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# The experimental determination of structural design parameters for roof covering systems

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Thesis presented in the fulfilment of the requirements for the  
Degree of Master of Science in Engineering at the  
University of Stellenbosch, South Africa

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**November 2011**

## Declaration

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## Synopsis

All structures are designed for a particular set of load combinations. For roof structures the critical loading combinations are predominantly wind actions. The accumulative effect of wind actions, by wind entering through dominant openings to exert pressure on the inside of roof structures together with the suction of wind vortices on the outside of the roof, can contribute to extreme load combinations. Frequently recorded failures on roof structures suggest that either the loads are underestimated or the resisting capacity of the roof coverings is overestimated. The focus of this study is directed on the latter, determining the effective resistance of roof coverings in the form of sheeting against a Uniformly Distributed Load (UDL) such as wind actions.

To determine the carrying capacity of a roofing structure, the standard approach used involves experimental tests on certain configurations with two or more spans. The structural test set-up is loaded with sandbags until failure is reached.

For the design of roofing systems, design tables are used that list the maximum allowable purlin spacing. The purlin spacing is presented in the form of a fixed value in units of length and is shown independent of a UDL that the roof needs to be designed for. The need to a new approach to determining the resistance of roof covering systems was identified.

The resistance of roof coverings for the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS) depends on a number of parameters such as the bending resistance, the stiffness of the sheeting in bending and the carrying capacity of the fastening system. To evaluate these structural parameters, experimental tests were performed. A full-scale experimental test set-up, capable of simulating a UDL on roof sheeting, was developed. The experimental test set-up consists of four different configurations, each specifically schematized to evaluate a certain structural design parameter. The magnitude of the structural design parameters depends on the applied UDL and the span length, which is the distance between consecutive supports of the sheeting system. Therefore, by using the structural design parameters determined experimentally, a set of design tables could be generated. The design tables produce the maximum allowable span length of a roofing system that uses a desired UDL as a variable. By using the design tables, the purlin spacing for any roof structure can be calculated given its design loading combination. The calculated purlin spacings are now a function of the basic parameters that determine the resistance of the roof sheeting.

# Acknowledgements

I would like to thank the following people whose contributions have made the successful completion of this project possible.

## **My studyleader, Prof PE Dunaiski**

Prof Dunaiski provided a strong guiding hand throughout the project. I could always rely on the better advice, academically and even more personally. His enthusiasm to solve problems is infective, which was crucial for my learning phase. A truly great studyleader.

## **Dr JA van Breda Strasheim**

Writing up information of two years of research in a well structured and logical manner was not as easy as expected. Dr Strasheim was kind enough to provide imperative advice with the completion of the thesis.

## **Staff of the structural laboratory**

All staff members of the structural laboratory deserve a big thank you. Theoretical solutions are not always practical solutions. The lab has helped disintegrating and simplifying, the problems that theory imposes on the practicality, numerously.

## **Mr Danie Joubert and Clotan Steel**

His enthusiasm and endless support provided immense motivation to complete the project and to keep looking for answers and solutions. All contributions by Clotan Steel and Mr Joubert are highly appreciated.

## **My parents, family and friends**

I would like to thank my parents, family and friends for their amazing support. Without them, I couldn't have commenced the best time of my life yet. There is no possible way of telling how much I appreciate their presence. Parents never stop being parents.

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## Definitions and symbols

**Fastening system** consists of any bolt, screw, or formed mechanism such as a clip that connects sheeting to the supporting structure.

**Sheet** a single profiled metal element used as covering on a roof or a side wall. Also referred as a panel or cladding element.

**Sheeting system** a set of sheeting fixed to a suitable supporting structure by means of a fastening system.

**SLS** Serviceability Limit State as described in *SANS 10160-1* (SANS 10160-1, 2008)

**ULS** Ultimate Limit State as described in *SANS 10160-1* (SANS 10160-3, 2008)

**UDL** Uniformly Distributed Load, for which the symbol used is  $W$  in kPa, or  $w$  in kN/m

**De-indexing** releasing of the interlock between two adjacent sheets

**Oil-canning** elastic deformation in the form of local buckling of sheeting

**SFD** Shear Force Diagram

**BMD** Bending Moment Diagram

**$M_{A1}$**  applied bending moment at midspan also referred to as positive bending moment in this study, considering wind uplifting actions.

**$M_{A2}$**  applied bending moment at internal support also referred to as negative bending moment in this study, considering wind uplifting actions.

**$M_{R1}$**  resisting bending moment at midspan also referred to as positive bending moment in this study, considering wind uplifting actions.

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$M_{R2}$	resisting bending moment at internal support also referred to as negative bending resistance in this study, considering wind uplifting actions.
$P$	concentrated load or point load
$R$	resisting capacity of the fastening system
$L$	clear span length measured between the centres of supports

# 1. Introduction

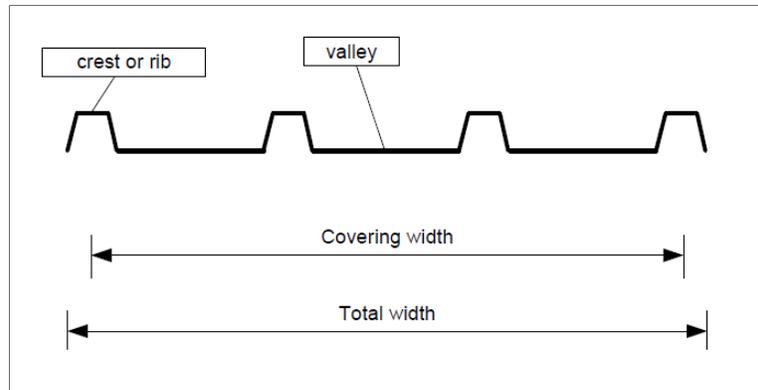
At the highest point in a structure, roofs are exposed to extreme load combinations consisting of wind loads, service or maintenance (live) loads as well as high temperature fluctuations. Depending on the type of roof covering preferred, it needs to be stiff enough to cope with distributed loads yet also offer adequate flexibility to accommodate temperature expansions. Modern aesthetic needs require different approaches of confronting these combinations of loading challenges. A competitive market in the profiled sheeting industry is developing constantly. A continuous development of new products required, products that are resistant to loading, look good on the structure and have a higher cost-efficiency.

To increase the cost-efficiency, new products for roof and wall covering systems are continually introduced into the market. Before new products can be safely used in the industry they have to be tested. A full-scale experimental test set-up was developed and used to test the carrying capacity of a covering system in the form of profiled metal sheeting.

## 1.1 Roof coverings in the form of sheeting

The type of covering chosen for a structure depends on a number of parameters. For a typical town house the major issue for instance might be aesthetics. Since houses are generally low in elevation, hardly reaching a height of 10m, and situated in densely populated areas, wind forces never get to be critical. For industrial sites, however, the roof coverings need to be cost-efficient, easy and fast to erect and be able to withstand extreme weather conditions including wind actions.

The focus of this research is primarily directed to the covering systems used in industrial roof structures, where the roof of the structures typically have a very large surface area making it specifically vulnerable to extreme wind forces. Industrial warehouses usually have a roof and wall covering system in the form of profiled metal sheeting. The profile of these metal sheets is designed to resist uniformly distributed loads (wind actions) that act in a direction being perpendicular to the sheeting. The section of a typical metal sheeting profile known as Inverted Box Rib (IBR) sheeting is shown in Figure 1 below.



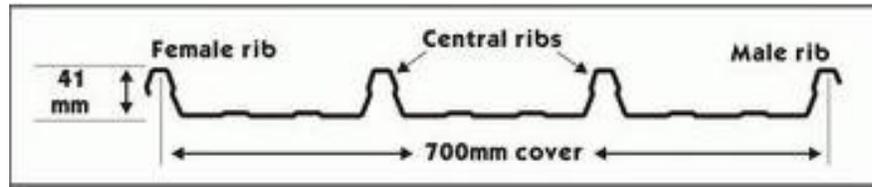
**Figure 1: IBR sheeting section profile**

There are a number of different ways which are used to fix the sheeting to a supporting structure. Roof sheets are fixed through the crest (also referred to as rib), whilst wall panels are conventionally fixed through the valley elements. The means of fastening the sheeting to a supporting member is discussed in the following section.

## 1.2 Fastening systems

All roof fastening systems can be classified into two categories, positive fixing and non-positive fixing (also referred to as concealed fix or secret fix). Positive fixing methods are considered the conventional method and regarded as the most widely used in the industry. Positive fixing for roof coverings is used in conjunction with IBR or corrugated sheeting profiles, and involves nails or screws driven through the crest of the sheeting profile into a purlin support. Perforations are thereby unavoidable in the crest of the sheeting. Roof structures are subjected to daily temperature changes which causes thermal expansion and movement. Positive fixing limits the thermal expansions, therefore the perforations at the fixing points are worn out and thereby become a threat to leakage in the long term.

For non-positive fixing methods there is no perforation of the sheeting which means no bolt, screw or any other fastening mechanism is visible from the outside of the structure. A number of different fastening systems are available in the market. For non-positive fixing, the sheeting profile is folded or formed so that a female and a male end can be distinguished on both the longitudinal edges of the sheet. Figure 2 below shows a typical roof sheeting profile used for a concealed-fixed roof covering.



**Figure 2: Roof sheeting profile (non-positive fixing)**

The male rib is typically fastened by means of a clip, cleat or fastening bracket, and the female rib of the adjacent or next sheet is folded or clipped above the male rib. The female rib thereby conceals the fastening system (bracket).

For non-positive fastening systems, the sheeting is not fixed in the longitudinal direction. This introduces a freedom of translational movement of the sheeting i.e. the sheets can slide and expand freely. This freedom of movement eliminates stress concentrations at fastening points as compared to positive fixing during expansions in the metal due to temperature fluctuations.

Every roofing system consists of the sheeting and the fastening system. The sheeting itself often forms part of the fastening system as just described (non-positive fixing) where a female rib forms an interlocking seam with the male rib. The resistance that the roofing system has against wind actions depends on a number of factors. These factors, as well as the interaction between them, can be determined using an experimental test set-up.

### **1.3 Structural performance of roof covering systems**

Roof covering systems are primarily designed to withstand high wind forces. Wind forces act on large surface areas and in a direction normal to the roof. All roof coverings need to be designed strong enough to resist these loads. The resistance of profiled roof sheeting, against uniformly distributed loads i.e. wind actions, depends on a number of strength-defining structural parameters. The main structural parameters that govern the strength of a roof covering are the resistance that the sheeting system has against bending and the carrying capacity that the fastening system can hold. The parameters depend on the type of material used as covering system, the dimensions and thickness of the sheeting profile as well as the type of fastening system used. This makes the parameters unique to each individual covering system.

As previously mentioned, the parameters govern the resistance that roofing systems have against uniform loading. Therefore, to be able to design a roof covering system, all parameters need to be determined. An experimental test set-up that is capable of evaluating these structural parameters for every covering system was used in this study.

## 1.4 Experimental testing of the carrying capacity of roof coverings systems

The experimental set-up used to evaluate all structural parameters of a roofing system consists of a full-scale covering system model. The model is loaded to an extent that causes the covering system to reach ultimate failure conditions.

To obtain the structural design parameters the loads simulated in the experimental test set-up need to resemble a wind action as closely as possible. Uniformly distributed loads are therefore ideal, but to successfully apply a perfectly uniform load onto an experimental test set-up is unpractical and difficult. Approximations are therefore used that simulate a uniform loading. The aim is to find a loading scheme that affects the loaded specimen like an actual wind i.e. generates the same structural response as a wind load would.

The structural parameters, resistance to bending and the fastening system capacity, need to be determined in order to be able to design the carrying capacity of a roof covering system. To test the parameters, more than one experimental test set-up configuration is needed. Each configuration is designed for the particular purpose of testing the capacity a certain structural design parameter as will be discussed in Section 5.

All information on the details and schematizations of the experimental test set-up are specified in a code of practice or a national standard. The South African *SANS 10237 – Metal roof and side cladding* (SANS 10237:201X, 201X) is discussed and compared to the guidelines and specifications given in the European, American and Australian standards.

## 1.5 International compatibility and similarity

The standards mentioned above prescribe guidelines on the apparatus to be used, configurations of the test specimen, the size of test specimen, measurements that are to be taken and so forth. These specifications and guidelines in the standards vary from country to

country. A reason for this variation can be different wind conditions, different land topographies or even conservatism. In spite of these differences, variation depends mostly on the amount of research spent in this specific field. A direct comparison was done to be able to associate the local proceedings to a worldwide level.

The standards chosen to compare the South African design approach with are the American *ASTM E 1592* (ASTM E 1592, 2005), the German *DIN 18807.2* (DIN 18807-2, 1987), and the Australian *AS 4040* (AS 4040.0, 1992). The experimental test set-up discussed in the previous section should conform to the requirements of at least one of these standards.

## 1.6 New design approach

The design of roof coverings in the industry is currently based on the use of design tables provided by the supplier of the coverings system. The design tables only detail the maximum purlin spacings allowed for a certain roofing system. These purlin spacings are provided independent of any loading that the roof needs to be designed for. Engineers did not make use of the design codes and standards for the design of covering systems, since all cladding were simply built according to the maximum allowable purlin spacings as provided by the design tables of the supplier. This design approach has been found inadequate and unsafe to wind actions in several instances. A new design approach is proposed.

With the structural parameters determined by the a testing scheme discussed in this study, a set of design tables for each specific sheeting profile and fastening system can be drawn up. These design tables enable the design of any roofing system and rely on the strength capacities of the individual components of the covering system. The configurations that are proposed and discussed can determine the Ultimate Limit State (ULS) and Serviceability Limit State (SLS) capacities of any roof system that is tested. These capacities are used to produce a new generation of design tables presented in terms of a load and a purlin spacing.

## 1.7 Summary

The experimental determination of the structural design parameters of a roof covering system is discussed in this report. It was found that the results of a number of tests done on an experimental test set-up could be used to design a roof covering system against uniform loading, in specific wind actions. The results yield structural design parameters that can be

used to draw up a set of design tables for the specific roof covering system that was tested. A new design approach can be incorporated by the use of the new design tables obtained from the experimental test set-up.

To obtain a clear overview and understanding of the test results, the structural performance of roof cladding under static uniformly distributed loads needs to be understood. This report consists of a literature study, leading to the discussion of test results. Section 2 is a literature study where information of a testing scheme, that was used to evaluate the carrying capacity of roofing systems, is discussed. The problems found in the literature and practical experiences that could be improved are highlighted in Section 2. A new design approach is suggested which makes use of a more complex testing scheme. The experimental test set-up was developed according to guidelines specified in the code of practice *SANS 10237: Addendum A* (SANS 10237:201X, 201X). The specifications in the *SANS 10237* were compared to guidelines in America, Germany and Australia in Section 3. The experimental test set-up, discussed in Section 5, was developed consisting of four different configurations. Each configuration is dedicated to test the capacity of a certain structural design parameter. All boundary conditions and theoretical schematizations are defined. This report is concluded by the discussion of the test results and the possibilities thereof regarding the development of a new generation of design tables for metal roof cladding.

## 2. Literature review

A study into past roof failures and the history of approaches for testing the capacity of roof coverings was undertaken. The findings of publications on the testing of roof coverings are very limited. Some however could be used to elaborate on testing procedures. The following section summarizes failures of roof structures in the industry.

### 2.1 Roof covering failures

The failure of roof structures in South Africa occurs frequently. According to a recent article in the Steel Construction journal, issued by the Southern African Institute of Steel Construction (SAISC), “people who are familiar with the building industry know that many roofs are damaged by wind each year” (de Clercq, 2011). Insurance companies continue to disburse failures, although roof coverings fail repeatedly, simply because there is a lack of information in the reason of failure.

The reason for failure differs, yet the majority is due to the fact that the carrying capacity of the covering system is overtaxed by wind actions. The resistance of covering systems against uniform loading, like wind forces, depends on the carrying capacities of the individual components that make up the sheeting-fastener system. The reason for ultimate failure could therefore be the supporting structure, the fastening system or the sheeting system. Ultimate roof system failure occurs once any of the components mentioned fail.

Unfortunately, forensic investigations performed on failed roof structures are rarely undertaken in detail and, furthermore, the reports of the investigations are kept confidential. Typically limited publications are available on the reason why a roof has failed and what component of the whole roofing system caused failure.

It is postulated that the regular occurrence of roof covering failures indicate that roof design resistances are exceeded. A non-conservative design for roof structures can either be because of a design calculation error by the responsible engineer, or the fact that the design parameters available for the roofing system is unreliable. Since there are multiple roof failures in South Africa, not all designed by the same engineer, the regular occurrence of failures suggest that the parameters available for the design of roof structures are not up to standard.

