also depends on the different loads that will be acting on the column as well as the connection at the other end of the column head. (Lewis, A.F.G. and British Precast Concrete Federation 1966)

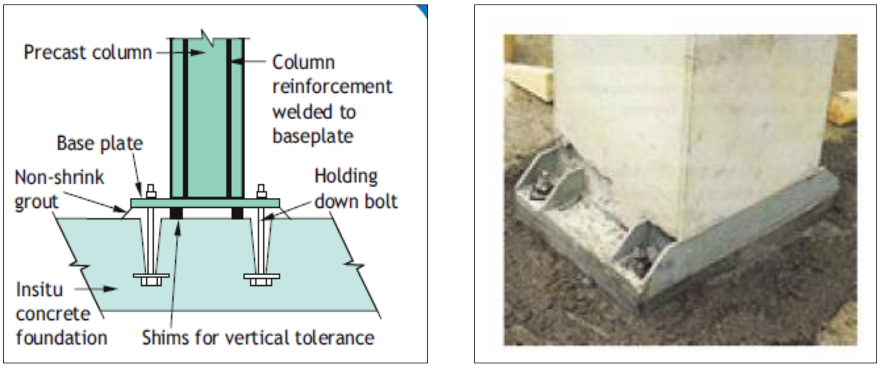



**Figure 2.9 - Some illustrations of precast concrete baseplate (The Shockey Precast Group 2001)**

Figure 2.9 shows a typical baseplate connection and also indicates the different components of the baseplate connection type. During the design process of the base plate it is essential to investigate all the forces that will act in the column in order to find the correct boundary conditions and calculate the size of the baseplate that will be constructed. (Björn 2006)

### *2.4.3.3 - Projecting steel bar connections*

The projecting steel bar connection consists of bars projecting from a foundational footing with precast columns fitting on top of the foundation. The projecting bars are cast into the foundational footing with exact tolerances and the column with fitted holes then perfectly slides into these holes. A typical presentation of the assembly and parts of this connection is shown in Figure 2.10.

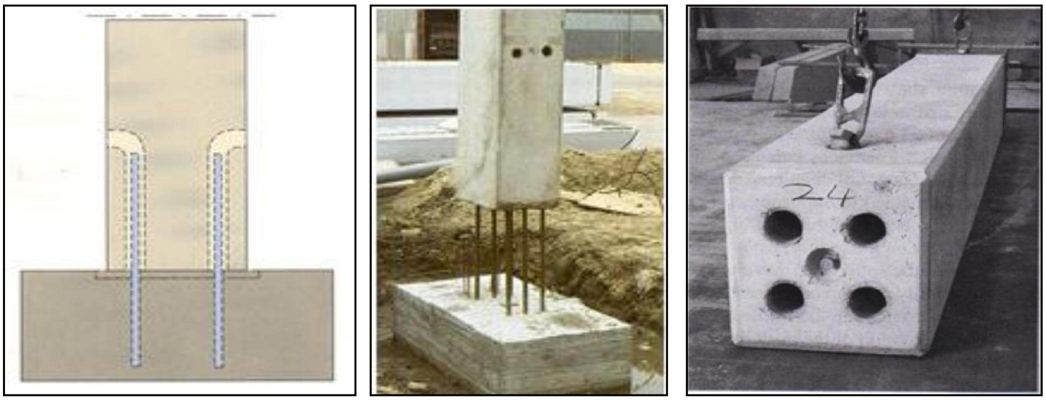



**Figure 2.10 - Illustrations of projecting bar connections (Van Acker 1996)**

According to (Lewis, A.F.G. and British Precast Concrete Federation. 1966) the characteristics of the projecting bar connection are listed as the following:

- Projecting starter bars must be perfectly positioned,
- Erection and assembly must be done carefully to prevent the bending of the bars,
- The connection is concealed,
- Sheaths and the gap under the column must be grouted properly.

The starter bars are cast into the base of the foundation by the contractor given the correct specifications and measurements. The size and also the quantity of the bars are determined by the design engineer to meet the desired structural requirements. The precast concrete columns are then erected on the base with the bars projecting into the dowel tubes provided in the column as shown in Figure 2.10. The voids that are left are filled with grout or mortar to ensure structural continuity is achieved, which is essential for load transfer.

The projecting steel bar connection method is mainly used in medium to high rise buildings where the entire frame of the structure is designed to be braced and pinned connections are required. The problem with these connections are that the erection is rather complex as the bars can easily bend which leads to inaccurate placing of the columns. (Lewis, A.F.G. and British Precast Concrete Federation. 1966)

### *2.4.3.4 - Concluding remarks on foundation-to-column connections*

The typical type of connection that is required between the foundation and precast column mainly depends on the type of boundary condition, either being fixed or pinned. One of the main concerns for this type of connection is thought to be the stability of the column during installation. The column should remain in a perfect upright position during the whole erection period, if this fails to occur it may have detrimental effects on the rest of the precast concrete structure caused by eccentricity and tolerance issues. These problems may be avoided if proper bracing is used to provide sufficient stability until the column is strong enough to support its own weight. The main purpose of this connection is to transfer the applied forces from the column into the load bearing foundation of the structure, thus an appropriate and effective connection is of utmost importance. (FIB - Féd. Int. du Béton 2002)

## 2.4.4 - Column-to-column connections

These vertical connections, also called column splices are very similar to the column-to-foundation connections. These connections poses most of the advantages including the confinement of concrete, thin dry packed joints, continuity of high tensile reinforcement and is easy to manufacture and erect. The disadvantages typically associated with this connection type include: the need for temporary support and high accuracy of projecting bar position. Splices may be made in this way at virtually any level in the frame and are not restricted to column-to-column connections. (Walraven 2013)

Continuity of vertical components is of utmost importance and is usually required to ensure stability of the overall precast concrete building. Therefore it is important to ensure that the connections are done properly to avoid any defects that may occur and may lead to greater problems or even structural failure. Column splices are provided by means of coupling, reinforcement splicing, projecting steel bars, bolting or welding together mechanical connectors that are cast to the separate connecting elements (Tovey, A.K. and Elliot, K.S., 1992). The connections between beams and columns have a major influence on the column-to-column connections as it can either be continuous throughout the whole height of the structure or connected to beams between each storey of the building. The types of column-to-column connections that have been identified include the following:

1. Column shoe connections
2. Welded plate connections
3. Projecting bar connections

The main difficulty with the column-to-column connections is the contact between the joints (Brzev 1994). It is a challenging task to get full contact between the column faces during the construction process.

### *2.4.4.1 - Column shoe connection*

Column shoes are mostly standardized, pre-engineered connections for precast concrete column bases as well as column splices. They can be used to connect precast columns to foundations or to splice precast columns (column-to-column connections). The assembly of the column shoes and anchor bolts provide a moment stiff connection immediately after bolting, thus avoiding the need for bracing. This mechanical connection makes it easy to plumb and level columns by simply tightening or loosening the anchor bolt nuts. (Björn 2006)

When the precast columns are correctly positioned, the joints should be grouted as soon as possible to develop the full strength of the connection and act as a reinforced concrete section. The joint between the column base and structure below should thus be grouted right after the installation has been finished. After the connection has been fixed, the connection parts and grouting will work as a reinforced concrete structure. Column shoes can also be placed separately into the ends of the columns. Figure 2.11 show how these column shoes typically look like.

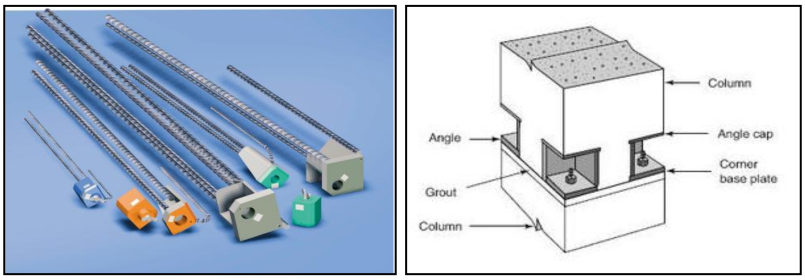



**Figure 2.11 - Illustration of column shoes (Peikko Group 2013)**

The Peikko group (2013) has devised a solution for column splices (column-to-column connections) in the precast concrete construction industry. Columns are usually very large and difficult to handle during the erecting process of the structure because of their length and weight. With the column's large dimensions and weight there is also the possibility of camber occurring in the column (a camber means the column is slightly curved or bent). The column shoe connection that is used by the Peikko Group was initially designed to break up the column in smaller pieces and connect them through use of the column shoe connection. An illustration of this can be seen in Figure 2.12. (Peikko Group 2013)

**Figure 2.12 - Peikko group column shoe connection (Peikko Group 2013)**

The bottom column has anchor bolts that are cast into the one column head, which are projecting to fit into the shoe of the other top column. The shoe can be adjusted to ensure an accurate fit and the connection is then fixed by fastening the nuts and washers to the anchor bolts. The adjustment of the column to the correct position or height is possible. The joint between the two columns is grouted before any additional column loads are applied and this will ensure that the column act as a reinforced concrete structure. This type of connection may be considered as an expensive detail in South Africa due to the steel components required for this connection type. (Peikko Group, 2013)

### *2.4.4.2 - Welded bearing plate connection*

These types of connections are not often used but may be considered as an alternative for a column-to-column connection.  Welding on site are usually not preferred, (Wium, J.A., 2013) making this a rather unpopular connection method in the South African construction industry. Two base plates are cast at the end of each column head and anchored by steel bars that are welded to the plate. The two columns are placed in position and then welded around the perimeter of the plates (Tovey, A.K. and Elliot, K.S., 1992). The welding strength between the two plates must be strong enough to resist all the forces and bending moments that will be acting on the column. Another variation of this connection type can be implemented, where bolts can also be used to fasten the plate as shown in Figure 2.13.

The connection shown in Figure 2.13 is very similar to the column shoe connection except the column shoe is replaced by two steel bearing plates on either side of the columns that will be connected and welded to each other.

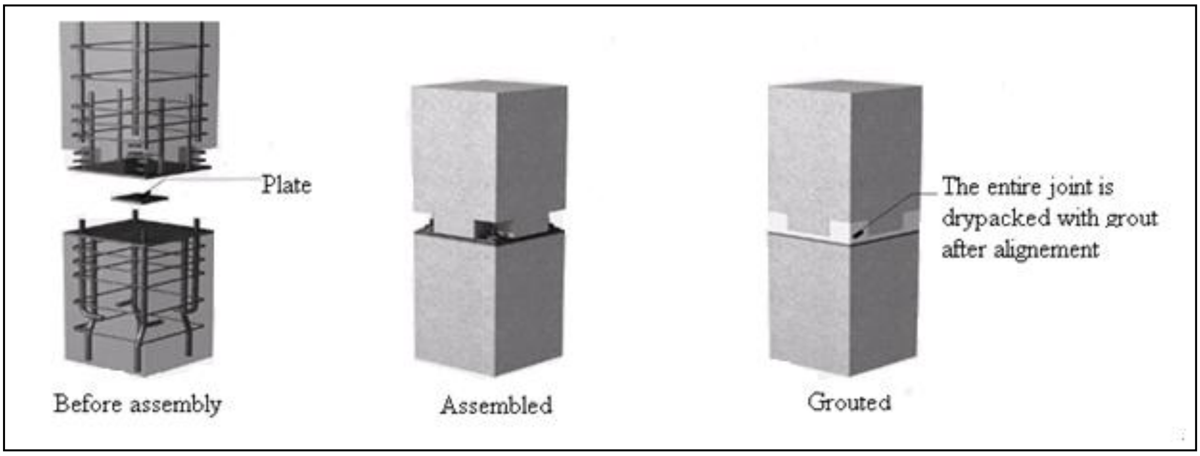



**Figure 2.13 - Graphical illustration of the welded bearing plate connection (Paradigm 2008)**

These types of connections are not often used in the construction industry, mostly because of other available connections that are more common and easier to design and construct. There is also not much information available on this method in the South African industry and thus only a brief overview could be given.

### *2.4.4.3 - Projecting bar connections*

The connection is the most generally used as well as most economical of all the column-to-column connections. The projecting steel bar connection is typically used for two instances including the following two categories:

- Continuous column connections, and
- Single storey columns

The continuous column connection is typically used when the column is required to span over the whole height of the structure. When a continuous column connection is designed, it is usually broken down into two parts. The one end of the connection or column end has inverted sockets, where the projecting bars can fit into as shown in Figure 2.14.

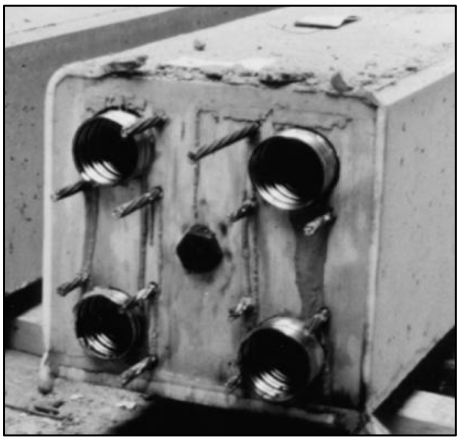


**Figure 2.14 - Corrugated splice sleeve in column (Billig 1955, Brzev 1994)**

The other end of the connection or column head has projecting bars protruding from the column head that will eventually be inserted into the sockets of the other column head. Figure 2.15 gives a basic illustration of the connection and how the two different pieces are inserted. This connection is typically used for connections where there is not any large bending moments and the vertical loads are not applied over the whole column. This connection is frequently being implemented for the top floors of a precast building. (Björn 2006)

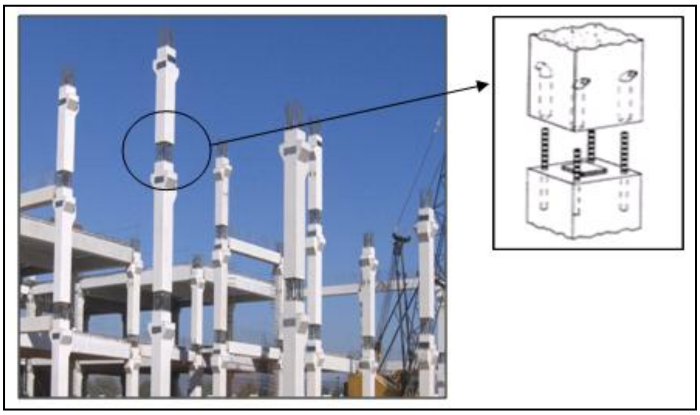


**Figure 2.15 - Projecting bars column-to-column connection (The Shockey Precast Group 2001)**

For single storey columns, a different connection is often used. Figure 2.15 shows how these single storey columns are connected at each level of the building using projecting bars or in some instances normal reinforcement can be used. Continuous beams span over the columns and are connected by using high strength steel bars projecting from the bottom column to the connecting one at the top of the beam. The voids of the sockets are then filled with non-shrinking grout to ensure full force transfer and structural continuity.

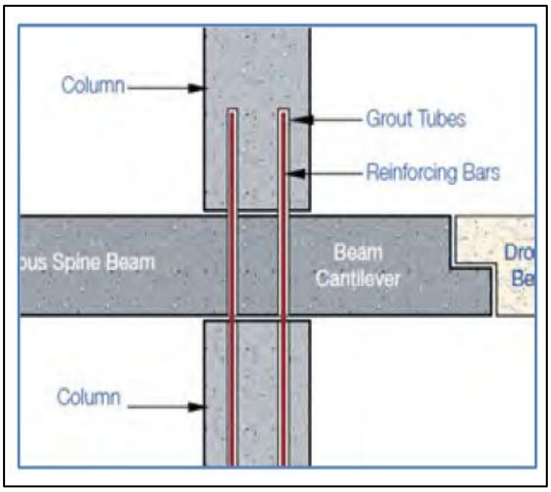



Figure 2.16 shows how the projecting bars are used to ensure a connection between a column and a continuous beam in a precast concrete building.

**Figure 2.16 - Single storey column connection with projecting bars (Björn 2006)**

### *2.4.4.4 - Concluding remarks on column-to-column connections*

The design of the beam and column connections must be done before the column-to-column connections in order to determine if the column connection will be continuous throughout the whole height of the building or if it is connected at each level of the building. (Björn 2006)

The different column-to-column connections that were discussed in the section can be used to create effective column splices. There is however difficulties and concerns when creating column splices in a precast building. The splice should however not affect the strength of the overall column and should not create any problems with stability and tolerance requirements. During construction it should be ensured that the column remains upright and stable and that the contact between the two columns is sufficient before the splice is eventually grouted, bolted or welded.

The column shoe connection from the Peikko Group (2013) is a very effective type of column-to-column connection and it is easy to install and ensures quick erection of the structure’s columns. It may however be possible that this type of connection is too expensive for the South African construction industry and these costs can be seen as a barrier during the decision making process to determine the most cost-effective construction method.

## 2.4.5 - Column-to-beam connections

There is a very wide range of beam-to-column connections, varying in complexity, cost and structural behaviour. The connection between the beams and columns basically depends on the specific magnitude and nature of the applied loads and also the boundary conditions identified at the connection zones.

The (European Commission - Joint research centre 2012) conducted that this type of connection contains a very distinguished sub-division that can be given as the following:

- **<u>Type I</u>:** The vertical member is continuous, and horizontal components are framed onto it. This is termed a “beam end” connection.
- **<u>Type II:</u>** The vertical member is discontinuous and the horizontal components are either structurally continuous or separated across the junction. This is termed a “column head” connection.

These two cases will be discussed separately because of the differences in structural behaviour. Other alternative connections that are being used in the international precast industry have been investigated to provide solutions for complex connections or to enlarge the variety of the beam-to-column connection types.The two different types of beam-to-column connections (Type I and Type II) is shown in Figure 2.17.

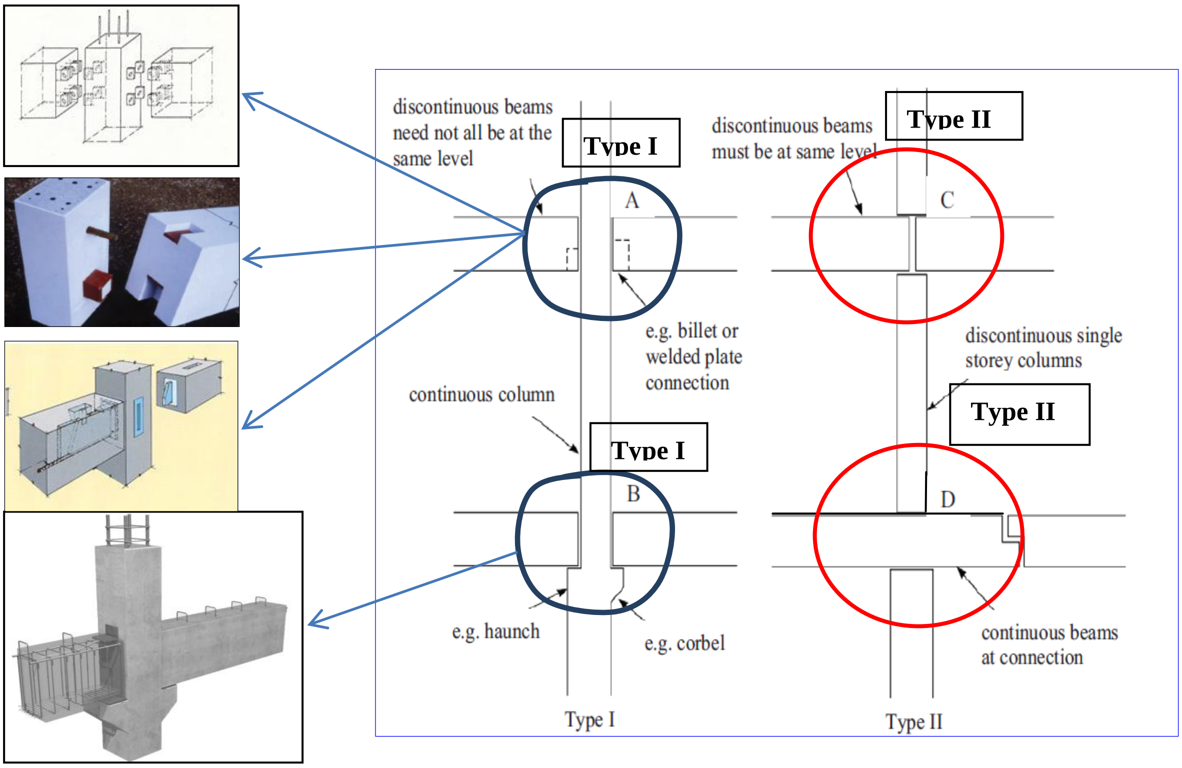



**Figure 2.17 - Generic types of Beam-Column connections (Task Group 6:2: A.Van Acker et al 2010)**

### 2.4.5.1 - Type I: The continuous column connection

The continuous column connection is most frequently required when heavy loads need to be supported or in some cases where long-span beams are being used. The continuous column connection normally consists of two types of connections and this is also illustrated in Figure 2.17:

- Type I can either be a steel billet connector (or any other steel connector), a welded plate connection or a hidden corbel connection, typical examples of these three connections is also shown in Figure 2.17.
- Type I can also consist of a continuous column that has a built in column corbel situated at the levels where the beams will be connected, this is also shown in Figure 2.17.

A corbel is a concrete structure extending out of a wall or column to carry a projecting element. In this case the corbel is built extending out of the column to carry the projecting beam. The corbel connection must be able to prevent spalling, cracking, fracture etc. The use of corbels are sometimes restricted in structures where it is required that they must stay within the dimensions of the beams in order to reduce the total height of the structural zone. (Irish Precast Concrete Association (IPCA) 2007)

For the welded plate connector, a thin plate is anchored to the beam using large diameter rebar, typically 25 mm high tensile or depending on the size of the beam (The Shockey Precast Group 2001). The plate is site welded to a projecting steel billet and expansive infill concrete is used to fill the gap between the column and the beam. The hidden corbel connection is a connection detail created by a Norwegian company called Spencon Systems (2012). The corbel is a structural insert that is separately cast in to the column and the beam and assembled on site.

The steel billet connector as well as the hidden corbel connection is rarely used in the construction industry, mainly because it is very expensive and designers in the South African construction industry don’t always possess the necessary knowledge and experience with this type of connection method. (Angelucci 2014)

### 2.4.5.2 - Type II: The continuous beam connection

The continuous beam connections, seen in Figure 2.18 are used when the beam is required to be continuous over a support, usually when it is forming a cantilever and therefore it is typically designed as a fixed moment to provide resistance. The beams are placed on a mortar joint on top of the column with projecting bars protruding from the column that fits into sleeves through the beam and lastly the sleeves are filled with grout to provide stability in the vertical direction. These joints are formed by seating the components on steel shims or neoprene pads and filling it with a dry-packed mortar. (Elliot 2002)

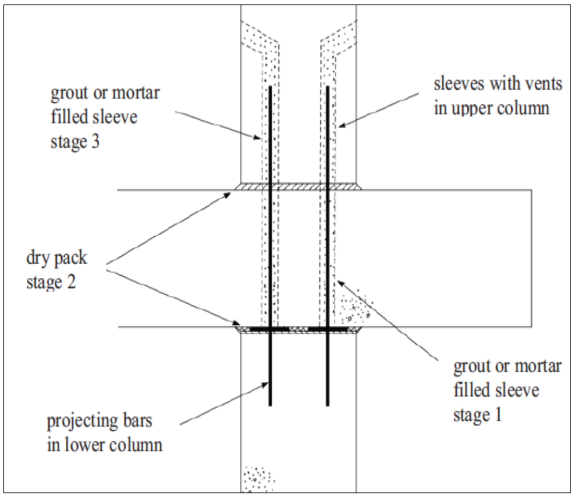



**Figure 2.18 - Illustration of continuous beam connection (Van Acker 1996)**

The beams may in some instances also be cast in-situ depending on the nature of the structure. Figure 2.18 shows the continuous beam connection, with projecting bars embedded in the lower column of the connection.Unlike the discontinuous beam end connections the column head connection may be designed with, or without contributions from floor slabs and tie steel. (New Zealand Concrete Society and the New Zealand Society for Earthquake Engineering 1999)

### *2.4.5.3 - Concluding remarks on the column-to-beam connection*

The two connections that were investigated are typical connections used for beam-to-column connections either for continuous or non-continuous columns. Each connection has different characteristics and different functional parameters that usually depend on the geometry of the concrete structure. The concrete corbel can be used in most instances where the column is continuous, but if the client or engineer is not satisfied with the corbel forming part of the column (architectural, structural, aesthetics etc.) the beam can also be connected using a notch in the column anchored by the use of ties which projects into the column.

A very important aspect to consider for this type of connection is ensuring sufficient reinforcement at the support. This aspect is considered important because adequate load transfer is required to resist the different forces acting on the connection. The grout that is filled in the connection shown in Fig. 2.18 should be monitored carefully to avoid any defects that may have a detrimental effect on the strength of the connection as well as the overall structural stability. The other barrier that was encountered during the investigation of this connection is limited space (corbel connection) and column eccentricity due to the overlapping of the reinforcement in the column itself.

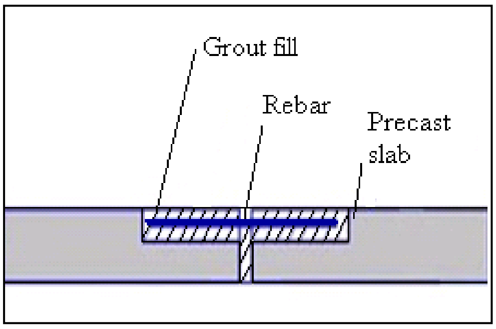
### 2.4.6 - Connections between floor elements (floor-to-floor)

Precast floor slabs including hollow core slabs and floor plates (also known as half-slabs) are normally designed and constructed as simply supported and one-way spanning. The detailing of floor systems must be carefully managed and done in accordance to strict design specifications. There must be sufficient shear connections between the connections of the floor components in order to create monolithic action of the floor. A monolithic floor is a concrete slab which is cast as a single continuous slab of concrete, without any casting or control joints (Homewyse 2010)

The precast concrete floor slabs are usually designed according to the following criteria: the reinforcement in the slab is mostly in the forms of rebar or pretension tendons and is positioned in the bottom of the units to give a sagging (positive) moment of resistance (Concrete Manufacturers Association (CMA) 2002). Top reinforcement is sometimes provided in hollow core units to protect it against flexural cracking due to handling, and to cater for shrinkage, creep and thermal effects.

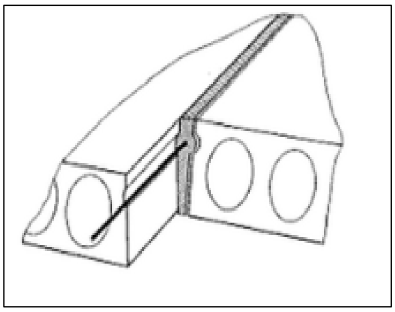
The joints or connections that are created between adjacent precast floor elements are usually not heavily loaded. The connection should however require the capacity to resist differential deflection and also attain the capacity to resist forces acting on the floor in the horizontal connections (Concrete Manufacturers Association (CMA) 2002). The connections between floor slabs can be achieved through various connection types and the most popular connections have been identified as the following:

(a) Concrete or grouted connections
(b) Welded or bolted connections
(c) Reinforced topping
(d) The loop connection



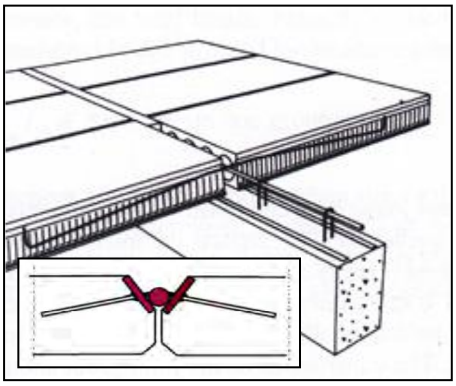

**(a) -** This is a typical figure of a grouted or concrete connection between solid floor slabs. In this case the grout or concrete fill has some additional rebar inserted to add additional strength to the connection.

**Figure 2.19 - Concrete or grouted connection with rebar (Mishra 2012)**



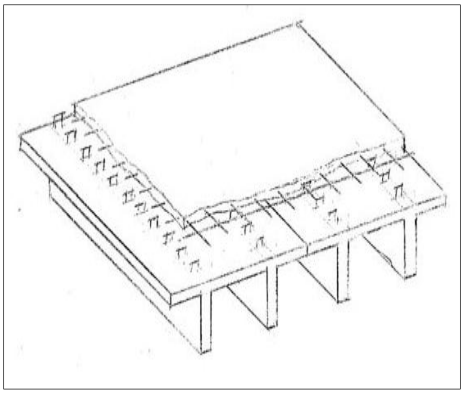
**(a) -** This is a typical floor-to-floor connection found in the interior part the structure. This connection is mainly designed to withstand the shear forces between the interconnecting floor slabs of the building (this is however a variation of the grouted connection available in the martket). This connection is regularly used for precast hollow core slabs.

**Figure 2.20 - Shear joint between floor slabs (FIB - Féd. Int. du Béton 2002)**



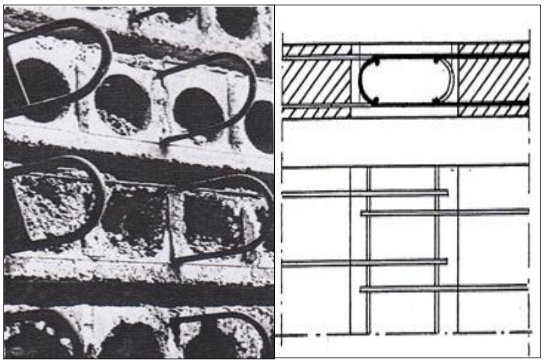
**(b)** – This figure presents a picture of a welded or bolted connection between two prefabricated floor slabs. These bolted connections usually include the use of pre-tensioned floor slabs too, as shown in Figure 2.21. This connection can be used for either solid floor slabs or hollow core slabs.

**Figure 2.21 – Welded or bolted connection (Walraven 2013)**



**(c) –** Figure 2.22 shows the detail of a roof or floor slab made of precast elements interconnected by a concrete topping cast over the upper surface. The concrete topping, with its reinforcing steel mesh, provides a monolithic continuity to the floor that involves the precast elements if properly connected to it.

**Figure 2.22 – Reinforced topping (G.S. Cheok, W.C. Stone, S.K. Kunnath 1998)**



**(d)** – Figure 2.23 shows a picture of a typical loop connection between floor slabs, it also shows how the loops of the prefabricated floor slabs are interlocked with each other. The gap between the loops is usually reinforced with rebar and filled with concrete or non-shrinking mortar.

**Figure 2.23 – The floor element loop connection (FIB - Féd. Int. du Béton 2002)**

### *2.4.6.1 - Concluding remarks on connections between floor slabs*

The precast floor units must be connected in such a manner that it certifies acceptable overall capacity of the entire precast or hybrid concrete structure. The interaction and connection of the precast floor slabs as well as the supporting structure can be critical to the overall structural design and integrity. The floor slabs provides stability and robustness to the overall concrete structure, making the design and connections between floor slabs an important part of the structure. Various concerns have been identified when considering the design of the floor structure or elements of the floor structure. These concerns include the following:

- **i.** Considering the load bearing capacity of the floor,
- **ii.** Taking into account the overall structural integrity,
- **iii.** The distribution of the identified horizontal forces through diaphragm action, and
- **iv.** The transverse distribution of shear forces between the adjacent precast floor units

It is thus important to understand that not only bending moments and shear force capacity of the floor units should be considered but the total coherence, including the connections of the overall floor unit. (Irish Precast Concrete Association (IPCA) 2007)

## 2.4.7 - Beam-to-slab connections

The beam-to-slab connections have already been partially identified in section 2.4.4 of the report where connections between precast floors have been discussed. This is usually the case because the precast floor elements are mostly supported by means of beams and, or columns, thus most of the floor connections are also located at the support including the beam-to-slab connection.

Beam-to-slab connections can however be divided into two different types, including the connections at the edge of the structure and the connections situated in the internal parts of the building. Both these different connection types form a fundamental part of the precast concrete building. The connections between the slabs and the beams of the structure are generally done by making use of ties and reinforcement or may include variations of simply supported units. This ensures that the applied loads are transferred adequately and also ensures structural continuity. The prefabricated floor slabs (such as hollow core floor slabs) doesn't usually contain projecting bars that can be tied or grouted to the neighbouring elements, therefore friction (simply supported connection) between the elements can be created to ensure that the structural integrity and overall continuity remain intact. This friction can be created by grouting the ties into the hollow voids situated in the hollow core floor slabs or making use of bearing pads or strips. There will however be distinguished between beam-to-slab connections at the, (i) edge of the structure and (ii) internal parts of the structure during the next part of the section.

### *2.4.7.1 - Beam-to-slab connection at the edge of structure*

There is two fundamental design approaches to consider when analysing the beam-to-slab connection at the edge of the structure:

**(a) –** The first design is where the floor is simply supported on the beam, usually by means of a bearing pad or another concrete element (either precast or in-situ). The floor slab is not interconnected to the beam and the beam mainly acts as a support structure for the floor slab. In this case no special reinforcement is required for the connection or joint. This connection is mostly preferred for low rise buildings, not more than 2 to 3 storeys high.

According to Jaco Carstens (Topfloor, 2014), the South African building industry have been making more use of precast hollowcore slabs. The popularity for hollow core slabs is mostly due to the fact that it doesn't include complicated connection details and is very quick and easy to install. This type of precast floor slab is also designed to be simply supported either on a structural beam (beam-to-floor connection) or load bearing masonry walls (very popular in the building industry of South Africa). A typical presentation of a simply supported floor slab, including hollow core is shown in Figure 2.24.

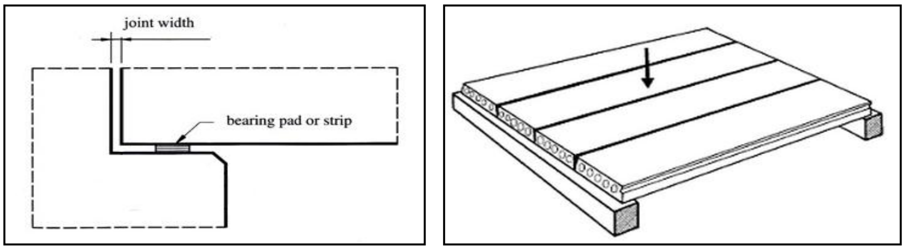



**Figure 2.24 - Illustration of a simply supported beam-to-floor connection (Walraven 2013)**

**(b) –** The second connection criteria for the beam-to-slab connection at the edge of a structure can be described when the floor is firmly connected to the beam and the beam is considered as an integrated part of the floor. This connection is usually created by means of ties and reinforcement between the two elements. There is however an alternative method available that makes use of a bolted connection type shown in Figure 2.25 (a). Figure 2.25, (b) shows how a hollow core floor slab can be connected to the beam by making use of ties and reinforcement, and eventually filling the voids with concrete or mortar.

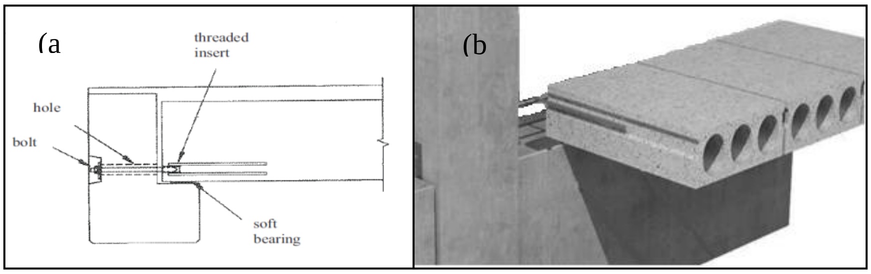



**Figure 2.25 – Beam-to-slab connection at the edge of the structure (Mishra 2012)**

### 2.4.7.2 - Beam-to-slab interior connections

When describing the connection as an interior connection it actually implies that the connection is located in the inner dimensions of the building. The interior beam-to-slab connections are most commonly found where precast floor slab ends are connected to an interior beam. Interior beam-to-slab connections can also be formed with the slab ends resting on an internal concrete or masonry wall, but for the purpose of this study only the connections to beam elements will be considered.

The connection or tying of the connections normally differs from the connections found at the edge of the structure because the connections are continuous over the support of the beam. Hollow core slabs and other forms of composite beams are some of the beam-to-slab connections that can be used for this type of connection.

#### *(i) - Hollow core slabs*

When hollow core slabs are manufactured, there are usually some openings provided in the top flanges of the floor slabs. These openings are left to make room to place reinforcement and concrete to provide the necessary stability or composite action of the precast floor slabs at the slab-to-beam connection area. Figure 2.26 shows the openings created in the top flange of the hollow core slab.

**Figure 2.26 – Openings created for reinforcement in hollow core slabs (Nakano, Matsuzaki 1996)**

The ties are either placed in the longitudinal joints in the hollow core slabs or by means of voids found in the slab. The ties are continuous over intermediate supports and anchored to transverse ties at the edge supports. (Concrete Manufacturers Association (CMA) 2002) Figure 2.27 shows two different alternatives of creating beam-to-slab connections using hollow core slabs.

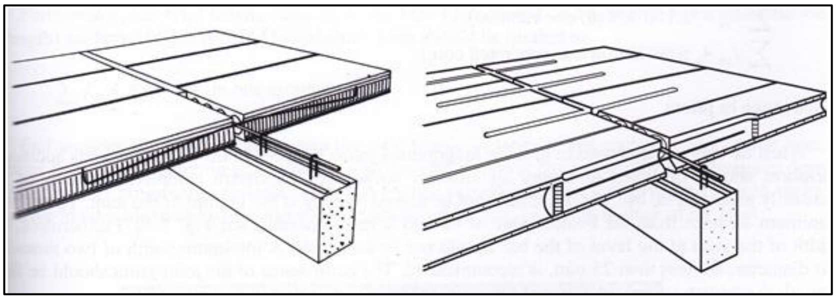


**Figure 2.27 – (a) Longitudinal joints, (b) Anchored in the voids (Walraven 2013)**

The anchoring of the floor units at the beam supports can be done by one of the following ways:

- The anchoring must be directly between the beam and the concreted voids found in the hollow core slab,
- Overlying reinforcement between the loops, or
- Jointing the longitudinal ties with the loops.

The fixed length of the reinforcing bars can be taken as one anchorage bond length and the openings at the flanges are designed to be large enough to ensure that the concrete filling can be compacted sufficiently to ensure sufficient strength.(Concrete Manufacturers Association (CMA) 2002)

### *(ii) - Composite beams*

The design purpose of a composite beam connection is to increase the section modulus of the structure and also to provide additional strength. Varying design procedures for this kind of connection has been given by (Elliot 2002) as:

- Only the in-situ concrete that fills the joint above the composite beam is taken into account
- When there is a structural topping on top of the floor, the in-situ concrete used to fill the joint as well as the structural topping must be taken into account for the composite beam action
- The floor slabs act as flanges of the beam

Figure 2.28 demonstrates the composite action of the beam-to-slab connection with a structural topping.

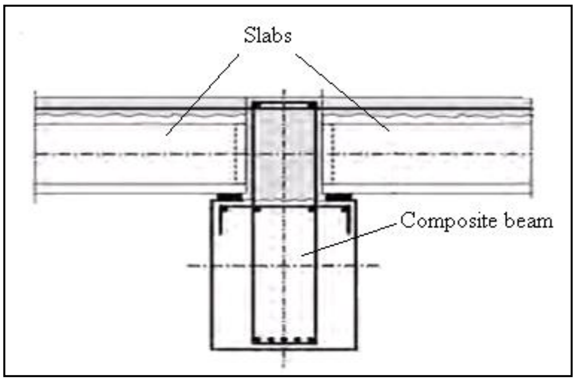



**Figure 2.28 – Composite beam beam-to-slab connection (FIB - Féd. Int. du Béton 2002)**

## *2.4.7.3 - Concluding remarks on beam-to-slab connections*

The load combinations that will be applied to the structure as well as the connections of the floor elements are an essential consideration when choosing the most appropriate beam-to-floor connection type. Another important determining factor for this specific connection type is the placing of the reinforcement, mainly because it varies for a connection found at the edge of the structure and connection that is a continuous interior connection. The purpose and use of the structure, e.g. high rise building, parking lot, school etc. will also have a large effect on the type of connection that will be chosen to be designed and constructed, at the edge of the building as well as internally.