The strength of roof structures is determined by experimental testing procedures. The tests yield results that can be used to determine how strong the roof system is against loading. A study into the testing procedures performed in practice is discussed.

## 2.2 Testing of metal roof and side wall cladding systems

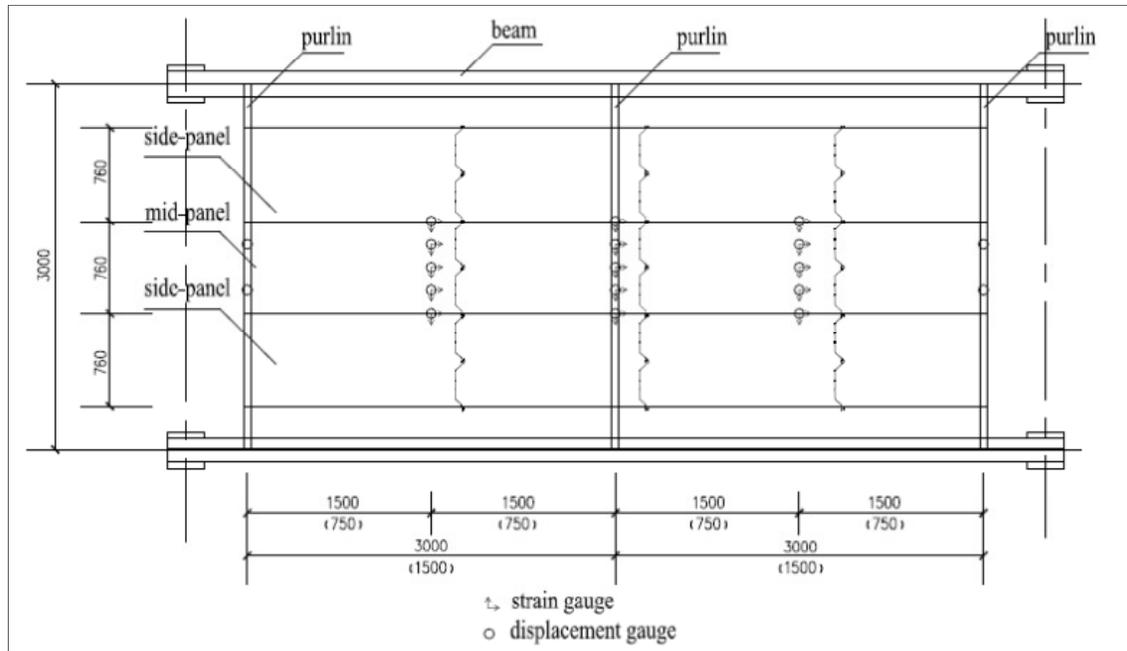
To test the carrying capacity of roofing systems an experimental test set-up is used. The layout and scheme differs slightly in different countries or testing institutes. However, the basic principles are found to be the same. Unfortunately, the number of publications dealing with roof sheet tests are limited. The layout used, the load application and the measurements taken in each publication is discussed and compared.

### 2.2.1 Experimental test set-up

Codes of practice and design standards specify guidelines on the detail of how the experimental test set-up should be configured. The guidelines differ slightly in different countries. More on the specifications in codes and standards can be found in Section 3. Two different test set-up configurations used in the industry, are discussed and compared. The first set-up was developed in China at the Tongji Construction Quality Inspection Department in Shanghai and was reported by X Song, L Chen and Q Zhang (Song, Chen, & Zhang, 2010). The second set-up is used by the Council for Scientific and Industrial Research (CSIR) in South Africa and reported by A Goliger (Goliger, 2009).

#### 2.2.1.1 *Tongji Construction Quality Inspection*

The Tongji Construction Quality Inspection Department in Shanghai, China, has developed a set-up that consists of two spans as shown in Figure 3 below. The set-up consists of two main rafters or beams that support three purlins. The distance between purlins, also referred to as span length is 3m. The metal roof sheets, in this case each having a covering width of 760mm, are fixed to the purlins by the fastening method prescribed by the supplier of the sheeting system.

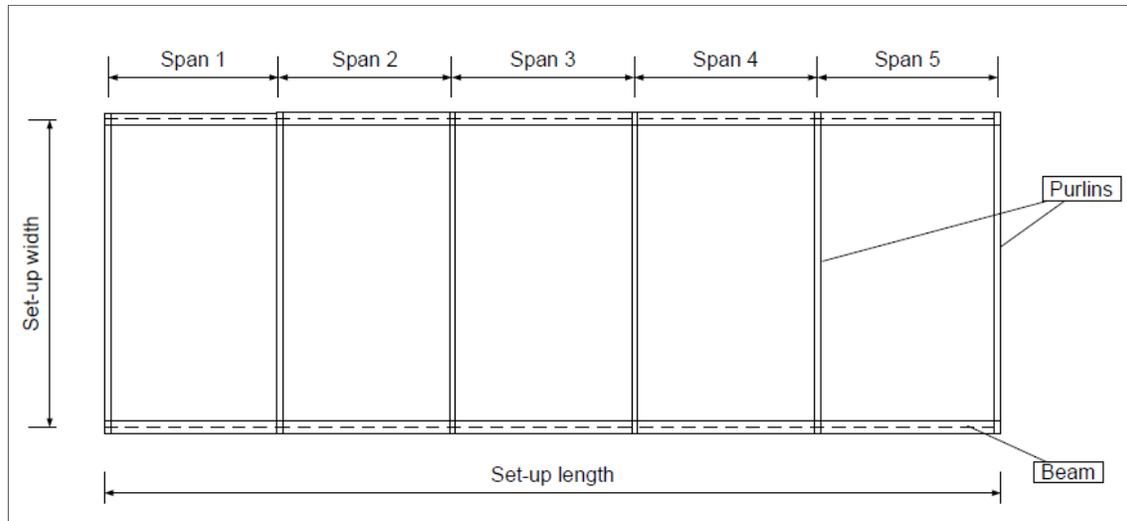


**Figure 3: Structural layout of experimental test set-up from the Tongji Construction Quality Inspection Department (Song, Chen, & Zhang, 2010)**

In the set-up shown in Figure 3, three sheets (two side-panels and one mid-panel) are fastened to the purlins. The centre purlin serves as the observational target, since the fastening system is expected to fail under simulated wind uplift loads. The middle purlin is subjected to the highest factored load in a simply supported double span configuration, therefore failure in the fastening system is promoted.

#### **2.2.1.2 Council for Scientific and Industrial Research (CSIR)**

The Council for Scientific and Industrial Research (CSIR) in South Africa has developed quite a similar test set-up. Instead of two spans as shown in Figure 3, the set-up used by the CSIR has five spans as can be referred to in Figure 4 below. The five spans used measured 1160mm, 1805mm, 1795mm, 1800mm, 1075mm from Span 1 to Span 5 respectively (Goliger, 2009).



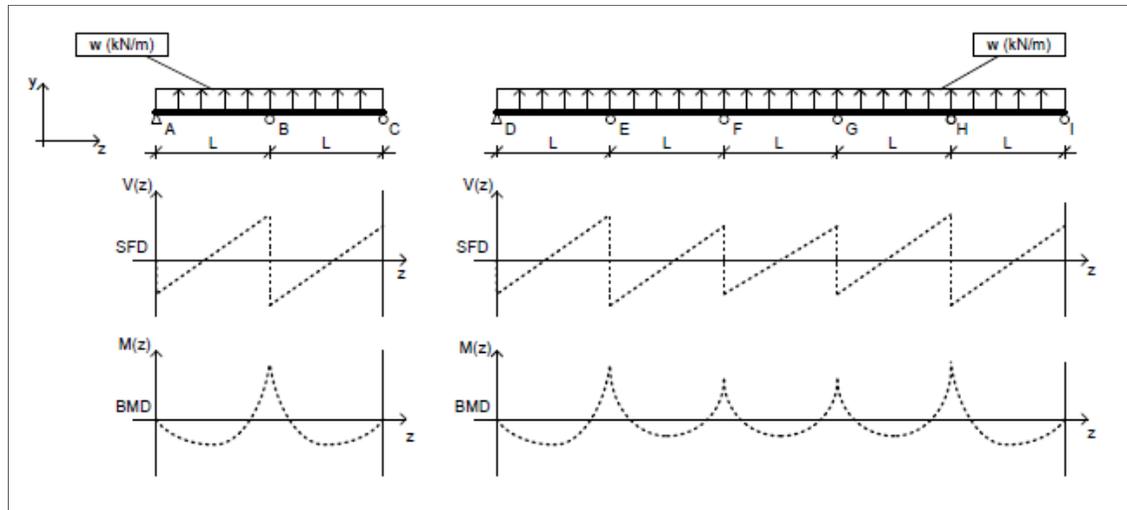
**Figure 4: Structural layout of experimental test set-up from CSIR (Goliger, 2009)**

Five sheets are installed spanning over the five spans with an overall width of 2200mm. Two more sheets are installed, compared to the set-up of the Chinese Tongji Construction Quality Inspection Department. The two additional sheets make five sheets in total and thereby provide three central sheets that are loaded and two edge sheeting to simulate effective fixing on each of the sides.

### **2.2.1.3 Discussion**

The similarities in the set-ups is that in both configurations there are three overlapping sheets that are loaded. Furthermore, both configurations provide more than one supported span. This forms an equivalent continuous beam configuration where the purlins act as simple supports and the sheeting as an elastic-plastic beam. For a continuous beam, the centre support (in Figure 3) or the first interior support (i.e. the second purlin from left or right in Figure 4) is subjected to both the highest bending moment ( $M$ ) as well as the highest reaction force ( $R$ ). The interaction of both  $M$  and  $R$  is therefore a load concentration that causes failure in the system.

Figure 5 shows the typical Shear Force Diagram (SFD) and the Bending Moment Diagram (BMD) for a two span and a five span continuous beam as determined by Euler's elastic beam theory.



**Figure 5: SFD and BMD for 2 and 5 span continuous beam**

As shown in Figure 5, the reaction at the centre support (B) or first interior support (E and H) are accompanied by high bending moments. Table 1 below details the exact theoretical calculated reactions and bending moments for the continuous beams shown in Figure 5.

**Table 1: Reactions and bending moment for a 2 and 5 span continuous beam (in Figure 5)**

Two-span beam		
Support	Reaction $wL$ (kN)	Bending moment $wL^2$ (kNm)
A	0.375	0
B	1.25	-0.125
C	0.375	0
Five-span beam		
D	0.39	0
E	1.13	-0.1052
F	0.97	-0.078
G	0.97	-0.078
H	1.13	-0.1052
I	0.39	0

The values computed and shown in Table 1 motivate the use of the configurations as discussed. These configurations promote failure at the centre purlin (Figure 3) or the first interior purlin (Figure 4) respectively.

The configuration used by the CSIR has reduced span lengths for the endspans. The interior spans were configured to roughly 1800mm, whereas the endspans were 1160mm and 1075mm respectively. In practice, a shortened endspan-length is a known precaution to

provide for the fact that the reaction force and the bending moment at the first interior support for a continuous beam both reach their maximum (as shown in Figure 5). It is therefore assumed that the configuration of the test set-up was designed to follow the practical application in the industry.

### **2.2.2 Load application**

Testing the response of roofing systems against design wind loads requires a load simulation as close to a real wind force as possible. There are three main types of loading schemes, namely point-loads, line-loads and uniformly distributed loads. Applying a point-load to simulate wind loads is relatively unproblematic and is therefore very often used in the experimental testing of roof structures. The loaded outcome, although is not as uniformly distributed as a wind load. The problem in applying a uniformly distributed load is the large surface area that is to be loaded, considering that a full scale set-up is required. A number of simplifications are therefore known to be used, for instance applying a number of point-loads to chosen nodes on the set-up thereby approximating a uniformly distributed load. The load application as used by the Tongji Construction Quality Inspection Department in China and the CSIR in South Africa is discussed.

#### ***2.2.2.1 Tongji Construction Quality Inspection***

The Tongji Construction Quality Inspection Department in Shanghai uses sand bags to simulate a uniform load. Two kinds of sand bags are used weighing 10kg and 26kg respectively. The time interval between each loading increment is 10 minutes. The sheeting specimen is loaded until failure is reached. Failure includes local buckling, panel yield and fastening system failure. The exact position where the sand bags are being placed on the set-up is unfortunately not specified in the publication.

Both positive uniform pressure and negative uniform pressure was applied to the experimental test set-up. For the scope of this study, only negative loading is considered to simulate wind uplift. To accomplish a simulated wind uplift, the experimental test set-up is turned upside down and the sand bags are loaded onto the inside of the sheeting consecutively.

#### ***2.2.2.2 Council for Scientific and Industrial Research (CSIR)***

The CSIR also used sand bags to simulate wind actions. The bags weigh between 22kg and 25kg. Figure 6 below shows the initial loading distribution on the test set-up (refer to Figure 4

for the layout of the set-up). The approximate size of the sandbags give an indication of the size of the contact area affected. A sequential loading scheme was used that had a predetermined position for each sandbag.



**Figure 6: Example of the loading procedure by the use of sandbags**

As shown in Figure 6, the sand bags are also arranged on the inside of the sheeting with the experimental test set-up turned upside down. This is to simulate the effect of wind uplifting pressures.

### **2.2.2.3 Discussion**

Considering a possibly very large surface area of the experimental roofing test set-up, a single sandbag acts as a point-load on the sheeting. By increasing the quantity of the sandbags, and placing them next to each other, a simulated uniformly distributed dead loading scheme is accomplished. The main advantage of using sand bags as a loading actuator is their simplicity. Sandbags are easily obtainable and they are employed on the roof structure very straightforwardly.

The drawbacks for using sandbags are firstly that a sandbag is still not a true representation of a wind load. Stacking the roof set-up with sandbags results in a stepwise load increment, and the effect of this low loading resolution is that for every bag added failure can occur very abrupt. Testing for the capacities in roof fastening systems, a finer resolution of the load increment is recommended.

Another disadvantage of using sandbags is the limitation to observing failure in the sheeting. Testing for wind loads, the test set-up is built with the upside down and loading the inside of the roof structure. The loaded sandbags block a direct line of sight to the point of failure. Also, a clear view from the bottom is unsafe since imminent failure is unpredictable and abrupt. Figure 7 and Figure 8 below show the state of the sheeting system after failure is reached on the configuration by the Tongji Construction Quality Inspection Department and CSIR respectively.



**Figure 7: Ultimate failure in the sheeting system (Song, Chen, & Zhang, 2010)**



**Figure 8: Ultimate failure in the sheeting system (Goliger, 2009)**

### **2.2.3 Testing process, measurements and failure**

The testing process in both the configurations was similar. Sand bags were loaded onto the set-up, where efforts were made to place the bags to achieve some sort of uniform loading spread.

#### ***2.2.3.1 Tongji Construction Quality Inspection***

The sand bags are loaded in a stepwise incremented manner. The mode of failure was the fastening system failing ultimately. The fastening system consisted of a fastening bracket, or clip, that clipped in to hold the sheeting in place. The clip was straightened, therefore not capable of holding the sheeting anymore. Figure 9 shows the straightened clip. Unfortunately, no more information is available on how the clip looked like before failure.



**Figure 9: Straightened fastening clip after failure of fastening system (Song, Chen, & Zhang, 2010)**

Each tests was repeated twice were the mean value was used. Tests were done with varying span length, sheeting thickness and sheeting material strengths. A summary of the test results are shown in Table 2 below.

**Table 2: Test results for Tongji Construction Quality Inspection Department (Song, Chen, & Zhang, 2010)**

Span length (m)	Sheeting thickness (mm)	Material strength (N/mm <sup>2</sup> )	Failure load (kN/m <sup>2</sup> )
3	0.6	300	0.91
1.5	0.5	340	2.28
1.5	0.6	460	2.74

Measurements of the deflections and strains were recorded at midspan of both spans and at the central purlin support. Five transducers to measure the deflection and the strains were installed and spread equally over the mid panel to attain the average value measured. Test measurement transducers are shown in Figure 3. Any data or post-testing analysis of the deflections and deformations were however not reported.

### **2.2.3.2 Council for Scientific and Industrial Research (CSIR)**

Similar to the loading scheme discussed for the Tongji Construction Quality Inspection Department, the loading scheme was introduced incrementally. When reaching each loaded increment, the test set-up was completely unloaded and permanent deformations were

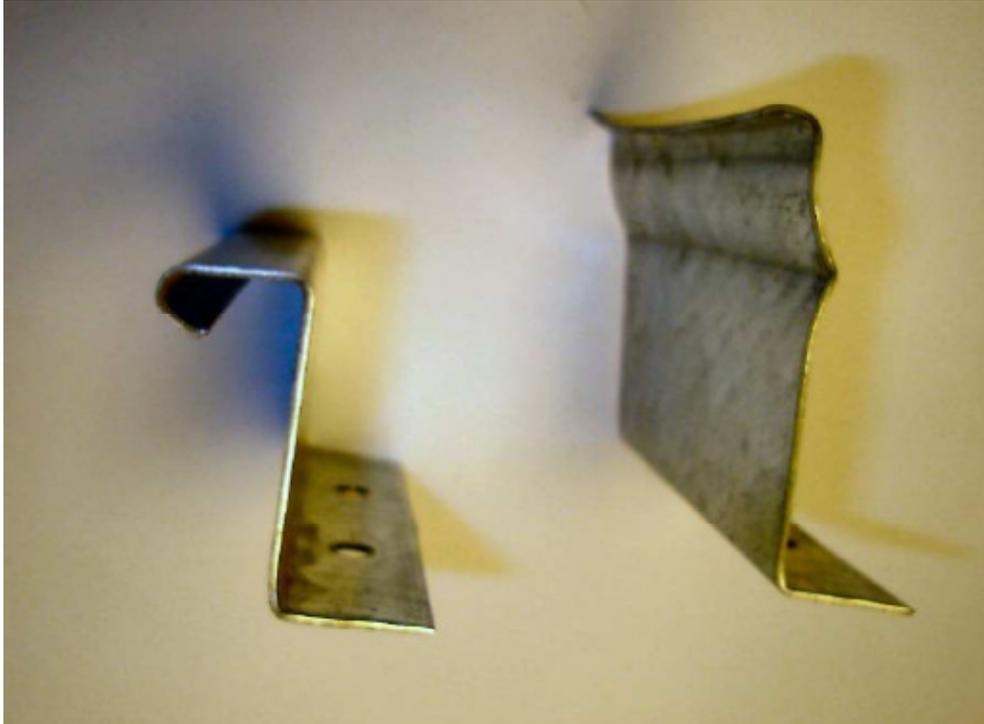
measured. The sheeting was fastened using clips or fastening brackets. The permanent set of the sheeting above the central brackets was measured. It is assumed that the central brackets, as mentioned in the publication, refer to the brackets holding the central sheet at the purlin where maximum deformations are expected. The purlin (in Figure 4) that is subjected to the highest load is expected to deform most. Considering the given span lengths, the two centre purlins are subjected to the highest factored load. Therefore, it is assumed that the measured permanent set was on either one of the central purlins, just above the fastening brackets holding the central sheet.

Table 3 below details the measured permanent set above the central brackets for each corresponding equivalent uniformly distributed load. Ultimate fastening system failure was observed at the equivalent uniform load of  $3.3\text{kN/m}^2$ .

**Table 3: Test results for the CSIR (Goliger, 2009)**

Load ( $\text{kN/m}^2$ )	Permanent set (mm)
0.95	0
1.35	0
1.55	27
2.3	50
3.3	-

Failure was initiated by the fastening bracket straightening to release its grip as shown in Figure 10 below.



**Figure 10: Straightening of fastening bracket after and before failure (left and right clip respectively) (Goliger, 2009)**

### ***2.2.3.3 Discussion***

The experimental test set-up was unable to record and observe the effective deformations in the material due to decreases and increases in loading. The effective relationship between the equivalent uniform loading and the corresponding deflections could also not be observed and is therefore not reported. Also, no indication was given in the publication on the number of test repetitions to obtain a statistical reliability of the test results.

## **2.3 Summary**

Suspensions in the safety of current roof coverings indicate that either there is a lack of understanding in the stressed behaviour of roof structures, or the information available on the structural performance of roof coverings is flawed and incomplete. Both the mentioned reasons rely on the accurate and comprehensive testing of roof structures. The testing procedures that the roofing industry in South Africa depends on were discussed and compared to a similar capacity testing approach reported in China.

### **2.3.1 Loading scheme**

In both configurations, the sandbags that were used to simulate a wind action do not represent a uniformly distributed load. The problem is considered not so much the contact area of the loading, but rather the relatively large load increments and the sequence of the exact position the sandbags are applied to. The structural response of the loaded specimen, subjected to a one-sided loading scheme compared to a true wind action, is unknown. A higher resolution of the incremental load steps should be investigated.

### **2.3.2 Failure modes**

The failure of the covering system, in both configurations discussed, occurs at the interior supports as mentioned. Fixed span lengths were chosen to ensure that the internal supports of the experimental test set-up are subjected to high reactions causing ultimate failure in the fastening system. For long span lengths, however, failure can occur in the form of bending before the fastening system fails. Figure 11 below shows the failure of the sheeting in the form of bending (at midspan) before the fastening system reached its maximum capacity on the configuration used by the Tongji Construction Quality Inspection Department. Unfortunately, no information has been provided if the loading has been commenced after bending failure was observed. A detailed description of possible failure modes of cladding systems on a typical roof structure can be found in Section 6.2.



**Figure 11: Failure in bending referred to as “collapse of panel” (Song, Chen, & Zhang, 2010)**

For the experimental test set-up used by the CSIR, fixed span lengths were chosen as mentioned. For the specific span length configuration, failure in the fastening system was observed. However, a roof supporting structure in practice, with different span lengths, might cause the reactions and bending moments to be redistributed. Any redistribution could result in a different failure mode. The point of failure was thereby not tested and therefore it can not be predicted. This suggests a possibility to a non-conservative design.

It can be reasoned that the two configurations discussed leave room for improvement in the testing roof covering systems. A new experimental test set-up is proposed as part of this study. The new experimental testing scheme is required to conform to a number of specifications and guidelines detailed in codes of practice and standards. The specifications in the South African code of practice are compared to the standards of other countries in the next section.

## 3. Roof cladding test method specifications

All testing that is performed on any type of roofing system needs to conform to regulations and guidelines specified in documents referred to as codes or standards. The code that specifies testing procedures in South Africa is the code of practice *SABS 0237:1991 – Roof and side cladding*. This standard is outdated and has been revised. The revised version is currently in the public comment phase as a draft code of practice and is referred to as the *SANS 10237:201X – Metal roof and side cladding*.

The experimental test set-up proposed in Section 5 conforms to all the regulations and guidelines stated in the new South African draft code of practice mentioned. How these guidelines differ to the guidelines detailed in standards from other countries will be discussed. The guidelines that specify testing procedures contained in the American, the German, the Australian and the South African standards are compared.

### 3.1 American standard

The American Society for Testing and Materials (ASTM) International publishes a standard that specifies procedures for testing the carrying capacity of roofing systems. The *ASTM E 1592:05 - The Standard Test Method for Structural Performance of Sheet Metal Roof and Siding Systems by Uniform Static Air Pressure Difference* (ASTM E 1592, 2005) is the standard under consideration.

#### 3.1.1 Scope

The scope of the standard is the assessment of the structural performance of sheet metal profiles as well as the fastening systems under uniformly distributed static pressure. The fastening system is referred to as the anchor-to-panel attachments, where the anchor is the means used to fasten the panel or sheeting to the supporting structure.

The guidelines stated in the standard are applicable to standing seam, trapezoidal, ribbed or corrugated metal panels with thicknesses ranging between 0.30 mm and 1.27 mm. The guidelines do not account for multiple-layer systems as in the case of insulation between two metal sheeting layers.

### 3.1.2 Terminology

The *ASTM E 1592* defines a set of terms of all elements and components in a typical roofing system as well as a description of the various failure criteria. To fully describe failure in a system, all components that play a role in triggering failure need mentioning.

Roof structures consist of the supporting structure, the fastening system and the sheeting. The sheeting is fixed to the supporting structure by the use of a fastening system. For the fastening system, the *ASTM E 1592* defines the device used to fix or fasten the sheet (sheet is also referred to as panel) to the supporting structure the anchor. The anchor is a “fastener, bolt, screw, or formed device such as a clip that connects panels to the support structure.”(ASTM E 1592, 2005) In some cases, the sheeting profile is formed in a way that it can fold over one another and form a so-called interlocking seam along the fold. The interlocking seam is then also considered as a part of the fastening system. Ultimate failure in the roof system can occur as a result of the anchors failing, or when sheeting itself fails.

A number of different failure types are considered when testing the capacity of roofing systems against uniform loading. In general, the sheeting system is considered to have failed when there is “fracture or disengagement of any of the components where the system is no longer capable of sustaining load, or the system no longer functions as a weathertight membrane”.(ASTM E 1592, 2005) For the fastening system, anchor failure is considered when there is “any failure at the anchor device including separation of the device from the panel, of the device itself, or of the connection to the structural support.”(ASTM E 1592, 2005) “Unlatching failure” is considered when there is a “disengagement of a panel seam or anchor that occurs in an unloaded assembly due to permanent set or distortions that occurred under a previous load condition.”(ASTM E 1592, 2005)

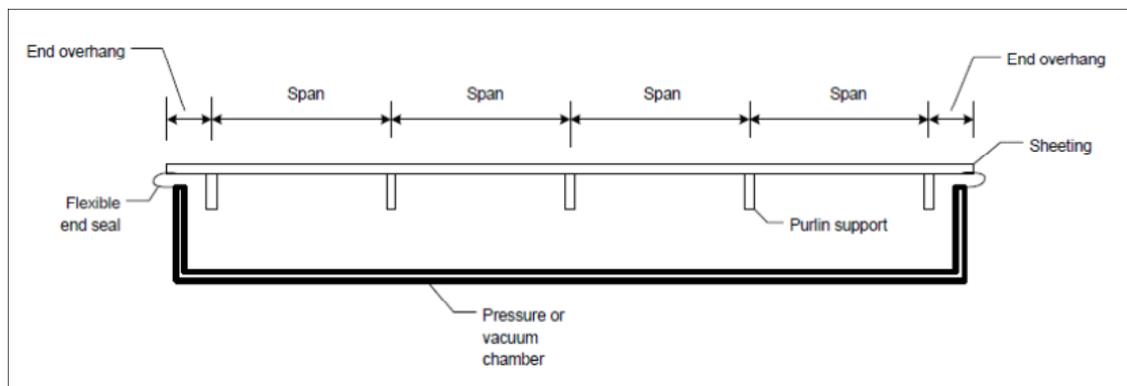
Two different load conditions are considered to cause failure. The “ultimate load is the difference in static air pressure (positive or negative) at which failure of the specimen occurs” (ASTM E 1592, 2005), where failure is regarded as general failure described above. “Yield load is the pressure at which deflection increases are no longer proportional to the increase in pressure.”(ASTM E 1592, 2005) The panel deflection is defined to be “the displacement under load measured normal to the plane of the roof or wall surface of a longitudinal structural

element as measured from a straight line between structural supports.” Yielding of any material in the system is not considered failure.

### 3.1.3 Apparatus

The *ASTM E 1592* describes a test set-up, or apparatus, that is of a general nature. The major components that are considered to be standard in the apparatus are specified. They include a test chamber, the air system, the pressure measuring apparatus, deflection measurement apparatus and the location where certain readings are to be taken.

The test chamber may vary from being an airtight chamber, air bags or a box in which or against which the test specimen is mounted. Figure 12 is a diagram used to show an experimental test set-up. The apparatus shown consists of a four-span system where the roof sheeting are fixed to five parallel purlin supports. The supports are enclosed in an airtight chamber by a elastic seal as shown in Figure 12 below.



**Figure 12: Test chamber in *ASTM E 1592* (Fig.1 Schematic of test apparatus) (*ASTM E 1592*, 2005)**

Two inflation taps are specified to be located at opposite ends of the chamber to prevent the air pressure from exerting a direct force on the sheeting. The air system should be able to maintain a constant pressure to apply the load uniformly. The purlins are chosen sufficiently rigid to prevent excessive deflection under loading.

As for the measurement of the test data, the pressure-measuring apparatus is specified to measure within a tolerance of  $\pm 2\%$  of the design pressure. Deflection and distortion measurement includes the measurement of following:

- the deflection of the crests between the supports within 0.25mm tolerance

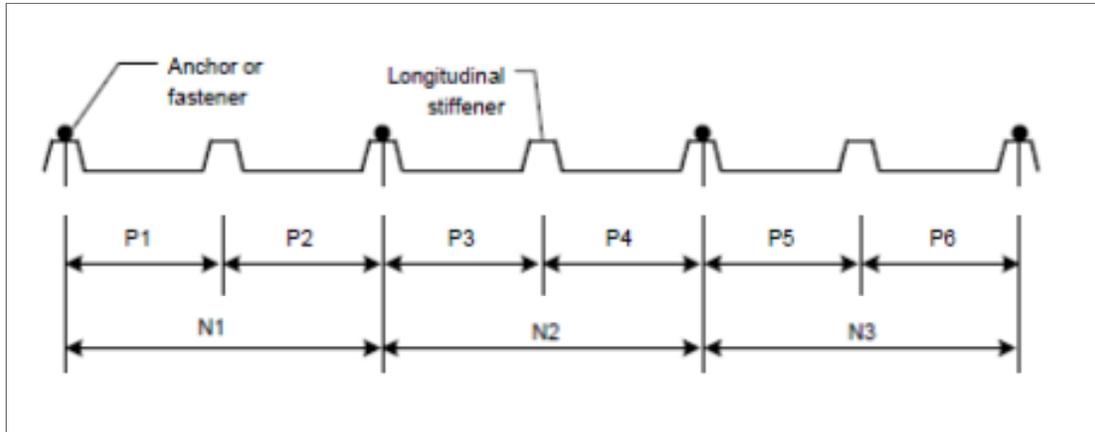
- movement of the crests at the supports within 0.25mm tolerance
- valley distortions within 1.5mm tolerance
- the spread of crests, if required, within 1.5mm tolerance

All measurements should be taken so that the readings are not influenced by any exterior factors like movement of the test set-up or the supports.

### 3.1.4 Test specimen

The test specimen is also referred to as the cladding system which is to be tested. According to the specifications listed in the *ASTM E 1592*, the full specimen is to be loaded including the overhangs (see Figure 12). All components of the specimen, including the sheeting, the fastening system and also the method of construction, shall be of the same dimensions, materials and all details as used on an actual building.

For the purpose of evaluating the bending capacity or the fastening system, the specimen width is required to consist of at least three full sheets (panels) and five structural elements. The *ASTM E 1592* specifies the term structural element as “the width of a panel profile as measured between the centre lines of repeating longitudinal stiffeners for continuously supported panels in a positive load test or the width between anchor attachments to repeating stiffener elements in a negative load test.”(ASTM E 1592, 2005) Figure 13 below shows an example of the difference between the structural elements for a positive uniform loading and a negative uniform loading. The width of the structural elements for positive loading are shown and referred to as P1 to P6, whereas the structural elements for negative loading refer to as N1 to N3.



**Figure 13: Structural Elements as to *ASTM E 1592:05* (Fig2.) (ASTM E 1592, 2005)**

As for the allowable length of the test specimen a table that details the “minimum number of equal spans” is given in the *ASTM E 1592*. The specified number of spans and their lengths shown in the standard are summarized in Table 4 below.

**Table 4: Summary of span lengths and number of spans**

Ends with crosswise restraint	2	1
Span length L (m)	Nr of equal spans	
$L > 3.7$	2	2
$3.7 > L > 2.4$	3	2
$2.4 > L > 1.8$	4	3
$1.8 > L > 1.5$	5	3
$1.5 > L > 1.2$	$7.3152/L$	3
$1.2 > L > 0.9$	$7.3152/L$	4
$0.9 > L > 0.6$	$7.3152/L$	5
$0.6 > L$	$7.3152/L$	$1+2.4384/L$

*Note: ends with crosswise restraint refer to ends with “any attachment in the flat of a panel between structural elements that controls or limits pan distortion under pressure.”*

The case where the sheeting extends slightly beyond the purlin support is considered an open end condition. Any flashing or ridging are considered a crosswise restraint because the flashing influences distortions in the valleys of the sheeting under loading.

The *ASTM E 1592* allows the reinforcement of open-end conditions to prevent non typical, or unwanted, failures that do not represent the testing of the true resistance of the cladding. Acceptable reinforcement methods include the stiffening of the valleys to prevent local

buckling in the case of positive uniform loading. Another allowable reinforcement is the fastening of the interlocking seam at the crest of the profile. Seam fastening and reinforcing should be kept within 100mm from the end of the sheet. The effect of all reinforcements must nevertheless be validated and shown that it does not affect the proper stressed behaviour of the specimen. The results of the additional validation tests should be recorded and documented in the case of reinforcements used.