### 2.4.8 - Conclusions on different precast connections

It can be seen from the list of connections discussed in section 2.4, that connections between precast concrete elements occur in varying different connection zones, forms, sizes, restraints, designs etc. The connections that were discussed have not all been previously used and introduced in the South African construction industry. There is however several engineering companies that are more frequently incorporating the use of precast concrete into their construction projects, thus creating more exposure for development of new and older type of precast connections.

As a conclusion for the different types of connections found in different connection zones located in a typical  precast or hybrid concrete building, a list have of all the mentioned connection types have been compiled and specified in Tables 2.2 to 2.8. The tables include all the type of connections that have been discussed and identified between the precast elements listed in Section 2.4 of the report. The tables includes a typical picture of how the connection looks like and also provides positive and negative aspects that are most commonly associated with the specific connection type. The summarised information, including the positive and negative listed aspects may act as a guideline to assist contractors or designers to choose appropriate connections for a specific type of precast or hybrid concrete building. It does however not provide explicit design guidelines for designers or contractors, but may offer valuable assistance in decision making for these mentioned parties.

The connections that have been identified and listed in this chapter are typical connections found between precast elements located in precast or hybrid concrete frame buildings. These connection types will be used and referred to throughout the extent of report. The connections that were discussed during sections 2.4.3 – 2.4.7 of the chapter, was found to be the most popular connections that are frequently being used in the local as well the international precast concrete construction industry.

**Table 2.2 – Foundation-to-Column connection types**

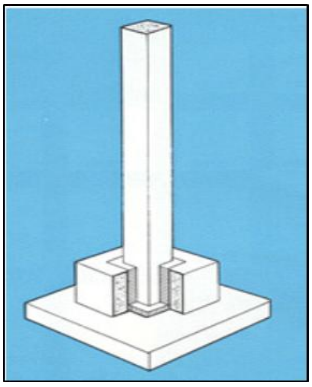
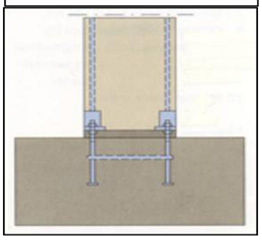
| Foundation-to-Column connections | | | |
|---|---|---|---|
| | | **Positives** | **Negatives** |
| **Pocket foundation** |  | - Moment resisting foundation<br>- Connection has minimum tolerance issues<br>- The connection is fixed to ensure stability<br>- Erection is quick and easy | - Foundation work is often deep for precast pocket to be inserted.<br>- If the size of the column becomes too big, it becomes uneconomical to use.<br>- Column must be perfectly straight before erecting and casting the void of the pocket. |
| | | **Positives** | **Negatives** |
| **Baseplate connection** | <br> | - Provides instant stability to the column and structure itself<br>- Least troublesome of foundation-to-column connections<br>- Used by engineers as an alternative method for this type of connection<br>- Similar to steel baseplate uses in steel frame construction | - Very small tolerances are allowed when the base bolts are installed<br>- Essential to analyze load transfer of column onto the baseplate as well as the boundary conditions required for connection of footing<br>- Can become too large when the columns dimensions become big. |
| | | **Positives** | **Negatives** |
| **Projecting steel bars connection** |  | - Connection is solid and concealed<br>- Designed to be braced and thus pinned connections are needed | - Projecting starter bars must be perfectly positioned<br>- Erection must be done carefully to prevent the bending of the bars<br>- Concerns with filling the voids effectively |

**Table 2.3 - Column-to-Column connection types**

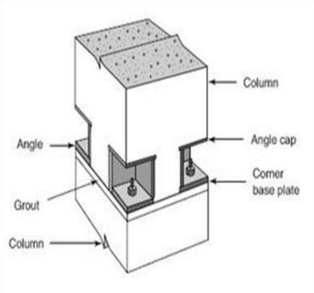
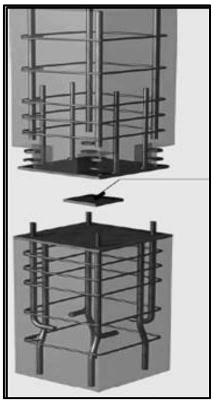
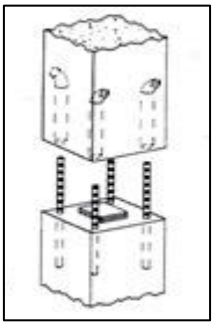
| Column-to-Column connections (column splices) | | | |
|---|---|---|---|
| | | **Positives** | **Negatives** |
| **Column shoe connection** |   | - The column shoes and anchor bolts provides a moment stiff connection thus avoiding the need for bracing<br>- This connection makes it easy to plumb and level columns by simply tightening or loosening the anchor bolt nuts<br>- The column shoe connection was initially designed to break up the column in smaller pieces (column splices) | - With the column's large dimensions and weight there is also the possibility of camber occurring in the column<br>- High accuracy and workmanship is required during installation<br>- May be considered as an expensive detail in South Africa due to the steel components |
| | | **Positives** | **Negatives** |
| **Welded plate connection** |  | - This connection is very similar to the column shoe connection except the column shoe is replaced by two bearing plates on either side that is welded together. | - These types of connections are not often used but are an alternative method<br>- Welding strength between the two plates must be strong enough to resist all the forces and bending moments that will be acting in the column<br>- Welding on-site in South African industry is not preferred. |
| | | **Positives** | **Negatives** |
| **Projecting bar connection** |  | - The most generally used as well as most economical of all the column-to-column connections<br>- Connection is typically used for connections where there is not any large bending moments and the vertical loads are not applied over the whole column | - High accuracy in design and construction<br>- Small tolerances is allowed<br>- Not suitable for high rise concrete structures. More effective for single storey columns. |

**Table 2.4 – Column-to-Beam connection types (Type 1)**

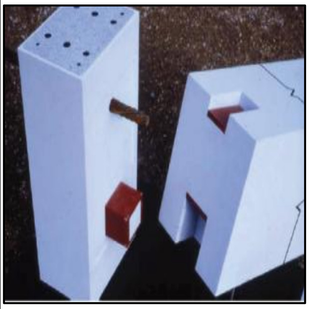
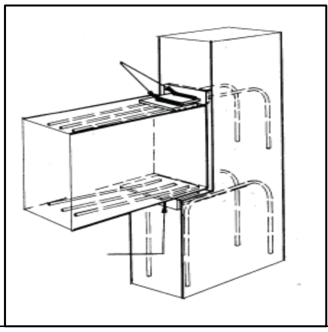
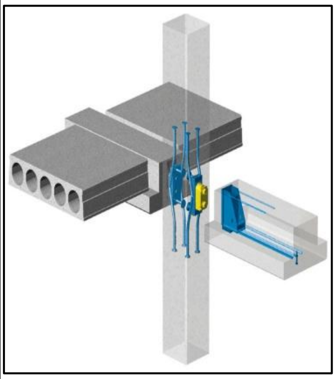
| Column-to-Beam connections | | | | |
|---|---|---|---|---|
| | **Steel billet connection** |  | **Positives**<br>- In many cases connections that have been designed as pinned joints, demonstrated considerable strength and stiffness.<br>- Easy to assemble and erect | **Negatives**<br>- Not very popular in the South African market<br>- Too expensive for the local market<br>- Mostly simply supported, moment transfer may be problematic |
| **Type I: Continuous column** | **Welded plate connection** |  | **Positives**<br>- Longitudinal forces are constrained<br>- The steel plate, which is welded to the column can slide in the 'tray' in order to prevent negative moments from developing | **Negatives**<br>- This solution is only possible in case of smaller forces<br>- More popular for construction with steel elements, e.g. columns and beams<br>- Welding on-site is not preferred in SA |
| | **Hidden corbel connection** |  | **Positives**<br>- Offers superior adjustability at site, enables straight precast mould<br>- Can achieve high connection resistance even with slender cross sections<br>- Speed up construction time | **Negatives**<br>- Expensive connection to install<br>- The dimensions of the beam and connection desires very careful design (small tolerances)<br>- Not popular in local construction industry (expensive connection detail) |
| | **Corbel connection** |  | **Positives**<br>- Designed using the strut and tie method<br>- Can provide a strong support system for large beams<br>- Several guides available for corbel design, meaning it is a very popular design method | **Negatives**<br>- This connection can be visually intrusive<br>- It reduces headroom locally at the column head<br>- Creates much more complex mould requirement |

**Table 2.5 - Column-to-Beam connection types (Type 2)**

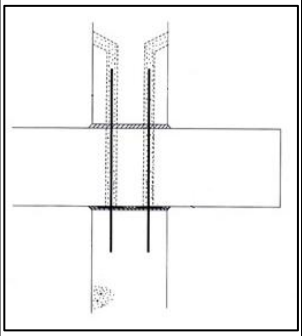
| | | | **Positives** | **Negatives** |
|---|---|---|---|---|
| **Type II: Continuous beam** | **Beam is required to be continuous over a support** |  | - This connection is used mainly in portal frames<br>- This connection provides stability in the vertical direction | - If beam span become too large it is difficult to install<br>- This connection can become rather complicated when the connection area is designed with additions to compensate for floor slabs and tying steel |

**Table 2.6 - Connection types between floor slabs**

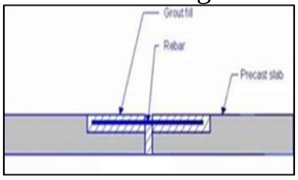
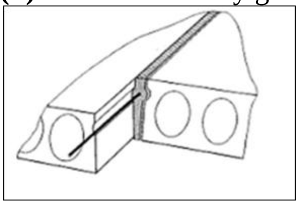
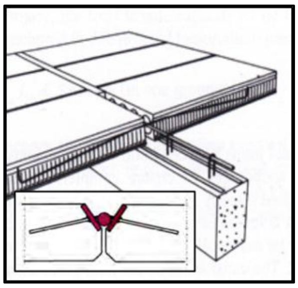
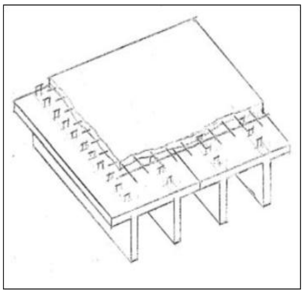
| Connections between floor slabs | | | |
|---|---|---|---|
| | | **Positives** | **Negatives** |
| **Concrete or grouted connections** | **(a)** – Concrete grout with added reinforcing   **(b)** – Slabs with only grout  | - The grout between the floor slabs creates a shear connection<br>- Very easy connection to install<br>- Grout with additional reinforcement, creates stronger connection | - This connection may not be sufficient in strength for high rise structures<br>- Important to consider thermal movements of the slabs, this may affect the grouted joint<br>- Curing of the concrete grout is important |
| | | **Positives** | **Negatives** |
| **Welded or bolted connections** |  | - Bolted or welded connections usually include the use of pre-tensioned floor slabs<br>- Can be used for solid or hollow core floor slabs | - Not very popular connection for floor slab connections<br>- More complicated to install than other floor connections<br>- Installation process requires skilled labour |
| | | **Positives** | **Negatives** |
| **Reinforced topping** |  | - Concrete topping, with its reinforcing steel mesh, provides a monolithic continuity<br>- Inclusion of a continuous reinforcing mesh on a precast slab will increase the degree of restraint provided by the slab. | - Expansion joints should be included between floor slabs to avoid floor slabs forming cracks<br>- Structural topping needs to be cured to reach full strength |
| | | **Positives** | **Negatives** |
| **Loop connection** |  (Gaps are filled with concrete of mortar) | - The loop - connection is able to transfer tensile forces, bending moments and shear forces<br>- Interlocking of loops provides great connection strength<br>- It is used for solid slabs where continuity is demanded | - The connection can fail due to rupture of the reinforcing bars, crushing or splitting of the joint concrete in the plane of the overlapping loops<br>- Transverse reinforcement is necessary for structural behaviour |

**Table 2.7 – Beam-to-slab connection types (at the edge of the structure)**

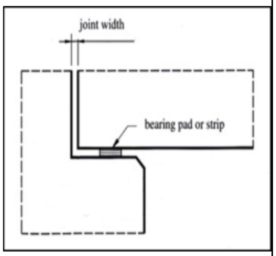
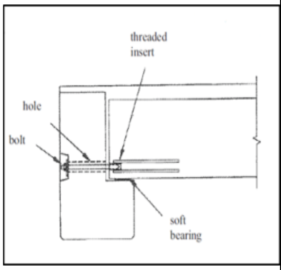
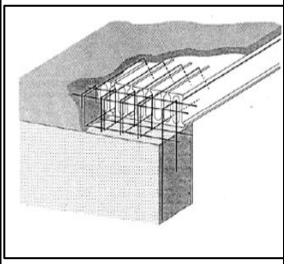
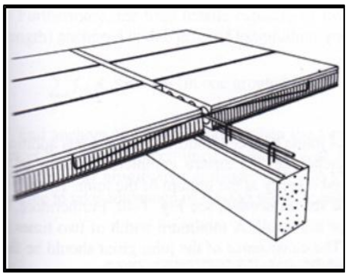
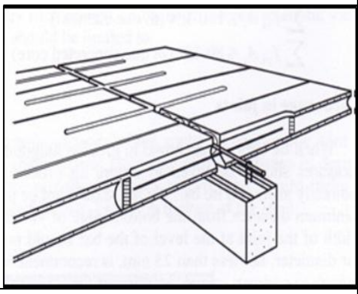
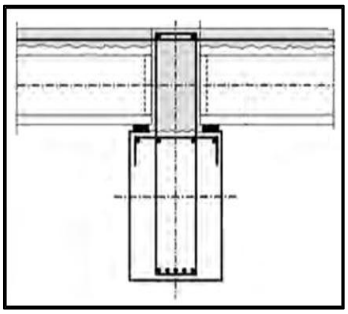
| **Beam-to-Slab connections** | | | | |
|---|---|---|---|---|
| **(i) At the edge of the structure** | **Simply supported beam (Mostly hollow core slabs)** |  | **Positives** | **Negatives** |
| | | | - Very quick to install and construct<br>- Popular for use of flooring<br>- No special reinforcement is required<br>- Simply supported connections have less redundancy and require more attention to tolerances | - This connection is mostly used in structures where there are only 2 or 3 storeys<br>- Designer must be aware of the need to detail the end supports for crack control<br>- Designer should also be aware of torsional effects and probable eccentric loading on the edge of the beam |
| | **Bolted connection** |  | **Positives** | **Negatives** |
| | | | - The floor is firmly connected to the beam and the beam is considered as an integrated part of the floor<br>- Has most of the same aspects than the simply supported beam | - Not very popular connection and rather expensive<br>- Installation can become complicated<br>- Designers should compensate for pull out shear of the bolt |
| | **Ties and reinforcement** |  | **Positives** | **Negatives** |
| | | | - The floor slab becomes an integrated part of the structure<br>- Acceptable for construction in seismic areas | - Requires more design aspects<br>- Lengthens the construction time<br>- More costly than other connections of this type |

**Table 2.8 - Beam-to-slab connection types (interior connections)**

| | | | Positives | Negatives |
|---|---|---|---|---|
| **(ii) Interior connections** | **Hollow core slabs** | (a) – Longitudinal joints<br><br>(b) - Anchored in the voids<br> | - Transverse shear steel, facilitates the transfer of the forces between the slab and the beam<br>- The open core of the hollow core slab enables full composite actions with the support beam to be developed.<br>- Anchorage provides extra strength and stability over the beam support | - Hollow core slabs, in certain conditions can only carry a pre-determined load. If these loads become too large the connections may fail<br>- The connection design must be done accurately to ensure structural integrity of the building |
| | | | **Positives** | **Negatives** |
| | **Composite beam connection** |  | - The design purpose of a composite beam connection is mainly to increase the section modulus of the structure<br>- The floor slabs can act as flanges of the beam, provide sufficient strength and stability for this type of connection<br>- Used when hollow core slabs are not sufficient | - More effort and time goes into the design and construction of this method<br>- This type of connection is not that popular in the building industry |

## 2.5 – Chapter Conclusions

This chapter provides an outline and reference on the topic of precast concrete elements and precast concrete connections, and this chapter will continually be used as reference during the remainder of the report. The basic considerations and description of precast connections given in section 2.3 of the chapter, provides an accurate inclusion of appropriate guidelines that are required to design and construct efficient and structurally sound precast concrete connection types. The different types of connections that were identified and discussed during this chapter are connections that are frequently being implemented in the local as well as the international precast concrete industry.

For every connection zone that was identified (e.g. column-to-beam, column-to-column etc.) there were 3 or more connection types identified and listed. Every connection type is unique and contains its own significant positive and negative aspects for the design and construction processes (provided in Tables 2.2 to 2.8). The listed connection types make use of various connection methods and components, that include components such as; non-shrink grout, bolts, reinforcement bars, welding, structural steel inserts, bearing pads, in-situ concrete fills etc., thus providing the designer and contractor with a variation of types and forms of precast connections. It was however identified that certain connection types only provide solutions for applicable connection areas or elements located in the precast structure. Using this information it was identified that certain precast frame types or precast structural systems make use of specific connection types, thus the inclusion of Appendix A, where different precast structural systems were identified and preferred connection types were also listed.

During the literature study and identification of different connection types, it was found that there are various aspects to consider during the design and construction phase of precast connections. This study will focus on the implementation and preferences of precast connections in the South African construction industry. To obtain valuable information on the design and construction of precast connections in the local construction industry a questionnaire was formulated for a survey amongst participants in the engineering and construction industry of South Africa. Chapter 3 will thus include the results from the questionnaires that were handed out to participants in industry. The answers from the questionnaires will help identify typical problems and concerns encountered by consultants and contractors in terms of precast concrete and precast connection design and construction.

# CHAPTER 3 – INDUSTRY SURVEY'S

Figure 3.1 presents the contents of this chapter:

**3.1 - Survey boundaries and limitations**

**3.2 - Survey results obtained from participating**

**3.3 – Survey results obtained from participating**

**3.4 – Comparison between responses from Contractors and Consultants**

**3.5 - Chapter Conclusions**

**Figure 3.1 – Chapter 3 contents**

Following the discussions and results that were given in the Literature study (Chapter 2), it was found that there is a lack of participation and information available on the design and construction of precast concrete in the South African civil engineering industry. To address this problem, it was established that the best way of obtaining information of precast construction in the South African industry, would be to send questionnaires to industry participants or either arrange an interview with the participant. The questionnaires were divided into two categories, the two categories that were used included: (i) the design of precast and precast connections, and (ii) the construction of precast and precast connections.

A list of various contractors and consultants, working for various types of companies were set up and the questionnaires were eventually e-mailed to them. The designers or consultants were sent the questionnaire containing information on the design aspects of precast concrete and precast connections. The contractors were sent the questionnaires that included the construction aspects of the precast concrete or precast connections. Interviews with some of the participants (contractors and consultants) were also arranged. During the arranged interviews the same questions stated in the questionnaires were handed to the industry participants and a discussion on the questions was recorded and the questionnaire was completed. After all the information had been obtained from the questionnaires and the questionnaires had been completed and edited, the results were analysed and listed in the following section of the report.

## 3.1 – Survey boundaries and limitations

The following aspects and limitations should be kept in mind when reading the results and conclusions obtained from the questionnaires:

- Only contractors and consultants working in the South African civil engineering industry were invited to participate in the survey;
- Various contractors and consultants were contacted, representing different companies in the engineering and construction industry;
- A selected group of industry participants including various contractors and consultants started a precast concrete discussion group in South Africa. This group was established to encourage and develop the use of precast in South Africa. A number of participants was chosen form this group to complete the questionnaire for this study;
- The questionnaire was developed to obtain qualitative data from the industry participants, data that includes the design and construction preferences of precast concrete and precast connections;
- A total of 16 form the 20 contacted consulting engineers participated in the questionnaire, this resulted in a feedback percentage of 80%;
- A total of 12 form the 18 contacted contractors participated in the questionnaire, this results in a feedback percentage of 66.67%;
- Two of the participants represents companies that do the design, supply and construction of the precast elements themselves, so they were listed as both a contractor and a consultant because they are involved in both these activities;
- A standard list of connection types was included in both the questionnaires. The participants were asked to distinctively rate the design (consultants) and construction (contractors) preferences of the various precast concrete connection types that were listed. (The typical rating scale used for the design or construction of the precast connections was included in the questionnaires and a graphical illustration of the different connection types is included in Annexure B);
- The answers given in the questionnaires are the personal views and opinions of the people that participated in the questionnaire. The opinions were given from the participant's previous experience and knowledge of precast concrete design and construction;
- The opinions given form the consulting engineers and the contractors that participated in the questionnaire may not always reflect the opinion from other people in the industry.

Table 3.1 includes a list of all the consulting engineers that participated in the survey and Table 3.2 includes a list of all the contractors that participated in the survey.

**Table 3.1- List of consulting engineers that participated in the survey**

| List of consulting engineers that participated | |
|---|---|
| **Name of participant** | **Company** |
| Christiaan de Villiers | UWP Consulting |
| Ettiene van der Klashorst | Universiteit Stellenbosch |
| Gerrit Steyn | KLS Consulting Engineers |
| Harold Ronne | SMEC (Bloemfontein) |
| Henry Fagan | Henry Fagan and Partners |
| Jaco de Villiers | Aurecon |
| Johan de Lange | BVi Consulting |
| Johan Hartman | Element Consulting |
| Kassie Coetzee | Element consulting |
| Lyonell Fliss | Lyonell Fliss Associates |
| Magdaleen Duvenhage | BVi Consulting |
| Malcolm Loubser | SKCM Engineering |
| Paul van Rooyen | S.P.E |
| Schalk Marais | AECOM |
| Attilio Angelucci | Cobute (Design and supply) |
| Jaco Carstens | Topfloor (Design and supply) |

**Table 3.2 – List of contractors that participated in the survey**

| List of contractors that participated | |
|---|---|
| **Name of participant** | **Company** |
| Anonymous participant | Anonymous Contractor |
| Anonymous participant | Anonymous Contractor |
| Attilio Angelucci | Cobute (Design and supply) |
| E. Van Rooyen | Grinaker LTA |
| Gerald le Roux | Ruwacon |
| Grant Bergh | Group5 |
| Jaco Carstens | Topfloor (Design and supply) |
| Jannie Joubert | NMC |
| Johan Brink | Stefanutti Stocks |
| Les Wardhaugh | Power Construction |
| Peter Burnham | Stefanutti Stocks |
| Robert Muirhead | Grinaker LTA |

All of the participants had a choice whether they would like to stay anonymous or whether they can be referred to in the answers included in the discussion of the information obtained. Only two of the contacted participants wished to stay anonymous during the study. During the next part of the report, the results of the questionnaires will be analysed, presented and compared.

## 3.2 – Survey results obtained from participating Consultants

The questions presented in the following part of the report focussed on the design of precast concrete and precast concrete connections. The answers that were obtained from the questionnaires of the consultants in the industry are discussed in the following section of the report.

**- <u>Question 1:</u> During the conceptual design phase, do you regularly consider making use of precast concrete elements for concrete structures or buildings?**

The following statistics were obtained from the results of question 1:

- It was found that 7 from 16 or 44% of the consultants said that they do consider making use of precast concrete during the conceptual design phase of the project.
- It was also found that 7 from 16 or 44% of the consultants said it mostly depends on the type of project or structure that will be designed and constructed.
- Only 2 from 16 or 12% of the consultants said that they do not really consider making use of precast as an alternative option during the conceptual design phase.

**Table 3.3 – Summary of results obtained from consultants**

| Consultants answer on question 1 | |
|---|---|
| **YES** | **44%** |
| **PROJECT DEPENDENT** | **44%** |
| **NO** | **12%** |

From the results given in Table 3.3, it can be seen that most of the consultants do consider making use of precast concrete during the conceptual design phase, but the same number of consultants also said that it mostly depends on the type of structure that will be designed and constructed. It can be seen that 44% of the consultants that participated in the survey stated that they do consider making use of precast concrete in the conceptual design phase of the project, thus showing that precast can be considered as an alternative method of construction.

**- <u>Question 2:</u> Given the option, do you prefer designing for in-situ concrete or precast concrete construction? Please motivate your answer.**

The following statistics were obtained from the results of question 2:

- In-situ: 8/16 = 50% preferred to mostly design making use of in-situ construction,
- Precast: 3/16 = 19% preferred to design with precast over in-situ concrete construction,
- Depends on situation: 5/16 = 31% said it depends on the situation and the design of the structure or building. This group said they firstly analyse the whole structure before deciding which method (in-situ or precast concrete) will be most beneficial to use.

**Table 3.4 – Summary of results**

| Consultants answer on question 2 | |
|---|---|
| **IN-SITU** | **50%** |
| **DEPENDS ON THE SITUATION** | **31%** |
| **PRECAST CONCRETE** | **19%** |

From the results given in Table 3.4, it was concluded that a number of the consultants was open for the idea of designing with precast concrete. However, considering that a number of consultants are open for the idea of precast design, 50% of the consulting engineers that participated in the survey still prefer designing with in-situ concrete method. A large number of participants also stated that it mostly depends on what type of structure or building is to be designed and constructed.

**- <u>Question 3:</u> Which type of precast concrete elements have you used/designed most frequently? (E.g. precast columns, beams, slabs etc.)**

When analysing the results obtained from the question, the majority of designers concluded that they have mostly designed for more simple precast concrete elements including: (i) hollow core slabs, (ii) precast slabs, and (iii) small beams and columns.

The designers that have more experience in a wider variety of precast elements, specializes in the design and construction of precast concrete elements, structures or buildings. A few of the consulting engineers that participated has had previous experience in designing more complicated forms of precast concrete elements and precast structures. More complicated forms of precast construction usually include: precast bridge sections, entire precast buildings or structures, large precast columns and beams etc. From the results discussed in question 3 it can be concluded that the majority of consulting engineers in the industry have had limited experience and exposure with designing precast concrete elements. This may provide an indication that there may be a lack utilization of precast in the construction and building industry of South Africa.

**- Question 4: In general, what is your biggest concern or difficulty when designing a structure or building with precast concrete elements?**

Considering the results that were found during this question, there were concerns identified that repeated during the participant's answers. It was decided to make a list of the most popular concerns that were mentioned by the participants that completed the questionnaires. The concerns that were identified during the answers were listed accordingly. If the concern or difficulty was continually mentioned throughout the answers of the different questionnaires, the number of mentions the concern received was counted as votes. The concern that was mentioned the most in all of the questionnaires, received the most votes etc. Table 3.5 was developed by listing the most popular concerns identified form the questionnaires and assigning votes to the concerns as they were mentioned in the answers of the different questionnaires.

**Table 3.5 - Most important concerns for consultant's during design of precast concrete**

| Rank | Description of listed concerns that were identified | Number of votes |
|---|---|---|
| 1 | Connection details | 10 |
| 2 | Contractor's ability to construct the precast method | 8 |
| 3 | Seismic considerations for precast concrete construction | 6 |
| 4 | Tolerances | 5 |
| 5 | Scope changes | 4 |
| 6 | Detailing of levels | 3 |
| 7 | Stability of elements during installation | 3 |
| 8 | Size and mass of precast concrete elements | 2 |
| 9 | Creating structural integrity | 1 |
| 10 | Force transfer between precast elements | 1 |
| 11 | Transport of precast elements | 1 |
| 12 | Flexibility of precast elements | 1 |
| 13 | Height of building or structure | 1 |

From Table 3.5, it can be seen that the consulting engineers that participated in the questionnaire, identified that the connections between the precast elements should be considered as one of the most important concerns when designing a precast concrete buildings or elements of the building. The result obtained from this question confirms the need for further research concerning the design and construction preferences of connections in precast concrete construction. Another big concern for the consulting engineers is the ability of the contractor to successfully construct the precast concrete building or precast elements. These results illustrate that the consulting engineer thinks that the problem is not so much with the design of precast concrete but rather with the contractor's ability to construct the precast concrete building or structure.

**- Question 5: In your opinion, which of precast and in-situ concrete construction delivers the best option in terms of quality, time efficiency and cost?**

The participants were asked to state which of precast or in-situ concrete delivers the best cost, quality and time-efficiency according to their opinion. The answers of this question have been summarised in Table 3.6.

**Table 3.6 - Time, quality and cost comparison of precast and in-situ**

| Consulting engineer's choice of precast vs. In-situ | | |
|---|---|---|
| | **Precast concrete** | **In-situ concrete** |
| **Cost** | 33% | **67%** |
| **Time-efficiency** | **100%** | 0% |
| **Quality** | **92%** | 8% |

From Table 3.6 it is seen that the majority of the consulting engineers that participated in the questionnaire, stated that the cost of in-situ concrete construction is less when compared to precast concrete. In terms of time efficiency and quality, most of the consulting engineers stated that precast concrete is a much better option to consider and also delivers better quality than in-situ concrete. Some of the participants also stated that if precast construction is applied correctly it can be more time-efficient than in-situ construction.

Some of the more important comments that were given from selected consulting engineers that participated in the questionnaire are as follows:

**- "**Both these methods mostly deliver the same standard, but it also depends on what type of structure or building is to be constructed" **-** (Carstens 2014)

**- "**Both are equal, I don't think it is a quality, cost or time consideration, but rather a conceptual consideration" **-** (De Villiers 2014)

**- "**Precast have the ability to deliver good quality and can be very time efficient, given that it is well planned" **–** (Van der Klashorst 2014)

- "The conception of precast to be faster is not always the case, but in a large project where repetition is abundant, precast definitely saves time" **–** (Carstens 2014)

**- "**It depends on the project, the building design itself, the professional team and the contractor" **–** (Marais 2014)

- **"**For small projects such as single storey houses, the method of precast works out better, but for bigger multi-storey structures the in-situ method still remains the better structural option" **–** (Ronne 2014)

**- <u>Question 6:</u> How much experience do you have in terms of designing precast concrete connections?**

The majority (±70%) of the designers and consultants that were interviewed or that completed the questionnaire said that they didn't have much experience with the design of precast concrete connections. They did however mention that they have mainly designed simpler forms of connection details that include precast elements or connections found with designing precast hollowcore floor slabs, small simply supported beams etc. Observing the results from the questionnaires it can be seen that not many designers have frequently designed precast buildings that include the design of more complicated precast connection details. Their preferred connection detail is mostly narrowed down to simply supported or load bearing units.

It was also noted that two or more designers said that precast concrete structure and connection design is a specialist field, stating that there are people in the engineering industry that focuses on precast concrete design and construction. Some consultants also said that they usually source out the work that includes precast concrete design, because they often don't have sufficient knowledge, skills and expertise to do the design themselves. Analysing this result, it can be observed that there is however a problem or rather a shortage of specialists in the engineering industry that have sufficient knowledge and skills to design precast concrete and precast connections for buildings and structures. One of the major factors that contribute to this problem is perhaps the lack of guidelines that are provided for precast design and construction, as well as a lack of implementation of precast concrete in the engineering and building industry of South Africa.

**- <u>Question 7:</u> According to which code, practice or guideline do you usually design precast concrete connections to ensure that it has sufficient strength, robustness and quality?**

A Total of 12/16 = 75% from all the designers or consultants that completed the questionnaire said that they design precast structures (precast elements) and connections between precast elements according to SABS or SANS design codes. The majority of consulting engineers also stated that the South African design codes does provide sufficient rules and guidelines for the design of precast concrete buildings or structures, but has a shortage in terms or providing the correct guidelines and rules for designing connections between precast concrete elements. Thus requiring that the SABS or SANS design codes should include some revision in terms of the design and detailing or different types of precast connections.

It was also noted that a number of the designers/consultants that completed the questionnaire, base their designs and concepts of precast connections on other international design codes such as the British Standards or ACI codes. Mr. De Villiers (De Villiers 2014) stated that in their office they often design precast elements and precast connections, based on the basic engineering principles.

**- <u>Question 8:</u> Would you say there is a lack of knowledge and implementation of precast concrete construction in the South African building industry? Please motivate your answer.**

When analysing the results from question 7, it was found that **15/16** or rather **94%** of the consultants that completed the questionnaire, said that the South-African civil engineering industry does have a lack of efficient knowledge and implementation of precast concrete design and construction. This result illustrates and proves that there is a definite lack of implementation, development and knowledge of precast concrete in the engineering and building industry of South Africa.

Some of the main reasons and motivations that resulted for this lack of knowledge and implementation of precast in the South African industry, were given by some of the consultants/designers that participated in the survey. The most important factors or key concerns that were identified include the following:

- Engineers in South Africa don't have the relevant knowledge to design precast and there is limited courses, seminars or teachings that provides the industry with sufficient guidelines and knowledge,
- There is a lack of experience and exposure with the design of precast concrete and precast connections,
- There is a lack of implementation of precast concrete in the engineering and building industry,
- Engineers in the industry have not developed the required skills and knowledge to develop this concept adequately,
- Shortcomings in available construction contract types for the use of precast in the industry,
- There is a communication gap between consultants and contractors in terms of the use of precast concrete,
- The fact that in-situ have been used for many years and people in the industry have become comfortable with using this method,
- It is easier (and safer) to use the conventional method of in-situ especially if the person do not understand the principles of a new system,
- In-situ has little boundaries as to its application, flexibility, constructability etc. and it has been found that fewer problems for in-situ have been noted by the engineer,
- There is a shortage in the number of specialised precasting manufacturers,
- Precast is suitable for certain applications, the correct applications are not properly marketed,

- Precast only offer solutions for very specific problems.

These listed concerns are all very valuable and applicable; they also provide subjective opinions of why precast concrete construction in the South African engineering industry is struggling to compete with other alternative construction techniques.

**- <u>Question 9:</u> If compared internationally, does South Africa make less use of precast construction? Is there anything we should or can do, to promote the use of precast and is there need for improvement of connection design?**

The opinions that were given by the consulting engineers that participated were listed as the following:

- There is still too little knowledge of this system in the South African market,
- Cost is one of the main factors - The cost of precast construction is still too much when compared to in-situ concrete construction. Developing precast systems that may provide better cost alternatives, may lead to more frequent usage of this method.
- Lack of exposure and implementation – there is a limited number of manufacturers, deliverers and designers of precast concrete in the engineering industry of South Africa. Limited resources results in limited usage of precast, thus implementing the most applicable precast systems for the South African industry and doing the correct marketing for precast applications may lead to an increase precast usage.
- Cheap labour forces the industry to make use of more labour intensive construction methods such as in-situ.
- Engineers and specialists in the engineering industry are reluctant to new ideas.
- There is a shortage of experts with sufficient skills in the field of precast concrete construction.
- Inability of contractors to construct with precast concrete.
- Precast concrete has limited applications - Precast concrete applications are mostly effective in simply supported structures. It may be that that the correct applications for precast are not marketed very well.
- Promote the construction of precast units by means of pilot projects, design courses at University level can be implemented and it can be beneficial for foreign companies to start similar precast companies or solutions in the South Africa construction industry.

All the answers stated in the list above addresses typical problems or concerns associated with precast concrete design and construction. Analysing the comments and opinions given form the consultants that participated in the questionnaire, it can be said that the general conclusion is that there is an evident lack of implementation and development of precast concrete in the South African construction industry. All the above mentioned reasons, some significantly more, contribute to the ineffective application of precast concrete in the South African construction and building industry.

**- <u>Question 10:</u> From previous experience or knowledge, can you provide any additional information concerning precast concrete connections?**

The following comments and statements were made from some of the experts in the civil engineering industry:

**Christiaan de Villiers (UWP Consulting):** "(i) the bottom line is there are seismic restrictions the designer should be aware of. (ii) Cost plays a big factor in any project and especially in the building industry, (iii) Connection design is critical, you have to get it right!, (iv) Lastly in terms of precast there is no redundancy, and often no alternative load paths in the overall precast structure, compared to in-situ structures."

**Jaco de Villiers (Aurecon) : "**When designing with precast, you must plan to accommodate tolerances. When working with precast, you are usually working with small tolerances."

**Johan Hartmann (Element Consulting): "**From experience and previous seminars I've attended I can say that Hollowcore slabs are promoted intensively, but other than that we haven't had much exposure to other precast concrete elements as well as connections."

**Lyonell Fliss (Fliss and Associates): "**In addition, precasting can be efficient only if the "Design and Construct" method is applied. However most Clients prefer the old system of Design by Consultant and select the Contractor through a tender based on Consultant's tender design. After this process, there is no time to re-design a conventional in-situ as precast and in any case the selected contractor may be inadequate or take advantage of the change by increasing the cost."

**Malcolm Loubser (SKCM Engineers): "**Precast concrete connections are normally simply supported and therefore the movement of the elements together with crack control plays a very important part in design of the connections."

**Harold Ronne (SMEC):** "Uncertain as to the moment connection capacity in comparison to that of a conventional concrete connection."

The comments made by the consultants/designers in the industry, (similar to question 8) identify certain problems which they have recognized either through previous experiences or knowledge of precast concrete and connections of precast elements.

**- <u>Question 11:</u> The consultants/designers were asked to rate different types of precast connections typically found in a precast concrete frame building. The results and preferences that were obtained will be discussed.**

The connection types that were identified and used during the questionnaires are given in Annexure B at the back of the report. The questionnaires that were given to the consulting engineers focussed on the design of various connection types listed in the literature study (Chapter 2). The concept of connection design were handed to the consulting engineering participants and the concept of connection construction were handed to the contractor participants

The following question only focuses on the consulting engineers and the design of the precast concrete connections. Table 3.7 presents the type of rating that were used to rate the different connection types, a rating of 1 being a highly unlikely connection type to design and a rating of 5 being most likely connection type to design. The average ratings of the different connection types are also colour rated accordingly, the colour also depends on the amount of connections that is considered in the specific connection zones. (e.g. in certain cases blue will indicate the highest rated connections, and in other cases green will indicate the highest rated connection, depending on the amount of connections that were identified in that specific connection zone)

**Table 3.7 - Rating scale for designing of precast connections**

| Rating scale | |
|---|---|
| **1** | **Highly unlikely to design** |
| **2** | **Not likely to design** |
| **3** | **Average to design** |
| **4** | **Likely to design** |
| **5** | **Most likely to design** |

The results are illustrated as an average value obtained from all the consultants' ratings that participated in the questionnaires. The average value is given as a total out of 5 and the connection type with the highest rated value were found to be the most popular or most likely connection type to be designed. The connection type with the lowest rated value was the connection type that the majority of the participants rated as the least favourable to design. Tables 3.8 to 3.12 include the different type connections that were identified in the literature study (Chapter 2). A graphical presentation of the different connection types that have been listed in the tables are given in Annexure B at the back of the report. Also included in the different tables, is popular comments that were made by some of the consultants/designers that participated in the questionnaire. The comments can either be a positive or a negative aspect of the specific connection that is under consideration. The different connections and their ratings are provided on the next few pages.