### 3.1.5 Procedure

A number of guidelines are described regarding the testing procedure. The load is applied in increments, where the deflections are measured at each loading stage. For every increment, the load is removed to measure permanent deformations. Each load increment should not exceed one sixth of the maximum specified test load. The incremented loading procedure is repeated until failure or the specified ultimate load is reached. When failure is imminent, it is allowable to remove the deflection measuring apparatus and to increase the load gradually and continually until failure. At this testing stage, the yield load must have been reached already. Also, after initial failure has been reached, it is allowable to sustain loading as to obtain more testing data. Refer to Section 3.1.2 for the terminology and description of failure and the ultimate load.

## 3.2 German standard

The “Deutsches Institut für Normung (DIN)” (or German Institute for Standardization) publishes a standard that specifies testing procedures of roofing systems. The *DIN 18807-2:1987-06 - Trapezoidal sheeting in buildings; Steel trapezoidal sheeting; execution and evaluation of ultimate strength tests* (DIN 18807-2, 1987) is the standard under consideration.

### 3.2.1 Scope

The scope of the standard is the execution and evaluation of the experimental tests to determine the carrying capacity of trapezoidal coated-steel sheeting. The sheeting being tested is used for roofing as well as for wall cladding and is predominantly subjected to static stresses. Compound roofing systems where trapezoidal steel profiles are used together with other materials such as concrete or synthetic materials are not covered in the standard. If cladding systems are reinforced by the use of other structural aids, the effect of the stiffening effect may be considered as specified in the standard.

### 3.2.2 Experiment types

A number of individual experimental configurations are specified and discussed in the Sections 3.2.2.2 to 3.2.2.6. Each of the configurations serve a particular purpose of the evaluation of the ultimate strength of profiled sheeting systems.

#### 3.2.2.1 Tolerances, supporting structures and lay-out of test specimen

All tolerances regarding the dimensions of the sheeting profile are specified in *DIN 18807-1:1987-06 - Trapezoidal sheeting in buildings; Steel trapezoidal sheeting; general requirements; determination of the bearing strength by calculation*. A more detailed discussion of these are however not within the scope of this report.

The width of a test specimen consists of one rib-width ( $b_R$ ) or a multiple thereof. One rib-width is shown in Figure 14 below.

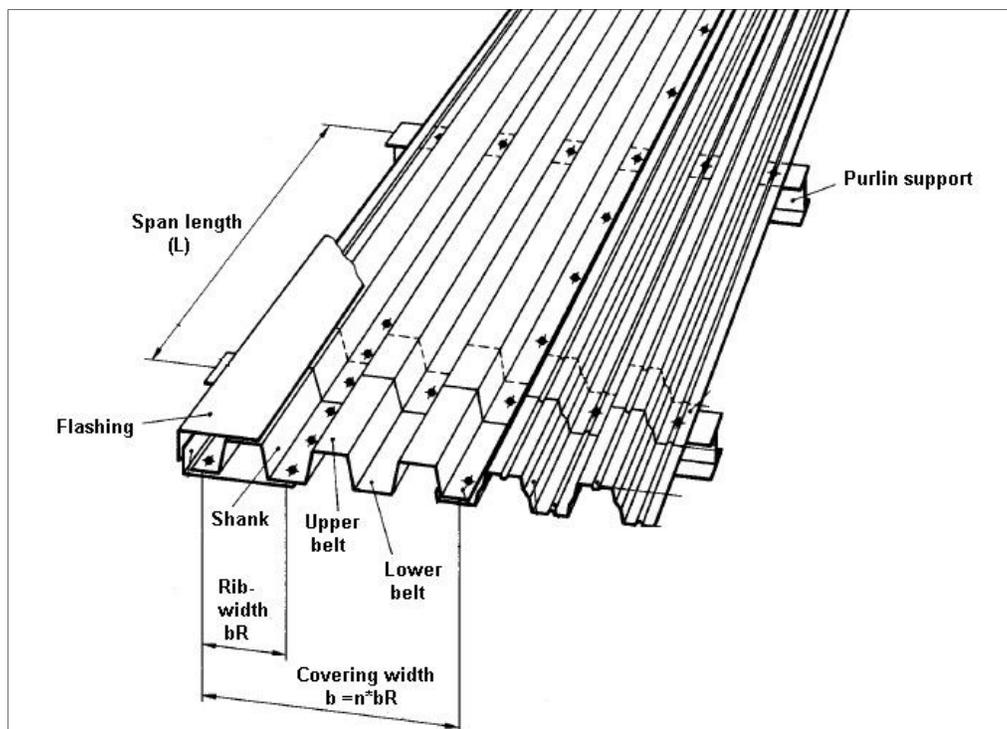
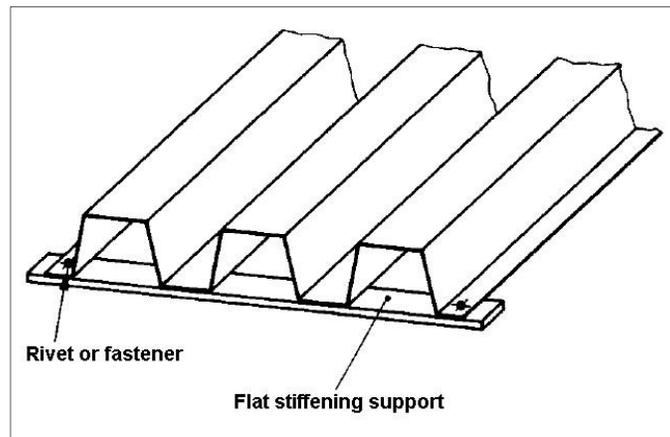


Figure 14: Steel-trapezoidal profile construction in *DIN 18807-1* (Bild 1.) (DIN 18807-1, 1987)

Any free edges along the length of the spanning specimen (between the purlin supports) are to be supported at the areas where compression is expected because of bending. If the profile of the sheeting does not allow such sampling, the edges may be reinforced as discussed and illustrated in the following section.

The reinforcement of the specimen is allowed by the use of other structural aids as shown in Figure 15 below. The reinforcement should, however, not add to the carrying capacity of the specimen as compared to conventional employment. The special attention should be directed to preventing more overlapping of sheets than is possible on a conventional building.



**Figure 15: Example of reinforcement in *DIN 18807-2* (Bild 1.) (DIN 18807-2, 1987)**

In practice, trapezoidal sheeting is most commonly used as structural surfacing members in combination with flashing and ridging elements as to strengthen the free edges of the members. Another reason for using flashing elements are of aesthetic nature, they give any cladding set-up a rounded-off appearance. It is therefore acceptable to reinforce the free side edges of the test specimen as to limit any side-expansion which could promote earlier failure during testing procedures. It should be ensured that any strengthening does not affect the carrying capacity compared to a conventional cladding set-up.

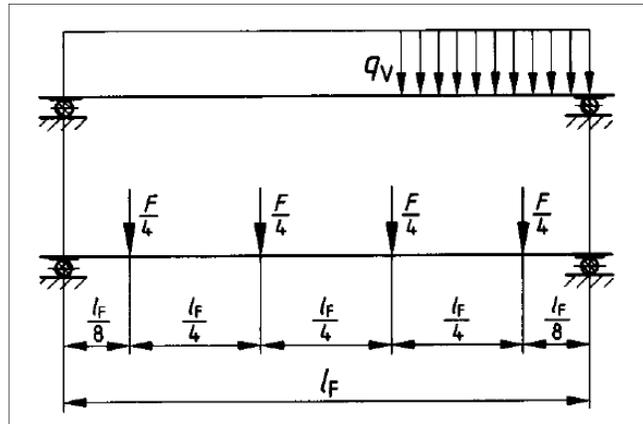
### **3.2.2.2 *Single span configuration***

The simply supported single span test set-up serves to evaluate the maximum bending moment  $M_{dF}$  at midspan of the set-up as well as the evaluation of the effective moment of inertia of the trapezoidal sheeting profile  $I_{ef}$ .

#### **3.2.2.2.1 *Structural lay-out***

The structural lay-out consists of a single span simply supported configuration. The set-up is to be loaded with either at least four line-loads distributed between the two purlin supports or a uniformly distributed load. The point where each of the four line-loads are to be located is specified to be such that the same maximum applied bending moment is applied as compared

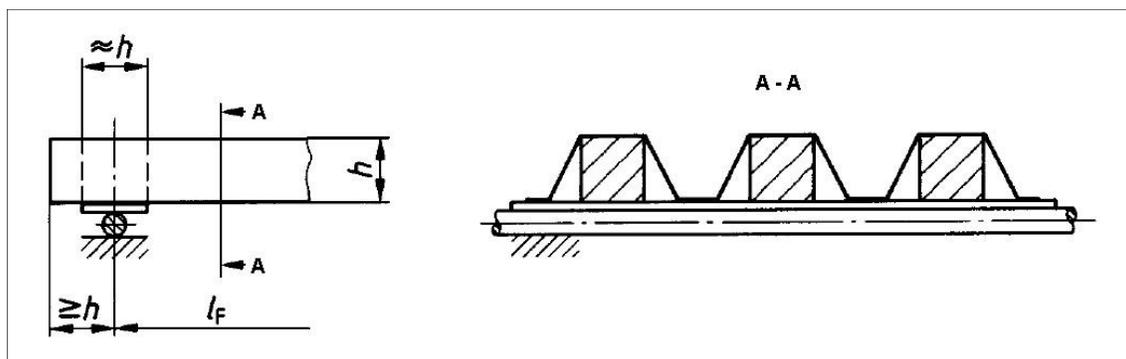
to the uniformly distributed load. Figure 16 below shows the a typical scheme suggested by *DIN 18807-2* for the application of the loads. Note that,  $q_v$  denotes the uniformly distributed load,  $F$  represents the magnitude of the line-load applied and the span length between the purlin supports is shown as  $l_F$ .



**Figure 16: Simply supported single span lay-out – application of loads in *DIN 18807-2* (Bild 2.) (DIN 18807-2, 1987)**

#### 3.2.2.2.2 Support conditions

All supports should only limit translation in the vertical direction, but should be free in horizontal as well as all rotational degree of freedoms about all axes. This corresponds to a conventional simple support provided by a roller as shown in Figure 17 below.



**Figure 17: Support conditions for simply supported single span lay-out in *DIN 18807-2* (Bild 3.) (DIN 18807-2, 1987)**

The roller support should act on the upper belt that is suggested to be accomplished by the use of wooden blocks as shown in section A-A in Figure 17. The contact area between the wooden block and the profiled (trapezoidal) sheeting should have the width of the upper belt of the profile (refer to Figure 14 and section A-A in Figure 17 above), and the length approximately

equal to the height of the profile ( $\approx h$ ). However, the wooden blocks should not limit any horizontal movement of the vertical shank elements. The profiled sheeting should have an overhang beyond the end of the support that is suggested to be at least as long as the height of the profile ( $\geq h$ ).

### 3.2.2.2.3 Load application

In the case where a uniformly distributed loading scheme is chosen, it should be ensured that the planned load distribution over the whole loaded area is preserved during the complete testing process compensating for increasing deflections of the sheeting system.

In the case where line-loads are used as loading scheme, the load should be applied to the lower belt of the trapezoidal profile. Wooden blocks, as shown in Figure 18 below, can be used. In Figure 18,  $b_v$  denotes the width of the test specimen,  $F$  the magnitude of the applied line-load and  $h$  is the height of the trapezoidal profile.

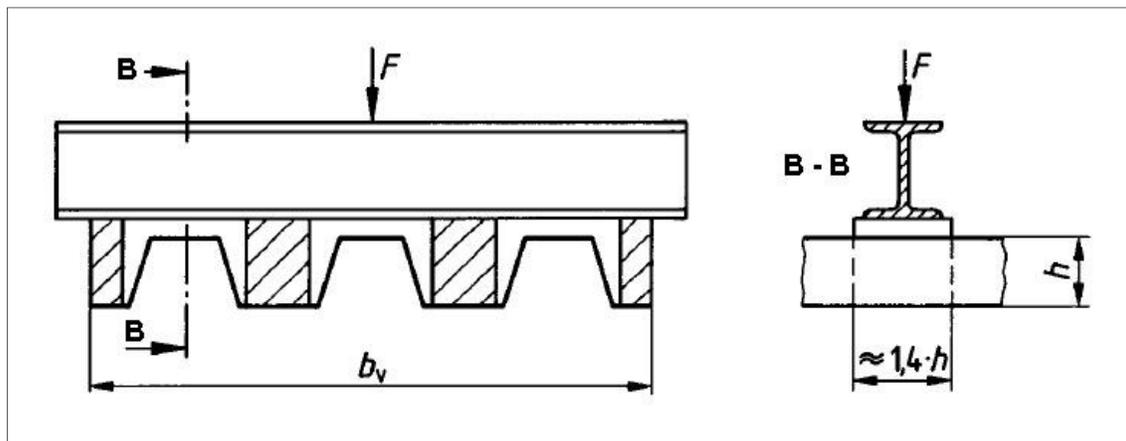


Figure 18: Load application for simply supported single span lay-out in *DIN 18807-2* (Bild 4.) (DIN 18807-2, 1987)

In the case where airbags are used as a means of load application, the action shall be applied to the upper belts of the test specimen.

### 3.2.2.2.4 Deflection measurement

The deflection is to be measured at midspan between the two supports of the single span lay-out. At least two measurement points should be used positioned on either longitudinal (spanning) edges of the test specimen. The deflection relative to the middle of the test specimen is to be considered. Provisions should be made to the set-up in the measurement of

the deflections to prevent the recording of local deformations. This can be achieved by the use of additional structural elements as for instance illustrated in Figure 15 previously.

### 3.2.2.3 Internal support configuration

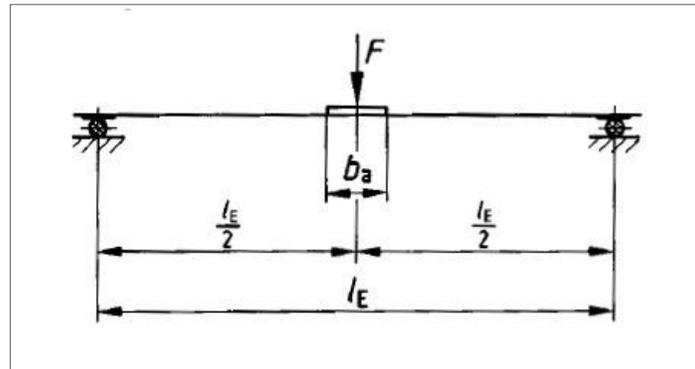
The multiple span continuous test set-up serves to evaluate the maximum bending moment  $M_B$  at an internal support of the set-up. This depends on both the reaction of the interior support  $R_B$  as well as the width of the support  $b_B$ .

#### 3.2.2.3.1 Structural lay-out

The multiple span configuration is used to simulate the negative bending moment at an internal support for continuous beams. The shortest allowable span length can be calculated by (also refer to Figure 19):

$$l_E = b_B + 4 \cdot h$$

Eq.: 1



**Figure 19: Structural layout for one span of continuous beam set-up in *DIN 18807-2* (Bild 5.) (DIN 18807-2, 1987)**

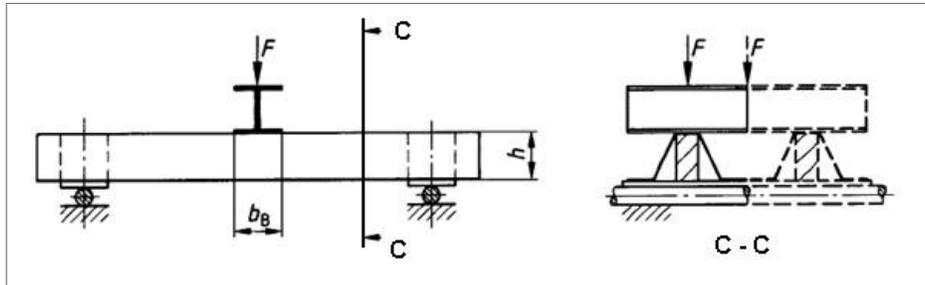
Note that,  $b_B$  denotes the width of the support acting on the trapezoidal sheeting,  $b_A$  is the referred to as the width of the line-load  $F$  acting on the trapezoidal sheeting and  $h$  stands for the height of the trapezoidal sheeting profile.

#### 3.2.2.3.2 Support conditions

All support conditions are to be incorporated as discussed in Section 3.2.2.2.2.