**Table 3.8 - Average design ratings for column-to-footing connection types**

| Connection type | Column-to-footing | | | Rating Scale | Popular comments on connection types |
|---|---|---|---|---|---|
| | # consultants | sum of rating | avg | | |
| Pocket foundation | 16 | 48 | 3.00 | Average | (i) Dimensions may become too big if column becomes too large, (ii) Can become moment fixed connection if embedment depth is increased |
| Steel baseplate | 16 | 47 | 2.94 | Least popular | (i) More effective for steel columns, (ii) Lack of moment continuity into the foundation |
| Dowel connection | 16 | 56 | 3.50 | Most popular | (i) Theory of reinforced concrete can be applied, (ii) This connection can be used to transfer moments and therefore results in the most cost effective structure, (iii) Problems may occur when filling the voids |

**Table 3.9 - Average design ratings for beam-to-column connection types**

| Connection type | Beam-to-Column | | | Rating Scale | Popular comments on connection types |
|---|---|---|---|---|---|
| | # consultants | sum of rating | avg | | |
| Steel billet | 16 | 35 | 2.19 | Least popular | (i) Require a perfect fit, (ii) Not familiar with connection type, |
| Welded plate | 16 | 41 | 2.56 | More favourable | (i) Tolerances may be a problem, (ii) Can only be used as simply supported, (iii) Welding problem for transfer of moments that are present |
| Hidden corbel | 16 | 39 | 2.44 | Average to design | (i) Have not used it before, looks like it can be a very expensive detail, (ii) complicated design. |
| Corbel connection | 16 | 67 | 4.19 | Most popular to design | (i) Prefer this because of :<br>1. No exposed steel,<br>2. Transfer of moments possible,<br>3. High shear resistance. |

**Table 3.10 - Average design ratings for column-to-column connection types**

| Connection type | Column-to-column | | | Rating Scale | Popular comments on connection types |
|---|---|---|---|---|---|
| | # consultants | sum of rating | avg | | |
| Column shoe | 16 | 45 | 2.81 | Average | (i) Stability of structure could be a problem, (ii) Filling the column shoe gaps may be problematic,(iii) Complicated design |
| Welded plate | 16 | 34 | 2.13 | Least popular | (i) Site welding can be problematic and is not preferred , (ii) Corrosion concerns, (iii) Tolerances may become a problem |
| Dowel connection | 16 | 56 | 3.50 | Most popular | (i) This connection can be used to transfer moments , (ii) Problem with filling voids, (iii) Theory of reinforced concrete can be applied |

**Table 3.11 - Average design ratings for floor-to-floor connection types**

| Connection type | Floor-to-floor | | | Rating Scale | Popular comments on connection types |
|---|---|---|---|---|---|
| | # consultants | sum of rating | avg | | |
| Grouted connection | 16 | 63 | 3.94 | Most popular to design | (i) Used often, (ii) Can transfer moments if designed correctly, (iii) Easy and straight forward connection. |
| Welded or bolted | 16 | 32 | 2.00 | Least popular | (i) Site welding can be problematic, (ii) We do not prefer welded/bolted structural connections |
| Reinforced topping | 16 | 60 | 3.75 | Average to design | (i) Toppings often negate the advantages of going precast, (ii) Used to control cracks between precast elements. |
| Loop connection | 16 | 61 | 3.81 | More favourable | (i) Regularly used for floor slabs, (ii) Used to control cracks between precast elements, (iii) Practical, inexpensive and no maintenance. |
| Rib and Block | 16 | 63 | 3.94 | Most popular to design | (i) Generally used in the industry, (ii) Finished product is inferior to in-situ cast or hollowcore floors, (iii) Rib and block entails many design detailing. |

**Table 3.12 – Average design ratings for slab-to-beam connection types**

| Connection type | Slab-to-beam | | | Rating Scale | Popular comments on connection types |
|---|---|---|---|---|---|
| | # consultants | sum of rating | avg | | |
| Simply supported | 16 | 66 | 4.13 | Most popular to design | (i) Good for simply supported beams with tolerance for movement, (ii) Most likely connection, (iii) Designed to be a movement joint |
| Bolted | 16 | 32 | 2.00 | Least popular | (i) Tolerance is normally a problem with very little change to rectify, (ii) No to be considered when moment transfer is required |
| Ties and reinforcement | 16 | 63 | 3.94 | Likely to design | (i) Our preferred method of connection, (ii) Likely in moment transfer connections, (iii) Theory of reinforced concrete can be applied |
| Hollow core slab | 16 | 61 | 3.81 | More favourable | (i) Works well for precast landings, with an in-situ structural topping, (ii) Lightweight and cost effective, (iii) Frequently use on load-bearing |
| Rib and Block | 16 | 58 | 3.63 | Average to design | (i) Definitely has a place in the industry, (ii) Most likely in house slabs, (iii) Frequently use on load-bearing walls |

## - Conclusions for consulting/design engineers on precast concrete and connection preferences

When analysing the results that were obtained from the questionnaires handed out to various consulting engineers in the local engineering industry, it was found that the majority of the participants has had previous experience or some exposure in designing with precast concrete. Some of the participants have had more experience than others and one of the main the reason for this is that people in the engineering industry classify the design of precast to be either complicated or that it requires more extensive design detailing. It was also stated that some of the participants said that they consider precast concrete and precast connection design as an expert field.

Another aspect that was noted is the fact that the majority of the consultants prefer designing or working with in-situ concrete, even though most of them said that precast delivers a better quality product and also produces a more time efficient product. This may be due to the statement that some of the consultants are reluctant to new ideas and still prefer and feel more comfortable designing in-situ concrete structures and buildings. To improve this lack of implementation and use of precast concrete in the industry, one of the consulting engineers mentioned that they should make use of pilot projects to provide the industry with an illustration of what precast concrete construction could deliver as an alternative construction method. If these pilot projects can prove to be successful, it can be used as an example to show consulting engineers as well as contractors that precast may be effectively implemented in the local construction and building industry.

When looking at the average connection ratings and taking the comments into consideration, some preferred connection methods or types can be identified. The following conclusions and preferences on the different connection types were found from the consultants' questionnaires:

- The consultants prefer designing precast connections that include some form of in-situ aspect, this includes connections such as the dowel connection, the concrete corbel connection, and the rib-and-block connection for floor solutions. The majority also prefer grouted or reinforced topping connections.
- The participants also prefer connections that do not include too much detailing and is fast and easy to construct, this includes simply supported connections and precast concrete corbels.
- Connections that include structural steel inserts, bolts and welding are not very popular and most of the connections that include these elements were rated the lowest in all of the connection zones.
- Moment and force transfer is a big concern for the consultants. The connection should be able to transmit or resist all the applied forces and should be designed for effective flow of forces.
- Connections that require small tolerances are also not preferred. If the tolerances are slightly out, it may have a big effect on the connection details and layout of the precast units.

The consultants that participated have much experience in terms of design of concrete buildings, but they do however have limited experience specifically in terms of precast concrete and precast connection design. Nevertheless the input from the consultants is considered to be valid for this study due to their years of experience in the industry.

## 3.3 – Survey results obtained from participating Contractors

The questions included in the following part of the section focus on the construction of precast concrete and precast concrete connections. The answers were obtained from contractors that are currently working or have previously worked in the South African civil engineering industry.

**- <u>Question 1</u>: When pricing an in-situ concrete construction project, would you evaluate precast concrete construction as an alternative? And vice-versa?**

This question was asked to establish the popularity and use of precast concrete among contractors in the South African construction industry. The following results were obtained from the question:

- It was found that 5/10 or **50%** of the contractors said they do consider precast concrete as an alternative method when typically pricing a construction project.
- It was noted that 4/10 or **40%** of the Contractors said it mostly depends on the type of project that will be priced.
- Finally it was stated that 1/10 or only **10%** of the contractors said they don't even consider precast concrete as an alternative construction method for their projects and that mostly make use of in-situ concrete construction.

**Table 3.13 - Summary of results obtained from contractors**

| Contractors answers on question 1 | |
|---|---|
| **YES** | **50%** |
| **PROJECT DEPENDENT** | **40%** |
| **NO** | **10%** |

From the results given in Table 3.13 it can be noted that the majority of the contractors do consider precast concrete as an alternative construction method when pricing a project. It was also found that 40% of the contractors that participated in the questionnaire said that it mostly depends on the type of structure or building that will be constructed.  Only a minor 10% of the contractors said that they do not even consider making use of precast

**- Question 2: Given the option to choose, would you prefer making use of precast or in-situ concrete construction? (Please motivate your answer)**

- From the results obtained from the questionnaires it was found that 6/12 or 50% of the contractors that participated in the questionnaire preferred making use of in-situ concrete construction.
- It was also found that a mere 2/12 or 17% of the contractors said that precast delivers better time saving, cleaner installation process, good quality, less resources
- Finally it was found that 4/12 or 33 % of the contractors said that precast are better for some projects and in other instances in-situ is preferred. Basically it depends on what type of structure will be built and what technique will be more cost effective.

**Table 3.14 - Summary of results obtained from contractors**

| Contractors answers on question 2 | |
|---|---|
| **IN-SITU** | **50%** |
| **DEPENDS ON THE SITUATION** | **33 %** |
| **PRECAST CONCRETE** | **17%** |

When looking at the results given in Table 3.14 it was noted that the majority of the contractors prefer making use of in-situ concrete construction. The main reason for this may be the fact that in-situ construction has been used for many years and the contractors have become more comfortable and experienced with this construction method. A large number of the contractors that participated also said that it depends on the type of structure or building that will be constructed.

**- Question 3: Which type of precast concrete elements do you (or have you) use most frequently? (E.g. precast columns, beams, slabs etc.)**

It was found that there is a wide variety of precast concrete elements being used by the contractors that participated in the questionnaire. There is however a few popular precast concrete elements that have been implemented more frequently than others. The following list provides the different type of precast elements listed by the contractors. These precast elements were rated according to the number of times the contractors stated the usage of the specific element during the questionnaire. The list of precast elements is organised from more popular to less popular precast concrete elements. The results for the ratings were established by analysing the answers of the questionnaires that were completed by the participants:

- Precast floor slabs: Mostly Hollow core and pre-stressed slabs,
- Smaller type of precast beams,
- Columns, either precast or tilt-up columns,

- Wall panels,
- Precast stair cases and balustrades,
- Bridge beams,
- Portal frames

**- <u>Question.4:</u> In general, what is your biggest concern or difficulty when constructing a structure with precast concrete elements?**

The most important or biggest concerns for the construction of a precast concrete building were identified and listed by the contractors during the questionnaire.

Considering the results that were found during this question, there were some concerns identified which repeated during the participant's answers. A list of the most popular concerns that were mentioned by the participants that completed the questionnaires was obtained. The concerns that were identified during the answers were noted and listed accordingly. If the concern or difficulty was continually mentioned throughout the answers of the different questionnaires, the number of mentions the concern received was counted as votes. The concern that were mentioned the most in all of the questionnaires, received the most votes. Table 3.15 was developed by listing the most popular concerns, identified form the questionnaires and assigning votes to the concerns as they were mentioned in the answers of the various questionnaires.

**Table 3.15 - Most important concerns for contractors during construction of precast**

| Rank | Description of concern that were identified | Amount of votes |
|---|---|---|
| 1 | Correct and accurate levels | 8 |
| 2 | Accurate tolerances | 7 |
| 3 | Stability during installation | 6 |
| 4 | Connecting the precast elements properly | 6 |
| 5 | Construction sequence | 5 |
| 6 | Transport of precast elements | 3 |
| 7 | Crane capacity and access | 3 |
| 8 | Consultant buys in into concept | 2 |
| 9 | Colour consistency | 1 |
| 10 | Correct standards and quality | 1 |

Table 3.15 includes the top ten concerns that were mentioned during the results of the questionnaires. From Table 3.15 it can be seen that the contractors that participated in the questionnaire listed that correct and accurate levels are the most important aspect to consider when constructing precast concrete elements or parts of a precast building. The answers of the contractors did not list the construction of precast connections in the top 3 concerns, but rather stated that the setting out, stability and accuracy of the precast elements during construction are very important aspects to consider.

These concerns may also have a big impact on the assembly and construction of the connections between the precast elements if not done proper and accurately. The construction sequence and the connection method were also listed as a big concern for contractors. These two factors are done accordingly and have a significant impact on each other. The correct construction sequence and proper connection of the precast elements also has a considerable impact on the construction time of the precast structure or building.

Another important aspect that may affect the construction process is the transport of the precast elements. The precast elements should be restricted to certain sizes and the design should be simplified to compensate for the transport as well as the lifting and placing of the precast elements. All the concerns listed in Table 3.15 should be considered as high importance and it provides the contractor as well as the design engineer with guidelines as to which aspects are important to consider during the design as well as the construction phase of the project.

**- <u>Question 5:</u> In your opinion, which of precast and in-situ concrete construction delivers the best quality, time efficiency and cost?**

The question asked that the participants should state which construction solution, namely precast or in-situ delivers the best quality, best cost and provides the best time-efficiency in terms of construction. Table 3.16 was developed using the results that were obtained from the questionnaires.

**Table 3.16 - Comparing between in-situ and precast construction**

| Time, Quality and Cost according to Contractors | | |
|---|---|---|
| | **In-situ construction** | **Precast concrete construction** |
| **Quality** | **10%** | **90%** |
| **Cost** | **90%** | **10%** |
| **Time-efficiency** | **20%** | **80%** |

The percentages presented in Table 3.16 illustrate the percentage of contractors that preferred to make use of either in-situ construction or precast concrete construction. According to the answers obtained from the contractors that completed the questionnaire the following conclusions can be made:

- The majority or 90% of the contractors stated that precast concrete construction delivers better quality and finishing compared to in-situ construction.
- The majority or 90% of the contractors said that projects completed by means of in-situ construction are less costly compared to precast concrete construction. Many of them said that it may evidently save some time using precast concrete but additional transport and lifting equipment may result in additional costs that ultimately make the use of precast more expensive.

- In terms of time efficiency, 80% of the contractors said that precast concrete construction is often less time consuming, thus saving time on the overall project duration.

Observing the results from this question, it can be seen that in terms of quality and time-efficiency the majority of the contractors that participated, prefer precast over the use of in-situ construction. However it was found that cost is usually the most important factor during any construction project, and that the contract usually allows the lowest bidder to obtain the job. The results in Table 3.16 show that 80% of the contractors said that making use of in-situ construction is often cheaper and delivers a better cost alternative compared to precast concrete. The fact that the South African construction industry has cheap labour requirements and that the economy as well as the government encourages more labour intensive work to support job creation, it is also preferred to rather make use of more labour intensive work which results in-situ construction. The use and frequent implementation of precast concrete is found to be limited in the construction and building industry of South Africa. However, if the concept of precast is applied correctly and the best precast systems are properly marketed, it may have the potential to be favourably compared to in-situ construction.

**- <u>Question 6:</u> How much experience do you have in terms of construction with precast concrete connections?**

The majority or approximately **70%** of the contractors that completed the questionnaire stated that they haven't had much or have had few or limited experience and exposure in terms of precast concrete and precast connections. From the answers of the questionnaires it can be seen that the most popular precast elements they have worked with seem to be precast slabs, hollowcore slabs and small beams and columns. There is however a few contractors that have completed successful precast projects which included the use of various types of precast concrete elements along with more complicated precast connection types. Some of the projects that were completed by some of the contractors include the following:

- **Mr. Gerald le Roux from Ruwacon (2014)** said they recently completed a 45ML reservoir with precast columns (44 columns), beams and roof slabs (11m span) which entailed connections between precast elements and also precast connections to in-situ elements.
- **An anonymous contractor stated that they** previously completed the New Johannesburg Academic Hospital; apart from lift cores the rest of the structural elements were mostly precast. They also constructed precast façade panels to the new engineering block west campus Witwatersrand University. And also numerous bridges, road over rail and road over river, including precast concrete balustrades.
- **Mr. Robert Muirhead from Grinaker LTA (2014)** also worked on a large precast project for MTN where all the beams and slabs were precast concrete, a total structure of approximately 2500m² were constructed form mostly precast elements.

From the results it can be concluded that the minority of the contractors have actually been exposed to or participated in large projects which included the use of more intricate and structural precast concrete and connections. This result thus illustrates that precast concrete has not been implemented with much success in the construction industry of South Africa. One of the contractors also mentioned that a reason for this lack of implementation and usage of precast concrete may be due to the impression that the consulting or design engineers rather prefer designing with in-situ concrete, thus not exposing the contractors to precast concrete construction. Although the minority of contractors have previous experience with precast construction, they are experienced individuals whose opinion on some of the construction aspects can nevertheless be considered of much relevance.

**- <u>Question 7:</u> Do you have difficulties installing and constructing the connections between precast elements? What is your biggest concern when constructing these connections?**

The contractors that participated in the questionnaire have identified a few important aspects that should be considered when designing as well as constructing precast concrete connections. The following factors were identified as highly important factors to consider during the construction of connections between precast elements:

- Connection type should have acceptable tolerances,
- Skilled people are required for the construction and assembly of connections,
- Extremely high accuracy is required in terms of setting out levels and surveys,
- Positioning of the precast concrete elements,
- Connections should be designed as simple as possible,
- Correct lifting equipment is required.

These concerns have thus been identified by the majority of the contractor to be the most important aspects to consider when installing or constrcuting a connection between two or more precast concrete elements.

**- <u>Question 8:</u> According to which code, practice or guidelines do you assemble/construct the precast elements and overall structure to ensure that it has sufficient strength, robustness and quality?**

From the results obtained from the questionnaires it can be seen that the majority of the contractors prefer constructing the precast structure and connections according to the SABS and SANS codes and regulations. Some of the contractors also rely on the designer or the professional team to provide them with the sufficient code or guidelines on how to construct the precast concrete structure or partial precast concrete elements. The SABS 0100-1 (2000 Edition) design code does provide guidelines for the use, handling and construction of precast concrete elements but lacks in the subject of connection assembly and construction.

Future improvements to the SABS and the SANS codes may be implemented to accomodate more effective and applicable guidelines for the construction or assembly of precast connections. Chapter 5 of this report does include considerations for the design and construction aspects of precast concrete and precast connections according to the SABS 0100-1 (2000 Edition)

**- <u>Question 9:</u> Would you say there is a lack of knowledge and implementation of precast concrete construction in the South African engineering industry? Please motivate your answer.**

It was found that 95% of all the contractors questioned, stated that there is a lack of exposure and implimentation of precast concrete in the construction and building industry of South Africa. This result makes it evident that there is a shortage of precast construction in the engineering industry of South Africa. The contractors also stated their own opinions and comments on why they think this lack of precast is occuring:

- This is mostly due to a shortage of experts with sufficient knowledge of design and construction of precast concrete in the industry.
- There is a lack of exposure for designers and contractors.
- Some engineers are reluctant in learning new techniques, and they rather trust their older ways of doing things.
- The marketing done for precast is not done properly.
- Labour rates are generally cheap and the government encourages job creation.
- Consultants mostly prefer designing of in-situ construction.
- People in the industry tend to have an unwilling attitude to learn new alternative construction methods.
- There is a shortage of standardized precast concrete elements in different construction projects, making it more expensive method of construction.
- The cost of precast construction is still too much when compared to in-situ concrete construction.
- Lack of continuity of work in terms of precast concrete.

Considering all the listed concerns associated with precast concrete constrcution, it can be concluded that there is a shortage or lack of precast construction in the South African industry. Various reasons can be associated with this problem that is being faced, but the utilization, further development and more succesful implementation of precast concrete in the South African construction industry may encourage more industry participants to consider making use of this method.

**- <u>Question 10:</u> From previous experience or knowledge, can you provide any additional information concerning precast concrete connections?**

The contractors were asked to provide important aspects which should be considered when making use of precast concrete construction. The following important comments or conclusions were given either from the contractor's previous experiences or aspects that they considered to be significant when working with precast concrete in the construction industry:

- Connections should be designed to be as simple as possible,
- Allowable tolerances should be allowed for connection details,
- Make use of more standardized precast concrete connection types (saves time and effort),
- Provide a simple instalment process,
- Expose engineers and people in the industry to more precast solutions, provide workshops or implement ways of learning more about precast concrete,
- By making more use of repetition of precast elements, eases the design as well as the construction process.
- People tend to steal material and equipment on site, things such as scaffolding, propping, reinforcement, cement etc. Implementing more precast, the problem of theft on construction sites can be reduced,
- Accuracy plays the biggest part of success, accurate programme planning is also very important. Accuracy in terms of setting out the levels during the construction and also accuracy when installing the precast concrete connection is vital,
- You need highly paid / skilled staff to do it properly. Train more people to become skilful in the use of precast concrete,

The above listed aspects are merely some guidelines that can be used or implemented to promote more successful carrying out of precast concrete construction in the engineering and building industry of South Africa.

**- <u>Question 11:</u> The contractors were asked to rate different types of precast connections typically found in a precast concrete frame building. The results and preferences that were obtained will however be discussed during this question.**

The connection types that were identified and used during the questionnaires are given in Annexure B at the back of the report. The questionnaires that were given to the contractors focussed on the construction of the connection types. The concept of connection design were handed to the consulting engineering participants and the concept of connection construction were handed to the contractor participants

The following question only focuses on the contractors and the construction of the precast concrete connections. Table 3.17 illustrates the type of rating that were used to rate the different connection types, a rating of 1 being a highly unlikely connection type to construct and a rating of 5 being the most likely connection type to construct. The average ratings of the different connection types are also colour rated accordingly, the colour rating also depends on the amount of connections that is considered in the specific connection zones. (e.g. sometimes blue will indicate the highest rated connections, sometimes green will indicate the highest rated connection, depending on the amount of connections that were identified in that specific connection zone)

**Table 3.17 - Rating scale for construction/assembly of precast connections**

| Rating scale | |
|---|---|
| 1 | Highly unlikely to construct |
| 2 | Not likely to construct |
| 3 | Common to construct |
| 4 | Likely to construct |
| 5 | Most likely to construct |

The results given in Tables 3.18 to 3.22 are presented as an average value obtained from all the contractors that participated in the questionnaires. The average value is given as a total out of 5 and the highest rated connection type given in the results were found to be the most popular or most favourable connection type the majority of the contractors preferred to construct. The lowest value given in the results were obviously the connection type that the majority of the contractors listed as the least favourable to construct or assemble. The following tables include the different connection types identified in literature and a typical graphical illustration of the type of connection is shown in Annexure B. Also included in the different tables, is popular comments that were given by some of the contractors that participated in the questionnaire. The comments can either be a positive or a negative aspect of the specific connection that is under consideration. The different connections and ratings are given on the next few pages.

### Table 3.18 - Average construction ratings for Foundation-to-Column connection types

| Connection type | Foundation-to-column | | | Rating Scale | Popular comments on connection types |
|---|---|---|---|---|---|
| | # contractors | sum of rating | avg | | |
| Pocket foundation | 12 | 20 | 1.67 | Least popular | (i) Easy installation, (ii) Time consuming to create the pocket detail, (iii) Reduction of floor area. |
| Steel baseplate | 12 | 24 | 2.00 | Average to construct/assemble | (i) Quick installation and protection of steel base plate is additional cost, (ii) Not very familiar with this connection, (iii) More popular with steel construction. |
| Dowel connection | 12 | 38 | 3.17 | Most popular | (i) Similar to steel reinforcement cast into precast column, (ii) Easy to install, however requires accuracy on starter bar placement |

### Table 3.19 - Average construction ratings for Column-to-Column connection types

| Connection type | Column-to-Column | | | Rating Scale | Popular comments on connection types |
|---|---|---|---|---|---|
| | # contractors | sum of rating | avg | | |
| Column shoe | 12 | 25 | 2.08 | Average to construct/assemble | (i) Have not used this type of connection before, (ii) quick and easy to install, (iii) stability may be concern during construction |
| Welded plate | 12 | 14 | 1.17 | Least popular | (i) Additional trade/contractor, welding on site is not preferred, (iii) welding requires expert = additional costs. |
| Dowel connection | 12 | 34 | 2.83 | Most popular | (i) Similar to steel reinforcement cast into precast column, (ii) Accuracy of bar and pocket placement critical, (iii) Quick erection time. |

### Table 3.20 - Average construction ratings for Column-to-Beam connection types

| Connection type | Column-to-beam | | | Rating Scale | Popular comments on connection types |
|---|---|---|---|---|---|
| | # contractors | sum of rating | avg | | |
| Steel billet | 12 | 22 | 1.83 | More favourable | (i) No experience with this type of connection, (ii) Beam must be tilted so as not to foul the pin which would make erection time consuming. |
| Welded plate | 12 | 19 | 1.58 | Least popular | (i) May be used in heavy industrial buildings, (ii) Placement is quick. Beam would have to be supported until welding is complete, therefore crane time is consuming. |
| Hidden corbel | 12 | 20 | 1.67 | Average to construct/assemble | (i) Very unfimiliar type of connection, (ii) small tolerances is allowed, (iii) may be an expensive detail to use in SA. |
| Corbel connection | 12 | 46 | 3.83 | Most popular to construct/assemble | (i) Used before in industrial buildings, (ii) Similar to in-situ concrete corbel, (iii) Popular connection type in the industry, (iv) Used extensively, simple to install |

## Table 3.21 - Average construction ratings for Floor-to-Floor connection types

| Connection type | Floor-to-floor | | | Rating Scale | Popular comments on connection types |
|---|---|---|---|---|---|
| | # contractors | sum of rating | avg | | |
| Grouted connection | 12 | 38 | 3.17 | Likely to construct/assemble | (i) Very often used, (ii) Used for Top floor solution, (iii) Quick and easy to install. |
| Welded or bolted | 12 | 17 | 1.42 | Least popular | (i) Skilled labour is required, (ii) Labour intensive, (iii) Welding and bolts complicate the construction process, (iv) Too intricate connection type |
| Reinforced topping | 12 | 40 | 3.33 | Most popular to construct/assemble | (i) Frequently used for precast floor slabs, (ii) Often used. Topping provides surface for floor finishes, (iii) Create monolithic floor slab. |
| Loop connection | 12 | 37 | 3.08 | More favourable | (i) Similar to coffer slabs, (ii) Time consuming, (ii) Topping still required. Provides good connection between transverse beam and planks |
| Rib and Block | 12 | 36 | 3.00 | Average to construct/assemble | (i) Quick and easy to construct, (ii) Widely used in housed and rest of building industry. |

## Table 3.22 - Average construction ratings for Slab-to-Beam connection types

| Connection type | Slab-to-beam | | | Rating Scale | Popular comments on connection types |
|---|---|---|---|---|---|
| | # contractors | sum of rating | avg | | |
| Simply supported | 12 | 44 | 3.67 | Most popular to construct/assemble | (i) Easy and fast to construct simply supported elements, (ii) Ease of erection. Widely used, (iii) Preference because of simplicity. |
| Bolted | 12 | 23 | 1.92 | Least popular | (i) Does not compensate for movement in connection area, (ii) Small tolerances are allowed, (iii) High precision required. |
| Ties and reinforcement | 12 | 36 | 3.00 | Average to construct/assemble | (i) Widely used, (ii) Typically used, however requires formwork and additional concrete trades |
| Hollow core slab | 12 | 39 | 3.25 | Likely to construct/assemble | (i) Very quick and easy to install, (ii) Popular in low rise buildings, (iii) Widely used, (iv) Light commercial applications. |
| Rib and Block | 12 | 37 | 3.08 | More favourable | (i) Easy to construct, (ii) Common method of floor slab construction where fast track programme is required, (iii) Not a preferred method for heavy loadings. |

**- Conclusions for contractors concerning precast concrete and connection preferences**

When observing and analysing the results that were obtained from various questionnaires handed out to contractors in the industry, it was noted that some of them have had limited experience and exposure in terms of precast concrete construction. It was also found that there is a big lack or shortage in terms of applying different kinds of precast connection types during the construction of the precast elements or buildings. Seeing that the initiative of using precast concrete during a project is decided in the early stages of planning, the contractors thus have limited participation in whether they would like to make use of precast concrete or not. The majority of the contractors also said that they don't mind working with precast but the consulting engineers usually prefer designing with in-situ concrete. Most of the contractors are more familiar and comfortable with using cast in-situ concrete and have only had limited precast exposure, mainly including precast elements such as hollow-core slabs, small columns and beams and other simply supported precast units.

According to the results that were obtained from the questionnaires it was found that if precast were compared to in-situ in terms of quality, time-efficiency and cost, the majority of contractors preferred precast construction in terms of quality and time-efficiency but said that precast construction is still too expensive. This specific cost factor will probably be one of the most significant factors why precast are not yet applied as an effective alternative construction method. This is however very unfortunate because most of the construction projects completed in South Africa mainly depend on the lowest cost alternative. The other significant factor that was mentioned and resulted in the lack of implementation of precast concrete is the fact that people in the industry are reluctant to new ideas. There is however only a limited amount of participants that is willing to learn and implement new and innovative ideas.

Looking at the results from the preferences of precast concrete connection types, it can be seen that most of the connections that were preferred, were connections that either have an in-situ component associated with it or the connection is a simply supported connection type. This result also identifies that the majority of contractors prefer the easier, faster method of connection types such as simply supported units or load bearing units. It can also be seen that precast concrete and connections of precast concrete still requires a significant amount of development, implementation and exposure before it can be effectively used and compared as an alternative for in-situ construction in the South African construction industry.

The contractors that participated have much experience in terms construction of concrete buildings and structures, but they do however have limited experience specifically in terms of precast concrete and precast connection construction. Nevertheless it was noted that all the contractors that participated are all experienced contractors with many years of experience in the construction industry. Therefore the input they gave on construction aspects can still be considered to be valid.

## 3.4 – Comparison between responses from Contractors and Consultants

It is often found that contractors and consultants do not agree on everything related to construction (Brink 2014). The results from the questionnaires that had been handed out to various contractors and consulting engineers in the South African engineering industry were discussed in sections 3.2 and 3.3 of this chapter. The results from the questionnaires were analysed and concluded, and the average ratings of the precast connections according to the design and construction aspects were also given in section 3.2 and 3.3, respectively. The following section of the report includes the answers obtained from the contractors and the consultants and the answers will also be compared to each other. This comparison between the contractors and consultants may act as a guideline to see whether these parties share the same concerns, or identify aspects on which they disagree. A short discussion and some final conclusions are also provided in this section.

### 3.4.1 – Consideration of implementing precast concrete during the conceptual design phase and pricing of a project

Table 3.23, illustrates whether consultants and contractors consider making use of precast concrete during the conceptual design and pricing phase of a construction project.

**Table 3.23 – Participants preference for in-situ or precast concrete**

| Consultants | | Contractors | |
|---|---|---|---|
| YES | **44%** | YES | **50%** |
| PROJECT DEPENDENT | **44%** | PROJECT DEPENDENT | **40%** |
| NO | **12%** | NO | **10%** |

Question 1 asked whether the participants would consider making use of precast concrete construction during the design and pricing of a project. The responses from the two groups are quite similar to each other and only a small number of contractors and consultants do not consider making use of precast concrete construction during the design and pricing of a project. It can be concluded that the majority or large portion of consultants and contractors are open to the concept of precast concrete construction. A fair percentage of contractors and consultants also said that the choice mainly depends on the type of project that will be designed and constructed.

### 3.4.2 – Preference of designing and constructing with precast or in-situ concrete

Table 3.24 includes results on whether the contractors and consultants prefer making use of precast concrete or in-situ concrete during a construction project.

**Table 3.24 - Preference of in-situ vs. Precast**

| Consultants | | Contractors | |
|---|---|---|---|
| IN-SITU | **50%** | IN-SITU | **50%** |
| DEPENDS ON THE SITUATION | **31%** | DEPENDS ON THE SITUATION | **33%** |
| PRECAST CONCRETE | **19%** | PRECAST CONCRETE | **17%** |

The question (Question 2) asked whether the consultants and contractors prefer designing and construction by either making use of precast or in-situ concrete. Looking at the results, it can be seen that the majority of contractors and consultants prefer making use of in-situ rather than precast concrete construction. A large percentage of both groups said that it depends on the situation or type of structure/building that was to be designed or constructed. This result provides an indication that both the contractors and consultants in the South African civil engineering industry prefer making use of in-situ rather than precast concrete construction. Only a few of the participants preferred the precast concrete concept, but it was identified that the participants who chose precast above in-situ construction, have had more experience with precast than some of the other participants.

### 3.4.3 – Frequently used precast elements during the design and construction phases

It was identified from the results obtained from both the contractors and consultants, that the most popular or frequently used precast elements include the following:

- **<u>Consultants:</u>** The majority of designers concluded that they have mostly designed for simpler precast concrete elements such as: (i) Hollow core slabs, (ii) Precast slabs, and (iii) Small beams and columns. From the results it can be concluded that the majority of consulting engineers that participated in the survey have limited experience with designing precast concrete elements and precast connections.
- **<u>Contractors:</u>** The following list provides the different types of precast elements that were identified by the contractors. The list is however arranged from more popular to less popular precast concrete elements used by the contractors that participated in the questionnaire: (i) Precast floor slabs (mostly hollow core and pre-stressed slabs), (ii) Smaller type of precast

beams, (iii) Columns (either precast or tilt-up columns), (iv) Wall panels, (v) Precast stair cases and balustrades, (vi) Portal frames.

Comparing the different kind of elements used by both the contractors and consultants, it can be seen that the variety of elements are limited and the most popular precast elements include precast slabs (mostly hollow-core), small columns, beams, precast stairs and some precast wall panels. This result indicates that there is a lack of exposure and implementation of precast elements in the construction industry, thus limiting the applications of precast concrete significantly.

### 3.4.4 – Biggest concerns for precast concrete and connection design and construction

The question asked the consultants and contractors to state their biggest concerns or difficulties when designing or constructing precast concrete elements or structures. Table 3.25 provides the top 10 concerns that were listed in the answers of the questionnaires that were received from both groups.

**Table 3.25 - Concerns for design and construction of precast concrete**

| Rating | Consultant's concerns | Contractor's concerns |
|---|---|---|
| 1 | Connection details | Correct and accurate levels |
| 2 | Contractor's ability to construct the precast method | Accurate tolerances |
| 3 | Seismic considerations for precast concrete construction | Stability during installation |
| 4 | Tolerances | Connecting the precast elements properly |
| 5 | Scope changes | Construction sequence |
| 6 | Detailing of levels | Transport of precast elements |
| 7 | Stability of elements during installation | Crane capacity and access |
| 8 | Size and mass of precast concrete elements | Consultant buys in into concept |
| 9 | Creating structural integrity | Colour consistency |
| 10 | Force transfer between precast elements | Correct standards and quality |

The two lists that are given in Table 3.25 were developed from the results that were obtained from the different questionnaires given to contractors and consultants. The identified concerns or problems were rated by means of votes given from the participants, the concern with the most votes were listed as the most important and the concern with the least votes were listed as least important etc. This method of rating and arranging the different concerns were discussed in sections 3.2 and 3.3 during the question results.

The following aspects were identified when the two different lists were compared to each other:

- The consulting engineers listed the connection details as the most important factor during the design phase and the contractors only listed connection concerns as they're fourth most important factor.
- The consulting engineers listed the contractor's ability to construct the precast method as their second most important concern. In comparison where the contractors listed a similar concern as the consulting engineer buying into the method of precast concrete only as their 8$^{th}$ most important concern. From this result it can thus be seen that the consulting engineers have a big concern with the contractor's ability to construct the precast method and connections. This result can also be interpreted in a way that the consultants questions the contractor's ability in working with precast, also stating that this may be one of the reasons why precast is not that frequently used in the South African construction industry (Fagan 2014).
- The contractors listed correct and accurate levels as their most important concern and the consulting engineers only listed it as their 6$^{th}$ most important aspect. This concern is listed as the most important concern for contractors because if the levels for the precast concrete elements deviate, it will affect the entire layout and positioning of the precast elements as well as the connections.
- The contractors listed accurate tolerances and stability of the precast elements during construction as an important concern where it was listed quite low by the consulting engineers.

It can thus be observed that there are definite similarities included in both these list, the only significant difference is the order of importance in which the two groups rated their concerns. These results may be due to the fact that the consultants are more concerned about factors that may affect the design of precast concrete and the contractors are more concerned about the factors affecting the construction process of precast concrete units.

### 3.4.5 – Comparing quality, time and cost of Precast vs. In-situ

The contractors and consultants were asked to state what construction technique delivers the best quality, least cost, and best time-efficiency according to their knowledge and previous experiences. Table 3.26 illustrates the answers that were given from the contractors and consultants that participated in the survey.

**Table 3.26 - Cost, quality and time comparison between in-situ and precast**

| Consulting engineers | | |
|---|---|---|
| | Precast | In-situ |
| Cost | 33% | 67% |
| Time-efficiency | 100% | 0% |
| Quality | 92% | 8% |
| **Contractors** | | |
| | Precast | In-situ |
| Cost | 10% | 90% |
| Time-efficiency | 80% | 20% |
| Quality | 90% | 10% |

Both groups agreed that in-situ concrete delivers the more cost effective construction alternative, but stated that precast delivers a more enhanced product in terms of quality and time-efficiency, given if it is designed and constructed properly. The fact that both groups stated that in-situ delivers a more cost effective product, may be identified as one of the main factors why precast construction is still relatively underutilized when compared to in-situ construction.

### 3.4.6 – Contractors and Consultants comments on lack of implementation and use of precast concrete in the South African construction industry

The question asked the contractors as well as the consultant to state if they think that there is a lack of implementation and knowledge of precast concrete in the South African construction industry. The answers of the two different groups were given as the following:

- **Consultants:** It was found that **94%** of the consultants that participated in the survey or that were interviewed said that the South-African civil engineering industry does have a lack of efficient knowledge and implementation of precast concrete.
- **Contractors:** It was identified that **95%** of all the contractors that participated in the survey, stated that there is an evident lack of exposure and implimentation of precast concrete in the civil engineering as well as building industry of South Africa.

The contractors and consultants that participated in the questionnaire were also asked to state some of their reasons why they think there is a lack of implementation and knowledge of precast concrete design and construction. Some of the more popular comments according to the consultants and contractors are listed in Table 3.27. (The ↔ symbol indicates similar reasons identified by the two groups)

**Table 3.27 - Popular reasons for lack of precast concrete in the construction industry**

| Most popular reasons for lack of precast in South African Industry | | |
|---|---|---|
| **Consultants** | | **Contractors** |
| .Engineers in South Africa don't know how to design precast and nobody teaches them how to do it. | ↔ | Lack of exposure for designers and contractors |
| Engineers in the industry have not developed the required skills and knowledge to develop this concept adequately. | ↔ | This is mostly due to a shortage of experts with sufficient knowledge of design and construction of precast concrete in the industry |
| Shortcoming in the contract types for use of precast as well as a communication gap between consultants and contractors in terms of the use of precast concrete. | | Some engineers are reluctant in learning new techniques, and they rather trust their older ways of doing things |
| The fact that in-situ have been used for many years and people have become comfortable with using this method. | ↔ | Consultants prefer designing for in-situ |
| It is easier (and safer) to use the conventional method of in-situ if one does not understand the principles of a new system. | | Labour rates are generally cheap and we are encouraged by government to create jobs |
| Precast is suitable for certain applications, the correct applications are not properly marketed. | | There is a shortage of standardized precast concrete elements in different construction projects, making it more expensive method of |
| Precast only offer solutions for very specific problems. | | The cost of precast construction is still too much when compared to in-situ concrete construction |

When considering the answers, it can be seen that there is similar concerns or opinions mentioned by the contractors as well as the consultants. One of the major aspects that was identified when considering the contents of Table 3.27 is that there is a present lack of implementation, knowledge and exposure of precast concrete design and construction in the engineering industry of South Africa. The following comments given in Table 3.27, concludes the opinion that there is a lack of precast in the construction industry of South Africa:

- "There is a lack of exposure for designers and contractors" (Burnham 2014)
- "It is easier to use the conventional method of in-situ if one does not understand the principles of a new system" (De Lange 2014)
- "The cost of precast construction is still too much when compared to in-situ construction" (De Villiers 2014)

## 3.4.7 – Comparison of connection ratings according to the consultants and the contractors

During the survey both groups were asked to rate the precast connections that were identified from the literature study (Chapter 2). The type of connections that were rated was connections that are typically found in precast or hybrid concrete frame buildings. A graphical illustration of all the types of connections can be also be seen in Annexure B. The participants were asked to give a rating out of 5, 5 being the most favourable connection to design or construct and 1 being the least favourable to construct. After all the ratings were obtained from the participants answers stated in the survey, the different connections types were awarded an average rating out of 5 (the rating scale for contractors and consultants are included in sections 3.2 and 3.3). The following part of the section, the average ratings of the contractors' choice will be compared to the average ratings of the consultants' choice.

### 3.4.7.1 – Column-to-Footing connection

The ratings given in Table 3.28, indicates the connection type that the; (i) consultants choose to design, and (ii) the contractors choose to construct. The ratings expressed in Table 3.28, are average ratings that were obtained from the answers of the completed questionnaires.

**Table 3.28 - Ratings of Column-to-Footing connection types**

| | | Consultants | Contractors |
|---|---|---|---|
| Column-to-Footing | Connection type | Average rating | Average rating |
| | Pocket foundation | 3 | 2 |
| | Steel baseplate | 2.94 | 2.4 |
| | Dowel connection | 3.5 | 3.8 |

**- Conclusions on column-to-footing connection types:**

The ratings that were given for column-to-footing connections are very similar for both the contractors and consultants. The contractors listed the pocket foundation as least popular because it is not used frequently and the detail may become too large if the column's dimensions become too big. Both parties listed the dowel connection as their most popular connection type to design and construct. The dowel connection includes a cast in-situ element and it was found that that both parties feel more comfortable using techniques that include elements of cast in-situ construction. There was however a few concerns with this type of connection, mostly the filling of the voids and also some tolerance issues were discussed.

### 3.4.7.2 – Column-to-column connection types

The ratings given in Table 3.29, indicates the connection type that the; (i) consultants choose to design, and (ii) the contractors choose to construct. The ratings expressed in Table 3.29, are average ratings that were obtained from the answers of the completed questionnaires.

**Table 3.29 - Ratings of Column-to-Column connection types**

| | | Consultants | Contractors |
|---|---|---|---|
| Column-to-Column | Connection type | Average rating | Average rating |
| | Column shoe | 2.8 | 2.5 |
| | Welded plate | 2.15 | 1.4 |
| | Dowel connection | 3.5 | 3.4 |

**- Conclusions on ratings for column-to-column connections:**

From Table 3.29 it can be seen that both groups listed the different connection types in the same order. It was found that welded connection types are not very popular and is not preferred by either the contractors or the consultants. Welding on site requires a specialist welder and usually leads to extra costs and requires time to install, this method is preferred for steel construction. The dowel connection was rated the most popular connection, mainly because it includes an in-situ construction component. The column shoe was identified as an unfamiliar connection type, and many contractors and consultants mentioned that it may be an expensive detail to implement in the South African construction industry.

### 3.4.7.3 – Beam-to-Column connection types

The ratings given in Table 3.30, indicates the connection type that the; (i) consultants choose to design, and (ii) the contractors choose to construct. The ratings expressed in Table 3.30, are average ratings that were obtained from the answers of the completed questionnaires.

**Table 3.30 - Ratings of Beam-to-Column connection types**

| | | Consultants | Contractors |
|---|---|---|---|
| Beam-to-Column | Connection type | Average rating | Average rating |
| | Steel billet | 2.2 | 2.2 |
| | Welded plate | 2.6 | 1.9 |
| | Hidden corbel | 2.4 | 2 |
| | Corbel connection | 4.2 | 4.6 |

**- Conclusions on ratings for beam-to-column connections:**

Again it can be seen that the steel billet and welded steel plate connection types are not very popular for design and construction processes, mostly because both requires welding details. The ratings for both parties are somewhat similar and both voted for the concrete corbel connection as the most favourable connection type. The contractors and the consultants mentioned that the corbel connection is widely used in the construction industry and it's relatively simple to design and construct. The corbel connection is usually designed by means of the Strut-and-tie method that will be further discussed in Chapter 3 of the report. This connection type is also preferred because it includes an in-situ concrete construction component.

## 3.4.7.4 – Floor-to-Floor connection type

The ratings given in Table 3.31, indicates the connection type that the; (i) consultants choose to design, and (ii) the contractors choose to construct. The ratings expressed in Table 3.31, are average ratings that were obtained from the answers of the completed questionnaires.

**Table 3.31 - Ratings of Floor-to-Floor connection types**

| | | Consultants | Contractors |
|---|---|---|---|
| Floor-to-Floor | Connection type | Average rating | Average rating |
| | Grouted connection | 3.94 | 3.8 |
| | Welded or bolted | 2 | 1.7 |
| | Reinforced topping | 3.75 | 4 |
| | Loop connection | 3.82 | 3.7 |
| | Rib and Block | 3.94 | 3.6 |

**- Conclusions on ratings for floor-to-floor connections:**

Looking at the results Table 3.31, it can be seen that the welded or bolted connection type are not preferred by both of the groups, mainly because welding on-site may be difficult and usually incurs extra cost. The bolted connection also requires high accuracy and small allowable tolerances during installation and assembly. The preferred methods include the grouted connection, reinforced topping and also the rib and block. These connections were identified as easy to design and install and also contain in-situ components which the contractors and consultants are more familiar with.

### 3.4.7.5 – Beam-to-slab connection type

The ratings given in Table 3.32, indicates the connection type that the; (i) consultants choose to design, and (ii) the contractors choose to construct. The ratings expressed in Table 3.32, are average ratings that were obtained from the answers of the completed questionnaires.

**Table 3.32 - Ratings of Beam-to-Slab connection types**

| | | Consultants | Contractors |
|---|---|---|---|
| Beam-to-Slab | Connection type | Average rating | Average rating |
| | Simply supported | 4.13 | 4.4 |
| | Bolted | 2 | 2.3 |
| | Ties and reinforcement | 3.94 | 3.6 |
| | Hollow core slab | 3.81 | 3.9 |
| | Rib and Block | 3.63 | 3.7 |

**- Conclusions on ratings for beam-to-slab connections:**

The bolted connection is not a very popular type of connection, and some of the main reasons given by the contractors and consultants include; (i) Does not compensate for movement in connection area, (ii) small tolerances are allowed, (iii) high precision is required. The preferred connection types were identified as the simply supported connection types, including the hollow-core slab and the rib and block method. Contractors and consultants mentioned that simply supported units are quick to install and easy to construct and the design process is not complicated either. The applications for precast hollow core slabs and the rib and block method may however have limited applications, but is especially used in low rise buildings such as houses, office blocks, hostel residences, schools etc. (Carstens 2014)

## 3.5 – Chapter Conclusions

There were however a limited number of contractors and consultants that participated in the survey, but the results that were obtained provided relevant conclusions and produced valuable information on precast concrete and precast connection concerns that are currently being faced in South African construction industry. Following the results that had been obtained from the surveys, some key findings and conclusions were made. The most significant conclusions and findings were listed as:

1. The majority of consultants and contractors still prefer designing and constructing with in-situ concrete. The participants stated that they are however willing to make more use of precast concrete, but the market does not always promote the use of precast concrete correct and effectively. Concerns such as: (i) familiarity in using in-situ, (ii) low labour costs, (iii) inexperience and insufficient knowledge on using precast and, (iii) a reluctance in learning new alternative methods all contribute to the lack of precast usage in the construction and building industry of South Africa.
2. It was found that there is a limited variety of precast concrete units that are frequently being used in the industry. The precast elements that are currently being used mostly include simpler forms of precast such as precast or hollow core slabs, small beams and columns and other various basic simply supported precast elements. The reason for this limited usage of precast elements, results mainly because precast concrete are not well marketed and there is insufficient training available. The majority of the survey participants also mentioned that they prefer making use of in-situ concrete, mainly because they have been using this method for decades and feel comfortable with its usage during the design and construction phases of a project.
3. Contractors and consultants have concerns with the use of precast concrete as well as the design and construction of connections. The two groups mostly agree on some of the concerns, but it was noted that the consultants are more focussed on the design aspects of the precast concrete which included aspects such as the connections, seismic considerations, force transfer and force flow etc. Contractors are however more focussed on construction or assembly considerations that included: accurate levels and setting out, tolerance issues, stability during the installation process etc. The concerns that were identified by the contractors and consultants do however relate with similar concerns that were identified during the literature study in Chapter 2 (connection concerns were listed in Chapter 2, Tables 2.2 to 2.8).
4. When the contractors and consultants were asked to compare in-situ and precast construction in terms of quality, cost and time efficiency the results were remarkably surprising. The majority of both groups stated that precast construction delivers better quality and time-

efficiency, but in-situ construction still delivers the best alternative in terms of cost. Cost is however the most considerable factor when pricing a project and is also one of the main reasons why consultants and contractors still tend to make more use of in-situ construction.

5. It was found that 95% of contractors and consultants that participated in the survey identified that there is a lack of understanding and implementation of precast concrete in the South African construction and building industry. Considering that the majority of participants said that there is a lack of implementation and sufficient understanding of precast concrete in the South African industry, it can be concluded that precast construction needs to be more effectively marketed and the required skills and correct applications needs to be implemented and developed. Too little use and slow development have made precast concrete construction to be considered as uneconomical, inefficient and too expensive in the South African industry.
6. Another major aspect that contributes to the lack of implementation and exposure of precast construction in the South African industry is the economy. A construction method should be economically viable in order to be implemented successfully. There is no doubt that precast concrete has its place in the industry, but from an economic perspective, as long as it makes more sense to make use of in-situ construction, precast will mostly play a secondary role.
7. Connections still remain a very important aspect in terms of design and construction of precast concrete. The contractors and consultants that participated in the survey mostly share the same connection preferences in terms of connections found in precast concrete frame buildings. This result was identified when the average ratings of the different connection types were compared to each other. It was found that precast connections that included a cast in-situ component or aspect were preferred over other alternatives. The same was found for connection types that do not include too complicated and intricate design and construction details. Simply supported connection types that are quick and easy to construct were chosen over bolted, welded or grouted connection types. Table 3.33 provides connection preferences that were obtained from the results of the survey.
8. It was found that the some of the contractors and consultants that participated in the survey had limited experience and exposure to precast design and construction. It was however found that all the contractors and consultants that participated, have many years of experience in the design and construction industry of South Africa, thus making their comments and recommendations relevant for this study.

**Table 3.33 - Preferred connection characteristics**

| Characteristics for preferred connection methods | |
|---|---|
| **Consultants** | **Contractors** |
| Connections should provide allowable tolerances | Connections should provide allowable tolerances |
| Connections must provide efficient force transfer and flow or forces | Connections that include in-situ components are preferred |
| Prefer designing connections that include elements of in-situ concrete | Standardizes connection methods – ensures quick and easy assembly |
| Prefer connections that provides good stability requirements | Provide accurate levels during setting out and assembly |
| Prefer connections that has a high shear capacity | Connections that ensures instant stability is preferred |
| Precast connections should compensates for movements (restricted and unconstrained) | Simply supported connection types are easy and fast to construct |
| The connection method should be able to compensate for scope changes during the project. | The size, complexity and all the components of precast element and its connection must be easy to transport |

The results that were obtained from the surveys have been effective and can be used as guidelines or recommendations to help improve the design and construction of precast concrete in the South African construction industry. When analysing the results of the connection types that were rated, it can be seen which types of precast connections the majority of the designers and contractors prefer to make use of. The preferred connection types can thus be further marketed and improved to assist industry participants to make more use of precast concrete in the South African construction and building industry. The results from the questionnaires also identified certain areas that require additional consideration during the design and construction phase of precast concrete and precast connections. The following important concerns were identified and will be discussed during the remainder of this report:

- The design forces and force considerations for precast connections (Chapter 4),
- Considering precast concrete connection design according to the South African design code, and comparing the South African codes to other international codes (Chapter 5),
- Consider alternative solutions or enhancement methods for precast concrete connections that may address or solve some of the problems that were raised during the answers of the surveys (Chapter 6).

# CHAPTER 4 – BASIC CONSIDERATIONS AND DESIGN FORCES OF PRECAST CONNECTIONS

This chapter includes basic considerations associated with the design of precast concrete connections. In this chapter a discussion on the critical aspects of design forces for connections will be included as well as the force transfer between concrete elements and the important role connections play during this process. A summarised view of the contents of this chapter is displayed in the Figure 4.1.

**4.1- Background to precast concrete connection design**

**4.2 – Design philosophy of precast concrete connections**

**4.3 – Force transfer and force connection behaviour**

**4.4 - Design of connection by means of the Strut-and-Tie method**

**4.5 - Chapter Conclusions**

**Figure 4.1 – Contents included in Chapter 4**

**Design aspects for precast concrete connections will be discussed in this Chapter. The focus will be mainly on applicable rules and guidelines for precast connections.*

## 4.1 - Background to precast concrete connection design

The type of connections used between precast concrete members is of much importance to the process of erection and assembly of the precast units. According to (Björn 2006) and (Elliot 2002), there is little doubt that one of the greatest disadvantages of precast concrete construction used to be the concerns including the connections between the precast elements. There has been great progress in terms of new and improved connections and new developments of various connection types have been frequently tested and implemented in the international precast construction industry. Contractors and designers do however tend to struggle with the design and construction of the connections found in precast or hybrid concrete buildings. (Elliot 2002)

It is necessary to clearly define the properties of the connections that are required for methods of erection and construction. According to (Elliot 2002) a short solution to improve and address the identified problems may include the following aspects, which are discussed below:

- Improve the structures' geometrical accuracy;
- Enhance stability during erection; and
- Apply more simplicity during design and construction

***(1). Geometrical accuracy* –** The geometrical accuracy is the fundamental requirement for a joint or connection of precast units. If the structural skeleton built up from precast members is not accurate in its dimensions, the panel sizes of the building will also be inaccurate. Geometrical accuracy also affects the structural integrity of the building, which in its turn is an important design aspect for any precast or hybrid concrete building.

***(2). Stability during erection* –** If the type of connection do not allow for immediate and automatic fixation of the precast elements in final position, additional measures have to be taken to assure the stability of the connected precast elements..

***(3). Simplicity in terms of design and construction*** – This influences not only the speed of erection but also the amount of skilled labour required to install the connection. Simplicity of design also goes hand in hand with standardization of precast elements and connections that are used. Maximizing the amount of standardized elements and connections between elements also improve the design process and speeds up the construction phase.

The above mentioned aspects should be taken into account during the design and construction of any precast concrete structure or building. During the design of a precast or hybrid concrete building, it is required that all the precast members should be designed to provide full structural continuity, it is thus important to verify the suitability of the precast structure by means of two designs:

1) One for the precast members itself, before the connections are made, and
2) One for the continuous structure after the connections has been completed.

When precast members are connected by rigid connections or joints to form a framed structure, the stresses in the concrete may be re-distributed by the effect of creep (creep may affect the rigid connection in such a manner that the connection may eventually fail). Connections should be designed always with a clear conception of the flow of stresses from one member into the other one. The more uniform the flow of stresses through the connection, the better the quality of the connection (Björn 2006).

A structural precast concrete connection consists of several components that interact with each other when the connection or joint is loaded. Typical connection components and methods that are found in precast concrete connection zones can be as follows:

- Mortar joints and joint fills,
- Tie bars,
- Steel reinforcement couplers,
- Anchor bolts,
- Welds or welding plates,
- Structural steel inserts,
- Reinforcement dowels,
- High strength concrete or grout, and
- Bearing plates

The appropriate connection type and connection components should be chosen according to the specific design and construction process and should also adhere to the laws of structural functionality and continuity. Different connection types are chosen to fulfil different requirements usually set by the client, designer or contractor. The chosen connection type will also be dependent on the type of precast structure that will be built as well as the purpose of the structure that will be built e.g. office block, flat block, school etc. Figure 4.2 provides an illustration of the different components present in a typical structural precast connection. The structural behaviour and the performance of the connection depend on the interaction between the components shown in Figure 4.2.

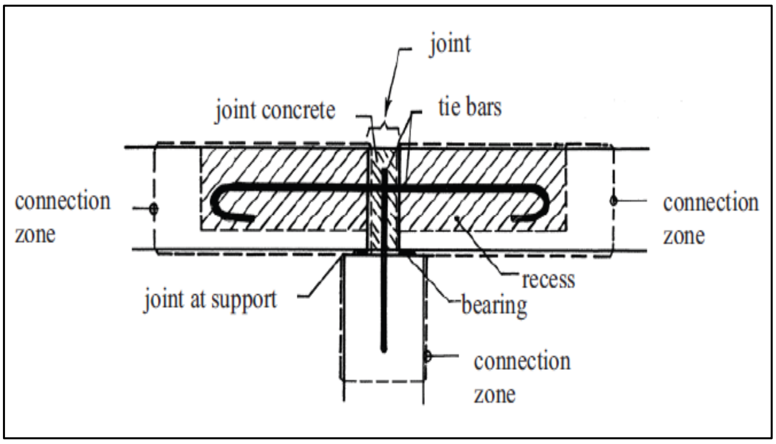



**Figure 4.2 - Structural connection with different components (FIB - Féd. Int. du Béton 2002)**

## 4.2 - Design philosophy for precast concrete connections

When designing precast concrete elements and connections, all loadings, load combinations and restraint conditions from the manufacturing of the elements right through to the end use of the structure should be considered. The stresses that develop in precast elements during the period from manufacturing until it is finally connected in the structure may be more critical than the service load stresses that were calculated. Special attention should also be given to the methods of stripping, storing, transporting and erection of the precast elements. (Engström 2007)

Another very significant factor is that precast concrete elements and their connections should be designed to adhere to tolerance requirements. The behaviour of precast members and their connections is very sensitive to tolerances, thus requiring that high accuracy should be attained during the design and construction processes (Engström 2007). The design should incorporate the effects of adverse combinations of fabrication as well as erection tolerances. Tolerances and their requirements should be listed in the contract, design documents, and may also be specified by reference to accepted standards (Paradigm 2008).

Figure 4.3 illustrates the different components that are included in the design process of precast concrete and precast connections. All the components listed in Fig. 4.3 will be discussed in the following sections of the chapter.

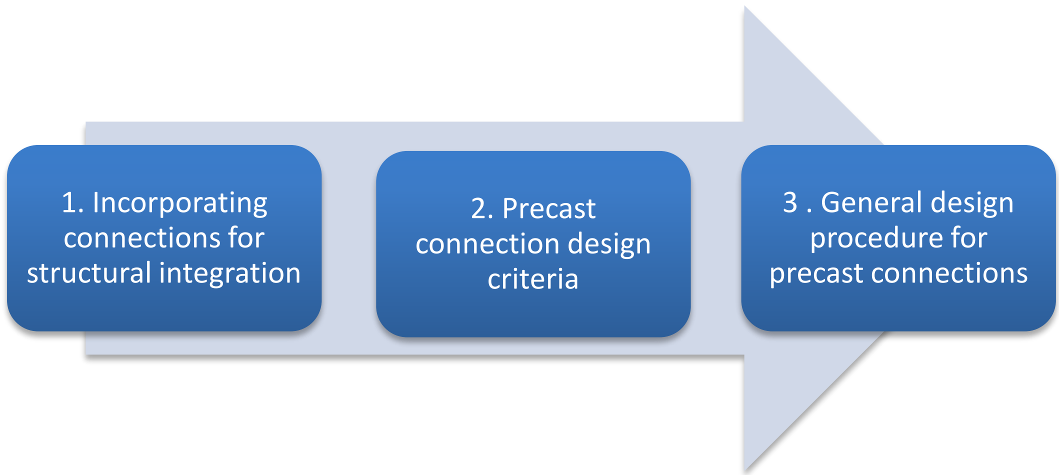



**Figure 4.3 – Components of precast connection design**

### 4.2.1 - Incorporating connections for structural integration

According to (PCI - Designing with Precast and Pre-stressed concrete 2010), the design of precast concrete structures mainly depends on the integration of the structural system as a whole, the connections as well as the individual precast concrete components.

The main structural difference between cast in-situ and precast structures is found in the way or method in which overall structural continuity is achieved. The cast in-situ method does not make use of connections, and the reinforced concrete structure is analysed and designed as a whole. For precast concrete structures, a conscious effort must be undertaken to ensure structural continuity when precast elements are put in place and connected together. The precast connection may act as bridging link between the elements, forming a structural "chain" eventually linking every element to the stabilising elements such as shear walls or core of the structure. (Brzev 1994)

The precast structure must eventually be robust and adequately designed against progressive collapse, structural failure, cracking and unacceptable deformations. The stability of the structural system and its different parts has to be approved during all stages of the erection process as well as its full service life. Consultation with the architect should be done in early stages of the project in order to bring the structural and precast concrete concepts together. According to (Task Group 6:2: A.Van Acker et al 2010), the most significant factors that should be considered for incorporating precast connections for structural integration includes:

- The position of the stabilising structural elements;
- The different types of precast elements that will be incorporated in the design and construction process of the structure or building;
- Connection or joint types that will be used to connect the precast elements;
- Limit state design forces and boundary conditions; and to
- Design the precast concrete structure for overall continuity and to achieve structural integrity.

The design of precast concrete connections found in a building are mostly not just about selecting suitable dimensions for the connection layout, but also considering the force path throughout the connection zone. This important aspect must be considered in a global view, including the whole connection as well as adjacent precast members. A precast connection is not only limited to the connection area itself but is considered to form an essential part of the entire precast or hybrid concrete structure. The examples shown in Figure 4.4, illustrates the importance of the flow of forces through the connection and relates this to the influence it may have on the performance of other structural precast members. (Elliot 2002)

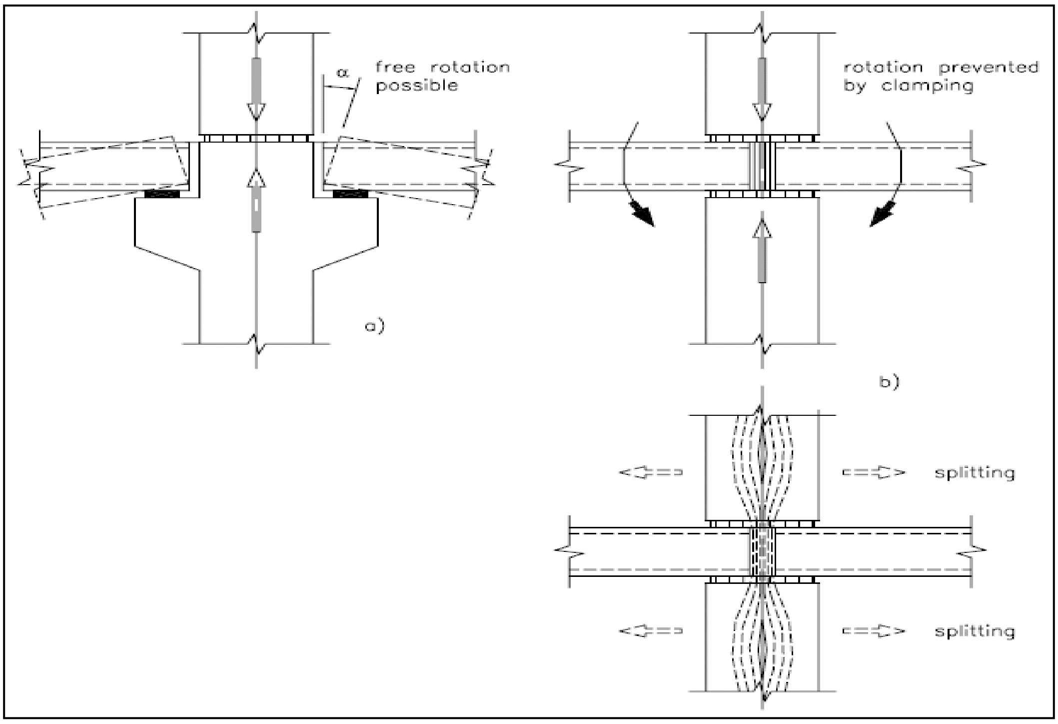



**Figure 4.4 - Two examples of hollow core floor connections (Task Group 6:2: A.Van Acker et al 2010)**

Looking at Figure 4.4 it can be concluded that sufficient attention should be spent on connection details such as the anchorage of tie bars, creating a strong connection method and also considering the connection zone of adjacent structural members. The forces found in typical tying connections, (support bearings, projecting bars etc.) that are transferred into the adjacent precast concrete elements should be secured by proper design and detailing of the connection zones. In the next section of the chapter, typical developed design criteria for precast connections are discussed.

### 4.2.2 – Precast connection design criteria

Precast connections should meet a selection of design as well as performance criteria. A suitable precast connection design should include the following important aspects (FIB - Féd. Int. du Béton 2002):

- The connection under consideration should be able to resist the ultimate design forces in a ductile manner,
- Precast concrete elements should be manufactured economically, this includes considering the handling, transport and erection processes of the element,
- Tolerances for manufacturing and site erection should not influence or affect the intended structural purpose of the connection, and
- The final connection appearance should satisfy; fire resistance, durability and other aesthetical requirements.

The design forces found in a concrete building can be summarised as the following; (i) the transfer of compressive forces, (ii) tensile forces, (iii) shear forces, (iv) bending moments, (v) torsional moments and, (vi) forces formed by intended and unintended eccentricities. The connection's ability to transfer forces should always fulfil the requirements set by the ultimate limit state (ULS) and the serviceability limit state (SLS) included in the design codes under consideration.

Additional capacity may be required to resist accidental loads. These accidental loads may occur due to foundation settlements, explosions, natural hazards or collisions. Such loads may be accommodated in the connections with a capacity for overload, by means of ductility within the connection, or by redundancy (alternate load paths) in the total structure or within the connection. (Task Group 6:2: A.Van Acker et al 2010)

## 4.2.3 – General design procedure for precast connections

It has been found that many precast concrete companies, manufacturers or designers have their own design philosophy according to their own capabilities, experience and knowledge of designing precast structures. According to (Walraven 2013) and (FIB - Féd Int. du Béton 2002) a typical precast design philosophy should include the following general guidelines:

1. The concrete structure under consideration should be designed as a precast concrete structure right from the beginning and should not merely be seen as an assembly of in-situ parts.
2. The variation of precast elements included in the overall precast structure should be kept to a minimum. This will ease the design as well as the construction phase of the structure.
3. The precast elements' shape and design should be kept as simple as possible. This could avoid over complicated design aspects and evidently save time and cost during the project execution. Figure 4.5 (figures a, and b) shows the difference between a simple precast design and an over complicated precast and connection design.

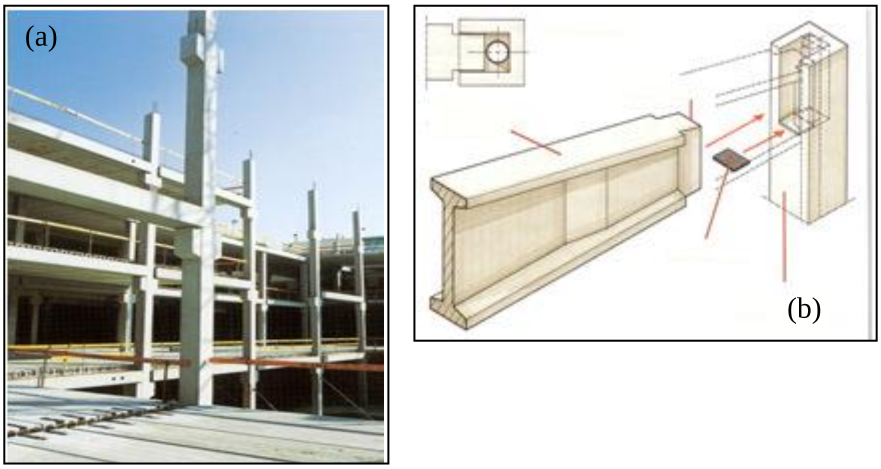



**Figure 4.5 - (a) illustrates a simple precast design, (b) more complicated precast design (Walraven 2013), (FIB - Féd Int. du Béton 2002)**

4. The precast elements should not be designed to be too large. There are restrictions due to transport of the precast elements and complications with the connections if the precast elements become too large.
5. Preferably use as little in-situ concrete as possible. In-situ concrete or high strength grout can be used for grouted connections as exception. In-situ concrete may often lead to delays and small volumes of in-situ concrete are more difficult to use than larger volumes.

**6.** Preferably design in such a way that the structure is stable during all stages. This is mostly focussed on stability of the precast elements as well as the overall precast structure. Figure 4.6 shows two different systems used for (a) inappropriate precasting system, and (a) system suitable for precast. (FIB - Féd Int. du Béton 2002)

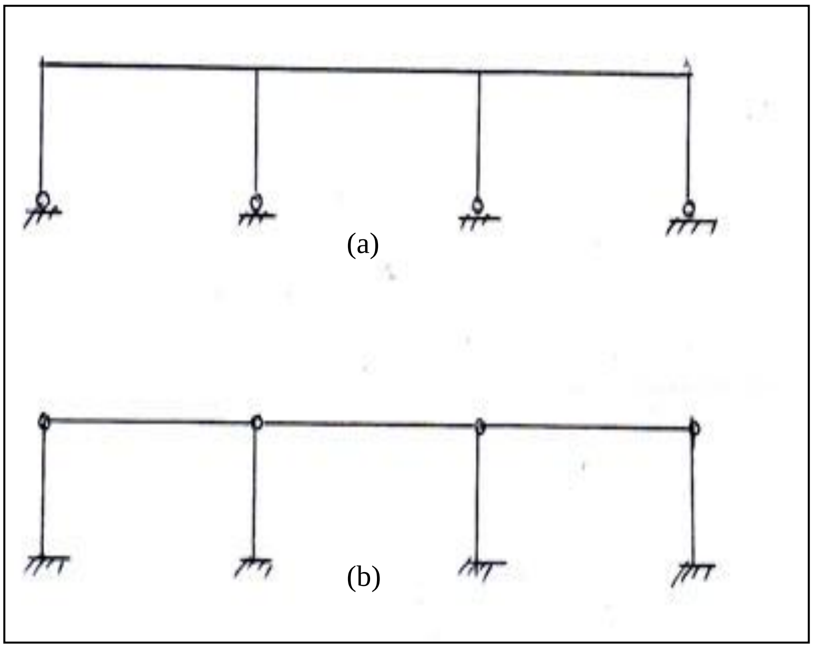



**Figure 4.6 - Preferable method for stable design (Walraven 2013)**

**(a) - Static systems inappropriate for pre-casting:**

- Columns have to stabilized in construction stage,
- Moment resistant connections, column-to-beam connections requires cast in situ concrete in small volumes

**(b) - Static system suitable for pre-casting:**

- Columns are stable in construction stage,
- Hinged connection is easily achieved by means of simple support.

**7.** Take due account of connection tolerances. The allowable tolerances for specific precast connections may be minimal due to restraints or limitations that should be met by the connection and its purpose. Different types of tolerances that should be accounted for are illustrated in Figure 4.7 on the next page.

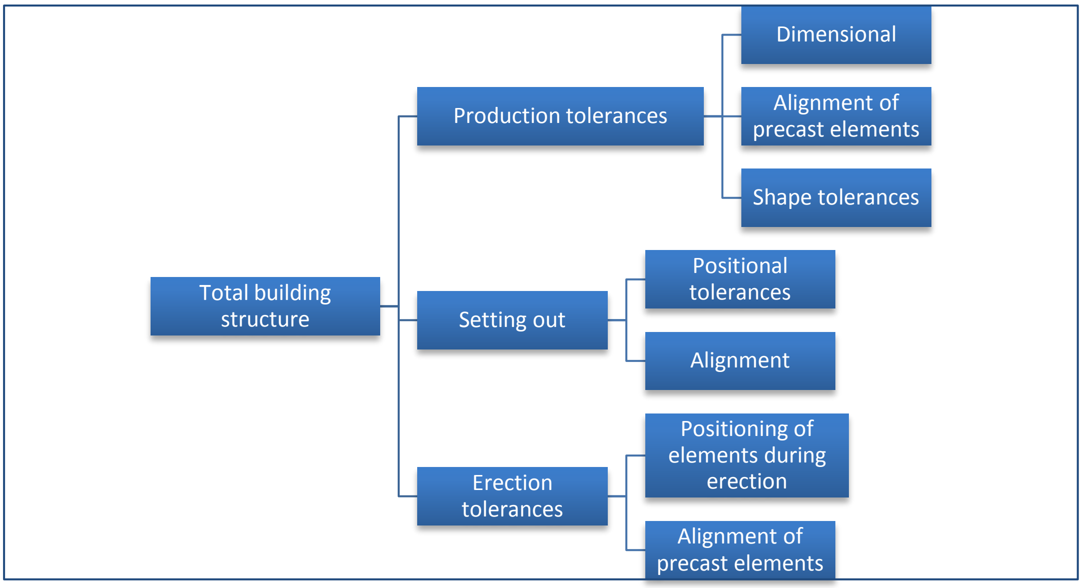



**Figure 4.7 - Appropriate tolerances for precast connections (European Commission - Joint research centre 2012)**

**8.** Use as much as possible standardized precast elements and connection types that are readily available. Standard precast products are usually cast in existing moulds. The designer can select the length, dimensions and load bearing capacity within certain limits. This information can be found in catalogues from the manufacturers of the precast elements.

This list of design guidelines may only be applicable to structures that are built using precast concrete elements. Some designers' or contractors' opinions about these guidelines or philosophies may differ, but it can evidently be used as an appropriate guideline or aid to help make essential decisions during different phases of the precast concrete project.

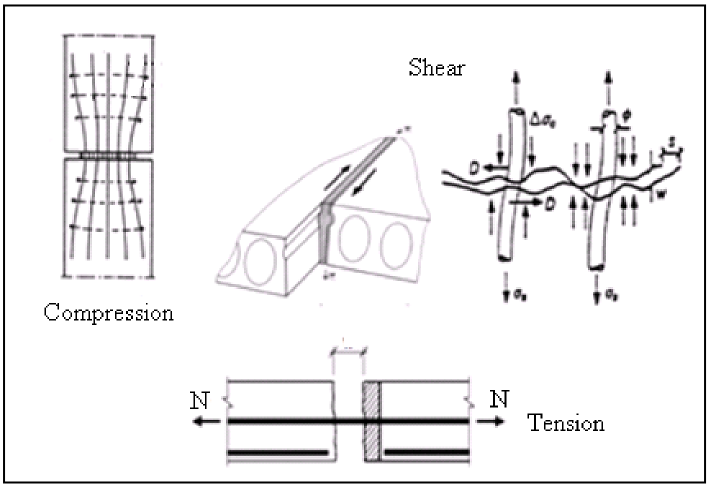
## 4.3 - Force transfer and force connection behaviour

This part of the report contains information on typical forces that are present in precast concrete connections and will discuss the subject of force transfer and the need for movements and constraints in connection zones of precast concrete elements.

### 4.3.1 - Force transfer types

As previously mentioned in Chapter 2 of the report, the connections between the precast members of a structure or building occupy a critical role to ensure overall structural integrity and continuity. To achieve this, design engineers should understand the influence of the connections on the flow of the forces that are applied by means of different loads and load combinations. The reinforcement used in the connection zones are mainly influenced by the different forces acting in or on the precast element and structure itself. It is thus of high importance to identify and investigate all the forces that may influence the precast system to prevent accidents and even structural failure from occurring. (Björn 2006)

The connection between precast elements shall be designed in such a way that they transfer the design forces occurring in the connection zone. The deformation of the connection elements shall also be smaller than the allowable limit, eventually so that the behaviour of the structural system is equivalent to a cast in-situ structural concrete system. According to (Task Group 6:2: A.Van Acker et al 2010), the connection characteristics can be categorised by the type of action it is designed to resist. Figure 4.8 illustrates different applied forces experienced in variations of precast concrete connection types. The forces occurring in a precast connection zone includes:




- Shear,
- Tension,
- Compression,
- Flexure,
- Torsion and,
- Transfer of bending moments

**Figure 4.8 – Illustration of different forces present in precast connections (Engström 2007)**

For many structural precast connections, the behaviour is usually dominated by one of the forces given in the list above. The connection may sometimes be classified by the dominating force present, e.g. "shear" connection, "compression" connection etc. However, the connection should be able to resist or transfer any combination of the following actions (Cheok, Stone et al. 1996):

***(I) - Shear:*** Shear transfer is typically necessary for connections or joints between wall elements as well as floor elements (connections between floor slabs). This includes longitudinal joints between hollow core slabs, because here shear is required, horizontally as well as vertically. Connections found between precast beam elements or floor elements that are covered with an in-situ topping may also require shear resistance to achieve acceptable behaviour in the final state of the structure or building.

***(II) - Tension:*** The connection's ability to transfer tensile forces is normally secured by means of numerous types of tie bars, anchor bars/bolts or some other type of steel connecting device. Tensile capacity of is often essential between wall elements that is used for stabilisation between floor elements and also between precast floors and their supporting structures. Even though it was not the intended design purpose, these connections can also be capable of transferring bending moments, depending on the position of the ties.

***(III) – Compression (bearing):*** It is general knowledge for engineers to know that concrete is stronger in compression than in tension. That is why extra measures are taken to design anchorage and extra reinforcement for connections mostly in tension. The transfer of compressive forces is however also a very important function of connections at horizontal joints, and attention needs to be paid to bearing stresses between precast members.

***(IV) - Flexure:*** Flexural resistance is usually required for instances such as when a precast column is fixed at the base (column-to-foundation connection) or when continuity is required at interior supports of beams and floors. Flexural movement of precast elements should always be compensated for in the design of precast elements and connections. For beam and column connections in moment resisting frames, flexural resistance is also required.

***(V) - Torsion:*** Torsional capacity is mostly required at support connections of simply supported beams or slabs that may be loaded eccentrically with respect to the sectional shear centre. This may occur in the case of one-sided ledge beams used for precast floors.

Figure 4.9 shows: (a) forces present in the overall precast structure as well as, (b) forces present in the local connection areas of precast concrete elements.

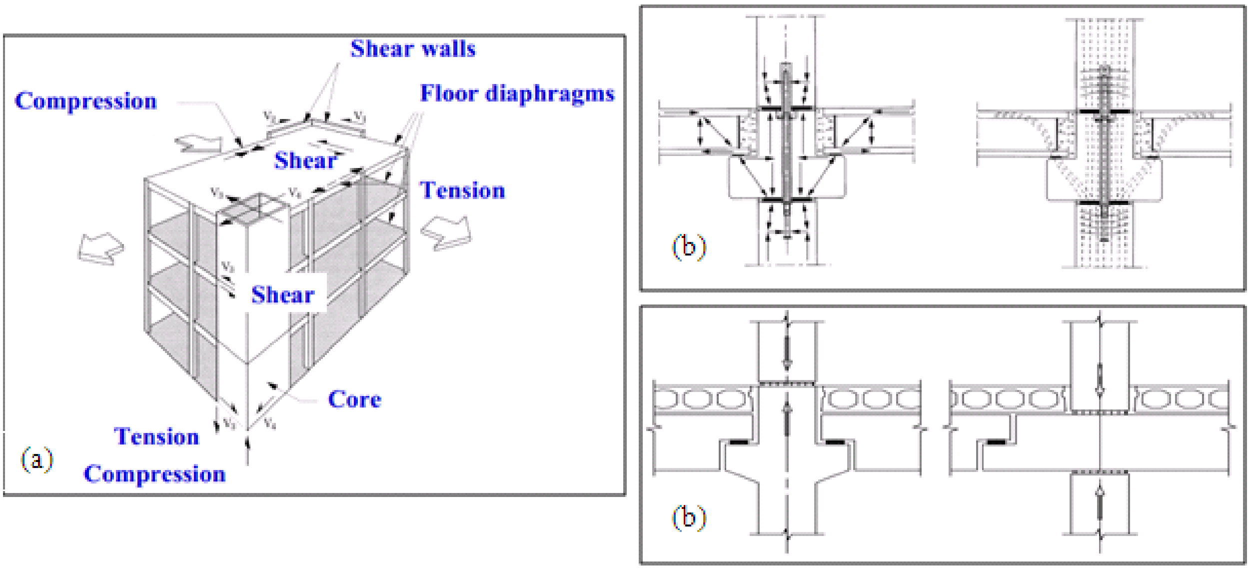



**Figure 4.9 – (a) Force paths in structural precast system, (b) force paths in local connection areas (Engström 2007)**

The following general design procedure and guidelines may be taken into account when designing connections for a precast or hybrid concrete structure or building (Engström 2007) and (Van Acker 1996):

1. Choose a viable connection detail for the specific connection zone present in the precast concrete structure or building. The choice should consider appropriate stress transfer mechanisms which can successfully transfer the design moments and forces. The designer will also have to consider conditions such as deformations, creep, shrinkage, thermal stresses etc.
2. Require a prediction of stresses in the connection element due to design moments and forces.
3. Obtain confirmation of the strength of the connection elements. This value should be greater or equal to the calculated element stresses.
4. Calculate additional deflection due to slip of the connection elements, which should also be within an allowable limit.