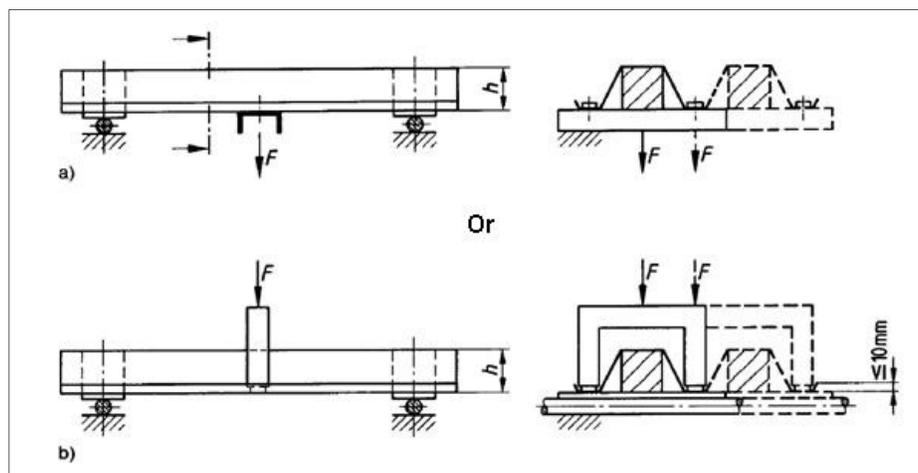
#### 3.2.2.3.3 Load application

Two different loading schemes are considered and are referred to as compressive force and tensile force. As for the compressive force, the load is to be applied to the upper belt as shown in Figure 20 below.



**Figure 20: Application of compressive force on continuous beam lay-out in *DIN 18807-2* (Bild 6.) (DIN 18807-2, 1987)**

For the application of the tensile force, the load is specified to act on the lower belt of the trapezoidal profile. The contact area of the force on the lower belt is chosen to be circular with maximum allowable diameter of the width of the lower belt less 10mm. Figure 21 indicates this.



**Figure 21: Application of tensile force on continuous beam lay-out in *DIN 18807-2* (Bild 7.) (DIN 18807-2, 1987)**

#### 3.2.2.3.4 Deflection measurement

All deflection measurements are to be incorporated as discussed in Section 3.2.2.2.4. The translation of the stiff member used to apply the line-load shall not be used to measure deflection.

#### 3.2.2.4 End support configuration

The end span configuration is used to test the capacity of the reaction  $R_A$  at the exterior support of a single span set-up.

#### 3.2.2.4.1 Structural lay-out

The configuration used in the end span set-up consists of a single span simply supported set-up. Figure 22 below shows the schematization of the test set-up.

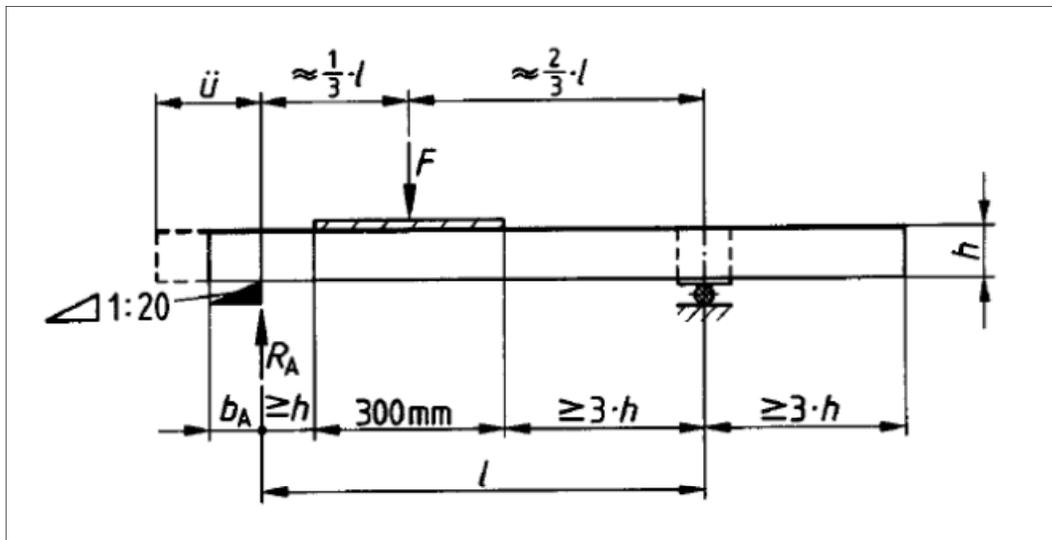


Figure 22: Structural lay-out of the end span configuration in *DIN 18807-2* (Bild 8.) (*DIN 18807-2*, 1987)

#### 3.2.2.4.2 Support conditions

The flattening effect of the trapezoidal profile as a result of horizontal expansion at the support under investigation ( $R_A$ ) is to be prevented. The support itself shall be shaped in the form of a wedge having a gradient of 1:20 as shown in Figure 22 above. The internal support, not being under direct investigation in this set-up, is specified to be of a roller type. At the internal support, failure of the profile is to be prevented through suitable measures.

#### 3.2.2.4.3 Load application

The load shall be distributed by using a distributing plate element that has sufficient bending stiffness to evenly apply the load directly onto the upper belt of the trapezoidal profile.

#### 3.2.2.4.4 Deformation measurement

The local deformation of the profile at the support under investigation shall be recorded to enable the computation of a load-deformation relationship.

#### 3.2.2.5 Continuous beam configuration

The *DIN 18807-2* describes tests in this section that may be used instead or on a complementary basis of the tests discussed previously in Sections 3.2.2.2 and 3.2.2.3.

The test proceedings and specifications for the continuous beam configuration are greatly a repetition to the testing procedures discussed in Sections 3.2.2.2 and 3.2.2.3 and will therefore not be discussed further. It is however strongly recommended to refer to the *DIN 18807-2 Section 3.6: Versuch "Durchlaufträger"* in the case of uncertainty.

### **3.2.2.6 Configuration to test walkability**

The experimental test set-up used to test the walkability is dedicated to determine the capacity of the trapezoidal profile to support a single person walking on the sheeting. The following two individual cases are to be investigated.

- Walkability during construction
- Walkability after construction, when the trapezoidal profiles are connected to all supports

#### **3.2.2.6.1 Structural lay-out**

The structural lay-out to be used is a single span simply supported system, with a concentrated load acting at midspan.

The specimen shall consist of a single complete profiled sheet as obtainable in the industry. Any stabilizing structural elements that are also available in the conventional construction of the cladding system are allowed to be used during testing.

#### **3.2.2.6.2 Support conditions**

The profiled sheet shall be laid on two supports each having a width of at least 40mm.

#### **3.2.2.6.3 Load application**

The load applied to the sheet is specified to be a concentrated load applied at midspan to the upper belt of the profile. The contact area of the load is rectangular with dimensions 100mm x 150mm, where the longer 150mm contact area length shall be in parallel to the direction of the ribs of the profile. To prevent stress concentrations at the edges of the load, a 10mm thick layer of soft material (for example felt) should be used between the load application and the sheet metal.

#### **3.2.2.6.4 Deformation measurement**

The vertical deformation is to be measured either at the load application or directly next to the load application.

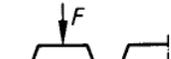
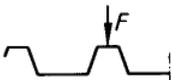
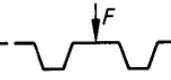
### 3.2.2.6.5 Walkability during construction

To test the capacity of the walkability after construction of the profiled sheet, the load is applied to a single rib closest to the side of the sheet. Any structural elements stabilizing horizontal expansion or movement are not allowed to be used. For the purpose of this test, the loading is to be applied using weights in a hanging configuration. A hole with diameter of 8mm may be drilled through the rib under investigation to accommodate the load application. Refer to Table 5 below for the assessment criteria.

### 3.2.2.6.6 Walkability after construction

To test the capacity of the walkability after construction of the profiled sheet, the load is applied to a single rib near the middle of the sheet. For more information, Table 5 below details the assessment criteria.

**Table 5: Assessment criteria for walkability in *DIN 18807-2* (Tabelle 3.) (DIN 18807-2, 1987)**

	Loading scheme	Load $F$ in kN	Assessment criteria
Loading on edge-rib of profiled sheet		1.2	significantly permanent deformations
		1.5	failure load
		2.0	failure load at sudden failure in the absence of any significant deformations
Loading on centre-rib of profiled sheet	 	2.0	failure load

## 3.2.3 Testing procedures

The *DIN 18807-2* lists a number of guidelines that describe the proceedings before, during and after experimental testing. In general all measurements, of the loads and the deformations as a result thereof, are to be recorded using suitable apparatus. Furthermore, the loading rate of any experimental test set-up should not be changed once the testing procedure has started.

### 3.2.3.1 Measurement of the profile geometry

All measurements that are found to be necessary to uniquely describe the profile of the section of the sheet shall be taken and recorded. Each profile for each plate thickness three sectioned samples are to be taken and measured. The samples should be taken from a distance of 200mm from the end of the sheet.

### **3.2.3.2 Loading sequence**

The rate of loading of  $1/50$  of the span length per minute at the expected point of maximum deformation should not be exceeded and also not be changed during testing.

### **3.2.3.3 Material testing**

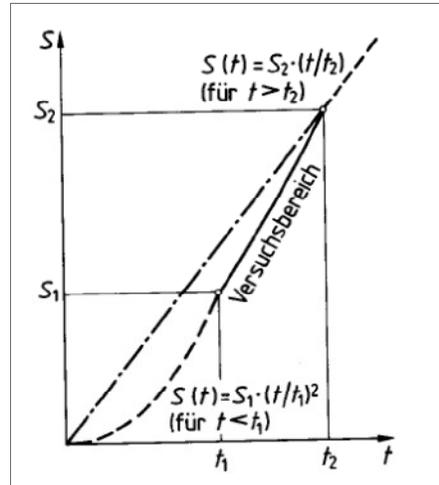
For each specimen that is tested, according to the specifications discussed under Section 3.2.2, a tension test of a flat sample (20mm x 80mm) of material is to be performed. Detailed proceedings are described in *DIN 18807-2*, which also refers to the tension test regulations of *DIN 50145* and *DIN 50114*. The samples for the tension test are to be taken from the longitudinal direction of the profiled sheeting.

## **3.2.4 Number of experimental tests**

The *DIN 18807-2* has a number of guidelines for the minimum number of identical tests that should be performed to obtain statistically reliable data.

### **3.2.4.1 Minimum number of different plate thicknesses to be tested**

According to the *DIN 18807-1* (Section 3.3.3), the number of different plate thicknesses to be tested is determined by the type of employment the profiled sheet is mainly used for. It depends on the following criteria. In the case where the difference between the thicknesses already tested is smaller than 0.25mm (for plate thicknesses  $t_N \leq 1.0\text{mm}$ ) or smaller than 0.5mm (for plate thicknesses  $t_N \geq 1.0\text{mm}$ ), interpolation is considered allowable to obtain the carrying capacities of non-tested plate thicknesses. Extrapolation to greater thicknesses should follow linearly, whereas quadratic extrapolation is to be used for smaller thicknesses.



**Figure 23: Interpolation for non-tested plate thicknesses in *DIN 18807-2* (Bild 11.) (DIN 18807-2, 1987)**

In Figure 23 above, the thicknesses already tested are referred to as  $t_1$  and  $t_2$  where  $t$  is the thickness sought after without the need of experimental testing. It should be noted that plate thicknesses of  $t_N \leq 0.6\text{mm}$  can not be used to determine the stressed behaviour of plates that are of greater thickness.

**3.2.4.2 Minimum number of identical tests**

The number of identical tests to be repeated for every parameter combination (type of experimental test set-up, span length used and plate thickness tested) must be chosen according to Table 6 below.

**Table 6: Minimum number of identical tests in *DIN 18807-2* (Tabelle 1.) (DIN 18807-2, 1987)**

Number of tested plate thicknesses	Number of tests
$\geq 3$	$\geq 2$
for $t_N \geq 0.6\text{mm}$ 2	$\geq 3$
1	$\geq 4$
for $t_N \geq 0.6\text{mm}$	$\geq 4$

**3.2.4.3 Minimum number of different span lengths to be tested**

For the linear relationship between the maximum bending moment at an internal support ( $M_B$ ) and the reaction at an internal support ( $R_B$ ) at least two spans are required (refer to Section ) to be tested per plate thickness according to the specifications discussed in Section 3.2.2.3 or 3.2.2.5 respectively. For the quadratic relationship between  $M_B$  and  $R_B$  at least three spans are

required (refer to Section ) to be tested per plate thickness according to the specifications discussed in Section 3.2.2.3 or 3.2.2.5 respectively.

The area between the longest and shortest allowable span length (refer to ) is to be divided up as equally as possible.

### **3.2.5 Evaluation of test results**

The German *DIN 18807-2* specifies guidelines on the evaluation of the raw test data to usable characteristic parameters which determine the carrying capacity of the trapezoidal sheet under investigation.

#### ***3.2.5.1 Determination of characteristic parameters***

The characteristic value  $S_c$  (which can be either the bending moment at midspan  $M_{df}$ , the bending moment at an internal support  $M_B$ , the internal maximum reaction  $R_B$  or the maximum end reaction  $R_A$ ) can be determined from the tested value  $S_V$  by the use of a statistical analysis. All detailed proceedings are discussed in *DIN 18807-2 Section 7.2*.

#### ***3.2.5.2 Determination of the bending moment at midspan***

The maximum bending moment at midspan  $M_{df}$  can be determined from the maximum loads applied to the single span configuration as described in Section 3.2.2.2.

#### ***3.2.5.3 Determination of the effective moment of inertia***

The effective moment of inertia  $I_{ef}$  can be calculated from a load-deflection relationship for the single span configuration as described in Section 3.2.2.2. Note that only the linearly elastic range of the data should be considered. The calculated theoretical value of the trapezoidal profile of the sheet shall be compared to the experimental value, where only the smaller of the two is considered.

#### ***3.2.5.4 Determination of the bending moment and reaction at an internal support***

The maximum bending moment and reaction at an internal support ( $M_B$  and  $R_B$  respectively) can be determined from the maximum loads applied to the internal support configuration as described in Section 3.2.2.3 or the continuous beam configuration as described in Section 3.2.2.5.

### 3.2.5.5 Interaction between the bending moment and reaction at an internal support

The relationship between the bending moment and the reaction at an internal support of a continuous beam is illustrated in Figure 24 below. Note that  $M_d^0$  is the maximum bending moment at the internal support when the reaction  $R_B = 0$ , and  $R_d^0$  is the respective maximum reaction at the internal support when the  $M_B = 0$ .

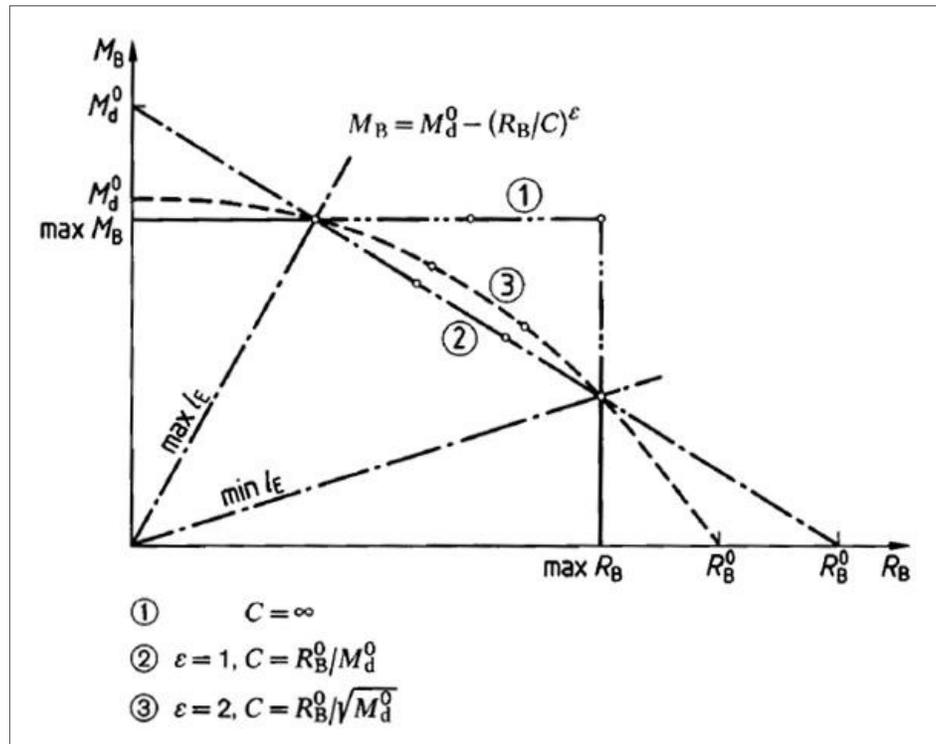


Figure 24: Interaction between  $M_B$  and  $R_B$  in *DIN 18807-2* (Bild 12.) (*DIN 18807-2*, 1987)

The *DIN 18807-2* furthermore describes proceedings to determine the carrying capacity of trapezoidal sheeting by evaluating the results of the continuous beam configuration.