Designing precast connections with regard to the ability to transfer forces should be based on the knowledge and understanding of basic force transfer mechanisms, specifically found in precast concrete elements and structures.

## 4.3.2 - Typical example of forces present in a precast connection zone

The interactions of different types of forces that are typically found in a precast concrete connection may be very intricate. The design and detailing of a precast connection is even more significant because of the number of variables and conditions that are typically included. The space available in a connection zone is also limited and ensuring proper anchorage and reinforcement also complicates the design process. Figure 4.10 illustrates the different forces, (discussed in section 4.3.1) present in a typical precast concrete connection zone.

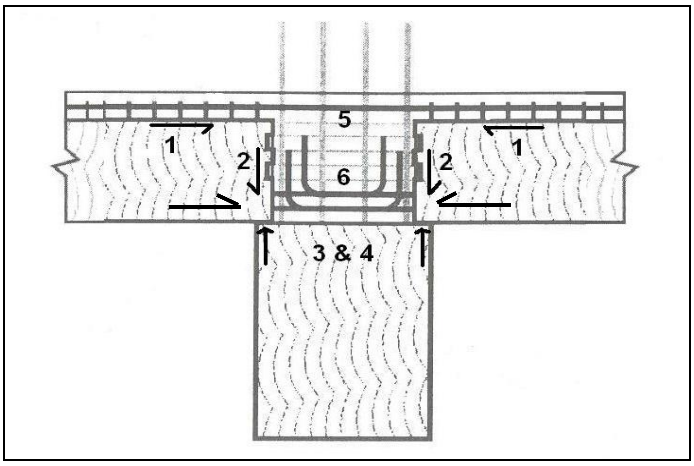



**Figure 4.10 – Typical precast concrete connection and forces acting on the joint area.(Engström 2007)**

The following forces that are numbered in Figure 4.10 may typically occur in the connection zones of precast concrete elements (Engström 2007):

1) Interface shear and bond stresses (between slab panels and supporting beam),
2) Vertical shear or shear friction,
3) Bearing forces,
4) Temporary bearing forces if no propping is provided,
5) Tension force (tension in top reinforcement),
6) Compression force in bottom concrete.

Connection design is considered to be a specialized field and requires expertise and understanding of structural precast design. The strut-and-tie model of analysis has been used as a solution to the problem of intricate connection methods and will be discussed in section 4.4 of this chapter.

### 4.3.3 - Need for movement and restrained deformations in connections

The need for movements in precast connections found in a precast structure or building is mostly due to the service load, concrete creep, shrinkage, temperature deviations, supporting units etc. Movements and deformations found in precast connections is a very important aspect to consider, not only for the design phase but for the entire lifetime of the precast building. Movements are an important factor because a precast connection zone is where various precast elements are assembled and may be constrained by each other. If the need for movement is however not considered when designing connections for precast units, a risk of damage to the connection zones may occur (Cheok, Stone et al. 1996). These damages may be especially dangerous when they occur at support regions which are shown in Figure 4.11.

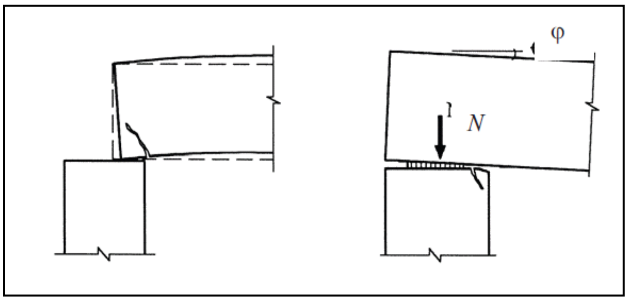



**Figure 4.11 – Example of damages at connection zones (FIB - Féd. Int. du Béton 2002)**

The need for movement in connection zones can be implemented by means of two ways:

**(i) - Detailing the connection so that the movements fully take place without any restraints:** In order for movements to freely occur in connections zones, sliding bearings or hinge details can be implemented. Force transfer can also be obtained by means of gaps, expansion joints, slots etc. This is usually done so that the force is not transferred before the need for movements becomes greater than expected. (FIB - Féd. Int. du Béton 2002)

**(ii) - The other extreme is to fully prevent movements between adjacent precast concrete elements.** During this instance the connection as well as the elements should be designed to resist the resultant restraint forces that will develop in the element or structure. The restraint forces may be significant but it was found that in practice it’s not always possible to prevent these movements from occurring.(FIB - Féd. Int. du Béton 2002)

When small movements is allowed by deformation of the connection details or connection zones, the restraint forces that is present will be significantly smaller than the theoretical values that were calculated under the assumption of full restraint (Engström 2007). A connection design that is primarily based on partial restraint will eventually result in a delivery of movements in the structural system instead of concentration movements specifically for joints or connections.

This may lead to cracking in grouted joints or cast in-situ concrete toppings of floors panels. For the purpose of this case, the precast concrete connections should be designed so that only single, wide cracks are prevented from occurring. Special consideration is required in areas where cross-sections are changed suddenly and where the need for movements can be particularly large. (Engström 2007)

#### *4.3.3.1- Unintended restraint action*

Precast concrete elements are mostly designed to be simply supported; this ensures quick delivery and fast erection of precast structures. There is usually a difference between the conceptual idea of connection behaviour and the eventual conditions of the completed or constructed connection – an example of this can be seen in Figure 4.12. During the concept design a simple mechanical model was assumed to have pinned support at the connection. However for several reasons which may include; the need for structural interaction between the walls and floors and also the necessity for structural integrity and robustness, the connections were completed using reinforced concrete to create a 'so-called' unintended restraint.

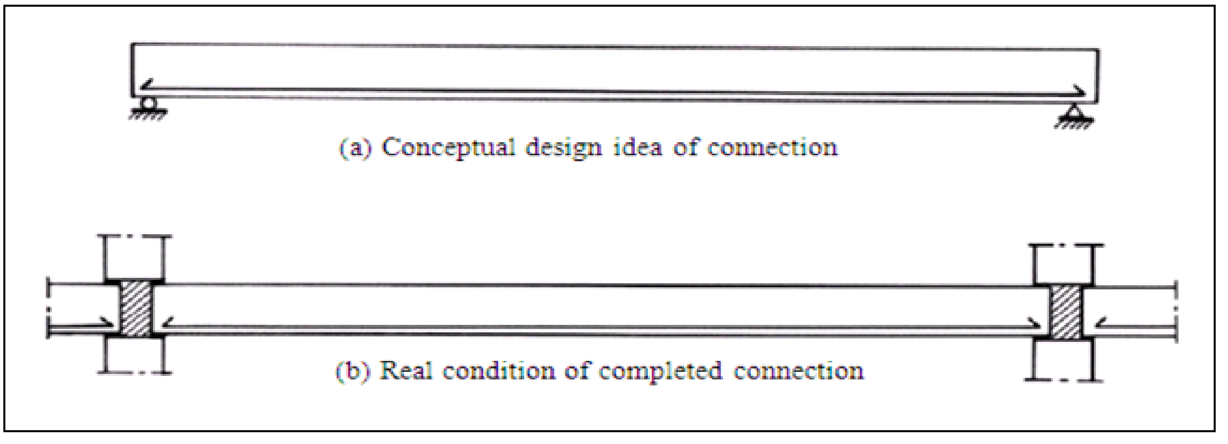



**Figure 4.12 - – Illustration of unintended restraint for connection detail (FIB - Féd. Int. du Béton 2002)**

In most instances the precast elements and connections are strong enough to resist the stresses that occur from the unintended restraint. In some cases the tensile stresses that developed may result in cracks and can be very dangerous if formed in load bearing elements. If the unintended restraints are ignored in the design of the connections and elements themselves, the consequences should be evaluated and suitable measures must be taken to avoid possible problems or failures. Unintended restraints in precast concrete connections are often overlooked and this effect may lead to ineffective connection design which can adversely have a result on the strength, continuity and integrity of the connection as well as other parts of the precast or hybrid concrete structure.

## 4.4 - Design of connections by means of the Strut & Tie method

The Strut-and-tie method (STM) is progressively being used for analysis and design of concrete structures with regions in which the basic assumptions of flexural theory are not applicable, which is called D-regions. These D-regions usually include regions near force discontinuities or near geometric discontinuities. The main advantage of the STM method should be its transparency and adaptability for its use in pre-stressed and precast concrete members. (K.C.G. Ong , J.B. Hao, P. Paramasivam 8 March 2005)

### 4.4.1 - Design concept of the strut-and-ie method (STM)

The strut-and-tie method has a specific method of designing the region or connection zone where forces are highly concentrated. The internal stresses due to the applied loading in the concrete structural elements are transferred through an assumed plane or space truss mechanism, to the supports. Forces in these connection zones often deviate (i.e. change directions). The spread of stresses often leads to high transverse stresses occurring in the connection zone. If the concrete tensile strength is reached, cracks will appear in the tension zones. In the case of improper detailing these cracks might result in damages, which in turn may limit the capacity of the connection and the precast element. (E.g. it may lead to concrete splitting and eventually connection failure)

For the purpose of designing according to the STM, different regions in the precast members should be identified. The two regions that have been identified, includes B-regions and D-regions in the concrete elements. According to (Task Group 6:2: A.Van Acker et al 2010), the definition of D-and B-regions is as follows:

***B-regions:*** In the B-regions, the hypothesis of Bernoulli of a linear strain distribution across the section can be applied. Here the sections can be analysed and designed according the traditional approach for reinforced or pre-stressed concrete cross-sections subjected to bending moment with or without an axial force. These regions can be designed using traditional methods for bending, shear and axial forces.

***D-regions:*** In the D-regions (discontinuity or disturbed regions) the strain distribution can deviate considerably from a linear one and other methods are required for analysis and design. Because of geometrical and static discontinuities in the structural connections, the connections zones in precast systems should be considered as discontinuity regions.

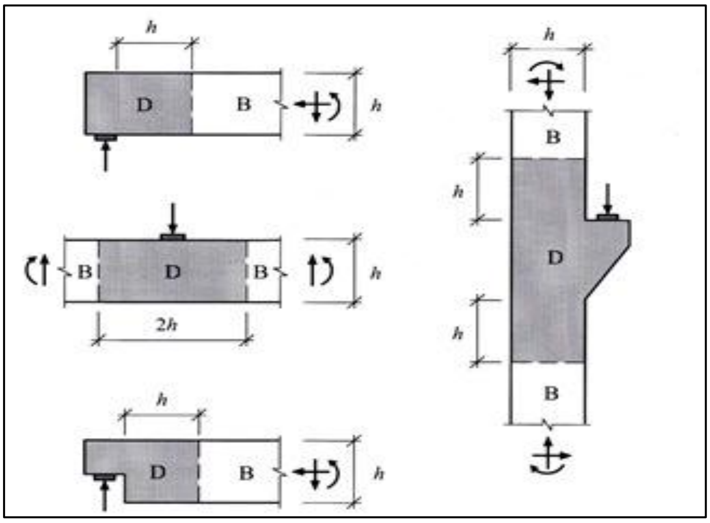



Figure 4.13 illustrates where these two regions are located in some of the precast elements. The STM are typically used for the design of D-regions where discontinuity in the elements are located

**Figure 4.13 - Example of D-regions in structural elements (Walraven 2013)**

The strut-and-tie method is an appropriate tool to design the connections zones located in precast concrete elements and also to check that the equilibrium conditions are satisfied in the ultimate limit state design. This method uses the flow of forces through the structural connection and helps the designer to understand the member behaviour and also to design proper detailing. The strut-and-tie method is most commonly used for precast connection details such as; (i) a column head, and also a (ii) column corbel shown in Figure 4.14. (Walraven 2013)

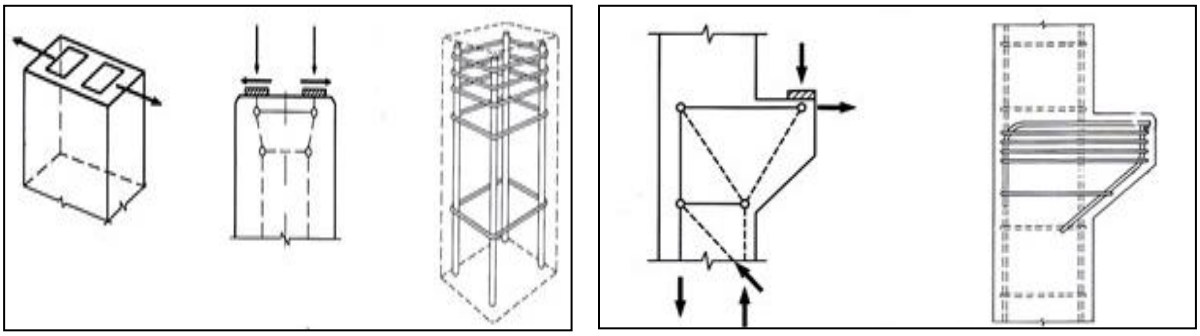


**Figure 4.14 - STM design, (i) column head and (ii) column corbel (Walraven 2013)**

The strut-and-tie method is based on the theory of plasticity, giving a theoretical lower bound solution. This actually means that the failure load is calculated on the basis that the capacity of the chosen strut-and-tie model will be smaller or equal to the theoretical correct failure load. The designer will choose a strut-and-tie model that simulates the stress field in the reinforced concrete and remains in equilibrium with the imposed design load and design and detail of the connection zones shown in Figure 4.13.(K.C.G. Ong , J.B. Hao, P. Paramasivam 8 March 2005)

The Strut-and-tie method consists out of a few elements and these elements include ties, struts and nodes, which are usually chosen with regard to their strengths. As long as the chosen stress field is in equilibrium with the applied load and no critical regions are overstressed above their strengths, the stress field is theoretically possible.

The model provides a rational approach and represents a complex structural member with an appropriate simplified truss model. There is no single, unique STM for most design situations. There are, however, some guidelines, techniques and rules available, which help the designer, develop an appropriate model. The basic design philosophy behind the STM has been described by (Fu 2001) as the following: It is a conceptual framework where the stress distribution in a structure is idealized as a system of:

1) (1). **Struts** – Member in compression (concrete). The strut serves as a compression chord of the truss mechanism which resists the moment and it also transfers shear to the support.
2) (2). **Ties or Stirrups** – Member in tension (reinforcement). The tie or stirrup acts as a tension transfer component and a critical component of STM is to provide sufficient anchorage for the ties or reinforcement.
3) (3). **Nodes** – Connection of strut and tie (concrete). The nodes are the location where forces of the STM are redirected.

### 4.4.2 - Strut-and-tie method model design

The successful use of the STM requires an understanding of basic member behaviour and informed engineering judgment. The process of developing an STM, in this case specifically for a precast concrete member is basically an iterative and graphical procedure. There are a few methods of designing a STM for a precast concrete member, these methods include; (i) Elastic Analysis based on stress trajectories, (ii) Load Path approach, and lastly the (iii) Standard Model method. (Fu 2001) The most standard STM analysis approach is described below (Fu 2001)

***<u>STM Analysis Approach:</u>***

**1.** Identify and isolate the D-regions in the precast element,

**2.** Sketch stress trajectories within the element,

**3.** Complete the internal stresses on the boundaries of the element,

**4.** Subdivide the boundaries and compute the force resultants on each sub-length,

**5.** Draw a truss to transmit the forces from boundary to boundary of the D-region,

**6.** Check the stresses in the individual members in the truss and calculate the tie forces,

**7.** Calculate the cross section of the tie and detail the reinforcement on the sketch of the element.

A basic illustration of the different steps in designing a column corbel for a precast concrete column is shown in Figure 4.15.

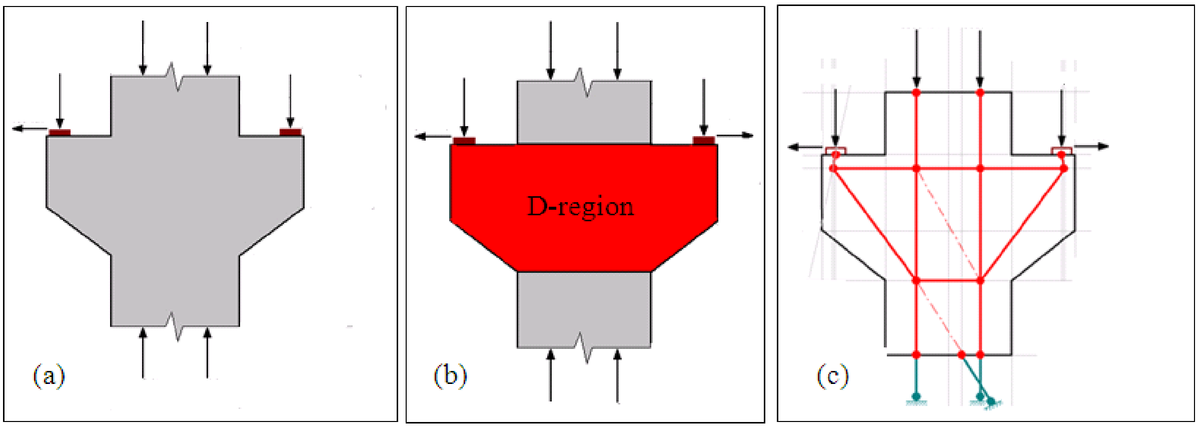



**Figure 4.15 – (a) different forces acting on the column corbel, (b) illustration of the D-region in the column corbel, (c) the finalised strut-and-tie model (Celik, O. and Sritharan, S. 2004)**

In Figure 4.15 (c) it can be seen that the strut-and-tie method allows the applied forces to be dissipated in different strut and ties that are designed to either be in compression or tension. This however allows applied forces to be broken down into easier to design and handle compression or tension forces in the connection area. The strut-and-tie method of design is also included in various international design codes such as the ACI 318 and the EN 1992-1-1 and will also be discussed in Chapter 5 of the report.

The strut-and-tie model can be developed for everyday design situations; firstly using the designer's experience following the load path visualisation of the flow of internal forces and also to provide adequate structural systems to carry the forces. However, in more complex design cases, this common sense engineering is often not enough to develop safe and efficient strut-and-tie models. The strut-and-tie model is considered as the basic tool in the design and detailing of structural concrete under shear and torsion. The application of the STM has however been limited to precast members with d-regions, including precast beams, beam girders, columns and column corbels. This chapter only includes the basic considerations for the STM method.

## 4.5 - Chapter conclusions

The aim and objective of this chapter is to provide the reader with sufficient knowledge and understanding of precast concrete connections in terms of the forces present, flow of forces, popular connection methods (strut-and-tie) and to understand overall connection parameters and functionality. A typical design philosophy according to (Walraven 2013) and (FIB - Federation Int. du Béton 2002), also provides guidelines, requirements and considerations that is essential for the design and construction of precast concrete and precast concrete connections. Connection design for precast concrete is said to be a rather difficult necessity in any precast structure. Thus providing the engineering industry of South Africa with the sufficient knowledge, skills and training is a very important aspect required to facilitate the improvement and development this concept.

Following the various important design aspects and considerations that were identified in this chapter, Table 4.1 summarizes the most significant concerns for precast concrete connection design and construction.

**Table 4.1 – Summary of most important design considerations for precast connections**

| Primary considerations | Description of consideration |
|---|---|
| **Suitability of precast structural design** | (i) A design should be done for the precast member itself, before connections are made and, (ii) another design for the continuous structure after the connections have been completed. |
| **Precast structural requirements during erection and construction** | (i) Geometrical accuracy is fundamental for joints and connections, (ii) Stability of the precast elements during erection, (iii) Simplicity in terms of design and construction |
| **Force flow** | A clear conception of the flow of stresses form one member into another one should be obtained. The flow of forces also relates to the influence it may have on the performance of other structural precast elements. |
| **Transmitting forces in connections** | The design of connections should be able to transfer forces due to, shrinkage, creep, temperature change, elastic deformations, eccentricities, wind forces and seismic activity. |
| **Tolerances** | The precast elements and their connections should be designed to adhere to acceptable tolerance requirements for precast construction. |
| **Accidental loads** | The connection design should also attain additional capacity requirements for accidental loads. |
| **Standard elements and connection types** | Use as much as possible standard precast elements and connection types that are readily available. This speeds up the construction process and also simplifies the design phase. |
| **Allow for movements** | Movements and deformations found in precast connections is a very important aspect to consider, not only for the design phase but for the entire lifetime of the precast building or structure. |

During Chapter 3 (results from the questionnaires) it was identified that precast connections is a concern for both consultants and contractors in the engineering industry of South Africa. Chapter 4 aims to provide valuable considerations included in Table 4.1 for construction and design of precast connections. Typical concerns including connection behaviour due to applied forces, the need for movements in connection zones and the design of precast connections by making use of STM have been discussed during this chapter. This information provides the designer or consultant with a background to important aspects and factors that requires consideration during precast concrete connection design and construction. Understanding the interaction, assembly and strength of the required connection type at any given connection zone in the precast structure or building is an essential aspect.

The use of the strut-and-tie method for precast connection types were also discussed during section 4.4 of this chapter. The strut-and-tie model is considered as a basic tool in the design and detailing of structural concrete under shear and torsion. The uses of the STM provide the designers with an effective connection alternative used primarily in design regions near discontinuities or D-regions. The application of the STM have been limited to precast members with d-regions, typically including precast beams, beam girders, columns and column corbels.

Another concern that was raised during the investigation was whether the design codes of South Africa do provide sufficient rules and guidelines in terms of precast concrete and precast connection design. The next chapter of the report will investigate the SABS 0100-1 (2000 Edition) design code, and the result will state whether this code does provide sufficient and effective rules and guidelines to assist consulting engineers during the design of precast concrete in the South African engineering industry.

# CHAPTER 5 - PRECAST CONCRETE DESIGN CODES: CONNECTIONS

This chapter focuses on precast concrete connections according to identified local as well as other international design codes. The aspects and design criteria of the local South African design code, namely the SABS 0100-1 (2000 Edition) are discussed during this chapter. The contents of South African code are compared to two other international design codes including the ACI 318:2008 (American Concrete Institute) and also the BS EN 1992-1-1 2004 (British Standard, Eurocode). The precast concrete design section, focusing on the precast connection section of the SABS 0100-1 (2000 Edition) is also evaluated and discussed. After the discussion, the contents of the code are compared to the other two international design codes, and from these findings conclusions are drawn as to how the local design code compares to the other international codes.

A summarised view of the contents of this chapter is shown in Fig. 5.1.

**5.1- Precast concrete connection design according to SABS 0100-1 (2000 Edition)**

**5.2 – Comparing the content of different international design codes**

**5.3 – Future improvements and recommendations for the SABS design** code

**5.4 – Chapter conclusions**

**Figure 5.1 – Contents included in Chapter 5**

This chapter primarily discusses aspects of precast concrete design as well as the design of precast concrete connections according to the SABS 0100-1 (2000 Edition) design code. It has been found that the SABS 0100-1 design code will eventually be replaced by a code similar to the Eurocode. For the purpose of this investigation the contents of the SABS 0100-1 (2000 Edition) are examined to determine if there are some aspects of the code which may be valuable to keep or implement into the new updated design code that will replace the SABS 0100-1. During this chapter the SABS 0100-1 (2000 Edition) will be referred to.

## 5.1 - Precast concrete connection design according to SABS 0100-1 (2000 Edition)

Robert E. Engelkrik (Englekirk 2003) stated that, "There exists no single formula for creating a good design, for the design process involves making a set of decisions on issues for which no absolute right answer exists. Thus the designer is continually seeking a comfortable rationally based design solution, and two identical solutions are not likely to be produced even successively by the same constructive designer." With this statement Engelkrik (Englekirk 2003) basically says that a design mainly depends on the designer's knowledge, skills as well as his ability to understand structural engineering to eventually incorporate and present a successful design.

The following part of the chapter will include design guidelines and rules specifically in terms of precast concrete connection design, included in SABS 0100-1 (2000 Edition). The SABS 0100-1 is a South African code of practice that specifies in the structural use of concrete, Part 1: Design. For the purpose of the study, which is largely focussed on precast concrete connections, only Clause 6 of the SABS 0100-1 design code will be considered. This section also includes: precast, composite and plain concrete constructions (design and detailing).

### 5.1.1 - SABS 0100-1 Design objectives

According to the SABS 0100-1 (2000 Edition), the limit state design philosophy that is set out in clause 3 of the code, also applies for precast concrete construction. In general, the recommended methods of design and detailing for reinforced concrete given in clause 4 and those for pre-stressed concrete given in clause 5 also apply to precast and composite construction. Subsections that are given in clauses 4 and 5 that do not apply are either specifically worded for in-situ construction or have been modified to incorporate precast concrete design.

The clauses included in the design code that contain information on the design of precast concrete connections are considered under the next section of the report. The following tables (Tables 5.1 to 5.5) will provide guidelines that are stated in clause 6 (6.Precast, composite and plain concrete construction) of the SABS 0100-1 (2000 Edition) of the design code. During the next section of the report, general comments and recommendations were given concerning the contents included in clause 6 of the SABS 0100-1 (2000 Edition) design code. The comments that are made may typically provide additional information or state where the code might require improvements in terms of precast concrete design and precast concrete connection design.

**Table 5.1 - General considerations of connections and joints (SABS 0100-1, 2000 Edition)**

| SABS 0100-1, Chapter 6 - Precast, composite and plain concrete constructions (design & detailing) | | |
|---|---|---|
| **Section** | **Sub-section** | **Code specification** |
| **6.1** | **6.1 - General**<br>6.1.2.3.1 -Connections and joints | The design of connections is of fundamental importance in precast construction and should be carefully considered. The engineer responsible for the overall stability of the structure should ensure the compatibility of the design and details of components. The responsibility for overall stability shall be clearly assigned when some or all of the design and details are not worked out by the engineer. |
| **6.1** | **6.1 - General**<br>6.1.2.3.2 -Connections and joints | Joints to allow for movements due to shrinkage, thermal effects and possible differential settlement of foundations are of as great importance in precast as in in-situ construction. In the design of beam and slab ends on corbels and nibs, take particular care to provide overlap and anchorage of all reinforcement adjacent to the contact faces. |

***- Comments on the contents of Table 5.1:***

From the passage given in the general information of precast concrete connections it can already be concluded that connections are one of, if not the most fundamental aspect of precast concrete design. The main purpose of the connections between the precast concrete elements is to ensure the structural integrity of the entire building. This meaning that the “members of structure or building shall be tied or connected together to improve the integrity of the overall structure” (PCA 2005). It is also mentioned that the structural integrity of a precast structure can be substantially improved by the location and detailing of member reinforcement in the connection areas. It is important that the connections should allow for permissible structural movements due to wind loads, shrinkage, creep, thermal effects (discussed in Chapter 4) and in some instances also allow movements due to seismic activity. Designers often tend to design precast structures and connections as merely cast in-situ structures that are broken down into different structural segments. Although precast concrete design does include major aspects of in-situ concrete design, the design procedure that follows are not always exactly the same for precast concrete elements and structures, especially the connections between the precast elements.

**Table 5.2 - Tie connections (SABS 0100-1, 2000 Edition)**

| SABS 0100-1, Chapter 6 - Precast, composite and plain concrete constructions (design & detailing) | | |
|---|---|---|
| **Section** | **Sub-Section** | **Code specification** |
| **6.1.2** | **6.1.2.4 - Stability**<br>6.1.2.4.3 -Tie connections | Ties should be joined, generally using one of the methods described 6.3.2 or 6.3.3 |
| **6.1.2** | **6.1.2.4 - Stability**<br>6.1.2.4.4 -Tie Connections | Ties that are connecting precast elements should be so arranged as to minimize out-of-balance effects. |
| **6.1.2** | **6.1.2.4 - Stability**<br>6.1.2.4.6 -Tie Connections | The connecting ties should be able to transmit the forces from the reinforcement in the precast units and to develop the required strength at all lapped joints. If enclosing links are used, the ultimate tensile resistance of the links should not be less than the ultimate tension in the tie. |
| **6.1.2** | **6.1.2.4 - Stability**<br>6.1.2.4.10 -Tie Connections | Durability should always be considered in the design and detailing of structural precast concrete connections |

***- Comments on contents of Table 5.2:***

Reinforcing ties in connection zones are not that frequently used for precast concrete elements and connections between the elements (Gurley 2013). However if ties are used to connect precast concrete elements, they should be carefully designed and placed to transfer or withstand the applied design loads; specifically the loads applied directly to the connection zone of the ties itself. The tying of connections should not create a weak link in the overall strength of the precast concrete structure, thus it should be ensured that all ties are done properly before the joint is eventually filled with in-situ concrete or mortar to create a strong and rigid connection type. Durability is also an influential factor when considering making use of structural ties for precast connections as it also has an impact on the stability and quality of a precast concrete building. The SABS 0100-1 (2000 Edition) provides sufficient durability provisions for precast concrete members that contain tie connections. The tie requirements are important consideration for achievement of inter panel shear resistance of precast floor panels.

**Table 5.3 - Joints between precast elements (SABS 0100-1, 2000 Edition)**

| SABS 0100-1, Chapter 6 - Precast, composite and plain concrete constructions (design & detailing) | | |
|---|---|---|
| **Section** | **Sub- section** | **Code specification** |
| **6.2.5** | **6.2.5 - Joints between precast units**<br>6.2.5.1.1 - General | Design the critical sections of precast units close to joints to resist the worst combinations of shear, axial force and bending caused by the ultimate vertical and horizontal forces. When the design of the units is based on the assumption that the joint between them is not capable of transmitting moments, either design the joint to ensure that it is so or take suitable precautions to ensure that if cracking develops it will not excessively reduce the unit's resistance to shear or axial force. |
| **6.2.5** | **6.2.5 - Joints between precast units**<br>6.2.5.1.2 - General | Where space is left between two or more precast members, which is to be filled later with in-situ concrete or mortar, make the space large enough for the filling material to be placed easily and compacted sufficiently to fill the gap without abnormally high standards or workmanship. The assembly instructions shall specify clearly at what stage during construction the gap should be filled. |
| **6.2.5** | **6.2.5 - Joints between precast units**<br>6.2.5.2 - Joints transmitting compression | A joint that transmits mainly compression is commonly used for horizontal joints between load-bearing walls as well as columns. Design the joint to resist all forces and moments implicit in the assumptions made analysing the structure as a whole and designing the individual units to be joined. |
| **6.2.5** | **6.2.5 - Joints between precast units**<br>6.2.5.2 - Joints transmitting compression | Pay particular attention to detailing of the joint and also joint reinforcement to prevent premature splitting or spalling of the concrete in the ends of the precast members. |
| **6.2.5** | **6.2.5 - Joints between precast units**<br>6.2.5.3 - Joints transmitting shear in slabs | A joint may be assumed to transmit a shear force between panels when, for example, a wall acts as a wind-bracing wall or a floor acts as a wind girder, provided that one of the provisions given below is complied with:<br>(1) Floor units transmitting shear in horizontal plane should be restrained to prevent their moving apart horizontally, and the joints between them should be formed by grouting with a suitable concrete or mortar mix.<br>(2) Seperation of the units normal to the joint should be prevented either by provision of steel ties across the ends of the joint or by the provision of a compressive force normal to the joint under all loading conditions |

***- Comments on contents of Table 5.3:***

When designing joints, the designer should be well aware of all the forces acting on the specific joint, these forces include shear, axial forces (compression and tension) as well as bending moments that occur due to vertical and horizontal forces applied to the precast element or connection zone itself. According to the code it is the designer/engineer's obligation to consider all the design forces explicitly applied to the joint. The engineer should also consider additional features of the joint, including taking the joint fill into account which usually consists of a concrete or mortar fill to ensure an effective and structural intact joint is constructed. It is explicitly stated that the designer should be aware of bending moments that may occur and also lead to cracks either in the connection zone or the precast member itself, thus stating that the joint should be ductile enough to transfer the moment to the primary load bearing element or structure such as beams, columns or the foundation of the building. The design for bearing elements and joints has been effectively developed and included, and the code does provide sufficient guidelines and rules for this specific type of precast connection and variations of it.

Special attention should be given to the detailing of the reinforcement in the load bearing joint, this ensures that the ends of the precast elements do not suffer from concrete splitting or spalling. In other words, the reinforcement should not be too dense in the connection area, as this may lead to insufficient concrete or grout filling in the connection zone that may adversely affect the strength of the connection. Joints between floor slabs are usually created to transmit shear forces through means of shear friction between the floor slabs. The floor-to-floor joint usually contains a mortar or concrete fill or in some instances a reinforced topping over the precast floor units. This ensures that the whole floor moves as a monolithic unit and does not allow for singular movement which may result into multiple structural problems including cracks, concrete spalling and insufficient strength requirements. Joints for in-situ concrete design are provided in clause 4 of the code, but do not provide variations for precast concrete connection types, which may be seen as a lack or shortage in the context of the code. The code also includes design specification for bearing of precast units that usually include bearing for simply supported beams and floor slabs (6.2.4.4 – Bearings for precast units). The SABS 0100-1 (2000 Edition) should consider including a section on the design and construction of pre-stressed hollowcore slabs as its gaining popularity in the South African building and engineering industry (Carstens 2014). Aspects associated with precast hollow core slabs that could be included in SABS 0100-1 (2000 Edition) include: (i) bearing width of slab support, and (ii) the need for structural topping. Another important aspect that could be included in the code is the details of material required for the compression flange of composite beams where hollow core floors panels are used.

**Table 5.4 - General structural requirements of connections (SABS 0100-1, 2000 Edition)**

| SABS 0100-1, Chapter 6 - Precast, composite and plain concrete constructions (design & detailing) | | |
|---|---|---|
| **Section** | **Sub-Section** | **Code specification** |
| **6.3** | **6.3.1 - General**<br>6.3.1.1 -Structural requirements for connections | When designing and detailing the connections across joints between precast elements, consider the overall stability of the structure, including its stability during construction or after accidental local damage. Stability provisions (6.1.2.4) should be taken into account and in addition, consider the severe forces and stresses that may be applied to units and connections during various stages of construction and handling. Ties all units together adequately as soon as they have been placed in their final position. |
| **6.3** | **6.3.1 - General**<br>6.3.1.2 - Design method | Design connections in accordance with generally accepted methods applicable to reinforced concrete (clause 4), pre-stressed concrete (clause 5) or structural steel. Where, by nature of the construction or material used, such methods are not applicable, prove the efficiency of the connection by appropriate tests. |
| **6.3** | **6.3.1 - General**<br>6.3.1.3 - Considerations affecting design details | In addition to ultimate strength requirements and the provisions regarding minimum tying together of the structure, (section 6.1.2.4) consider the following provisions:<br>**- Protection:** Connections should be designed so that the standard protection laws against weather, fire and corrosion are adhered to and that the structure is maintained.<br>**- Appearance:** Where connections are to be exposed, so design them that the quality of appearance required for the remainder of the structure can be readily achieved. This may often be done by emphasizing the connections rather than by attempting to conceal them. |
| **6.3** | **6.3.1 - General**<br>6.3.1.3 - Considerations affecting design details | **Manufacturing, assembly and erection,** during design methods of manufacturing should be considered as well as attention to assembly and erection methods in particular attention to the following points:<br>**(a)** Where projecting bars or sections are required, keep them to a minimum and make them as simple as possible; **(b)** Avoid fragile fins and nibs; **(c)** locate fixing devices of adequate strength in concrete sections; **(d)** consider the practicality of both casting and assembly; **(e)** most connections require a suitable jointing material, in the design allow sufficient space for such material to ensure that the proper filling of the joint is practicable. |

| | | |
|---|---|---|
| **6.3** | **6.3.1 - General** | The strength and stiffness of any connection can be significantly affected by workmanship on site. The diversity of types of joints and their critical role in the strength and stability of the structure place a particular responsibility on the designer to make clear those responsibilities for manufacture and erection, these details are thus essential to the correct operation of the joint. The following points should be considered during site instructions: (a) the sequence of forming; (b) critical dimensions, allowing for permitted deviations e.g. minimum bearing; (c) critical details, e.g. accurate location of a particular reinforcing bar; (d) the method of correcting possible lack of fit in the joint or connection; (e) the description of general stability of the structure, with details of temporary bracing if necessary; (f) full details of special materials for connections or joints. |
| | 6.3.1.4 - Site Instructions | |

***- Comments on contents of Table 5.4:***

One of the most important aspects that should be considered when designing with precast concrete elements is to ensure that overall structural integrity of the precast building is sustained throughout the design and construction processes. Along with structural integrity there are some other important aspects that include; constructability of the designed connection, stability provisions during all stages of construction as well as handling and transportation of the precast units. It was noted that in most precast construction processes, heavy lifting machinery is required to lift and place the different precast element and these elements should be kept stable until the elements are eventually placed and connected or fixed.

According to section 6.3.1.2 - Design methods, it is mentioned that the precast connection design should be done according to applicable reinforced concrete methods included in clause 4. Clause 4 mainly focuses on in-situ reinforced concrete design, but is frequently used a guideline to assist the design of precast concrete elements and their connections. If the connection cannot typically be designed according to clause 4 or 5 of the SABS 0100-1(2000 Edition), (or the connection is based on a new concept or idea), the designer should prove the connection to be efficient and capable through appropriate calculations and tests. The designer should however not always be limited to the provisions of the design code but should be able to understand and apply different structural design methods to ensure efficient precast concrete connection and member design.

In other aspects, the precast connection should also adhere to general rules and regulations which include; fire resistance, high strength structural requirements and aesthetical values. Lastly the connection design should be done keeping in mind the manufacturing, the on-site assembly and erection process of the connection type. Though it is preferred that the connection should be kept as simple as possible to avoid extensive and problematic assembly that can lead to other related problems during construction and maintenance of the structure. Repetition and standardization of certain precast elements and connections during a project also ensures simplicity and can help reduce time spent on the design as well as the construction of the precast building or parts of it.

**Table 5.5 - Structural precast concrete connections (SABS 0100-1, 2000 Edition)**

| SABS 0100-1, Chapter 6 - Precast, composite and plain concrete constructions (design & detailing) | | |
|---|---|---|
| **Section** | **Sub-Section** | **Code specification** |
| **6.3** | **6.3.2 - Continuity of reinforcement**<br>6.3.2.1 - General requirements | Where continuity of reinforcement is required through the connection, use a jointing method such that the assumptions made analysing the structure and critical sections are realized. The following methods may be used to achieve continuity: (a) lapping of bars, (b) sleeving, (c) threading of bars, (b) welding, or other methods that may include (d) mechanical reinforcing couplers etc. |
| | | ***Note for above: All mentioned methods of achieving continuity for reinforcement are further specified in the SABS 0100-1 in sections 6.3.2.2 - 6.3.2.5. |
| **6.3** | **6.3.3 - Connections with structural steel inserts**<br>6.3.3.1 - Joints with steel inserts | Joints with structural steel inserts generally consist of a steel plate or rolled steel section projecting from the face of a column to support the end of a beam. Design the reinforcement at the ends of the supported beam in accordance with clause 4. |
| **6.3** | **6.3.3 - Connections with structural steel inserts**<br>6.3.3.2 - Steel section design | Design the steel sections and any bolted or welded connections in accordance with the SABS 0162. (Apply the required bearing stresses given in the specific code) |
| **6.3** | **6.3.3 - Connections with structural steel inserts**<br>6.3.3.3 - Steel section design | Except where the design ensures that the reaction does not act at the end of the steel section, base the design of the supported unit on a span equal to its overall length, including any projecting steel section. For the design of the supporting unit and its projecting steel section, assume that the reaction is applied at the end of the projecting steel section. |
| **6.3** | **6.3.3 - Connections with structural steel inserts**<br>6.3.3.4 - Steel section design | In the design, consider the possibility of vertical splitting under steel section due to shrinkage effects and localized bearing stresses, e.g. under a narrow steel plate. |

***<u>- Comments on contents of Table 5.5:</u>***

Special attention should be given to the method of achieving continuity of reinforcement in a connection zone between precast elements. An appropriate jointing method for reinforcement is critical to ensure structural integrity and also ensure that the required strength and robustness is achieved. There are several ways of ensuring that the reinforcing achieves continuity throughout the precast element and especially connection zone, these methods have been listed in section 6.3.2.1 of the design code. The chosen method will effectively be determined by the type of connection as well as the position of the connection located in the precast or hybrid concrete building. Other determining factors for reinforcement continuity of a specific connection type usually include; the type of precast structure or building that is being constructed, size of the precast elements to be connected, height of building etc. All these factors have a significant role in the design and construction of connections that require reinforcement continuity.

Connections with structural steel inserts have been gaining popularity in the precast industry and new initiatives are still being invented and improved regularly, some of these initiatives include steel columns shoes, steel pin connections, the hidden steel corbel etc. (Peikko Group 2013). Structural steel inserts are said to be a more expensive type of connection method in the South African building industry and are not that frequently used or incorporated in precast structural designs (Gurley 2013). Steel sections and any bolted or welded connections should be designed according to the SABS 0162-1, Code of Practice for the Structural Use of Steel and are not included in the SABS 0100-1 (2000 Edition). Combining steel inserts with concrete, especially for connection zones, some problems may arise and these problems usually include; effective reinforcement of the connection area, sufficient concrete cover, effective anchor length of the steel insert, shrinkage of concrete etc.(Building and Construction Authority (BCA) 1999) It is the designer/engineer's responsibility to take these factors into account when making use of steel inserts for precast connection types. The contractor or manufacturer should also ensure that the structural inserts are installed correctly to avoid any detrimental effects the connection may have on the strength and integrity of the structure.

### 5.1.2 - Concluding remarks on contents of SABS 0100-1 (2000 Edition)

After careful consideration and discussion of the SABS 0100-1 (2000 Edition) design code it can be concluded form the results included in Tables 5.1 to 5.5, that connection design and construction are considered as one of the most significant aspects for a precast or hybrid concrete building. It seldom occurs that an entire concrete structure is fully constructed from precast, especially in the South African construction and building industry (Angelucci 2014). This somehow limits the use and implementation of precast concrete construction in the local construction industry.

Considering the contents of the SABS 0100-1(2000 Edition) design code, it has been found that the code does provide sufficient as well as efficient principles, guidelines and rules for the design of precast concrete as well as their connections. Mr. Angelucci (Angelucci 2014) stated that the problem lies not with the design code and regulations, but with the designers and consultants themselves. They tend to restrict or limit themselves by the rules and guidelines stated in the codes, rather than applying design guidelines from first engineering principles. A few aspects in the SABS 0100-1 (2000 Edition) that may require improvements or revision has been identified, and can be listed as the following:

i. Provision of design examples of popular precast connections in the South African industry,
ii. A listing of popular precast elements and connection types that are frequently used in the South African engineering and building industry,
iii. The design code should include more graphical illustrations and presentations of designs rules and guidelines.

These aspects will be further discussed in the next part of the report where the contents of the SABS 0100-1 (2000 Edition) are compared to other two international design codes.

If a designer wishes to use an alternative connection type, it should always adhere to code specifications but in the same time should not only be limited to it. Mr. Christiaan de Villiers (De Villiers 2014) confirmed that the SABS design code provides sufficient knowledge and design guidelines for precast concrete member design, but can aim to include more information on different connections and connection types. This may be one of many reasons why precast concrete is not that frequently used in the South African construction industry. De Villiers (De Villiers 2014) also stated that a good structural designer should however not always be limited or restricted to what is provided in the design codes but should clearly understand how a concrete structure functions and should be able to design precast elements and connections according to his or her engineering knowledge and experience. Thus confirming that every designer should adhere to what the design code entails but should not be limited or restricted to the exact information and guidelines provided by the code.

## 5.2 - Comparing the content of different international design codes

Design engineers have had several comments and concerns associated with the SABS 0100-1 (2000 Edition) design code. The results that were obtained from the questionnaires given in Chapter 3, several consultants mentioned that the SABS 0100-1(2000 Edition) requires revision in terms of precast and precast connection design. For the purpose of this study the code regulations and guidelines of precast concrete and connection design were considered.

The South African standards for structural design are based on design standards from different countries. The SANS 10162:2005 (The use of structural steel), for instance is based on the Canadian Standards, whereas the SANS 10100:2000 (Code of practice for the structural use of concrete) is based on older British Standard, BS 8110. The South African building standards are in a process of being revised and modified and will eventually be based on the Eurocode design codes namely the EN 1992-1 (Retief, Dunaiski et al. 2005). It was also found that the SABS 0100-1 (2000 Edition) will soon be replaced with a similar design code to the British Standards, EN 1992-1. For the aim of this study certain clauses or sections included in the SABS 0100-1 (2000 Edition) were identified to determine if it may need to be incorporated into the new design code that will soon be adopted in the South African construction industry.

Although the current SANS 10100 is based on the British BS 8110, it has been revised and adapted to the South African building environment. The precast concrete clauses included in the SABS 0100-1 (2000 Edition) and the EN 1992-1:2004 are very similar. Both the standards state that a precast concrete design should firstly adhere to the general design requirements included in the design codes. The codes also elaborate on different aspects of precast concrete design and construction. It was found that the EN 1992-1:2004 and the SABS 0100-1 (2000 Edition) contain similar design rules for precast concrete and connections, the contents of these two codes as well as ACI 318-2008 will be compared in the next section of the report. For the purpose of the report, only the sections on precast concrete and connections between precast elements will be considered.

Table 5.6 was set up to compare the different international design codes. Table 5.6 is divided into different sections that are included in the three different design codes. The sections that were created in the table include the following: General concerns, Structural analysis, General properties, Design properties, Connection properties, and other additional information. Following the comparisons made, conclusions and recommendations can be given. These conclusions and recommendations can be used to determine if the aspects included in the SABS 0100-1 (2000 Edition) can be incorporated in the new design codes that will be adopted in the South African engineering industry. Table 5.6 demonstrates the above mentioned information.

**Table 5.6 - Comparing different international design codes**

| | Description of code sub-clause | SABS 0100-1 | BS EN 1992-1-1 | ACI 318 |
|---|---|---|---|---|
| General | General design objectives of precast concrete | X | X | X |
| | Glossary of precast construction terms and uses | | X | X |
| | Stability provisions for precast concrete | X | | |
| | Limit state design of connections and joints | X | X | X |
| | The construction of precast concrete and connections/joints | X | X | X |
| Structural analysis | Structural analysis includes the structure's behaviour during all stages of construction | X | X | X |
| | Structural analysis includes the actual and theoretical behaviour of connections | X | X | X |
| | Structural analysis includes alignment deviations during construction | X | X | X |
| | Consider effect of horizontal movement on structural integrity | | X | X |
| General Properties | Materials | | X | |
| | Concrete strength properties | | X | X |
| | Shrinkage | X | X | X |
| Design properties | Restraining moments in precast slabs | X | X | X |
| | Precast concrete design objectives | X | X | X |
| | Wall to floor connection reinforcement design | X | X | X |
| | Obtaining shear transfer between precast floor elements | X | X | X |
| | Guidelines and considerations for achieving diaphragm action in a precast floor | | X | X |
| | The design of pre-stressed hollow core slabs | | X | X |
| | Structural integrity of precast concrete elements | | | X |
| | Placement of transverse reinforcement in slabs | X | X | X |
| Connection properties | Tying systems | X | X | X |
| | General rules for design and detailing of precast concrete | X | X | X |
| | General rules for connections that transmit shear forces | X | X | X |
| | General rules for connections that transmit compressive or tensile forces | X | X | X |
| | General rules for connections that transmit bending moments | X | X | X |
| | Welded connections for precast concrete | | | |
| | Additional rules for connections with steel inserts | X | | X |
| | General rules for shear interfaces | X | X | X |
| | General rules for half joints | X | X | X |
| | General rules for reinforcement at supports | X | X | X |
| Additional | Some graphical presentations of connection details | | X | X |
| | Bearing design for precast members | X | X | X |
| | Designing concrete corbels | X | X | |
| | Designing precast concrete with the strut-and-tie model | | X | X |
| | Designing pocket foundations | | X | |

### 5.2.1 - Comments on the comparison of the different design codes

The following comments will be made on the contents of the three different design codes included in Table 5.6, namely the (i) SABS 0100-1 (2000 Edition) structural use of concrete, (ii) EN 1992-1-1:2004, design of concrete structures, and lastly the (iii) ACI 318-2008, Building Code Requirements for Structural Concrete. The structural precast concrete elements such as columns, beams, floor slabs, walls etc. are mostly designed in the same way as for in-situ concrete elements. One of the main influential factors for precast concrete design is the connections between the precast concrete elements. The comments on the contents of the different design codes mainly focuses on design codes' precast concrete design for structural purpose as well as connection design and guidelines.

#### *(i) - General*

The general guidelines and rules included in the precast concrete section of the design codes typically provide overall aspects or considerations of precast concrete design and construction. Some of the general aspects included in all three codes typically include: (i) general basis of design of precast and connections, (ii) limit state design should apply, (iii) typical tolerances should apply for both precast members as well as the connections etc. Table 5.7 provides the comments on the different codes' general considerations for precast and precast design.

**Table 5.7 - General considerations included in the different design codes**

| General considerations according to the different design codes | |
|---|---|
| **SABS 0100-1 (2000 Edition)** | SABS 0100-1 (2000 Edition) has an advantage for providing a detailed section on the general requirements for connections and joints as well as stability provisions for precast members during design and installation. |
| **The EN 1992-1-1:2004** | EN 1992-1:2004 provides a very short and vague section on general requirements, but explains some of these requirements later in the precast section. The EN 1992-1-1:2004 also provides an extra section that includes glossary terms often used in the precast design section, but this may not be that important to distinguish between the three different design codes. |
| **ACI 318:2008** | ACI 318-2008 (same as the EN 1992-1:2004) provides a very short and vague section on general requirements, but explain some of these requirements later in the precast section. |

## *(ii) - Structural Analysis*

The section on structural analysis of a precast concrete building or structure mostly provides rules or guidelines for the behaviour and design of structural units at all stages of the construction phase of the precast building.

Table 5.8 - **Structural analysis comparisons of different design codes**

| Structural analysis according to the different design codes | |
|---|---|
| **SABS 0100-1 (2000 Edition)** | The SABS 0100-1(2000 Edition) provides sufficient structural analysis detail, this includes information on separate precast elements such as framed structures, beams, slabs and other precast units that eventually portrays the entire structure or building. |
| **The EN 1992-1-1:2004** | The EN 1992-1-1:2004 considers the structural analysis of the overall precast structure or building and behaviour of elements contained in the precast structure or building. This code includes analysis for: (i) behaviour of structural units at all stages of construction, (ii) behaviour of all structural units influenced by connection behaviour, and (iii) the uncertainties influencing restraints and force transfer between precast elements. |
| **ACI 318:2008** | The ACI 318:2008 has a similar approach except the analysis part is split up in the distribution of forces to be analysed in the different parts of the precast building. The different precast parts include; longitudinal and transverse tie units with lateral load resisting system, floor and roof diagrams, vertical tension requirements and also more importantly the structural analysis of connection details |

From the contents given in Table 5.8, it can be seen that all the codes have different approaches to addressing structural analysis, but all of them include the fundamental analysis requirements for a precast concrete structure or building. Other than that the different design codes are very similar but may vary on some smaller details due to the applicable preferences developed in the different international locations.

## *(iii) – General precast properties*

The general properties of precast concrete and connections typically include aspects such as: materials, shrinkage and creep, concrete strength, appearance, manufacturing etc. When considering the contents of Table 5.6, it can be seen that for concrete strength, shrinkage and creep, the EN 1992-1-1:2004 does provide more complete guidelines than the other two listed design codes. This may have an effect on the overall result on concrete curing as well as strength of the manufactured precast elements. It can be seen from Table 5.6 that SABS 0100-1 (2000 Edition) has a lack in terms of material and strength properties for precast concrete as a function of curing regimes. There is however a clause included in the SABS 0100-1 (2000 Edition) that does provide strength of material properties for reinforced concrete that may be efficiently applied for the manufacturing and curing of precast concrete elements too.

### *(iv) – Design properties*

The following design properties included in Table 5.9 have been identified from the different design codes. This is design properties that are significant in terms of precast concrete elements or parts of precast buildings.

**Table 5.9 – Design properties comparison of different design codes**

| **Design properties according to the different design codes** | |
|---|---|
| **SABS 0100-1 (2000 Edition)** | ➢ SABS 0100-1 (2000 Edition) does not explicitly cover the use and design of precast hollow-core slabs in the precast clause (section 6) of the code.<br>➢ SABS 0100-1 (2000 Edition) does however provide guidelines for fully or partially pre-stressed concrete elements that would include the design of pre-stressed hollow core slabs. |
| **The EN 1992-1-1:2004** | ➢ When considering the EN 1992-1-1:2004 design code it can be seen that the design of precast floors differs considerably when compared to the SABS 0100-1 (2000 Edition) as well as the ACI 318:2008.<br>➢ The EN 1992-1-1:2004 focuses on the overall design of hollow-core slabs to ensure efficient diaphragm action.<br>➢ This code includes several detailed sketches to aid the user in better understanding certain written concepts (horizontal interface shear) |
| **ACI 318:2008** | ➢ The ACI 318:2008 have included a section about structural integrity in their design code. This section states that the overall integrity of a precast concrete structure can be substantially enhanced by incorporating minor changes in the amount, location and detailing of member reinforcement as well as in the detailing of connection specifications.<br>➢ This code includes several detailed sketches to aid the user in better understanding certain written concepts. |

The design of precast concrete connections should always be done to ensure structural integrity and adhere to rules assuring overall continuity. The basic design properties for all these design codes are very similar, there is however a few design variations included in the different codes, but this may be due to the fact that the different codes originate and cater for different international preferences and environments.

### *(v) – Precast connection properties*

Incomplete or incorrect connection design may lead to larger structural problems and evidently overall failure. Precast connections is however the main focus of this report and the connection clause of precast concrete will be considered in more intricate detail when comparing the three different design codes in Table 5.10.

**Table 5.10 – Design properties for different design codes**

| **Design properties according to the different design codes** | |
|---|---|
| **SABS 0100-1 (2000 Edition)** | ➢ The SABS 0100-1 (2000 Edition) covers a variety of connection considerations including the following; considerations that affect design details, manufacture and assembly, site instructions, continuity of reinforcement and also connections with structural inserts and other innovative types of connections.<br>➢ This code also states that connection design should be done according to generally accepted methods applicable to reinforced concrete included in clause 4. Clause 4 entails applicable connection design methods for different forces or a combination of forces such as tension, compression, shear, flexure, torsion and bending moments.<br>➢ The continuity of reinforcement is an important aspect of connection design. Provisions for this aspect have also been incorporated in this section of the design code.<br>➢ The SABS 0100-1 (2000 Edition) has a lack of graphical presentation concerning connection detail. This may be a convenience but can improve the understanding and layout of some of the sections.<br>➢ Lastly, the SABS 0100-1 (2000 Edition) code does include guidelines for connections with steel inserts and other type of connections. |

| | |
|---|---|
| **The EN 1992-1-1:2004** | ➢ EN 1992-1-1:2004 provides a wider variety of connection considerations and details compared to the SABS 0100-1 (2000 Edition), this may be due to the fact that precast concrete have been developed, implemented and used more frequently in European countries than in South Africa.<br>➢ The following sections are included in the precast concrete part of the En 1992-1-1:2004 : Appropriate materials used for connections, some general rules for the design and detailing of connections and most important sections are included for connections that transmit different forces such as compression, tension, shear, bending moments.<br>➢ EN 1992-1-1:2004 also includes graphical presentations which help with understanding some design details that may seem vague when it is explained in written format.<br>➢ A good section about bearings for connections and design of bearings for connections of simply supported precast elements are also included in the EN 1992-1-1. |
| **ACI 318:2008** | ➢ The ACI 318-2008 design code permits a variety of methods for connecting precast members. These connections are intended for the transfer of forces both in-plane and perpendicular to the plane of the members.<br>➢ The code clearly states the connection design as well as a detailed section about bearing design for precast floor and roof members. This can be closely related or compared to the BS EN 1992-1-1:2004 in terms of bearing design for precast elements.<br>➢ The section of precast concrete connection design implemented in the ACI 318:2008 also has limited design requirements, but it refers to other parts of the design code that covers the design aspects of reinforced precast elements and connections.<br>➢ This code makes much more use of references to other parts of the code than the EN 1992-1-1:2004 and the SABS 0100-1(2000 Edition). |

The majority of the design requirements included in the SABS 0100-1 (2000 Edition) do comply with the EN 1992-1-1:2004 and this may be due to the fact that the SABS codes are partly based on British design and building codes and standards. It was also noted that the design guidelines given in the different design codes vary from each other.

## 5.3 - Future improvements and recommendations for the SABS design code

One of the most significant shortcomings of the SABS 0100-1 (2000 Edition) design code may be the lack of graphical presentation for the reader to understand some of the concepts that are explained in parts of the code. The EN 1992-1-1:2004 as well as ACI 318:2008 do provide graphical presentations to help explain or illustrate certain aspects included in the design codes. Some of the other factors that were also identified to be important during the design phase or which could be included to improve precast concrete member as well as the connection design are the following:

- Monolithic action of pre-stressed hollow core slabs,
- More information on the strut-and-tie method (previously discussed in Chapter 3 of report),
- Design for connection shear (in-plane shear and horizontal shear),
- Steel connection inserts, and
- Bearing of simply supported units

A small discussion on the SABS 0100-1 (2000 Edition) has been given, and it was identified that aspects of this code may require improvement due to the aspect's importance in precast concrete structures and connection design. These aspects are now discussed in the following paragraphs:

### ***(i) - Pre-stressed hollow core slabs***

The SABS 0100-1 (2000 Edition) design code does not explicitly provide a section on design of hollow core slabs. The code does however provide guidelines for fully or partially pre-stressed concrete elements that include the design of pre-stressed hollow core slabs. There are also many hollow core suppliers in the industry that do their own design and construction during a project. Pre-stressed hollow core slabs were originally developed as an alternative for the popular in-situ concrete floor panels that are frequently being used in the South African building and engineering industry. Today, the hollow core slab is an innovative method and encourages fast-tracking in construction projects and is preferred in many instances over other conventional building methods (CMA, 2008). Mr. Jaco Carstens (Carstens 2014) mentioned that pre-stressed hollowcore slabs are one of the most rapid growing precast elements in the South African building industry and its use has been very popular in low to medium rise buildings. Thus including more design and construction guidelines for pre-stressed hollow-core slabs in the SABS design codes may further enhance the use of this prefabricated concrete element.

Pre-stressed hollow core slabs mostly allows for: shorter construction times, high level of quality and consistent reduction of self-weight is possible, allowing manufacturers to cover up to 20m spans (Concrete Manufacturers Association (CMA) 2002). One of the main concerns of precast hollow core slabs was identified to be shear and shear capacity especially at the supporting ends or connections.

The shear strength capacity of these members is dependent on the transverse reinforcement placed in the ends of the slabs where they are to be connected or supported. Appropriate shear strength at the interface between a structural topping and the precast elements is required to secure composite action; stating that the horizontal and vertical shear of the joint between adjacent hollow core slabs should be sufficient to transmit the forces due to horizontal diaphragm action and load dissipation of concentrated loads. (Brunesi, Bolognini et al. 2014)

Figure 5.2, (a) illustrates the transfer shear between the hollow core floor slabs that is responsible for the diaphragm action and (b) illustrates the shear capacity and different failure modes of the joints between the hollow core slabs.

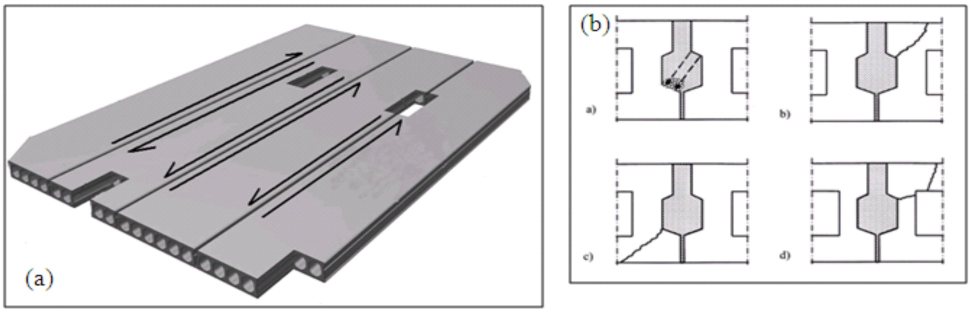



**Figure 5.2 - Illustration of shear capacity in precast hollow core slabs (Paradigm 2008)**

## ***(ii) - Connection Shear***

Shear transfer or shear capacity plays an important role in connections or joints between precast concrete elements. Different types of shear can be found due to different structural movements or forces applied and they can thus be distinguished as; (i) shear friction between elements, (ii) in-plane shear, and (iii) horizontal and vertical shear.  Some of the major factors that influence shear force transfer are the following:

1. The characteristics of the shear interface,
2. Characteristics of the reinforcement,
3. Mechanical properties of the concrete or grout,
4. Direct strength acting parallel and transverse to the shear interface.

The SABS 0100-1 (2000 Edition) does include the design of shear for reinforced concrete elements (section 4), and also for transverse shear in precast concrete slabs (section 6.2.5.3), it does however not provide for interface shear between precast slabs and a structural topping. Some of the more popular shear connection types that are being used in the industry and have been identified by Nakano and Matsuzaki (Nakano, Matsuzaki 1996) as: transverse steel bars, dowel action, shear-key, friction due to axial force and also adherence on the concrete surface. Figure 5.3 illustrates some of the above mentioned shear types typically found in precast concrete connections.

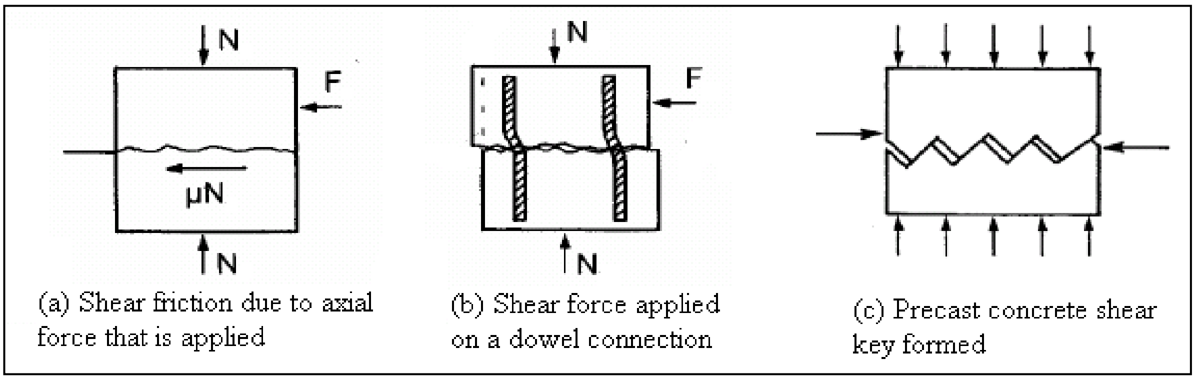



**Figure 5.3 - Identification and illustrations of shear found in typical precast connections (Walraven 2013)**

The EN 1992-1-1:2004 does include configurations of how shear and transverse shear is achieved by means of different type of connections (grouted, bolted, welded and reinforced connections). The SABS 0100-1 (2000 Edition) on the other hand does include a section on joints or connections that transmit shear, mostly in precast slabs (6.2.5.3 – Joints transmitting shear in slabs).

## *(iii) - Steel connection inserts*

Connections between precast concrete elements that incorporate structural steel inserts or embedded steel members have been used for many years in the precast industry. There is however several concerns involved when making use of this specific connection method. Some of the concerns that were identified by K. Marcakis (Marcakis, Mitchell 1981) include; proper anchorage of the structural inserts in the precast members, fireproofing, accurate tolerances, strength of the connection and parts of the connection etc.

A number of structural insert types for precast concrete connections have been developed over the years and some of the more popular connection types include:

- Column, beam and wall shoe connection (Peikko Group©),
- Steel baseplate connection,
- Hidden steel corbels (Peikko Group©, 2012 and Spencon Group,2009),
- Bolted connections,
- Steel reinforcement couplers

**Figure 5.4 - Typical illustration of steel connection inserts (Peikko Group, 2012)**

From the list above it can be seen that structural steel inserts play an important role in terms of connections between precast concrete elements, thus making it a considerable aspect to include in design codes such as the SABS 0100-1 (2000 Edition). The SABS 0100-1 (2000 Edition) does provide some guidelines for connections with structural steel inserts (section 6.3.3), but needs to provide more illustrations of this concept. The code however refers to the SABS 0162 for the design of bolted or welded connections, but does not cater for other types of structural steel inserts or connection types. Developing and improving the use and design of other structural inserts for the South African design codes may promote the use and implementation of this type of connection in the engineering industry. The different uses and modern applications of structural steel inserts for precast concrete connections will also be discussed in Chapter 6. During the findings of the survey in Chapter 3, it was found that neither designers nor contractors prefer this type of connection, mostly because it is costly, requires high accuracy during design and construction and these type of connection are not frequently used in South Africa.

## *(iv) - Bearings for precast concrete elements*

Many precast elements including beams and floor slabs are mainly connected by means of simply supported units or bearing design. Some of the aspects for bearing stresses in elements that are covered in the SABS 0100-1 (2000 Edition) code include; (i) the calculation of net bearing, (ii) the design of effective bearing length, (iii) prevention of spalling at supports etc.

One of the most popular developments in the South African precast market is the use of load bearing masonry walls that is used to support pre-stressed hollow core slabs. The use of this technique has gained popularity in low to medium rise (4-5 storeys) buildings such as houses, office blocks, hostel residents, schools etc. The benefits of the use of these pre-stressed hollow core slabs compared to cast in-situ concrete are mainly; faster erection time, easier construction sequence, greater confidence in the slab structure and also a better span to depth ratio (CMA 2009). The connections or joints of these slabs are very basic; the slab is basically supported on the masonry walls as illustrated in Figure 5.5.

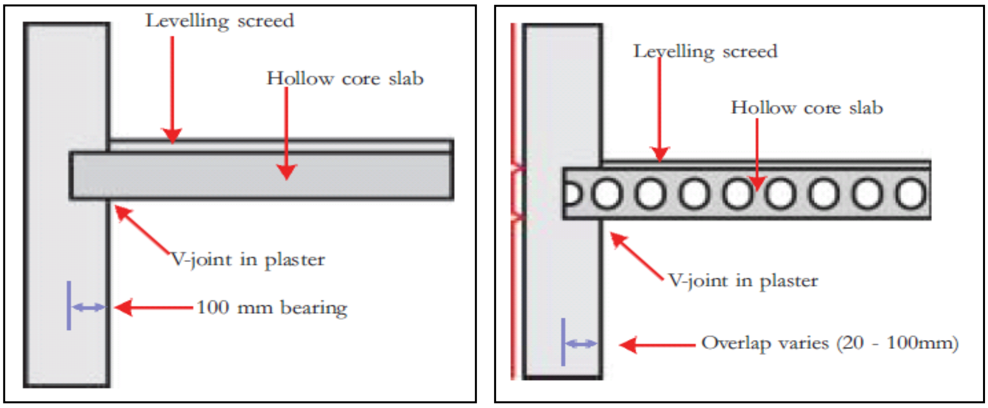



**Figure 5.5 - Masonry wall bearing connection of hollow core floor slabs (CMA 2009)**

This type of connection and construction type does however have limited applications (mostly used for low to medium rise buildings, can cover limited span lengths, simply supported connection type etc.) but can be used as an alternative cost and time efficient solution in the South African building and engineering industry. In an interview with Mr. Attilio Angelucci (Angelucci 2014), he stated that this type of precast construction along with its connection details is not viable in areas with seismic activity and that this may pose problems in structures built with this method. Designing efficient bearing capacity is a very important method for simply supported units. Simply supported units such as hollow core slabs are a very popular precast construction method in the South African engineering industry, making bearing design for precast elements a very significant aspect to consider during the design phase.

## 5.4 - Chapter Conclusions

Design codes and code specifications form the basis of any designed structure in the engineering industry, whether it is a cast in-situ, steel or in this case a precast or hybrid concrete building. Design codes, including the SABS 0100-1 (2000 Edition), ACI 318:2008 and EN 1992-1-1:2004 therefore provide a very important role during the design and construction of precast concrete and the connections between the precast elements. De Villiers (De Villiers 2014) stated that the designer should always adhere to design code specification but should however not always be limited by its contents.

Considering the content of the SABS 0100-1 (2000 Edition), that were discussed in section 5.1 of this chapter, it can be seen that some of the aspects included for design of precast concrete elements as well as the connections, may require improvement or revision. Improving and adding some enhanced precast design aspects to the scope of the SABS 0100-1 (2000 Edition) design code may help improve the construction and design of precast structures and connection zones.  From the discussion of the SABS 0100-1 (2000 Edition), the following contents of Table 5.6 were found to be present in the precast section of the design code.

**Figure 5.6 – Design requirements comparison of SABS 0100-1 (2000 Edition)**

| | Design code requirements for precast concrete design | Code provision of requirements |
|---|---|---|
| **1** | Interface shear and bond stresses | Although shear provisions are given for composite construction, with transverse steel (6.4.4.1), no provisions are given for interface between precast slabs and reinforced topping. |
| **2** | Vertical shear or shear friction | The code does provide design guidelines for vertical shear friction in connection areas. |
| **3** | Bearing forces | Bearing requirements are given in section 6.2.4.4 |
| **4** | Temporary bearing forces if no propping is provided | Bearing requirements are given in section 6.2.4.4 |
| **5** | Tension force | The code does provide provisions for tension forces in the connection area. |
| **6** | Compression forces | The code does provide provisions for compression forces in the connection area. |

From the contents of Table5.6 it can be seen that almost 90% of the information and requirements for precast concrete and connection design are available in the SABS 0100-1 (2000 Edition) code. A major aspect of the SABS 0100-1 (2000 Edition) code that requires revision and improvisation is the inclusion of more graphical presentations and figures. Figures are often used to illustrate aspects or explanations that are difficult to understand or visualise. The other consideration that can be included to improvise the code is providing the user with more examples of various precast connection types. This includes adding examples of popular connection types that are frequently being used in the South African precast construction industry

When considering Table 5.6, where the SABS 0100-1 (2000 Edition) are compared to other international design codes such as the EN 1992-1-1:2004 and the ACI 318:2008, it is noticeable that the SABS design code does have some shortcomings. From the three codes considered, it was concluded that the EN 1992-1-1:2004 is the code that provides certain aspects more thorough and provides information of precast concrete and connection design. This code also includes graphical illustrations of some important aspects. The adoption of the EN 1992-1-1 as revision of the SANS 10100-1 will enhance the current design information given in the SANS design code. It may help to facilitate the design and ultimately the construction considerations of precast concrete in South African industry.

# CHAPTER 6 – PRECAST CONNECTION ENHANCEMENT METHODS AND TECHNIQUES

Precast concrete construction is regarded as an effective alternative option to be considered for a wide range of applications in construction projects (Alfred A. Yee 2001). Finding an economical and effective method of connecting precast elements often is a rather intriguing process, as experienced during past precast construction projects (Fagan 2014) . However there are some methods available for enhancing precast connection types.

From the previous findings and investigations in Chapters 2, 3 and 4, it was found that various problems or concerns occur with the design and construction of precast concrete connections. It was decided to investigate and discuss alternative connection solutions that may enhance or improve some of the identified problems and concerns mentioned in the previous chapters of the report. This chapter include methods that can be used to enhance precast connection design and construction. Enhancement methods and solutions that will be discussed during this chapter include those listed in Figure 6.1.

**6.1- The use of self compacting concrete (SCC)**

**6.2 – The use of fibres in precast members or connection zones**

**6.3 – The use of Ultra High Performance Concrete (UHPC)**

**6.4 - The implementation of cable stayed and suspended post tension solutions**

**6.5 - The use of structural steel inserts in different connection zones**

**6.6 – Chapter conclusions**

**Figure 6.1 – Contents included in Chapter 6**

Each one of these solutions or methods has different applications for different types of connection requirements in a precast or hybrid concrete building. Each of the proposed connection enhancement methods will be discussed and additional information and applications for precast elements and connection design will also be included. Some problems that were identified in Chapters 3 and 4 typically associated with precast concrete and precast connections include:

- Ensuring sufficient connection strength,
- Too dense reinforcement in connection zones,
- Sufficient stability requirements,

- Sufficient shear capacity of the connection zone,
- The connection should ensure sufficient force transfer and flow of forces,
- The connections should compensate for movements and flexibility, and
- Prevent cracks form occurring in precast elements and connections zones.

These problems may be addressed by implementing one or more of the connection enhancement methods that are discussed during this chapter. The methods that will be discussed include: self compacting concrete (SCC), ultra high performance concrete (UHPC), the use of fibres in concrete (UHPFRC), the use of cable stayed and suspended post tension solutions and lastly the implementation of structural steel inserts for various connection zones.

## 6.1 - The use of self compacting concrete (SCC)

Self compacting concrete or SCC as it is known in the industry is an advanced type of concrete mixture that can flow and compact (consolidate) under its own weight, without any vibration. It is also designed to pass through complicated geometrical configurations including dense formwork whilst resisting segregation occurring. SCC have been implemented and used in a wide range of precast and ready-mix concrete applications. (Eric P. Koehler, Dr. David W. Fowler et al. 2007)

It has been found that the use of SCC results in improved construction productivity, more secure jobsite safety and results in enhancing the concrete quality for either precast or in-situ. These potential benefits should however be measured against higher material costs and also the need for greater technical expertise for quality control and other aspects. (Eric P. Koehler, Dr. David W. Fowler et al. 2007)

In some countries, SCC has been used in major construction projects, but the ultimate aim of developing the use of SCC is to remove the label of “special concrete” and implement SCC into a day-to-day concrete production. In countries such as the Netherlands and Germany, SCC has been developed and implemented for use in the precast concrete industry and have gained much popularity under precast manufacturers and contractors. The United States’ precast concrete industry is also leading in terms of SCC technology implementation and development. Frances Yang (Yang 2009) found that in 2000 only 10% of the United States precast industry had tried SCC and by 2003 the number had jumped to almost 90%, where 40% have been used on regular basis. Some of the main benefits when making use of SCC have been identified by Frances Yang (Yang 2009) as the following:

- Reducing the need for vibration of concrete,
- The ability to fill complex forms with limited accessibility,
- More even distribution in areas with dense reinforcement,

- Less surface voids and need for rubbing and patching,
- Improved workability (workability includes flow ability, mould ability, cohesiveness),
- Reduced labour and construction time.

### *- Applications of SCC in precast elements and connection zones*

Self compacting concrete has been frequently used in precast concrete and in-situ concrete construction (Eric P. Koehler, Dr. David W. Fowler et al. 2007). Some of the main reasons why SCC has been used for precast are that the quality that SCC delivers is better when manufactured in a controlled environment. The recent applications of SCC in precast elements and precast connections may improve the following aspects of precast concrete construction (Yang 2009):

- The easy workability of SCC makes it ideal to use in precast elements where dense reinforcement is required. The SCC also flows in corners or places often found in precast elements that are hard to fill with normal concrete.
- It reduces the amount of voids often formed when using normal concrete. Voids create weak areas in the concrete elements and also expose the reinforcement. Rework on the voids that formed is often time consuming and expensive.
- The high workability of SCC allows the use more complicated precast moulds.
- It has been found that SCC, (if the correct mix-design is used) improves the strength and durability of precast concrete members due to improved compaction and quality.
- The SCC can also be used in connection zones where complicated and dense steel reinforcement occur. The high flow ability of SCC makes it easy to fill the whole connection zone to eventually create a strong and effective connection area between the precast concrete elements.
- SCC may also be used as an alternative option for expensive grout fillings. SCC can be used to fill pockets or voids designed for precast concrete connection areas.

Figure 6.2 shows the self compacting concrete's workability, fluidity and its capability of flowing through dense reinforcement.

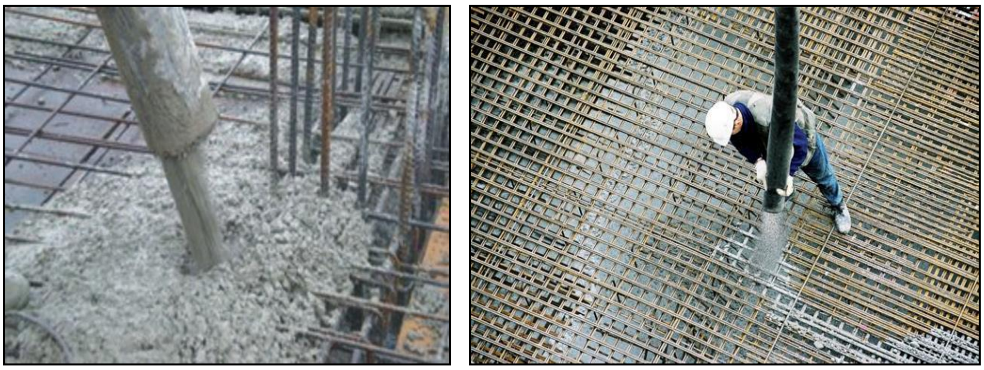


**Figure 6.2 - Illustration of SCC (Fairlfo SCC, 2013)**

## 6.2 - The use of fibres in precast members or connection zones

The constant development of new and improved types of precast concrete connections as well as connection material has led to several alternative connection options. One of the more recent developments have been the introduction of ultra high performance fibre reinforced concrete (UHPFRC) that is being used in precast elements as well as the connections of precast concrete elements. The development of UHPFRC has defined an active line of research which has been focusing on identifying applications that advance the material properties and provide alternative options for practical problems (L.F. Maya, C. Zanuy et al. 2013).

The use of UHPFRC for structural as well as architectural applications can be used as a viable and alternative method for precast elements and connections. The optimal use of this material rather focuses on local applications found in regions where the material costs and benefits related with its use seems economically beneficial. The UHPFRC possesses outstanding compressive and tensile behaviour and this has a significant effect on the bond characteristics of bar reinforcement. Several studies concerning the viability of UHPFRC in short reinforcement splices for concrete structures have been conducted. Whilst most of these studies focussed mainly on connections between precast slabs, the information of connections for larger flexural elements have been limited. (L.F. Maya, C. Zanuy et al. 2013)

In one of the most recent applications of UHPFRC was applying these fibres in connection areas such as beam-to-column connections or column splices where bar lapping was usually a big concern. By applying the UHPFRC in these identified connections zones, the following conclusions were noted by (L.F. Maya, C. Zanuy et al. 2013):

- Flexural precast concrete elements can be effectively connected by using UHPRFC to develop shorter reinforcement splices,
- The use of UHPRFC specifically in the splice region enables the reduction of the bar splice length required. As a result, continuity connections are assessed as a feasible and alternative method for specific precast connection construction.
- An interior beam-to-column connection for a precast concrete system was proposed, thus taking advantage of the short reinforcement splice lengths. The application of UHPRFC on the interior beam-to-column connection aimed to reduce in-situ labour as well as construction time, while at the same time overcoming some general drawbacks (including dimensional challenges) found in beam-to-column connections in precast structures.

It can thus be identified that although UHPRFC has limited applications, it does provides some effective solutions for precast connection types typically found in precast buildings. Some of the most popular fibres that are being used in the precast concrete industry include (Precast Concrete Institute (PCI)):

- Steel fibres (used for UHPRFC),
- Glass fibres,
- Synthetic fibres, and
- Natural fibres

For strength and durability reasons, steel fibres are mostly used for precast concrete elements, specifically in some of the connection areas that were identified. (Precast Concrete Institute (PCI))

## *- Summary and applications of UHPRFC*

Some of the identified benefits and applications of fibres in precast concrete and precast connections were listed by (L.F. Maya, C. Zanuy et al. 2013), as the following:

- The fibres can improve the structural and connection strength, including its flexural and tension strength,
- Increased impact resistance and controlled spalling risks,
- Increases the precast element as well as the connection area's durability,
- When steel fibres are included in the precast elements or in some special cases the connection areas too, the reinforcement requirements can be reduced,
- The ductility of the precast member and the connection may be improved,
- The crack widths and crack control can be reduced.