### 3.2.5.6 Determination of the maximum end reaction

The maximum end reaction  $R_A$  can be determined from the maximum loads applied to the end support configuration as described in Section 3.2.2.4. In the case, depending on the profile-shape of sheet the under investigation, where two distinct maximum values can be distinguished and one of them bigger than the other, the smaller is to be considered Serviceability Limit State (SLS) failure and the bigger one considered a load at Ultimate Limit State (ULS) failure.

### 3.3 Australian standard

Standards Australia publish a range of standards referred to as *AS 4040:1992 – Methods of testing sheet roof and wall cladding*. The *AS 4040* is sub-divided into four individual parts. The *AS 4040 Part 0 – Introduction, list of methods and general requirements* (AS 4040.0, 1992), the *AS 4040 Part 1 – Resistance to concentrated loads* (AS 4040.1, 1992), *AS 4040 Part 2 – Resistance to wind pressures for non-cyclone regions* (AS 4040.2, 1992) and *AS 4040 Part 3 – Resistance to wind pressures for cyclone regions* (AS 4040.3, 1992). Each of the four parts will be discussed within sections to follow.

#### 3.3.1 *AS 4040.0 – Introduction, list of methods and general requirements*

The test apparatus used to test the capacity of sheet roof and side cladding is the same for all tests performed, therefore the details on the set-up are described in *AS 4040.0* and to be applicable in all subsequent parts *AS 4040.1* to *AS 4040.3*.

##### 3.3.1.1 *Supporting structure*

“The supporting structure may be strengthened as long as the strengthening does not affect the performance of the cladding or change its mode of failure”. (AS 4040.0, 1992) Testing the carrying capacity of roof or wall cladding, the ultimate load tests are performed to evaluate the resistance of the sheeting system. The proceedings specified in the *AS 4040* range of standards are not intended to test the capacity of the supporting structure. The degree, however, to what the supporting structure may be strengthened is limited. Excessive deflections of the purlin supports may influence the stressed behaviour of the sheeting system. This should be considered in the design of the supporting structure.

##### 3.3.1.2 *Test specimen*

The capacity that the sheeting system under investigation has against concentrated loads and wind pressures is determined by the use of a full-scale experimental test set-up. The test set-up shall consist of the sheeting, the fastening system and the support system to be assembled together identically compared to the roof or wall the specimen is planned to be a model of.

##### 3.3.1.2.1 *Width of the specimen*

The width of the specimen shall consist a number of sheets fastened to the support system by at least four fastening points and at least one sheet overlap. For certain sheeting systems, the interlocking of the longitudinal edges of the respective sheets are an essential compound of the

fastening system. For interlocking systems, at least two overlaps should be provided in the specimen.

#### *3.3.1.2 Number of spans*

For testing the resistance of a sheet against a concentrated load a single span set-up with two supporting purlins is considered sufficient. For testing the resistance of the sheeting system against wind actions, a continuous set-up with no less than 3 supporting purlins (two spans) shall be used.

#### *3.3.1.3 Interpretation of results*

The tests are permitted to be repeated exactly for certain circumstances where the first specimen did not reach the ultimate load criterion aimed for. Subsequent tests with reduced loading are then allowable.

If the test data is to be used for the computation of design tables and values, the following conditions apply:

- (a) Data shall not be extrapolated
- (b) Data is allowed to be interpolated between the different spans in the following circumstances:
  - (i) The data is required for a single type of profiled sheet and fastening system
  - (ii) At least three different span lengths have been tested on the same sheeting system and provided that the failure mode in all completed tests was the same
  - (iii) The test loads must have been derived from the same criteria

The *AS 4040.0* gives some indications on failure modes in both the Serviceability Limit State (SLS) and the Ultimate Limit State (ULS) for sheeting systems. Failures under SLS include:

- Excessive deflections under load
- Excessive residual deflection
- onset of de-indexing, unclipping
- permanent local deformation
- or fracture of the cladding or its fixings

Whereas failure modes under ULS include:

- cladding pulling over the fasteners as a result of the reaction force

- clips disengaging
- de-indexing of the sheet interlocks
- fasteners pulling off the supporting structure

### **3.3.2 AS 4040.1 – Resistance to concentrated loads**

The test specimen and the supporting structure shall be as specified in Section 3.3.1 above.

#### **3.3.2.1 Loading system**

A concentrated load shall be employed in a direction normal to the sheeting. If the manufacturer of the sheeting specifies no path, the concentrated load is to be applied on the sheeting where maximum deflection or deformation is expected. The contact area of the load is to be circular with diameter of 100mm. To prevent stress concentrations at the edge of the contact area, a loading pad should be used between the sheeting and the load actuator. The loading pad is of rubber or similar material with a thickness of 50mm and Shore durometer hardness of 30.

#### **3.3.2.2 Measuring devices**

All deflections shall be measured with an accuracy of  $\pm 0.05$ mm. The applied pressure or loads are to be measured with an accuracy of 5%.

#### **3.3.2.3 Procedure**

The AS 4040.1 furthermore describes a number of guidelines of the size of the concentrated loads to be applied as well as SLS and ULS load factors that are included.

##### **3.3.2.3.1 Loading**

In general, the characteristic loads that are to be applied on the sheet are 1.1kN for a flat roof and 0.5kN for roofs that are inclined by more than 35 degrees as specified in AS 1170.1. The load is concentrated on the sheeting in any position.

The characteristic loads are multiplied by 0.7 (SLS) and 1.5 (ULS) respectively, to obtain the design loads. The test load, which is the load actually applied to the specimen, can then be obtained by multiplying the design load with the appropriate factor of variability. The factors of variability (as described in AS 1562.1 (AS 1562-1, 1992)) account for the variability of materials and are summarized for the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS) in Table 7 below.

**Table 7: Factors for variability in AS 1562.1 (Table 5.1) (AS 1562-1, 1992)**

Number of identical units tested	ULS	SLS
1	1.5	1.2
2	1.4	1.2
3	1.3	1.2
4	1.3	1.1
5	1.3	1.1
10	1.2	1.1

#### 3.3.2.3.2 *Serviceability Limit State*

The deflection should be measured between the sheeting fastening system and the supporting structure. Any deflections by the support system shall be eliminated and not be recorded. Furthermore, the displacements are to be measured at the point on the specimen that is expected to undergo the maximum movement. Measurements are to be taken –

- (a) before the application of the load;
- (b) after the load has been applied and zero creep was recorded for a period of 2min;
- (c) and 5 min after the removal of the concentrated load.

The permanent deflection of the sheeting (within 5min after removing the load) with respect to the supporting structure directly at the point of load application should be smaller than  $S/1000$ .

#### 3.3.2.3.3 *Ultimate Limit State*

The specimen is to be loaded with the test load for a period of not less than 1min.

### 3.3.3 **AS 4040.2 – Resistance to wind pressures for non-cyclone regions**

The test specimen and the supporting structure shall be as specified in Part 0 discussed in Section 3.3.1 above.

#### 3.3.3.1 ***Loading system***

A uniformly distributed load shall be applied to the specimen by any means desired. The distribution of the load shall be maintained regardless of extensive deflections occurring. When the loading is increased to such an extent that the sheeting system resists the load by membrane action instead of bending resistance, the outer supports shall be designed not to provide any stiffness to these membrane forces that would not be present in practice.

In the case that airbags are used, it must be ensured that the pressure measurement in the bags is not influenced by any airflow for instance at the inlet valve. It is recommended to measure the reactions on the set-up.

For ribbed profile sheeting, special attention is recommended to observe the effect of wind actions on the rib element.

### **3.3.3.2 Measuring devices**

Measuring devices are as discussed previously in Section 3.3.2.2.

### **3.3.3.3 Procedure**

The *AS 4040.2* furthermore describes a number of proceedings on the loading scheme and guidelines to determine SLS and ULS failure modes.

#### **3.3.3.3.1 Loading**

If sheeting is tested in a way that is different than its intended composition, the effects of own weight should be taken into account. Consider the scenario where the system is tested in an inverted position. The ultimate uniformly distributed load that is applied to the sheeting system should be compensated by subtracting a distributed load equivalent to twice the own weight of the sheeting.

The ultimate load that is to be applied to the specimen is the design wind pressure (as calculated according to the specifications listed in *AS 1170.2*) being multiplied by the appropriate factor of variability in Table 7 above.

#### **3.3.3.3.2 Serviceability Limit State**

The deflection should be measured between the sheeting fastening system and the supporting structure. Any deflections by the support system shall be eliminated and not be recorded. Furthermore, the displacements are to be measured at the point on the specimen that is expected to undergo the maximum movement. The measurements are to be taken –

- (a) before the application of the load;
- (b) when the pressure has been applied for 1min;
- (c) and 5 min after the removal of the uniformly distributed load.

The maximum allowable deflection of the sheeting with respect to the supporting structure should not be more than  $S/120 + p/30$  (where  $S$  is the span length and  $p$  the spacing between fasteners). The residual deflection 1min after the complete removal of all loads should be no more than  $S/1000$ .

#### *3.3.3.3.3 Ultimate Limit State*

The specimen is to be loaded with the test load for a period of not less than 1min.

### **3.3.4 AS 4040.3 – Resistance to wind pressures for cyclone regions**

Testing for the resistance of sheeting systems against loading in cyclone regions is mainly dedicated to the interaction between the sheeting and the fastening system. A multispan test set-up is used to test the bending moment in the sheeting and the carrying capacity of each fastener.

Airbags are recommended to be used as load actuator. To obtain a cyclic loading scheme, the test set-up can be displaced relative to the inflated airbags.

#### *3.3.4.1 Measuring devices*

Measuring devices are as discussed previously in Section 3.3.2.2.

#### *3.3.4.2 Procedure*

The *AS 4040.3* furthermore describes a number of proceedings on the loading scheme and guidelines to determine SLS and ULS failure modes.

##### *3.3.4.2.1 Loading*

The serviceability load that is to be applied to the specimen is the design wind pressure (as calculated according to the specifications listed in *AS 1170.2*) being multiplied by the appropriate factor of variability (refer to Table 7 in Section 3.3.3.3.1).

The ultimate load ( $P_t$ ) that is to be applied to the specimen is the design wind pressure divided by the material capacity reduction factor. If the material capacity reduction factor is not available, the design wind pressure is simply divided by 0.9.

##### *3.3.4.2.2 Serviceability Limit State*

The same specifications, guidelines and criteria as discussed in Section 3.3.3.3.2 apply.

### 3.3.4.2.3 Ultimate Limit State

The specimen is to be subjected to a cyclic loading sequence to promote failure in fatigue. The loading sequence is specified in Table 8 below.

**Table 8: Fatigue loading sequence in AS 4040.3 (Table 1) (AS 4040.3, 1992)**

Range of test pressure	Number of cycles
0 to 0.40 $P_t$	8000
0 to 0.50 $P_t$	2000
0 to 0.65 $P_t$	200
0 to 1.30 $P_t$	1

The single load cycle shall be kept for 1min, whereas for all other cycles the frequency of loading should not exceed 3Hz. In the case where two identical samples are tested, the final test pressure range may be adjusted to 0 to 1.2 $P_t$ , and if three identical test specimen are tested the range can be further reduced to 1.0 $P_t$ .

## 3.4 South African standard

In South Africa, the code of practice *SABS 0237 – Roof and side cladding* (SABS 0237, 1991) details specifications for the “design, installation and testing of profiled sheeting” which is intended for the use as roofing or side wall cladding. Annex A of the code specifies tests to determine the resistance to uniformly distributed loads as well as the resistance to point loads. The load-carrying capacities of profiled sheeting and its fixings are to be tested using the guidelines stated in the code of practice mentioned by means of an experimental test set-up.

### 3.4.1 Experimental test set-ups as to SABS 0237

According to the code (SABS 0237, 1991), testing the capacity of roofing systems against uniformly distributed loading, three experimental test set-ups are required. One for testing the resistance to positive uniformly distributed loads one for testing the resistance to negative uniformly distributed loads and a third for testing the resistance to point loads.

#### 3.4.1.1 Testing the resistance to positive uniformly distributed loads

To test the resistance of profiled roof sheeting against positive uniformly distributed loads, the code of practice specifies a set-up that simulates cladding conditions for a single – and a double-span configuration. Three sheets are to be fixed by means of the respective prescribed fixing method. The magnitude of the load, being applied to the top surface of the respective

sheeting configuration, is to be increased incrementally until the ultimate test load is exceeded. At every increment of the load, deflections should be measured and recorded at the point of maximum deflection.

The ultimate test load for which the sheeting system should be tested is stated to be twice the design wind load on the roof surface as specified in *SABS 0160:1989 Sections 5.1 to 5.4*. Failure is considered once any of the three sheets are loosened from their purlin supports. The sheeting should not blow off or become loose under wind pressure, or lose its water-tightness and, should a person tread or inadvertently fall on any part of the roof, the sheeting should not give way. (SABS 0237, 1991)

The test is to be repeated thrice for each of the single – and double span configurations to enable extrapolation of the results.

#### ***3.4.1.2 Testing the resistance to negative uniformly distributed loads***

The procedures for testing the resistance against negative uniformly distributed loads are similar to the procedures discussed in Section 3.4.1.1 above. The difference is that the simulated uniformly distributed load is not applied to the top of the sheeting but to the bottom surface of the sheeting thereby simulating uplift forces. It is advised to test the assembly in an inverted position.

The uniformly distributed load is to be applied in increments until reaching ultimate test load. Ultimate test load is considered to be the negative design wind load, as specified in *SABS 0160:1989 Section 5.5*, less twice the own-weight of the sheeting. At each increment of the test load the deflection is measured and recorded at the point of maximum deflection, and the load is to be kept constant for 1min before increasing the load to the next increment. Only if no signs of any permanent deformations are observed may the test load be increased.

The load is removed once any type of permanent deformation is observed. 5 min after the load has been removed, the sheeting is considered to have failed if the permanent residual deflection is larger than  $L/500$  where  $L$  is the span length. Furthermore, failure is considered once any de-indexing, unclipping, permanent local deformation, fracture or failure of any part of the sheeting, or failure of the fixings shall occur. (SABS 0237, 1991)

### 3.4.1.3 Testing the resistance to point loads

For testing the resistance of profiled sheeting against point loads a simply supported single-span configuration is required. A force of 0.9 kN is applied to the sheet. The force is applied to various positions on the sheet, on the crest, valleys and also on overlapping crests to find the point of minimum resistance. If no failure has occurred, the span length is increased and the loading procedure repeated until a critical span length can be identified.

To prevent stress concentrations at the edges of the load application area, a rubber pad with dimensions of 100mm x 100mm and 25mm thick is placed between the load actuator and the sheet.

### 3.4.2 Experimental testing as to the revised *SANS 10237*

The *SABS 0237* discussed in the previous section was last revised in 1991 and is therefore found out of date. A new standard is currently in the state of a draft code of practice and is referred to *SANS 10237 – Metal roof and side cladding* (SANS 10237:201X, 201X). The specifications detailed in the draft code *SANS 10237* were almost entirely adopted from the Australian *AS 1562.1* (AS 1562-1, 1992) and *AS 4040* discussed in the Section (3.3). *Addendum A: Testing of a cladding system* in the draft code of practice *SANS 10237* is largely similar to the range of *AS 4040.0* to *AS 4040.2*. Note that the only notable difference between the South African and the Australian standard is that the South African does not account for cyclone regions. All specifications listed in the *AS 4040.3* are therefore not found in the South African *SANS 10237: Addendum A*.

## 3.5 Summary

The guidelines specified in the American, the Australian and the South African codes of practice were found very similar regarding the basic principle of testing the carrying capacity of roof coverings. The experimental test set-ups discussed in Section 2 can be considered to conform to the specifications considering the information at hand. Depending on the span lengths of the experimental set-up and the configuration chosen, the test results can not be extrapolated and adapted to different configurations used in practice. Therefore the use of the test outcome, for the configurations as specified by the named codes of practice, is limited to the number of tests performed with ranging span lengths.

The German standard details proceedings and guidelines of a number of different configurations that enable to determine the resistance and strength of the individual components of the covering system. The resistance of a covering system against any loading depends on a number of structural design parameters. The parameters are the resistance of the sheeting against concentrated loads, the positive and negative bending capacity of the roofing system, the bending stiffness of the roofing system and the carrying capacity of the fastening system. The German code excels in specifying guidelines to test these parameters individually with a number of distinct experimental test set-up configurations as discussed. Each of the configurations yield the capacity that the covering system has for each of the structural parameters. The structural parameters enable the possibility to extrapolate the tested strength properties that were experimentally determined to any configuration required.

A problem has been identified with the testing procedures of roof coverings currently used in the South African industry. The test results do not provide sufficient information on the resistance and strengths to be able to design roof structures conservatively. The following section provides an overview on the problem of span lengths and how they affect the design and stability of roof structures in practice.