When concrete fibres (including UHPRFC) are applied in precast concrete connection zones it can improve some of the problems that typically occur in these connection zones. Some of these problems typically include: cracking, dense reinforcement, sufficient ductility requirements and ensuring sufficient strength. Thus introducing fibres in connection areas of precast concrete may provide sufficient potential to improve some of the identified problems that are typically found in precast members and precast connections zones.

During the industry surveys (Chapter 3), the contractors and consultants that participated in the survey identified some concerns in terms of precast connection design and construction. Typical problems that were identified during Chapter 3, that can evidently be solved or addressed by making use of UHPFRC include: (i) cracking or spalling or concrete in connections zones, (ii) providing sufficient reinforcement bond and strength in connection zones and also, (iii) transfer of forces, specifically flexure and tension.

## 6.3 - The use of Ultra High Performance Concrete (UHPC)

This type of concrete has been identified as one of the materials that are on the leading edge of concrete innovation. UHPC provides new technology that allows the precaster to expand new products and solutions. The material's combination of advanced properties allows the ability to design thin, complex shapes, curvatures and highly customized textures – some of these applications are very hard and somewhat impossible to achieve with traditional reinforced concrete elements (NPCA 2013). Ultra high performance concrete has a range of formulations and applications which may be used for a wide variety of architectural and structural applications.

The advantages that UHPC offer are numerous and typically include the following: (i) reduced global costs such as formwork, (ii) reduced labour requirements, (iii) reduced maintenance and, (iv) improving the speed of construction (NPCA 2013). UHPC has been implemented and used for more than a decade in the engineering industry and offers innovative solutions and products for precasters. Some of the precast elements that are manufactured using UHPC have been listed by (Mishra 2012) as the following:

- Bridge beams and decks,
- Solid or perforated wall panels/facades,
- Urban furniture,
- Stairs,
- Pipes and marine structures, and
- UHPC can also be implemented into other precast elements that include columns, floor slabs, beams and connection areas of precast concrete elements.

One of the main principles of this type of technology is based on systematic elimination of natural weaknesses associated with conventional concrete. The ductile behaviour of this material is a significant feature of this concrete, with the ability to deform and support flexural and tensile loads, even after initial cracking has begun. (Mishra 2012)

UHPC offers good plastic and hardened properties and can reduce some percentage of reinforcement in the precast member as well as the connection zone. By implementing UHPC, precasters can manufacture complex shapes that are very durable, cost effective and also require low maintenance. By implementing the wide application and reaping full benefits of UHPC, precasters can offer new and innovative solutions for precast elements used either for structural or architectural purposes.

***- Typical applications of UHPC in the construction industry:***

The use of UHPC has been implemented in numerous applications in the building as well as the civil engineering industry, some of its applications have been listed by (NPCA 2013) as the following:

- **Architectural UHPC applications –** UHPC's higher mechanical performances may result in a reduced number of sections, reduce reinforcement requirements and may also enable the design of cantilevered structures that aren't possible with conventional concrete. UHPC also enables the design and fabrication of ultra-thin elements that are highly durable and sustainable, thus also decreasing the own weight of the precast concrete elements.
- **Flexibility –** Using UHPC in various precast elements, various shapes and forms of precast concrete can be obtained with improved strength and robustness.
- **Artistic applications –** UHPC is also well suited for applications in modern and contemporary exterior and interior decor. The use of UHPC for external architectural panels and parts of structures has also been implemented in other countries.
- **Structural precast elements –** UHPC can be used as an alternative method for a wide range of precast concrete elements. The high strength, ductility, reduced weight and high durability makes it ideal for applications in precast structural use.
- **Other alternatives –** The use of UHPC in connection areas of precast or hybrid concrete buildings may also solve some of the barriers encountered in this area. Some of the solutions that may be offered when making use of UHPC includes: reducing dense reinforcement encountered in connection zones, provide sufficient strength and ductility for precast elements and connection zones, provide cracks forming and also create durable connections which ensures overall structural integrity.

The solutions that UHPC delivers are very similar to the solutions that UHPFRC and SCC delivers, except for the fact that UHPC delivers a stronger and more durable concrete. Ultra high performance concrete may deliver some alternative solutions in terms of precast concrete and connection construction if implemented and applied effectively.

## 6.4 -The implementation of cable stayed and suspended post tension solutions

Alternative solutions for precast concrete buildings and structures have lately been developed in the international precast concrete industry. Jointed "dry" connections that can be obtained by means of unbonded post-tensioning techniques have proved to supply exceptionally efficient and damage-resistant systems. The aspect of cable stayed suspended post tension solutions were initially developed for bridge systems, but with effective research and modifications it has been implemented for use in multi-storey precast concrete buildings. (Pampanin, Pagani et al. 2005)

The applications as well as the development of precast concrete multi-storey buildings have usually suffered, when compared to cast in-situ concrete counterparts, an inherent lack of redundancy in the main structural frame. The main structure typically consists of statically determined systems with the beams being simply supported or hinged to cantilever columns (Pampanin, Pagani et al. 2005).

### 6.4.1 - Recent developments in precast connections and systems

Many alternative solutions have previously been investigated to provide rigid connections between beam and columns. Most of them relying on cast in-situ techniques to provide equivalent "monolithic" connections. Two of the recent alternatives that were developed by (Ericson 2005) are listed as:

1. **Emulation of cast-in-place approach –** The connections used for this type of method can either be localized within the beam-to-column joint with either partial or total cast in place concrete or situated in the middle of the structural precast concrete member. A typical illustration of this connection is given in Figure 6.3. Nonetheless, due to their economic inconvenience and construction complexity, these systems have not been widely adopted.
2. **Jointed ductile and hybrid systems –** Recent developments of precast concrete solutions have effectively noted the competence of "dry" jointed ductile beam-to-column connections for moment resisting frames. This has been developed as an alternative of cast in-situ and has been based on post-tensioning techniques. An illustration of this jointed ductile system is illustrated in Figure 6.3. Figure 6.3 also illustrates the concept of the cable stayed connection type typically found in a beam-to-column precast connection.

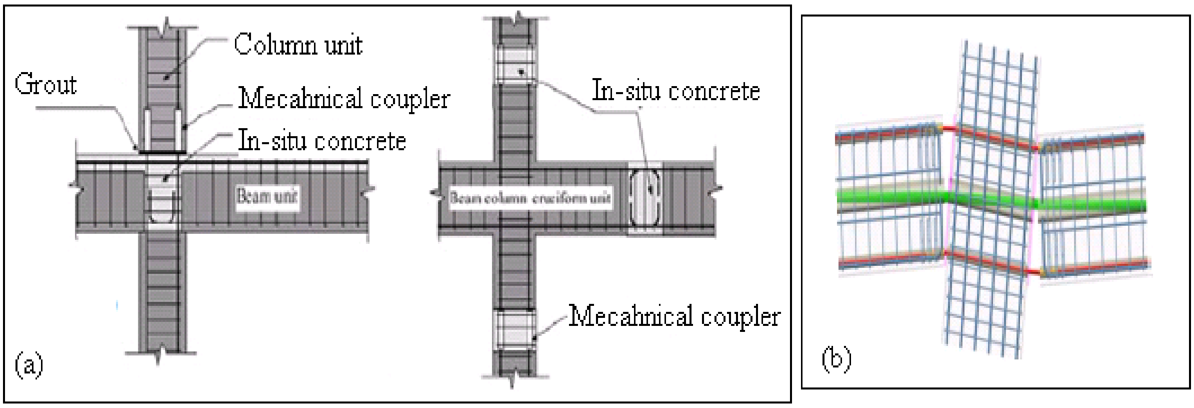
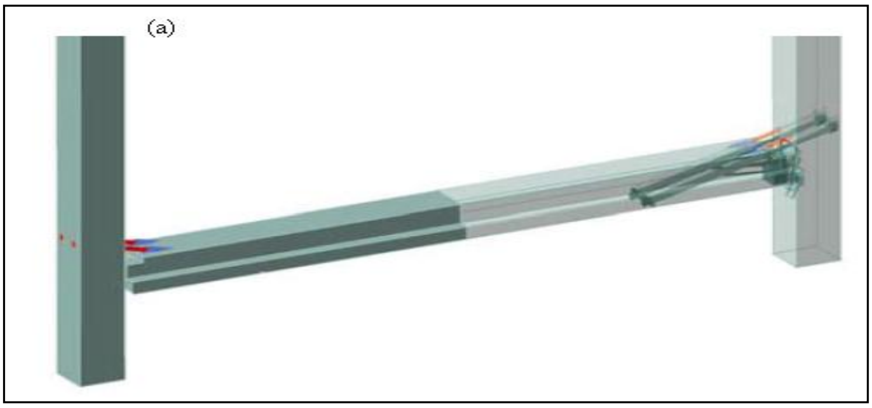



**Figure 6.3 – (a) jointed ductile system, (b) cable stayed connection type (Ericson 2005)**

### 6.4.2 - The development of the "Brooklyn system" (cable stayed and suspended post tension system)

Based on similar concepts of the recent precast connection developments mentioned in section 6.4.1, a peculiar connection solution and construction system have been studied and developed for gravity-load frame buildings. This concept has been named the "Brooklyn system", where cable stayed and post tensioned systems are being adopted. The description, design and development of this system initially started in 1998 on existing developments in the precast building solutions. This concept combines the structural concept and efficiency of cable stayed or suspended bridge system within a typical skeletal multi-storey precast building system. (Pampanin, Pagani et al. 2005)

Continuous post-tensioned tendons that are anchored at the exterior columns of the precast frame supplies an adequate moment resistance at the identified critical sections that are under combined gravity, seismic and low-to moderate lateral applied loads. Alternatively for typical short to medium span length type of buildings, a cable stayed solution can be adopted. The mentioned alternative solution is illustrated in Figure 6.4, figure (a) Includes a typical illustration of a cable stayed system, and (b) Illustration of post-tensioned system.



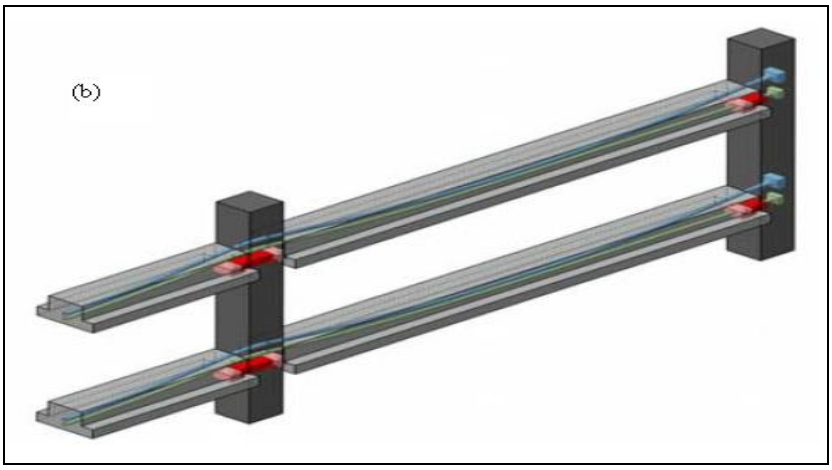




**Figure 6.4 - (a) Typical illustration of a cable stayed system, and (b) Illustration of post-tensioned system. (Pampanin, Pagani et al. 2005)**

## *<u>- Practical applications of solutions on-site:</u>*

It is said when both these systems are applied effectively, it provides good structural efficiency as well as flexibility in the architectural features. There are several positive applications of the "Brooklyn" system in other countries such as Italy and Switzerland which are based on either the cable stayed or suspended solutions. These systems have also been implemented into several building types that include; commercial buildings, office blocks, exposition buildings, industrial structures and hospitals. Different uses including buildings with varieties of plan configurations, beam bays, various floor spans and multiple storey heights have been designed and constructed using the cable stayed and suspended post tension systems. (Pampanin, Pagani et al. 2005)

Great flexibility can be achieved in the structural configuration, allowing complicated architectural requirements to be met. The presence of the inclined bars or continuous cables that is illustrated in Figure 6.5 (a, b, c and d) allows a considerable amount of reduction in the depth of the structural beams, eventually leading to more desired aesthetic solutions. Figure 6.5 illustrates the installation process of the "Brooklyn System" into a typical precast concrete building.

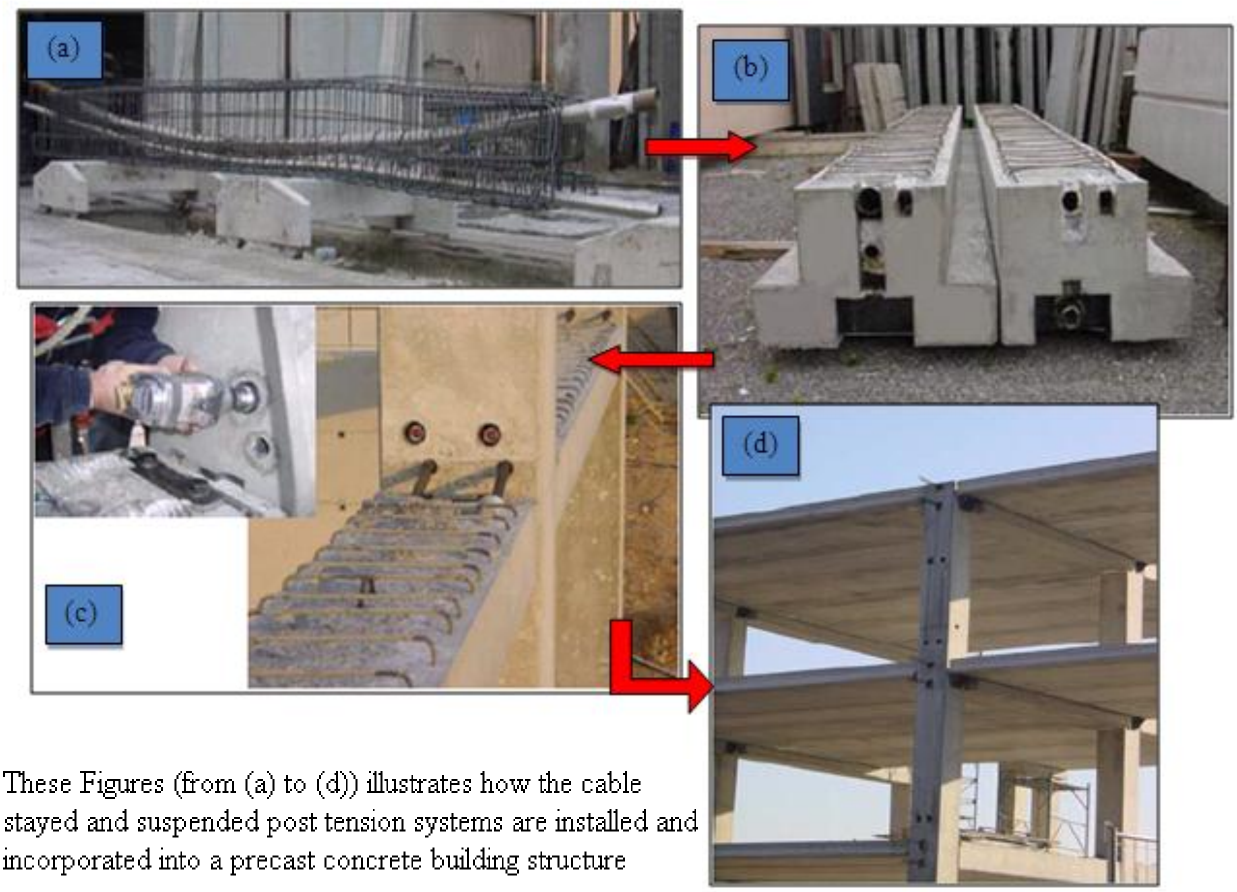



**Figure 6.5 - Installing of cable stayed connection (Pampanin, Pagani et al. 2005)**

The structural concept, behaviour as well as the efficiency of the system (both the solutions with inclined bars or unbonded post-tensioned tendons) has been validated by means of research and experimental tests performed on full scale one storey and one-bay frame systems (Pampanin, Pagani et al. 2005). In conclusion an overview was performed, including some practical applications of the system primarily designed for gravity, wind and seismic loads. The implementation of this system has not been done all that extensively but may offer an alternative solution for precast frame systems and complicated connection designs.

## - Suggested applications of the cable stayed solution in the South African industry

The system has numerous applications and offers great solutions for precast systems, but this research was developed in countries which make more use of precast and precast construction than South Africa. These countries include Switzerland, Italy, Britain, Canada etc., all countries that are basically leaders and innovators in the field of precast concrete construction (Paradigm 2008). This system could however be applied in the South African precast industry, mainly focussing on specific solutions. The application of the cable stayed and post tensioned system may be considered as solutions for:

- Areas where low levels of seismicity have been recorded. This system has been developed to be designed and constructed in areas with low seismicity. South Africa has regions of low seismicity, and this method may be implemented as a solution for precast buildings in these regions.
- Structural solutions for complicated architectural solutions. Precast structures that include complicated designs can be simplified by making use of this system.
- Effective connection methods for mostly beam-to-column connection types. Following the result that was found in Chapter 3 (industry surveys), identifying that precast connections are a big concern for consulting engineers in South Africa, this system and connection type may be implemented to solve some of these concerns.
- The presence of inclined bars or continuous cables can also significantly reduce the depth of the structural beams, leading to more desired aesthetic solutions and saving costs on reinforcement and concrete requirements.

With all the above mentioned possible solutions for precast concrete buildings focussing on the South African construction industry, there are some limitations for this specific method. This method may be seen as an expensive detail and designers may find it complicated to design. In the South African construction industry there is a limited number of designers with sufficient expertise to design and construct precast systems such as the cable stayed or post tensioned solution.

Based on the results from the surveys (Chapter 3), it was also identified that designers do not want to buy into making use of new precast structural systems. This system offers good advantages to precast structures and buildings, but its application may be limited in the South African construction industry.

## 6.5 - The use of structural steel inserts in different connection zones

Precast concrete elements that contain structural embedded steel inserts as alternative option for a precast connection type have been used for many years in the precast industry (Marcakis, Mitchell 1981). There is also a wide variety of types and applications of these structural inserts for precast concrete connections in the engineering industry. The typical applications of structural steel inserts can be used as: (i) simple bearing connections, (ii) bolted connections (iii) welded connections, and (iv) steel brackets or anchors. In some cases steel profiles can also be embedded in the precast concrete elements to typically create a precast connection type. I-sections, channels, angles or hollow section are most commonly used for such connections.

The variety of steel inserts used in precast concrete construction is numerous. The following part of the report will only include some of the more innovative ideas found in the international precast concrete industry. To ease the problem of identifying certain structural steel inserts for precast connections, the most popular and innovative types have been identified for different connection types found in a typical precast concrete building. The following connection zones have been identified (see Chapter 2):

a) Foundation-to-column connection
b) Column-to-column connection
c) Beam-to-column connection
d) Beam-to-floor connection
e) Floor-to-floor connection

Alternative structural steel inserts for every type of connection zone listed will be given in the following section.

## (a) - Foundation-to-column connection

The Foundation-to-column connection of a precast concrete building is a popular connection zone where structural steel inserts can be implemented to create rigid and strong connection types. The following types of connections with steel inserts have been identified for this connection zone:

- **The bolted socket connection type**

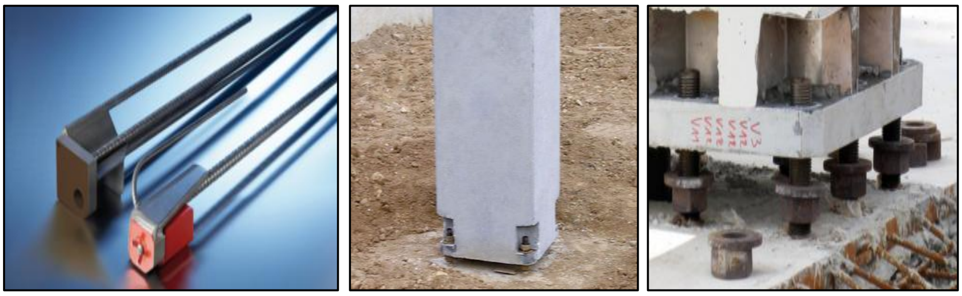


**Figure 6.6 - The column shoe connection developed by Peikko (Peikko Group 2013)**

The column shoe illustrated in Figure 6.6 was created and developed by a Norwegian company called Peikko. This is a very easy connection to install and quite simple to adjust/fix. The threaded steel part is installed in the footing of the building and the column with the imbedded column shoes is inserted and the bolts are tightened to create stability and continuity of the column.

- **The baseplate connection type**


**Figure 6.7 - Illustration of the baseplate connection type (The Shockey Precast Group 2001)**

The steel baseplate connection type is not very different from the column shoe connection type. The baseplate connection is a more popular connection type typically used in steel structures (steel columns), but have been successfully implemented in previous precast concrete column-to-footing connections.

- **Connections with mechanical couplers**

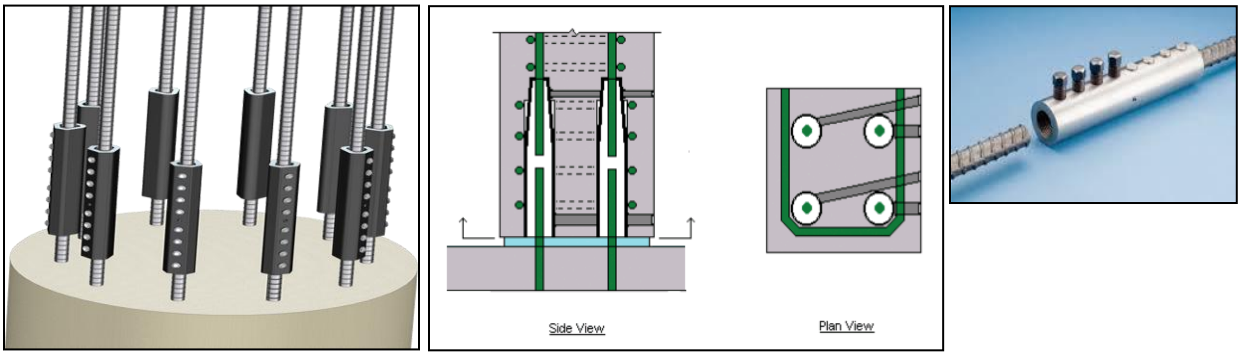



**Figure 6.8 - Graphical presentation of mechanical rebar couplers (Splicetek 2013) , (BarSplice Products Inc. 2011)**

Mechanical couplers are frequently being used in the industry to connect or splice reinforcing bars in connection or splice regions in a reinforced concrete structure or building. Mechanical couplers are not only limited for use in column-to-foundation connections but can also be applied in several other connections zones (column splices, reinforcement in slabs and beams, wall panels etc.). The mechanical coupler recognizes a way of connecting precast members to make them behave as if they were monolithically cast-in-place. (Splicetek 2013)

## (b) - Column-to-column connection

The Column-to-column connections that include the implementation of structural steel inserts for connection types are somewhat similar to the Column-to-foundation connections identified in the previous section (a) - The column-to-column connection, also called the column splice connection. This connection zone can include making use of steel insert connections including the following:

- The bolted socket connection type,
- The baseplate connection type, as well as
- The connection with mechanical couplers

These connection methods are similar to those listed in the previous section, (a) – Column-to-foundation connection. Eventually choosing one of the above listed connection methods may depend on some factors of the column being constructed such as its dimensions, length, structural purpose, position in overall structure and also its capacity.

### (c) – Beam-to-column connection

This connection is typically found where the column is connected to the beam of the concrete building. Alternatives for this type of connection includes making use of corbels, simply supported bearing connection, steel billet connection etc. The beam-to-column connections that alternatively include making use of structural steel inserts were identified as the following:

- ***Hidden steel corbel (Spencon System– Norway)***

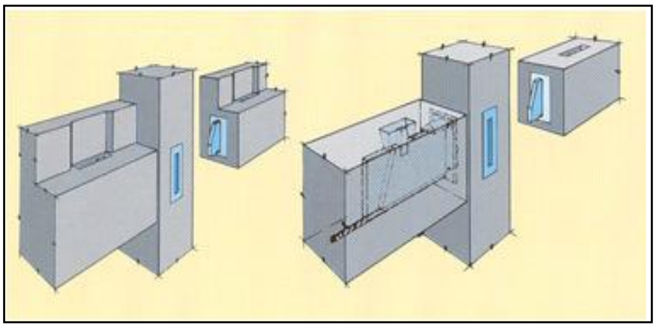


**Figure 6.9 - Hidden corbel connection type (Spencon Systems, 2009)**

- ***Hidden steel corbel (Peikko Group)***

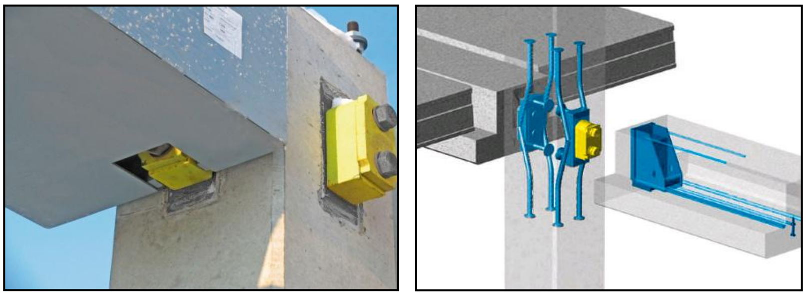


**Figure 6.10 - Hidden steel corbel (Peikko Group, 2012)**

- ***Hidden corbel (Developed by Chris Jurgens)***

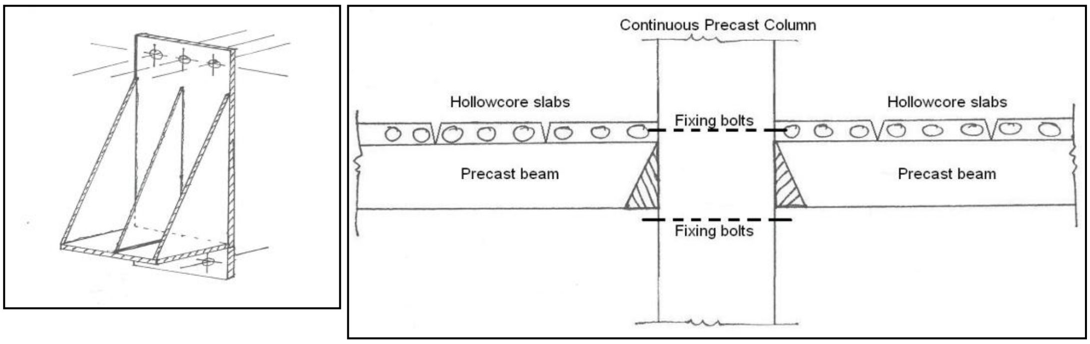



**Figure 6.11 - Hidden Corbel connection (Jurgens, 2008)**

Most of these corbel systems are either cast into the separate precast concrete members of bolted into the member.

- ***Steel inserts cast in column***

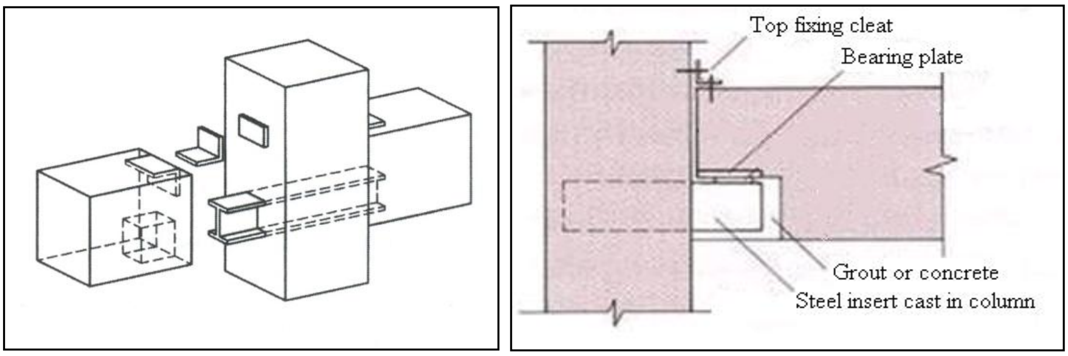



**Figure 6.12 - Structural steel inserts for precast connections (Building and Construction Authority (BCA) 1999)**

For this type of connection, the steel insert shown in Figure 6.12 is cast in the prefabricated concrete column and a steel bearing plate is installed in the beam to create a bearing surface for the connection. The top fixing cleat shown in both the figures (Figure 6.12) helps with lateral stability and also provides additional strength to the connection. (Building and Construction Authority (BCA) 1999)

## (d) – Beam-to-floor connection

Considering this type of connection, it has limited applications and implementations where structural steel inserts were used. This is mostly due to prefabricated slabs being simply supported by the beam element or the floor slabs are fixed using ties and reinforcement or a reinforced topping if a monolithic floor were to be formed. The following two methods have been used for this type of connection, but its applications has been limited in the industry:

- ***Bolted connection***

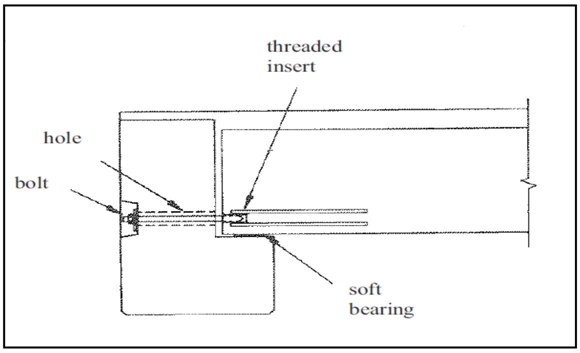



**Figure 6.13 - Bolted connection type (Beam-to-floor connection) (Mishra 2012)**

This connection type however also requires accurate placing and small tolerances is allowed during the design and construction phase.

➢ ***Slab corbels (Peikko Group)***

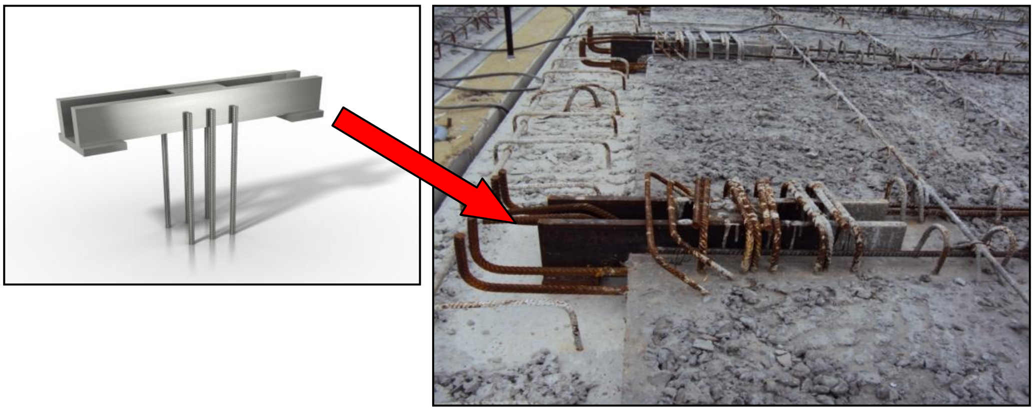


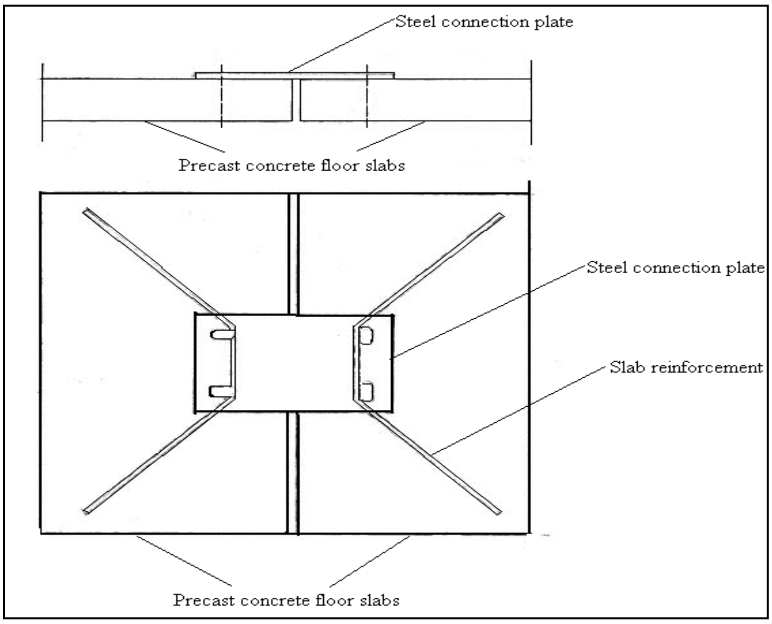
**Figure 6.14 - Slab corbels developed by the Peikko Group. (Peikko Group 2013)**

This connection type may be considered as an expensive detail, thus limiting its use in markets that thrive on using the lowest cost for construction or precast concrete buildings such as South Africa.

## (e) – Floor-to-floor connections

Connections between floor or slab elements are usually very simplistic and are generally done by grout filling, a reinforced topping or by means of ties and reinforcement. Some alternatives for this connection that makes use of structural steel inserts may include the following aspect:

➢ ***Bolted steel connectors***




A steel plate is placed on top of the floor slabs to be connected. Holes are inserted in the slabs with anchor loops for reinforcement. The plate has slotted holes and can compensate for tolerances. The bolts are placed through the holes and tightened to fix the steel plate and complete the connection.(European Commission - Joint research centre 2012)

**Figure 6.15 - Illustration of bolted connection for floor-to-floor connection (European Commission - Joint research centre 2012)**

## - Conclusions and comments on structural steel inserts for precast connections:

Many of the connection types that were discussed in section 6.5 were also included in the survey that was given to industry participants, mainly contractors and consultants (Chapter 3). Some of the participants commented and discussed applications of connections that included structural steel inserts. These comments and discussions given by the industry participants may provide important information and also offer solutions for precast connections that include structural steel inserts. Some of the typical concerns and positive aspects associated with the design and construction of connections including structural steel inserts were identified and are given in Tables 6.1 to 6.3. (This only includes the connections that were addressed in the surveys from Chapter 3)

**Table 6.1 - Positive and negative aspects on column shoe and baseplate connections**

| Column shoes and baseplate connections | |
|---|---|
| **+ Positive aspects** | **- Negative aspects** |
| Quick and easy installation process | Stability of the precast element may be problematic during the installation process |
| Provides good moment resisting connection method | The design for this type of connection may be too complicated |
| Effective connection type for low to medium rise precast buildings | Lack of moment continuity into foundation |

**Table 6.2 - Positive and negative aspects on bolted connection types**

| Bolted connection types | |
|---|---|
| **+ Positive aspects** | **- Negative aspects** |
| Connection can be adjusted before bolts are fastened | Bolted connections require a perfect fit, small tolerances are allowed |
| This connection can be disassembled, re-use is possible | Bolted connections are not preferred method for precast connections |
| If tolerances are correct, installation is quick and easy. | Skilled labour is required for installation |

**Table 6.3 - Positive and negative aspects on steel connections with welds**

| Steel connections with welds | |
|---|---|
| **+ Positive aspects** | **- Negative aspects** |
| May be used in heavy industrial buildings | Site welding can be problematic and is not preferred |
| If weld is done properly it creates a moment fixed connection | Welding complicated the construction process |
| Placement is quick. Element will have to be supported until welding is complete | Welding requires specialist = additional costs (preferred for steel construction) |

Tables 6.1 to 6.3 provide positive and negative aspects of connections that include structural steel inserts, the information were obtained from results obtained from the surveys given in Chapter 3 of the report. Analysing the survey results it was found that the participants in the South African construction industry do not prefer making use of steel inserts for precast concrete connections. Welded and bolted connections are the two main options which they do not prefer to use, mostly because it requires high accuracy, leads to additional costs, allows for small tolerances and because welding may require additional costs. Steel inserts for precast connections also has its positive aspects, but their applications are however limited for the South African construction industry. Applying these connection methods in the correct connection zones and improving their limited applications in the South African construction industry, can result in more frequent usage of these connection methods.

## Chapter Conclusions

Considering that the connections between precast concrete elements are very important part of any precast or hybrid concrete structure, this section of the report have identified a few methods that can be used to enhance precast concrete connection details. The proposed connection enhancement methods or alternatives may be implemented in specific connection zones where it was previously found to have problems with either the design or construction of the connection. Most of the investigated methods have been implemented in the precast industry with various measures of success, but due to its limited applications it may require more time and exposure to be successfully implemented. The following list provides typical enhancements that can be offered by implementing the various discussed methods in precast connection zones:

- **SCC** – This type of concrete provides; easy workability, it reduces the amount of voids often formed in concrete, improves the strength and durability of precast concrete members, SCC can also be used in connection zones where complicated and dense steel reinforcement occur and no compaction is required at high heights of the structure and hard to reach structural parts.
- **Concrete fibres** – The fibres can improve the structural and connection strength of precast, increases impact resistance and controlled spalling risks, it can increase the precast element as well as the connection area's overall durability, crack widths and crack control can be reduced and the ductility of the precast member and the connection may be improved.
- **UHPC** – UHPC offers good plastic and hardened properties and can reduce dense reinforcement found in connection zones, has the ability to deform and support flexural and tensile loads, the high strength, ductility, reduced weight and high durability makes it ideal for applications in precast structural use.
- **Cable stayed and post tensioning system** – If done properly, this method provides good structural efficiency as well as flexibility, can be applied in areas of low levels of seismicity (big precast construction concern), provides effective connection methods for mostly beam-to-column connection types and
- **Structural steel inserts** – A wide variety of structural steel inserts is available for various connection zones in a precast concrete structure or buildings. This connection types offers numerous applications and solutions for precast connections. Some of the positive aspects include; it provides a good moment resisting connection method, if connection tolerances are correct the installation is quick and easy.

It can thus be seen that every type of enhancement method or connection technique has its own applications and purposes. These methods or techniques, if correctly applied can improve and enhance precast connection properties and provide additional solutions for contractors and consultants in the South African construction industry. Some of these enhancement methods can offer solutions for the problems or concerns that were identified during the results obtained from the surveys (Chapter 3). Table 6.4 includes opinions that are based on the solutions that the enhancement methods can offer for the problems identified in Chapter 3:

**Table 6.4 – Enhancement method solutions for identified concerns**

| Connection concerns identified in Chapter 3 | Possible connection enhancement solution |
|---|---|
| Connections that include in-situ components are preferred | For this concern, SCC, UHPC and UHPRFC can be used |
| Prefer connections that provides good stability requirements | UHPC can be used for high strength and structural steel inserts can be used to ensure quick and efficient stability |
| Prefer connections that has a high shear capacity | The use of fibres in concrete may pose a solution for connections that require high shear capacity |
| Simply supported connection types are easy and fast to construct | Some of the structural steel inserts for connection types provide simply supported connections that are quick and easy to construct |
| Connections that provide efficient force transfer and flow or forces | SCC, UHPC and fibres in concrete may provide the connection areas with sufficient force transfer and flow of forces |

These enhancement methods and techniques have been developed to address some identified problems, typically found in precast concrete connection areas. The listed enhancement methods for precast connections may not always provide the best or most cost effective solutions for every type of precast connection, but should however be considered as a viable and effective solution in certain identified problem areas or circumstances.

Following the enhancement methods and techniques for precast concrete connections, the next chapter will include the final conclusions and recommendations made for connection concerns included during the design and construction of precast concrete.

# CHAPTER 7 – CONCLUSIONS

Design and construction preferences for connections in precast concrete connections were investigated in this study. This chapter presents a discussion and summary on the main findings of the study.

## 7.1 – The state of precast concrete in the South African construction industry

Following the study it was found that precast concrete have been under-utilized as an alternative construction method in the current construction industry of South Africa (Theodosiou 2013). Precast concrete construction addresses the majority of the important requirements for sustainable concrete structures, including durability, quality, speed of construction, appropriate finishes and cost effectiveness.

It was however found from industry surveys (Chapter 3), that one of the main reasons why precast and hybrid concrete are being under-utilized in the South African construction industry is the problems or concerns associated with the connections between precast or hybrid concrete elements. Thus providing the industry with sufficient knowledge, expertise and or guidelines for the design and construction of precast connections may improve the state of precast or hybrid concrete construction in South Africa.

## 7.2 – The importance of connections during precast concrete design and construction

Some of the several advantages that precast concrete construction offer may be lost due to inappropriate design and detailing of the precast concrete connections. The key purpose of structural precast connections is to transfer the forces that are applied to the precast elements and successfully obtain structural interaction between the precast elements (Engström 2007).

The precast connection's function is not merely to transfer loads, but also to develop continuity and ensure monolithic behaviour of the entire precast concrete structure (Englekirk 2003) In order for the connections to develop continuity and transfer the applied forces, the connection should secure the projected structural behaviour of the overall structure as well as the precast subsystems that are enclosed in the precast structure. The most important or desirable structural functions of precast connections and joints are:

(i) Direct transfer of loads (load paths and flow or forces),
(ii) Develop structural continuity and integrity,
(iii) Distribution of concentrated loads,
(iv) Allow for movements and unintended restraints,
(v) Ensure efficient rigidity and robustness for the connection zone

## 7.3 – Identifying and discussing the precast connection types that are frequently being used in the precast construction industry

The design and construction of precast connections is an aspect of precast or a hybrid concrete building that requires specific attention. Precast connections can be found in different parts of a precast building, called connection zones. There is a wide variety of connection methods available in the precast construction industry. The connection zones that were considered during the study include:

- Foundation-to-column connections,
- Column-to-column connections,
- Column-to-beam connections,
- Connections between floor slabs,
- Beam to slab connection

The connection zones that were studied are those that typically occur in precast or hybrid concrete frame buildings. The different connection types that were identified and listed in the study are the connections that were found to be the most frequently used in the precast construction industry, locally as well as internationally. The identification and discussion of the different connection types were used to develop applications, preferences and concerns associated with the various connection types. It also assisted the identification of positive and negative aspects associated with the connection under consideration (included in Chapter 2).The various connection types also formed a critical part of the survey that were handed out to industry participants (contractors and consultants).

## 7.4 – Industry survey results and interpretations

Following the identification and discussion of the various precast connection types, certain important aspects associated with the design and construction of precast connections were identified. To obtain valuable information and guidelines in terms of precast connection design and construction from the South African construction industry, industry participation was required. A survey was developed which focussed on different connection types and the identification of certain lacks of precast in the South African construction industry. The key findings from the surveys can be given as the following:

1. The majority of consultants and contractors still prefer designing and constructing with in-situ concrete. Concerns such as:
   - Familiarity with utilising in-situ construction,
   - Low labour costs,
   - Inexperience and insufficient knowledge of using precast and,
   - A reluctance in learning new alternative methods

2. It was found that there is a limited variety of precast concrete units that are frequently used in the industry. These precast elements currently being used, mostly include simpler forms of precast such as precast or hollowcore slabs, small beams and columns and other various basic simply supported precast elements.
3. Contractors and consultants have concerns with the use of precast concrete as well as the design and construction of connections. It was noticed logically so, that the consultants are more focussed on the design aspects of the precast concrete which included aspects such as the connections, seismic considerations, force transfer and force flow etc. Contractors are however more focussed on construction or assembly considerations that included; accurate levels and setting out, tolerance issues and stability during the installation process.
4. When the contractors and consultants were asked to compare in-situ and precast construction in terms of quality, cost and time efficiency the results were significant. The majority of both groups stated that precast construction delivers superior quality and time-efficiency, but in-situ construction still delivers the best alternative in terms of cost.
5. It was found that 95% of contractors and consultants that participated in the survey identified a lack of understanding and implementation of precast concrete in the South African construction and building industry. Considering that the majority of participants said that there is a lack of implementation and sufficient understanding of precast concrete in the South African industry, it can be concluded that precast construction needs to be more effectively marketed and the required skills and correct applications needs to be implemented and developed.
6. Connections still remain a very important aspect in terms of design and construction of precast concrete. It was found that precast connections that included a cast in-situ component or aspect were preferred over other alternatives. The same was preferred for connection types that did not include complicated and intricate design and construction details. Preference was given for simply supported connection types that are quick and easy to construct over bolted, welded or grouted connection types.

When analysing the results of the connection types that were rated (Chapter 3), it can be seen which types of precast connections the majority of the designers and contractors prefer. The survey resulted in the identification of various factors and concerns that have a significant impact on the design and construction phases of a precast or hybrid concrete building. These factors or concerns were listed as:

- Design considerations for precast connections (forces and force transfer),
- Precast concrete design codes' rules and regulations and,
- The effect of seismic activity on precast concrete and precast connections.

These concerns were further investigated in this research apart from seismic considerations.

## 7.5 – Basic considerations and design forces of precast connections

It was found that connection design and force considerations for precast connection zones are one of the major obstructions of precast concrete construction. Several of the participants that completed the survey (Chapter 3) stated that the main reason for this in the South African precast industry is the fact that designers have a lack of understanding and insufficient knowledge in terms of precast concrete and precast connections. Designing and constructing a precast or hybrid concrete building, focussing more on the connections, the most important factors were concluded as:

(i) The connection should be able to resist or transfer the applied forces in the precast element and the connection area itself,
(ii) The connections must be designed to create a monolithic structure or building,
(iii) The various connections that form part of the structure must ensure overall structural integrity and continuity,
(iv) The connection must be designed to compensate for movements or unintended restraints, and
(v) Lastly all the connections must adhere to aesthetical properties set by the client or architect

This information provides the designer or consultant with a background to important aspects and factors that requires careful consideration during precast concrete connection design and construction. Understanding the interaction, assembly and strength of the required connection type at any given connection zone in the precast structure or building is an essential aspect.

## 7.6 – Design code considerations

Design codes and specifications form the basis of any designed structure in the construction industry, whether it is a cast in-situ, steel or in this case a precast or hybrid concrete building or structure. Considering the content from the SABS 0100-1 (2000 Edition) that were discussed in section 5.1 of the report, it can be seen that some of the aspects included for design of precast concrete elements as well as the connections are included but are not used or recognized by designers.

The SABS 0100-1 (2000 Edition) provides sufficient design guidelines in terms of precast concrete and connections, but do however require designers to be trained or instructed on how to use the code to efficiently design for precast concrete. This may be one of the significant reasons why precast construction is not that effectively applied in the South African building and construction industry, compared to other countries. Revising and adding some of the identified inclusions given in Chapter 5 to the scope of the SABS 0100-1 (2000 Edition) design code may advance or improve the construction and design of precast structures and buildings in the South African construction industry. One of the most significant factors of the SABS 0100 (2000 Edition) that require improving, is including more graphical presentations of certain concepts. Graphical presentations often improve the designer’s ability to understand or visualize certain concepts included in the design code.

The adoption of the EN 1992-1-1 into the South African industry will be beneficial for designers, but it may also be useful to integrate some of the inclusions given in the SABS 0100-1. This way the industry does not adopt all the design requirements given in the EN 1992-1-1, but also reserve part of the guidelines given in the South African design code.

## 7.7 – Enhancement methods for precast connections

Considering that the connections between precast concrete elements are an important part of any precast or hybrid concrete structure, a section in the report was included to help identify certain methods or techniques that can be used to enhance precast connection types. The methods that were investigated include the use of, self compacting concrete (SCC), ultra high performance concrete (UHPC), fibres in concrete, cables stayed and post tensioned solutions and the use of structural steel inserts. These enhancement methods and techniques have been developed to ideally address some noted problems, typically found in precast concrete connection areas. These typical precast connection concerns may include; dense reinforcement, cracks forming in connection zones, ability to create a monolithic concrete structure, too complicated connection designs, creating standardized connections that are easy to design and construct etc. The following list identifies the enhancement methods that will be most suitable for the precast concrete industry of South Africa:

- The use of SCC in precast elements and connections with high density formwork and were compaction is difficult to apply,
- The use of UHPC may result in stronger precast elements and create connection zones that are more rigid and can resist or transfer implied forces more effectively,
- The use of fibres can increase the flexibility of the precast members, but will that have that big effect on the connection zones.
- Structural steel inserts and the cable stayed post tension solution offer good and effective connection enhancement methods. Their applications may be very specific and unique, especially in the South African construction industry.

# CHAPTER 8 – RECOMMENDATIONS

Recommendations are provided here to assist the development and implementation of precast elements and precast concrete connections in the construction industry of South Africa. Based on the findings of the study, the following recommendations are made:

## 8.1 – Recommendations for the South African construction industry

### 8.1.1 – Identifying efficient precast connection guidelines and preferences

From the results obtained from either the literature or the surveys handed out to industry participants, the following guidelines should be implemented to improve the implementation and utilization of precast concrete and precast connections:

- More frequent exposure to precast concrete and precast connections typically used in the industry,
- Provide the industry participants (contractors and consultants) with the sufficient guidance and knowledge in design and construction of precast connections,
- Organize workshops or seminars on the topic of precast and precast connections, which can help industry participants to develop their skills and knowledge on this subject,
- The construction industry can make use of precast pilot projects that can be used as reference for other precast projects. Successful pilot projects can be used to identify specific solutions for precast systems and also list some concerns that are typically associated with precast construction.
- Develop a manual with design guidelines that can assist engineers with the designing of precast connections. This manual can include a list of the most popular connection types that are frequently used in South Africa. The manual should include design rules and guidelines based on precast concrete structural design aspects, included in codes such as the SABS 0100-1 and the EN 1992-1-1, but focusing more on the connection aspects of the precast concrete.
- The concept of precast design and construction should be implemented at an early stage of learning such as universities, colleges and schools.

Developing guidelines and sufficient knowledge based specifically on the precast industry of South Africa, also providing the industry with more exposure of precast, can assist industry participants to develop the use of precast concrete as an alternative construction method.

### 8.1.2 – Revision of current design codes for precast concrete and precast connections

Design codes and standards act as the basis for every structural design that is performed, whether it is an in-situ concrete, steel or precast concrete structure or building. During the study it was found that there are some shortcomings in the SABS 0100-1 (2000 Edition) design code in terms of precast concrete and connection design. Comparing the South African code to other international design codes such as the ACI 318-2008 and the EN 1992-1-1: 2004, it was noted that the following improvisations to the SABS 0100-1 (2000 Edition) code can be made:

- Monolithic action of pre-stressed hollow core slabs,
- Including a revision of the Strut and Tie method,
- Improvise the design for precast connection shear (in-plane shear and horizontal shear), and
- Develop guidelines for structural steel inserts in precast connections

These listed improvisations were noted as the most important aspects, because it was listed to be the most popular or frequently used precast concrete elements and connections in the South African construction industry.

### 8.1.3 – Contractual requirements

Some of reasons why precast concrete and precast connections are not frequently used in the South African construction industry are due to unfamiliarity, lack of exposure and inexperience. Following the results of the survey, it was found that there are shortcomings in the available construction contract types for the use of precast concrete in the South African construction industry. This statement implies that the type of contracts that are available in the local construction industry do not always cater for the effective use of precast concrete during construction projects. Following that the contract types do not always cater for implementation of precast concrete which requires early contractor involvement, and this also contributes to the under-utilization of precast in the South African construction industry.

### 8.1.4 – Creating a database of precast connections

Improving the stance and utilization of precast concrete in the South African industry is an important aspect of this study. Identifying connection preferences during the design and construction phases of precast concrete construction was done to improve effective implementation of precast in the construction industry of South Africa. It was identified that one of the ways to improve the effective use and knowledge of precast connection design is setting up a national database. This database can typically include:

- Previous precast projects that were successfully completed,
- List various types of connections that were used during the completed precast projects,
- Typical connection design and construction guidelines also obtained from previously completed projects,

- The database can provide comments and concerns given by industry participants associated with the design and construction of typical precast connections,

This database can also be used as basis for a discussion room where industry participants can discuss encountered problems or provide assistance to others from previous experience on precast connections.

## 8.2 – Future research suggestions

The following list of recommendations were found during research and identification of factors included in the study. These suggestions or recommendations can be used to develop future research topics. The following suggestions were found during the study:

- Make an in depth investigation of precast connection design in seismic areas of South Africa. Investigate the effect of seismic activity in South Africa on the overall precast structure and precast connections. This investigation can also include a comparison on the stability, robustness and structural integrity of precast concrete with in-situ, in seismic areas.
- Consider development of technologies or computer programs that are developed specifically for the design of precast concrete connections.
- Develop research and testing on precast concrete connections by means of enhancement methods such as SCC, UHPC, fibres in concrete and developing efficient structural steel connection types for the precast industry of South Africa.
- There is limited information available on the performance of some of the listed connection types included in this study. Providing supplemental calculations or information about the strength/rigidity of the listed connection types as well as typical dimensions may be beneficial when trying to evaluate the benefits of precast concrete over traditional in-situ construction. This may be conducted as an additional study to also help identify and list preferred precast connection types according to their structural strength and performance.

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# ANNEXURE A - PRECAST CONCRETE STRUCTURAL SYSTEMS

The design of precast as well as pre-stressed concrete structures mainly depends on the integration of the different structural elements, and connections of these elements to form a structural system as a whole. Each aspect of the design and the construction should be considered and the functional requirements imposed by the use of the building must also be analysed.

It is critical that all the design loads imposed on the structure follows a load path throughout the whole structure, from their origin to the final support of the foundation. Although the code does not always require it, it is most desirable to design the precast members and their connections to achieve a ductile, rather that brittle failure mode. In addition to resisting the implied gravity loads, a major consideration in precast concrete building design is the lateral force-resisting system. There is an available variety of precast concrete designs that can be used to achieve these goals economically, effectively and also to ensure that structural integrity is achieved.(PCI - Designing with Precast and Pre-stressed concrete 2010)

Precast concrete manufacturers also have a critical role to play in the appropriate planning and implementation of precast concrete buildings. Involving the precast manufacturer at the early design stage of the structure is the most appropriate way to achieve an economical building solution. Early involvement also allows the manufacturer to schedule production of the different precast elements so as to maximise cost savings brought about by the use of standardised components and early completion.

In the past, precast concrete structures had a distinctive appearance as to other non-precast built structures. However, with recent advances in technology and techniques, precast buildings are now indistinguishable from those constructed using non-precast methods (PCI - Designing with Precast and Pre-stressed concrete 2010). Designers no longer work within tight constraints. Increasingly, the situation is that precast concrete manufacturers as well as designers are able to accommodate greater variety and complexity, effectively designing their elements to meet design requirements. Continuous investment and innovations have transformed the precast industry so that complex plan layouts and external treatments can now be accommodated.

The precast concrete industry has evolved and advanced so that precast concrete elements and all types of connections can now be incorporated in every building type. Whether the building has a regular or an irregular shape, the entire structure or elements of that structure, such as frame, floors, walls, stairs or balconies, can all be precast. (Irish Precast Concrete Association (IPCA) 2007)

# A.1 – Types of precast concrete structural systems

Precast concrete or in some cases hybrid concrete buildings are composed of some basic types of structural subsystems. These systems can be combined in different ways to obtain an appropriate and effective structural concept that fulfils the needs of specific building types. The most common precast systems have been identified as:

- **Beam and column systems** (beam elements, column elements and connections between the different elements)
- **Floor and roof systems** (floor elements, roof elements, connections between the different elements)
- **Bearing wall systems** (wall elements, connections between the different elements)
- **Facade systems** (facade wall elements, connections between the different elements)
- **Frame systems** (frame elements, connections)
- **Cell systems** (cell elements, connections)
- **Tilt-up precast concrete systems**

The above list is not unique as there are many variations possible to achieve the same objectives that architects and engineers are now successfully exploring (Menegotto 2006). During the next part of the section the above mentioned types of precast structural systems will be explained and elaborated.

## (I) – Beam and column systems

The main components of this structural system are mainly comprised from beams and columns, the beams and columns form the core of the structural systems. The typical connections found in these systems include; (i) beam-to-column connections, (ii) beam-to-beam connections, (iii) column-to-column connection, and (iv) column-to-footing connection.

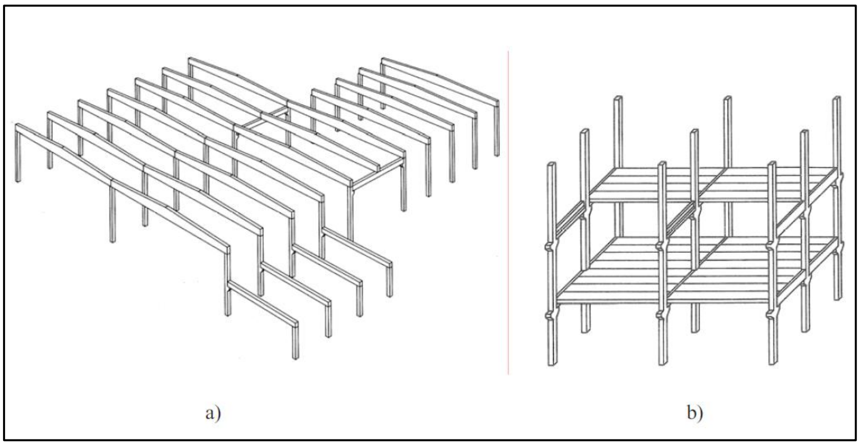



Figure A.1 (a) illustrates a single storey structure beam and column system and Figure A.1 (b) illustrates a multi storey beam and column system.

**Figure A.1 - Beam and column precast structural systems (Task Group 6:2: A. Van Acker et al 2010)**

## (II) - Floor and roof systems

The main purpose of a floor and roof system is to transfer the vertical load to the vertical load-resisting structural elements. Precast floors and roofs are often used as essential parts of the stabilising system to transfer horizontal loads by diaphragm action to the stabilising units.

Typical connections found in floor and roof systems can be identified as: (i) slab-to-slab at longitudinal interior joints, (ii) slab-to-edge element at longitudinal edge, (iii) slab-to-slab at interior support and, (iv) slab-to-end support. The most popular floor and roof systems include the following types:

### **(1) - *Hollow core floor system***

South-Africa makes a lot of use of hollow core slabs in the construction industry (De Villiers 2014). Hollow core slabs are said to be one of the most widely used and popular precast concrete elements in the construction industry of South Africa. The rest of structure is usually built using in-situ concrete, but the floor slabs and roofs are mainly constructed making use of hollow core precast slabs (Walraven 2013). Figure A.2 illustrates a typical connection detail of a hollow core floor system.

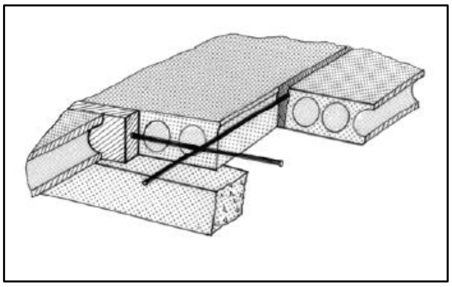


**Figure A.2 - Hollow core floor system (Björn 2006)**

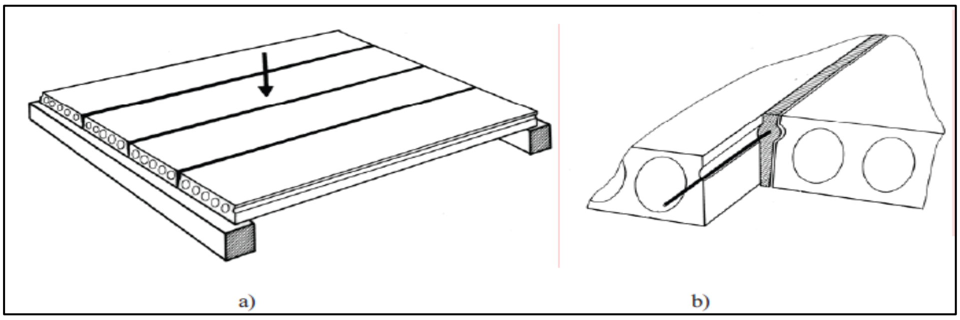



**Figure A.3 - Hollow core floor slab distribution of transverse loads (Elliot 2002)**

To obtain a transverse distribution of load effects in the case of concentrated loads and prevent uneven vertical displacements at the longitudinal joints, the hollow core floor connections must be designed to develop shear key action that ensures the interaction between adjacent elements, as seen in Figure A.3 (b).

**(2) - *Double-T floor system***

The system offers greater structural capacity at longer spans than hollow core or wide slabs, but often requires a deeper floor zone. Due to the Double-Tee's depth to length ratio, this floor slab is the only system which offers a solution for spans over 16m. Figure A.4 shows how these Double-T floor systems look like and how they are typically constructed or installed. (Walraven 2013)

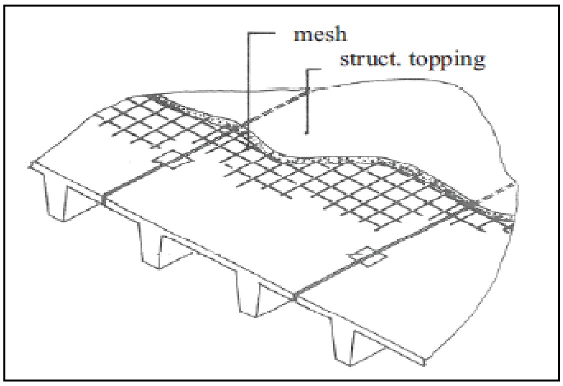



**Figure A.4 - Double-T flooring systems (Mishra 2012)**

**(3) - *Composite floor plate system***

In composite floor plate floors (also known as a hybrid-slab), precast concrete floor plates are used as formwork for the cast in-situ part and remain integrated in the composite floor section.

Structural toppings can be combined with precast units to produce precast composite floors. The advantage of precast composite floors is the increased bending and flexural stiffness. Structural toppings can also be specified to improve acoustic performance and reduce the vibration implied on the slab. In situ toppings will also improve thermal performance. (Walraven 2013)

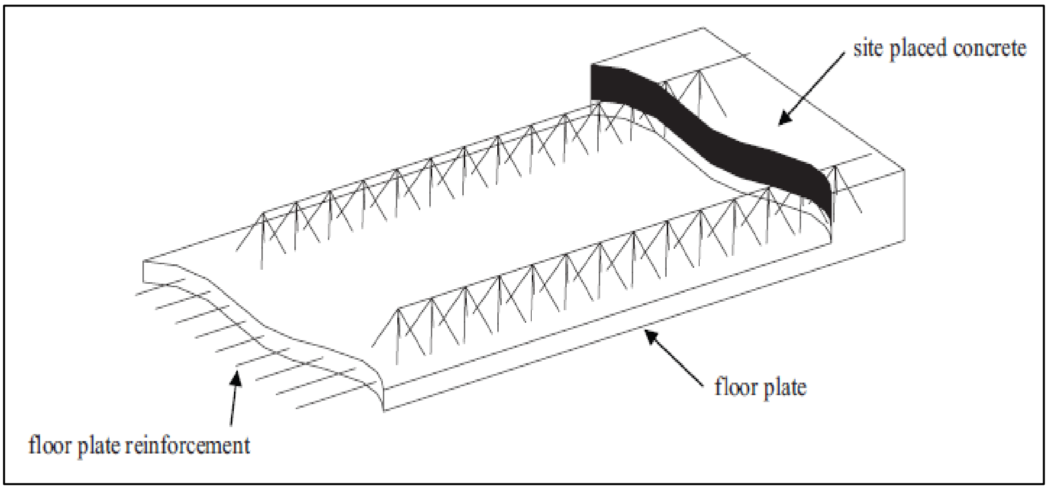



**Figure A.5 - Composite floor slabs with lattices (Menegotto 2006)**

## (III) – Bearing wall system and non-bearing façade walls

Often the most economical and effective application of architectural precast concrete is a load bearing component, which resists and transfers loads applied from other components. These load bearing members cannot be removed without affecting the strength or stability of the building, thus playing one of the most important roles in the strength and integrity of the entire structure.

Concrete components normally used for cladding applications, such as solid-wall panels, window walls, or spandrel panels, have an impressive structural capability. With few modifications, many cladding panels can function as load bearing members. The slight increase in costs for load bearing wall panels, due to extra sufficient reinforcement and connection requirements, can be offset by the elimination of separate structural frames (beams and columns) for exterior walls or by a reduction of interior shear walls. (PCI - Designing with Precast and Pre-stressed concrete 2010)

Load bearing panels can be supported by continuous footings, isolated piers, grade beams, or transfer girders. The bearing-wall units can start at an upper floor level with the lower floors framed with beams and columns. Figure A.6 (a) and (b) illustrates different type of load bearing wall systems.(PCI - Designing with Precast and Pre-stressed concrete 2010)

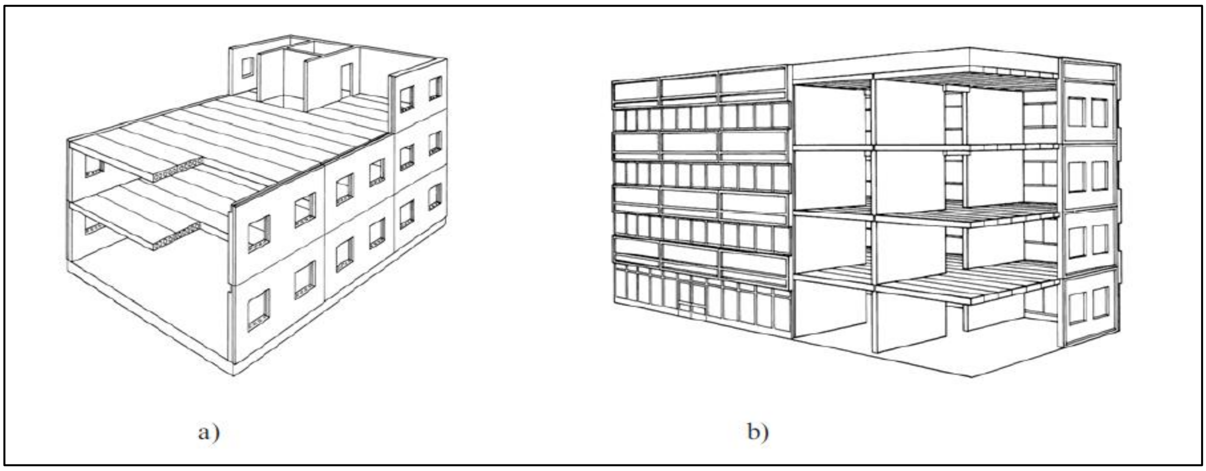



**Figure A.6 - (a) load-bearing façade wall, (b) load-bearing cross-walls (Menegotto 2006)**

Non-bearing walls are most generally designed to transmit their own dead weight, which means that the connections at the horizontal joints are required to resist the weight of the wall elements above the level of the wall. However, as an alternative, a non-bearing façade walls might be fixed to the neighbouring load bearing system in such a way that the dead weight of each wall element is supported by the main frame system. An example of a non-bearing façade wall system is shown in Figure A.7. (Task Group 6:2:

A.Van Acker et al 2010). The majority non-bearing façade does not actually contribute to the overall strength of the structure but is for aesthetical reasons only.

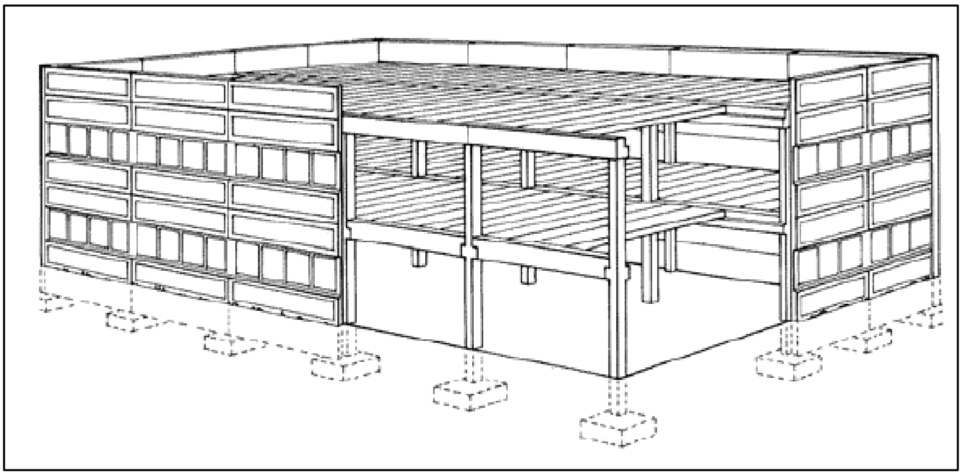


**Figure A.7 - Non-bearing façade walls (Menegotto 2006)**

## (IV) – Moment resisting frame systems

Precast concrete moment-resisting frame systems are found in skeletal or portal systems where 'frame action' is used for the stabilisation. This is obtained by combining spatial H-shaped elements, L-shape elements, or portal frames, etc. with monolithic connections at the intersections between beams and columns within the element. The elements are connected in locations where flexural resistance is not required at points at contra flexure. Alternatively the connections between beam and column elements may be designed and detailed to obtain the required continuity and moment resisting capacity.

## (V)– Cell systems

Precast concrete cell systems are composed of closed cell elements or open cell elements with U- or L-section. Complete structures can be made by combining cell-elements. However, it is more common to use cell elements for specific parts of the structure, for instance wet areas, and combine these with ordinary walls and floor systems.

The cell element system is not extensively used, because of transport problems and lack of flexibility in the layout of projects. Figure A.8 illustrates 3 different varieties of how the sell system can be implied. (Task Group 6:2: A.Van Acker et al 2010)

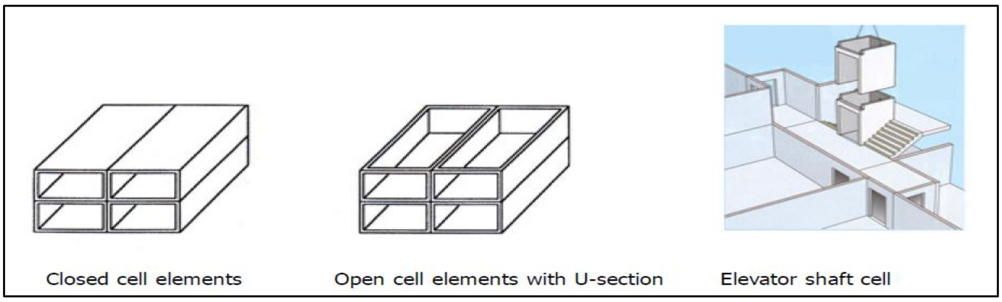



**Figure A.8 - Different types of applications of the cell-system (Walraven 2013)**

### (VI) – Tilt-up precast concrete systems

Although tilt-up systems are not explicitly manufactured in a factory or a precast concrete yard and the fact that it is actually cast on-site, the system still utilises the details of prefabrication and precast concrete construction. Tilt-up systems can be described as a type of load bearing construction which consists from simple on-site casting of rather large and slender reinforced concrete panels, beams and columns.

The tit-up system is casted on the building's in-situ floor slab or a temporary blinding can be also casted for the tilt-up panels to be casted on. The in-situ slab for the concrete building is casted conventionally (or the temporary blinding slab) and the surface is covered with a bond-breaker to avoid the tilt-up panels sticking to the floor slab. The formwork for the tilt-up panels are is laid down and cross-braced for stability and strength. The reinforcement of the tilt-up panel is placed in the formwork and lifting elements are also installed. After the concrete has been casted the panels are cured inside the formwork until it reaches sufficient strength. Eventually the formwork is stripped (at this point the panels are totally self supporting) and each panel are lifted or tilted carefully into position to be permanently installed. For the installation process, the panels are propped and connected to the floor, roof, columns or beams of the building.

If big construction projects were to make use of tilt-up construction, it is stated by Gibbs that tilt-up typically represents between 25% and 40% of the overall construction cost, depending on the building contents of the project. Therefore tilt-up systems may significantly contribute to cost reduction of the overall project.

**Figure A.9 - Different steps in tilt-up construction (Group 5, 2014)**

***- Concluding remarks on precast structural systems:***

Precast concrete structures enable fast and effective completion of many different types of buildings and other structures (Alfred A. Yee 2001). The precast construction industry has grown rapidly in the past few years and the amount of precast construction building techniques known to be used is vast. The type of precast structural system that will be used depends mainly on the type of structure, the function of the structure as well as the magnitude of the structure that will be built. All the precast systems that were discussed in this part of the report include the use of various types of connections between precast elements. Considering all the connection types that were identified in Chapter 2 of the report, it is the designer and contractor's responsibility to make use of the most effective and simplest connection type. It should also be kept in mind considering all the aspects contributing to the overall strength and integrity of the structure.

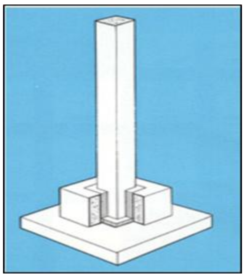
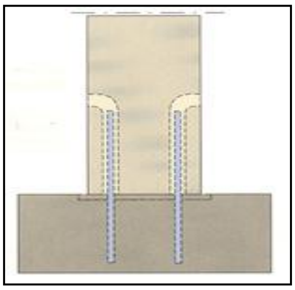
An effective design and construction of a precast concrete structure is achieved through the use of suitable connections to supply for all service, environmental and ultimate load conditions. Thus it can be said that the connections between the different precast elements are one of the most fundamental aspects of design and construction of a precast concrete building. The structural response will largely depend on the behaviour and the characteristics of the connections (Alfred A. Yee 2001). Concluding this section on precast structural systems, the following considerations should be taken into account when selecting an appropriate precast system:

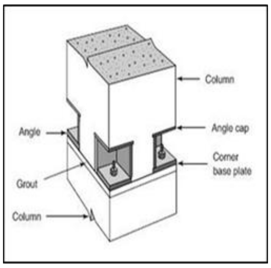
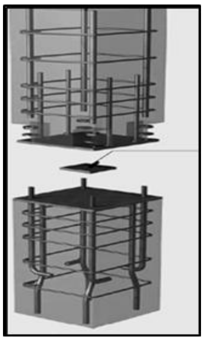
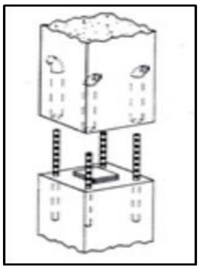
- What type of precast structure will be constructed?
- What is the main function of the precast structure or building?
- What type of precast concrete elements will be used for the precast system?
- Consider the most appropriate and effective connection types used in the precast system
- Simplify the process as much as possible, this includes making use of standardized precast elements, repetition of elements, easy assembly and creating connection types that is simple to install.

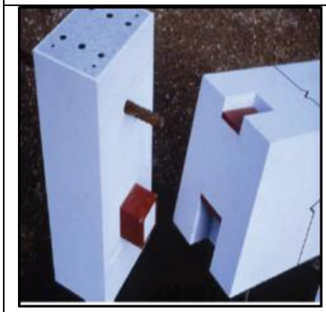
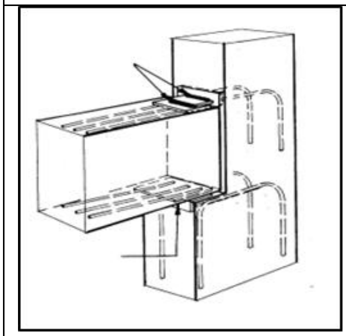
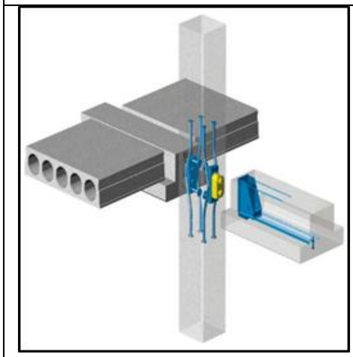
The above listed factors should be considered whenever embarking on making use of precast concrete construction. The factors can however be broken down individually to consider more intricate details, but may act as a guideline for contractors and designers to create an overall effective precast concrete system.

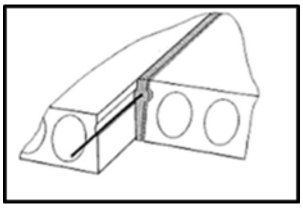
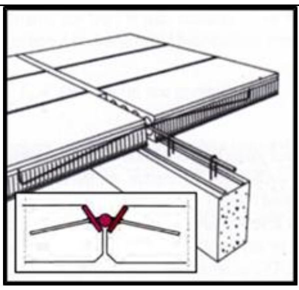
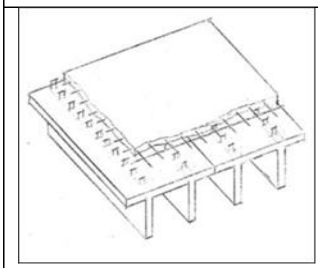
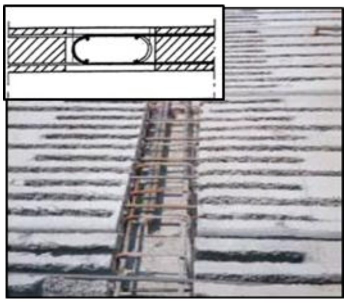
# ANNEXURE B – LIST OF CONNECTION TYPES INCLUDED IN THE INDUSTRY SURVEYS

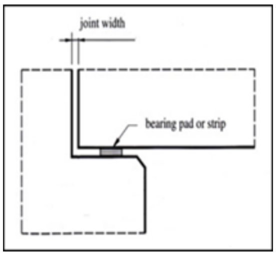
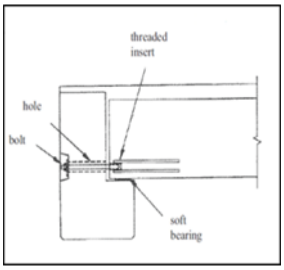
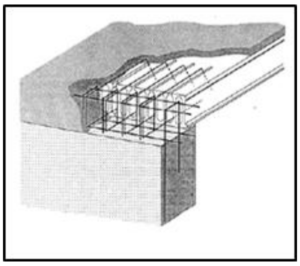
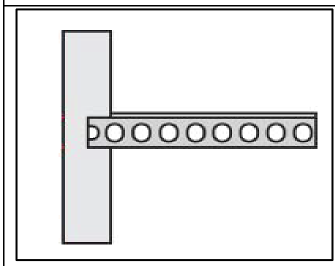
The following list of precast connections types were included in the questionnaires that were handed to selected consultants and contractors in the engineering industry of South Africa. The connections that were identified were chosen from the Literature study in Chapter 2 of the report. The same connections were used for all the questionnaires that were handed out. The following connection types, which typically occur in a precast concrete or hybrid concrete frame buildings, were used:

| Foundation-to-Column Connection | | |
|---|---|---|
| | **Rating** | **Comments** |
|  **Pocket foundation** | | |
|  **Baseplate connection** | | |
|  **Dowel connection** | | |

| Column-to-Column Connection | | |
|---|---|---|
| | **Rating** | **Comments** |
|   **Column shoe connection** | | |
|  **Welded plate connection** | | |
|  **Dowel connection** | | |

| Column-to-Beam connections | | |
|---|---|---|
| | **Rating** | **Comments** |
|  **Steel billet connection** | | |
|  **Welded plate connection** | | |
|  **Hidden corbel connection** | | |
|  **Corbel connection** | | |

| Floor-to-floor connections | | |
|---|---|---|
| | **Rating** | **Comments** |
|  **Concrete grouted connection** | | |
|  **Welded or bolted connection** | | |
|  **Reinforced topping** | | |
|  **Loop connection** | | |
|  **Rib and Block connection** | | |

| Slab-to-Beam Connections | | |
|---|---|---|
| | **Rating** | **Comments** |
|   **Simply supported** | | |
|   **Bolted or built in connection** | | |
|  **Ties and reinforcement** | | |
|  **Hollow core slab** | | |
|  **Rib and block slabs** | | |