## 4. South African roof covering design practice

This section serves as an introduction into the design and construction of roof coverings used in the industry in South Africa. The design approach for roof coverings used in the industry is reviewed and discussed. Also, problem areas are highlighted and possible solutions to the problems are proposed.

Apart from the specifications discussed to test the carrying capacity of roof covering systems, there are also a number of specifications listed in design standards that govern the design of roof structures. The approach of the design suggests starting by the calculation of the most critical actions onto a roof structure. The resistance of all structural components against the actions is then checked and verified. An introduction to the procedures currently followed in the industry to check the safety of roof coverings against wind actions is described and discussed below.

### 4.1 Review of the standard design approach

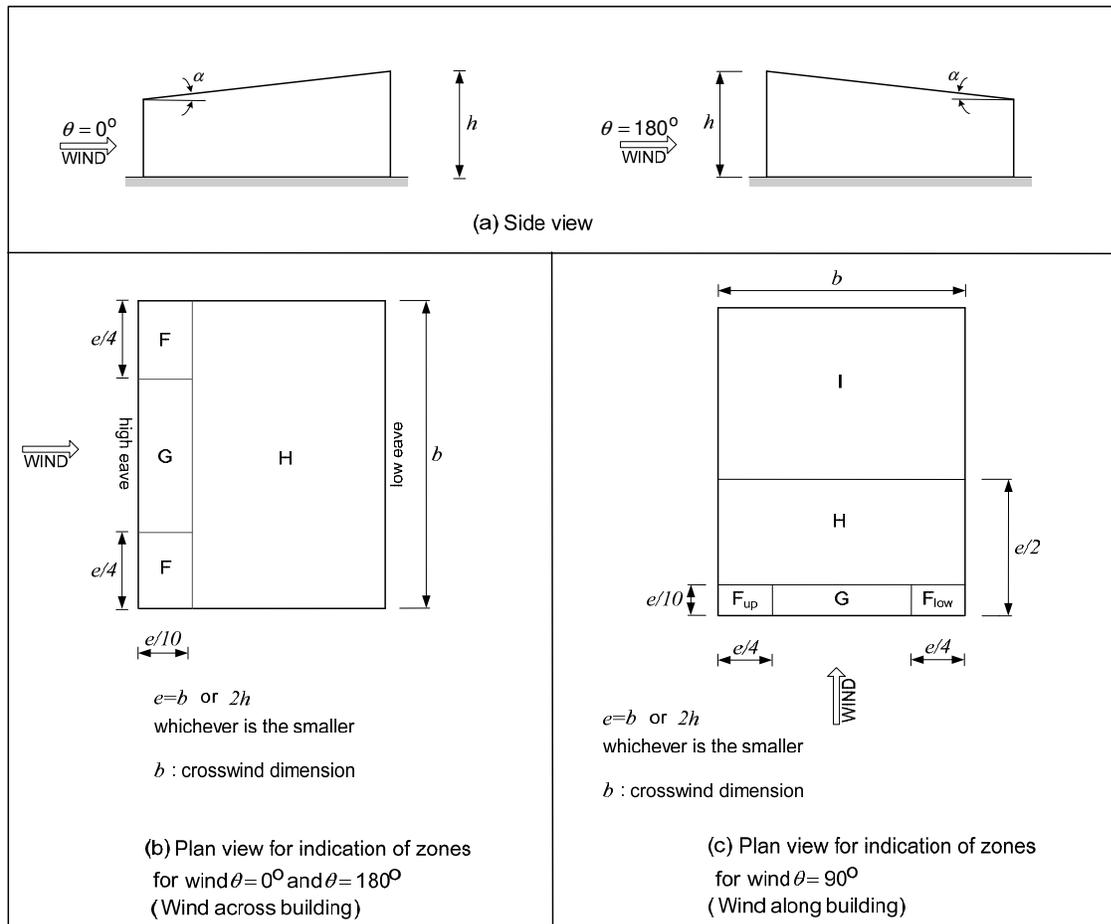
There are a number of aspects that need to be considered in the design of roofing systems. Structural engineers evidently start by calculating the critical loading combinations acting on the structure. Wind actions are generally the critical loading combination for roof structures. The following section elaborates more on the calculation of wind actions and their application.

#### 4.1.1 Wind actions as to SANS 10160.3

The design code *SANS 10160.3 – Wind actions* (SANS 10160-3, 2008) specifies maximum wind loads that all roof coverings are required to withstand. The uniformly distributed design wind load depends on factors like the terrain category, the elevation above sea level as well as the overall roof height. Also, the surface of the roof is subjected to uniformly distributed loads that can vary in magnitude depending on the position on the roof surface. Therefore, the total surface area of the roof is divided up into wind zones.

Considering the general layout or shape of a roof, the surface of roof structures is subjected to varying pressures. A wind blowing over a structure causes vortices generating on the edges of the surface of the roof. The ridge, or corners of the roof are inevitably more exposed to wind vortex action than a long flat surface. These turbulent wind actions cause an increase in the

applied pressure. Therefore, the total roof surface of a roof is divided up into a number of regions called roof loading zones. Figure 25 below shows the zones for a typical monopitch roof. Zones F and G in Figure 25 are subjected to higher turbulent wind vortices than zone H and I for instance.



**Figure 25: Roof loading zones (Figure 10 in SANS 10160.3) (SANS 10160-3, 2008)**

In Figure 25 above, a nominal wind speed is considered to blow over the structure as indicated. For each of the zones, F, G, H and I, an external pressure coefficient scales the nominal wind speed to a wind load that is applicable to the relevant zone. This wind load can be calculated and acts in a direction being perpendicular to the surface of the roof and is a uniformly distributed load on the area of the zone. Apart from the factors like the terrain category or the elevation above sea level mentioned previously, the magnitude of the wind load for each zone furthermore depends on the following:

- Direction of the wind blowing

- Amount of openings in the structure (either wall or roof)
- Size of the openings in the structure

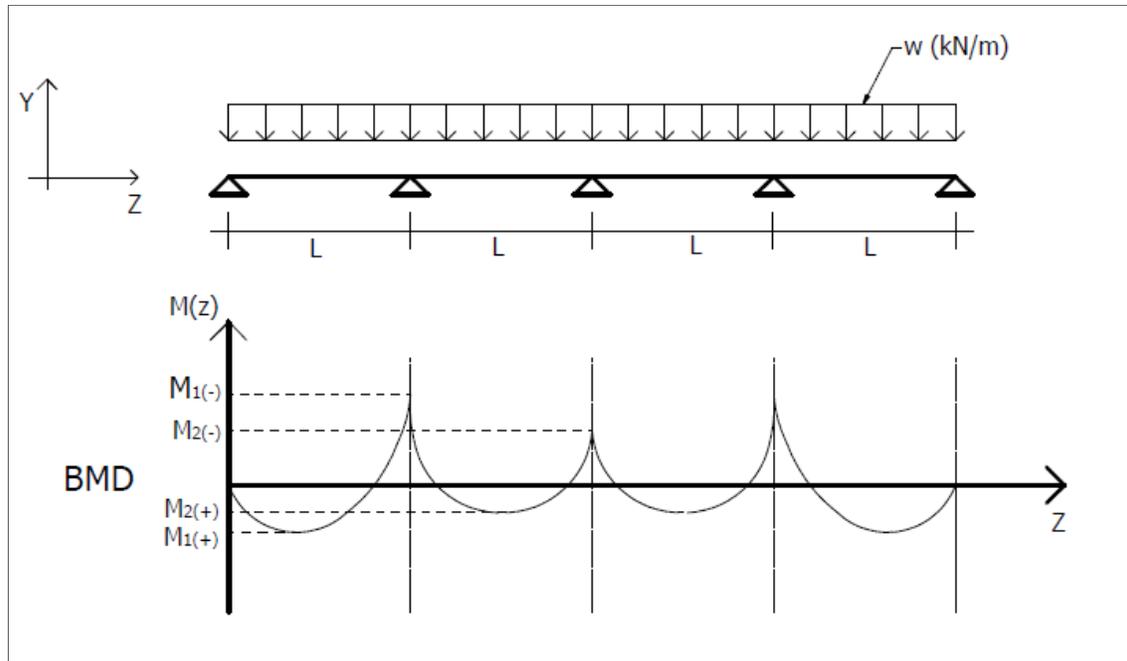
Considering all the named factors, the loading combination with the highest uniformly distributed load is chosen for the design. Appendix A contains more detail on wind load calculations. An example of a potential wind action for a monopitch roof structure is presented and detailed.

After the critical loading combination is known, the supporting structure can be designed to withstand the calculated wind actions. A closer spacing of the purlins or girts results in a higher resistance to the uniformly distributed load of a wind action.

#### **4.1.2 Purlin spacing**

Depending on the type of elements used in the supporting structure, the resistance of the structure can be calculated. For purlins, cold formed lipped channels are the usual choice for roof structures. High loading demands mostly result in failure by exceeding the bending capacity of the element. The failure of purlins in the form of bending can be encountered by several means. The most prominent of them are placing the purlins closer to each other, increasing the element size of the purlin or adding cross-bracing, in the form of lateral supports referred to as sag-bars. Lateral supports decrease the effective length of the element that is vulnerable to lateral torsional buckling. A shorter effective length therefore increases the bending capacity of the element.

The spacing of purlins is chosen depending on the capacity of the individual purlin. The higher the uniformly distributed load acting on the surface area of the roof, the more purlins are needed to bear the loads. The distribution of the purlins is not always kept to be in constant intervals. For a continuously supported sheeting set-up as shown in Figure 26 below, the last span is subjected to higher bending moments ( $M$  in units of kNm) than the interior spans provided the sheeting spans are of constant length ( $L$  in units of m). Therefore, the span length of the last span is often chosen a bit shorter than the intermediate spans between the purlin supports. Choosing different purlin spacings, or intervals, coincides with the fact that the total roof surface is not equally loaded as discussed in Section 4.1.1.



**Figure 26: Bending Moment Diagram (BMD) on continuous sheeting/beam**

Referring to Figure 25 in the previous section, it is apparent that the zones H and I represent the majority of the total surface area of a roof structure. The zones F and G that are exposed to turbulent wind vortices only make up an approximate amount of 15% of the total roof area. It is therefore uneconomical to choose a purlin spacing that is capable of withstanding these extremely loaded areas and to extend this purlin spacing to the rest of the roof surface (zones H and I). Common practice is to choose a purlin spacing that fits the degree of loading in the zones H and I. Sag-bars are then introduced in the zones F and G on the roof. If it is possible, bigger element sizes can also be used in highly loaded zones. Note that the purlin spacing is thereby kept constant over the complete surface area of the roof. Evenly spread purlins in the supporting structure are considered to sustain simplicity and cost efficiency.

#### 4.1.3 Roof sheeting and cladding

After the design for the purlin spacing is done, the design requirements for the roof covering system is checked. Choosing a certain roof sheeting profile depends on factors like the aesthetics of the roof structure, the ease of construction, the application and usability of the sheeting, the compatibility to add-ons like flashings and gutters and many more factors.

It should be kept in mind, the primary purpose of the roof cover should be to create a weather tight cover as to protect the interior of the structure and this is the main purpose that roof structures are being designed for. Wind loads cause the most critical loading combination for roof structures. Wind actions acting on a roof, as discussed in Section 4.1.1, are transferred to the supporting structure by means of the roof cover. Inevitably, the cladding chosen as cover should be strong enough to withstand all design actions on the roof structure. The capacity for each respective roof covering system depends on the resistance of the sheeting and the capacity of the respective fastening system. Each of these roof-covering components, both the roof sheeting as well as the fastening system, can contribute to a certain mode of failure. Failure modes are discussed in Section 6.2. To ensure that none of the failure modes for roof sheeting are reached, the supplier of each roofing system provides design tables that enable the design of roof coverings.

#### 4.1.3.1 Design tables

The design tables currently used in the industry detail the maximum purlin spacings allowed for a certain roofing system. The maximum allowable purlin spacings in the design tables are presented in the form of a fixed value in units of length. The purlin spacings listed are shown independent of the design wind load that the roof needs to be designed for. Table 9 below shows a typical example of a design table available from a roofing system supplier. The table details fixed values of maximum purlin spacings for four different sheeting thicknesses (ranging from 0.47mm to 0.8mm) for each type of span.

**Table 9: Example of a design table for a roof sheeting system**

Type of span	Gauge (mm)			
	0.47	0.5	0.58	0.8
Single span	1650	1650	1750	2200
End span	1700	1700	1900	2300
Internal span	1900	1900	2100	2600
Canilever	200	200	260	350

In the design tables, the purlin spacings are found to be set up for a uniformly distributed load that does not account for high-pressure vortices as discussed in Section 4.1.1. Some roofing systems guarantee a resistance against loads of up to 3kPa. However, the applied load on high-pressure zones (zones F and G in Figure 25) can reach wind loads of as much as 7kPa. Appendix A contains a worked example of the calculation of the maximum design wind loads for a typical monopitch roof structure.

The final check for the design of the roofing structure requires the purlin spacing allowable for the sheeting to be larger than the spacing of the purlins provided in the supporting structure. The degree of safety and conservatism of this design approach is depends partially on the values of maximum allowable purlin spacings listed in the design tables and the design of the supporting structure. The fact that the design of the covering system depends on a mere fixed value listed in a table presents a risk to the designing engineer because of the lack of comprehensive design parameters and information. Roof coverings can only be safely designed, using the available design tables, for all common-type structures that the tables account for. Any slight variation, in the roof structure or the loading combination, from the normal spectrum presents a risk because of the inability to adapt the design. Engineers do not have structural design parameters available for the safe design of any part of a structure that is not accounted for in the design table provided by the respective supplier.

As a result of the lack of information in the form of structural parameters the risk of failure in certain structures can be higher than anticipated. A further discussion of the safety of roof structures follows in the section below.

## 4.2 Structural reliability of current designs

Typical industrial roof structures are designed for wind loads with a return period of 50 years. Continual and recent failures of roof sheeting systems raise suspicion and suggest that roof structures are not designed and built conservatively in South Africa. Failure occurs because the capacities of the roof components are overtaxed. Expecting too much of the system indicates that there is a lack of knowledge in either the applied loads or the resistance of the roofing system to the loads.

To understand the failure in roof structures one should consider the planning, design and erection of a common roof. The general trend is that clients are confronted with a very competitive and populated market of roof system suppliers. Costs are starting to be cut by eliminating the professional guidance of engineers in the construction of roof structures. As mentioned earlier, design tables that are provided by roofing companies simply list purlin spacings, which are shown independent of the design wind load. The purlin spacings listed in the design table is, however, the only information the client needs and therefore looks no

further. Clients and contractors, however, are often unaware of critical loading conditions for roof structures and therefore need the advice of a professional engineer.

The result of the unawareness of roof loading zones is the following. Consider the two scenarios where failure occurs in either the supporting structure or the covering system of the roof. As for the supporting structure, as mentioned previously in Section 4.1.2, the current design approach suggest that the purlin spacing is calculated for the roof loading zones H and I (refer to Figure 25) and then reinforced with sag-bars or smaller spacings in higher loaded areas of zones F and G. The majority of contractors, and clients, are not aware of the roof loading zones in Figure 25, the purlins are therefore spaced according to the maximum allowable span-length as listed in the design table of the respective roofing supplier. This creates a safe design for the loads acting on the majority of surface of the roof, but not for the elevated loads acting on the edges of roof surfaces.

In the scenario of the covering system failing the same problem prevails. Clients and contractors are unaware of roof loading zones and as a result thereof the purlins that support the sheeting are spaced too far for highly loaded areas (refer to zones F and G in Figure 25).

Not all roofs fail as a result of unawareness. Considering the case where the design of the roof was performed by a professional structural engineer, failure is still possible and likely. As mentioned previously it is common practice for the supporting purlins to be spaced according to the loading on the majority of the roofs' surface (zones H and I). For the covering system, the purlin spacing is then checked to be smaller than the maximum allowable purlin spacing listed in the respective design table of the supplier. Regarding the supporting structure, engineers often specify sag-bars to be used to reinforce the bending capacity of the purlins in higher loaded zones. Note that the purlin spacing is thereby kept constant for the whole roof surface and conforms to the loading of the majority of the roof surface. Strengthening of the covering system is however not possible because the information obtained from the design tables is trusted strong enough for maximum wind loads. Since the maximum occurring wind loads can be far higher than most design tables account for, the lack of strengthening the covering system introduces the risk for the covering system in highly loaded zones.

### 4.3 Summary

By determining the maximum design loads for each roof loading zone, a purlin spacing can be calculated for the roof structure. Design tables from the respective cladding system suppliers are then used to check and verify if the purlin spacing provided by the supporting structure is sufficient for the sheeting.

Uncertainty is introduced by the lack of information in design tables. The maximum allowable purlin spacings listed are shown independent of any loads as shown in Table 9. The purlin spacing for the sheeting can therefore not be interpolated and adjusted for varying loading combinations on the surface of the roof. The varying pressure zones on every roof surface needs to be understood and quantified in a generic design table so clients are aware of the risk.

The fixed values listed as the maximum allowable purlin spacings in the design tables were found not conservative enough in certain circumstances. The maximum purlin spacings listed in the design tables are obtained from a series of experimental tests. The testing scheme used was discussed in Sections 2 and 3. A proposed new testing scheme is described in the following section. The proposed new scheme relates to the guidelines specified in the relevant standards and is developed to improve the reliability of current roof design practice.

## 5. Experimental test set-up

The design and construction of roof structures, specifically the covering system of roof structures, in South Africa relies on information that was found not reliable. Two changes are proposed. The first is to improve the testing procedures of roof coverings. Improvements to certain aspects compared to the testing scheme discussed in Section 2 could be identified and are elaborated furthermore herein.

The second change that was proposed involves a new design approach that makes use of the results obtained from the new testing procedures mentioned. The new design approach allows engineers to perform structural analysis on each of the elements within the roofing system according to conventional design principles.

A new design approach is being discussed which relies on parameters that are obtained by experimental testing. An experimental test set-up was developed of which the detailed structural layout is described and illustrated. The set-up produces the parameters, of every cladding system tested that are required for the new design approach, by the premeditated choice of certain boundary conditions as discussed in Section 5.3. The experimental set-up is designed to apply a certain load onto the test specimen, which consists of a set of fastened roof sheeting, by means of a load actuator as discussed furthermore in Section 5.6.

### 5.1 Proposed new testing approach

As discussed earlier, the design tables for the design of cladding systems that are currently available in the industry, lack information and are therefore unsafe. Engineers do not have any strength-defining factors available for the safe design of roof coverings. Strength-defining factors, better referred to as structural design parameters, would enable every structural engineer an exact and accurate design of roofing systems that relies on the strength capacities of the individual elements within the roofing system.

The structural parameters that the design of roof coverings for the ULS and the SLS depends on are mainly the bending resistance, the bending stiffness and the capacity of the fastening system. To obtain these structural parameters, a specified number of various full-scale tests need to be performed on the structural elements. A full-scale experimental test set-up which is

capable of simulating uniformly distributed loads onto a set of roof sheeting is proposed. The set-up needs to be capable of evaluating the structural parameters that govern the resistance of the sheeting to wind loads. The parameters are determined by testing procedures and can be used to design any roof covering system. The testing procedures require an experimental test set-up capable of simulating wind actions. The set-up consists of four different configurations, each having a purpose of evaluating a certain structural design parameter.

The experimental test set-up is designed and built according to regulations detailed in codes and standards as discussed in Section 3. The experimental test set-up conforms to the specifications and regulations detailed in the new draft code of practice *SANS 10237* (SANS 10237:201X, 201X). All details are discussed. The set-up is capable of testing the capacity of all vital structural components that determine the strength and resistance of roof coverings to loading. The results of the tests can be used to determine the structural design parameters as proposed in the new testing approach mentioned above.

## 5.2 Structural design parameters

The resistance of roofing systems against the design loading combinations depends on a number of structural design parameters. The parameters define the capacity for each of the respective components in the roofing system.

The five structural parameters are the resistance of the sheeting against concentrated loads, the bending capacity of the sheeting at midspan and at an internal support, the bending stiffness of the sheeting and the capacity of the fastening system. The five parameters will be discussed in more detail. Each of the parameters can be distinguished and classified into either Ultimate Limit State (ULS) or Serviceability Limit State (SLS). When the roofing system is loaded to such an extent that the maximum of anyone of the five mentioned parameters is reached, failure is either to ULS or SLS depending on the parameter.

### 5.2.1 Ultimate Limit State (ULS)

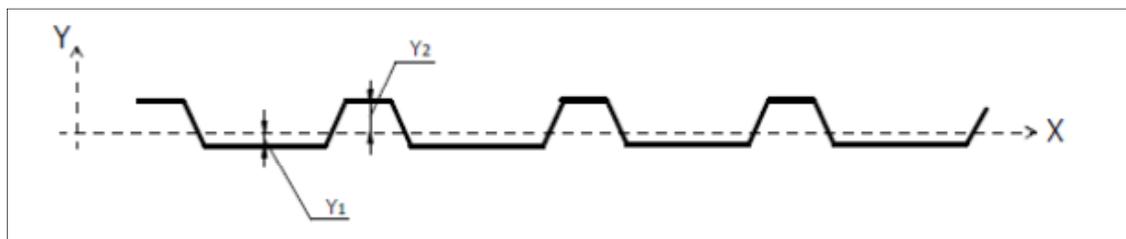
The following design parameters can be classified as ULS design parameters.

### 5.2.1.1 Resistance against concentrated loads

Point-load tests represent the actions induced onto roofing systems that are incidental actions induced during maintenance. A full-scale experimental test set-up applies. The set-up is capable of testing the capacity of roof coverings against concentrated loads.

### 5.2.1.2 Resistance against bending moment

Wind actions introduce a uniformly distributed loading to the covering system of a roof. The load subjects the sheeting to a bending moment. The resistance that sheeting has against bending depends on the dimensions of the profile of the sheeting, the thickness of the sheeting and the yield stress of the material used. Consider a typical roof sheeting profile in Figure 27 below.



**Figure 27: Section profile of typical roof sheeting**

*Note: The X-axis demarks a line through the centroid of the section, also referred to as the neutral axis.*

For most roof sheeting profiles the section is not symmetrical about the X-axis, which is the case when  $Y_1$  is not equal to  $Y_2$  as illustrated in Figure 27 above. The resisting bending moment capacity of the sheeting about the X-axis can be computed by:

$$M_R = \frac{\sigma I}{Y_i} \quad \text{Eq.: 2}$$

where  $\sigma$  is the yield stress of the material,  $I$  is the moment of inertia of the profile of the section and  $Y_i$  (either  $Y_1$  or  $Y_2$ ) is the distance from the neutral axis to the point of maximum compressive stress. With either the valleys or the crests in compression (refer to Figure 1 on Page 15), consider the two resisting bending moments  $M_{R1}$  and  $M_{R2}$ , where  $M_{R1}$  depends on  $Y_1$  and  $M_{R2}$  depends on  $Y_2$ . Equation 2 above suggests that for  $Y_1 \neq Y_2$ , the bending resistance  $M_{R1} \neq M_{R2}$  for a constant  $\sigma$  and  $I$  depending on the direction that bending occurs about the X-axis.

For the purpose of this study of simulating wind-uplifting actions, an applied positive bending moment  $M_{AI}$  causes a compressive stress in the valleys of the sheeting and the resistance is

therefore determined by  $M_{R1}$  and  $Y_1$ . Whereas, an applied negative bending moment ( $M_{R2}$ ) causes compression in the crests and the resistance is therefore determined by  $M_{R2}$  and  $Y_2$ . Exceeding the compressive capacity of the material in the structural element causes local buckling and thereby yielding of the material. Typically, the applied bending moment, resulting from the wind actions, should be smaller than the resisting bending moment of the sheeting to maintain stability.

### 5.2.1.3 Capacity of the fastening system

The systems for fastening the sheeting to purlins or girts can be classified as either a positive or non-positive (concealed fixing) fixing method. The capacity of the mechanism used to fasten the sheeting to its purlin support is considered a strength-defining parameter that determines the failure of the roof structure for the ultimate limit state.

## 5.2.2 Serviceability Limit State (SLS)

The following design parameters can be classified as SLS design parameters.

### 5.2.2.1 Deflection of the sheeting

The bending stiffness of the sheeting is a structural parameter that determines how rigid the sheeting is against deflections under loading. A sheeting profile having a high stiffness is very rigid and therefore undergoes very little deflections under loading. With the stiffness known, the maximum deflection for any roof set-up can be calculated.

## 5.2.3 Summary

The five structural design parameters can be classified into ULS type of failure or SLS type of failure as defined in Table 10.

**Table 10: Structural design parameters**

	Structural Design Parameter	Symbol	Unit	Failure
1	Resistance to concentrated load	P	N	ULS
2	Resistance to bending moment at midspan	$M_1$	kNm	ULS
3	Resistance to bending moment at internal support	$M_2$	kNm	ULS
4	Carrying capacity of fastening system	R	kN	ULS
5	Stiffness of sheeting system in bending	K	N/mm <sup>2</sup>	SLS

To obtain the structural parameters, a number of tests are performed on the experimental test set-up. To ensure failure occurs in each of the respective failure modes, four distinct configurations are used.

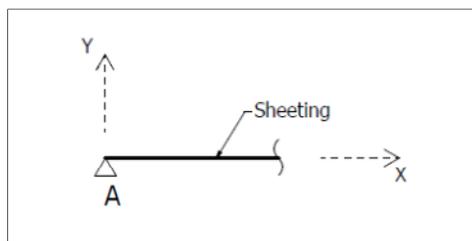
Before proceeding to the theoretical schematization of the experimental test set-up a short description of the fundamental boundary conditions needs to be clarified.

### 5.3 Boundary conditions

Fundamental boundary conditions need mentioning before providing a theoretical review of the experimental test set-up.

With reference to the experimental set-ups below, the following boundary conditions are defined:

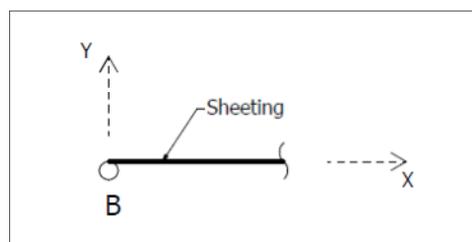
a) Vertical and horizontal restraint:



**Figure 28: Schematic representation of a hinged support at A**

Figure 28 above shows a typical hinged support. The translation in the X- and the Y- direction is restrained. On the experimental test set-up, a hinged support is simulated by fixing the sheets with the conventional fastening system as prescribed by the supplier of the roofing system. The sheeting is free to rotate at A about the axis being perpendicular to the global X- and Y-axes.

b) Vertical restraint:



**Figure 29: Schematic representation of roller support at B**

Figure 29 above shows a typical roller support. The translation in the Y- direction only is restrained. On the experimental test set-up, a roller support is simulated by simply preventing

any vertical movement of the sheeting in the loaded state. The sheets are free to move laterally, thereby eliminating any membrane action. The sheeting is free to rotate at B about the axis being perpendicular to the global X- and Y-axes.

## 5.4 Schematization of the experimental test set-up

As discussed, five structural design parameters (Table 10) define the strength of any given roof covering system. The schematization of the experimental test set-up is aimed to configure the set-up in such a way that it is capable of effectively testing the capacities of each of the structural design parameters individually. To evaluate the five structural design parameters independently, four distinct test set-up configurations are used. Their schematization is discussed.

For testing the true capacity of all components of a roof covering system the increase in strength provided by structural aids is aimed to be eliminated. Structural aids are secondary actions induced in the roofing system that could provide a supporting effect. Any unwanted or un-anticipated structural supports, or structural aids, of the test specimen would result in flawed and inadequate outcome. Examples of structural aids are membrane action within the sheeting or the support that flashing and ridging provides. The elimination of structural aids is accomplished by the deliberate choice of boundary conditions in the schematization of the experimental test set-up. More on this is to follow.

### 5.4.1 Configuration 1: Resistance to concentrated loads

Point-load tests represent the actions induced onto roofing systems that are caused by maintenance or construction incidents. Local buckling in the crest of the sheeting profile is the failure mode to be considered. Figure 30 below shows a simply supported single span configuration with a concentrated load introduced at midspan (B). The span length ( $L$ ) chosen is 1000mm.

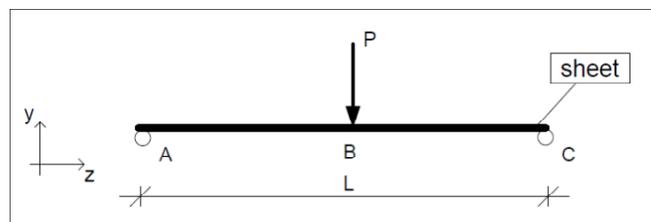
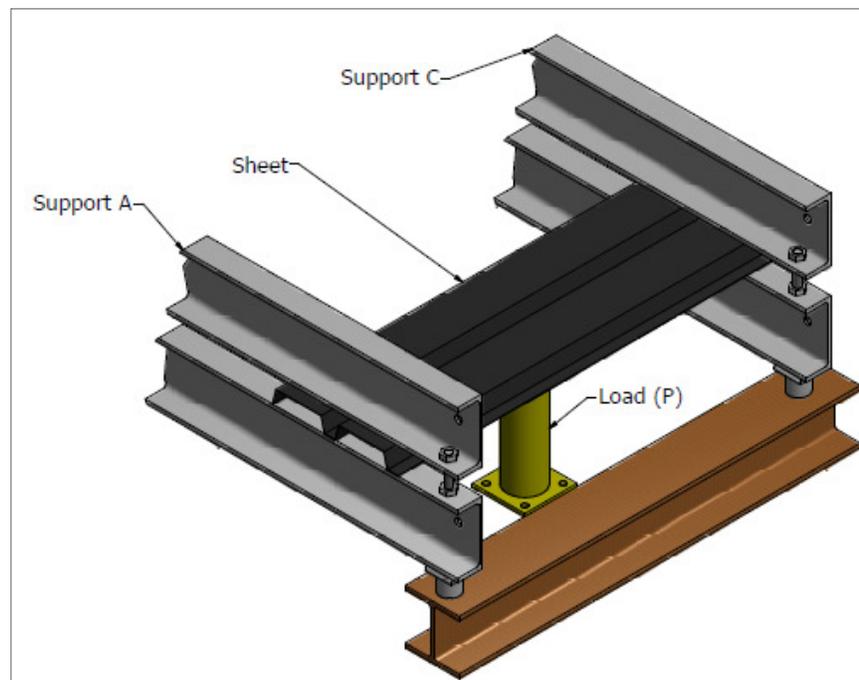


Figure 30: Schematization to test the resistance of sheeting to a concentrated load

Note, the support conditions are both chosen to be of a roller type. Theoretically, the sheet shown has no restraint in the z-direction. Practically, the sheet is not fixed by the conventional method at either end and therefore do not qualify as a hinged support as stipulated in Section 5.3.

The configuration used to test for concentrated loads consists of a simply supported single span roof system as referred to in Figure 30. Figure 31 below shows the implementation of configuration 1 of the experimental test set-up.



**Figure 31: Experimental test set-up: Configuration 1**

The support conditions at Support A and Support C are prepared to only limit the movement of the sheet in the y-direction (refer to Figure 30 regarding the directions and sign conventions). The sheet is however free to move in the z- and x-direction. Further technical details of the test set-up can be found in Appendix C.

#### **5.4.2 Bending moment capacity**

Section 5.2.1.2 discusses the resistance of the section of a sheeting profile against an applied bending moment. For a safe roof sheeting, the applied bending moment needs to be smaller than the resisting bending moment i.e.  $M_A < M_R$ . The sheeting of a typical roof in practice can be subjected to two distinct bending moments differing both in direction, concave upwards or

concave downwards, as well as in magnitude. An applied bending moment that forces the sheeting concave downwards would introduce compression in the valleys of the sheeting (refer to Figure 27) and is referred to as a positive bending moment ( $M_{A1}$ ). An applied bending moment that forces the sheeting concave upwards would introduce compression in the crests of the sheeting and is referred to as a negative bending moment ( $M_{A2}$ ).

From the above, it is clear that the aim of the experimental test set-up is to determine the magnitude of  $M_{R1}$  and  $M_{R2}$ . To determine the magnitude of  $M_{R1}$ , an  $M_{A1}$  needs to be applied increasing the magnitude until  $M_{A1} > M_{R1}$  and failure is reached. The same with the other direction where failure is observed when  $M_{A2} > M_{R2}$ . To apply the two distinct bending moments, two configurations are used. The one is referred to the bending moment at midspan ( $M_{A1}$ ) and the other the bending moment at an internal support ( $M_{A2}$ ).

#### 5.4.2.1 Configuration 2: Bending moment at midspan ( $M_{A1}$ )

The maximum applied positive bending moment ( $M_{A1}$ ) will occur at midspan between the supports of a simply supported sheeting set-up. Figure 32 below shows a simply supported single span sheeting set-up with a Bending Moment Diagram (BMD). The sheeting is loaded with a uniform loading  $w$  and has a span length  $L$ . The BMD is a graph that computes the bending moment  $M$  as a function of  $z$ . At midspan, where  $z = 0.5L$ , the maximum bending moment is equal to  $0.125wL^2$  as shown.

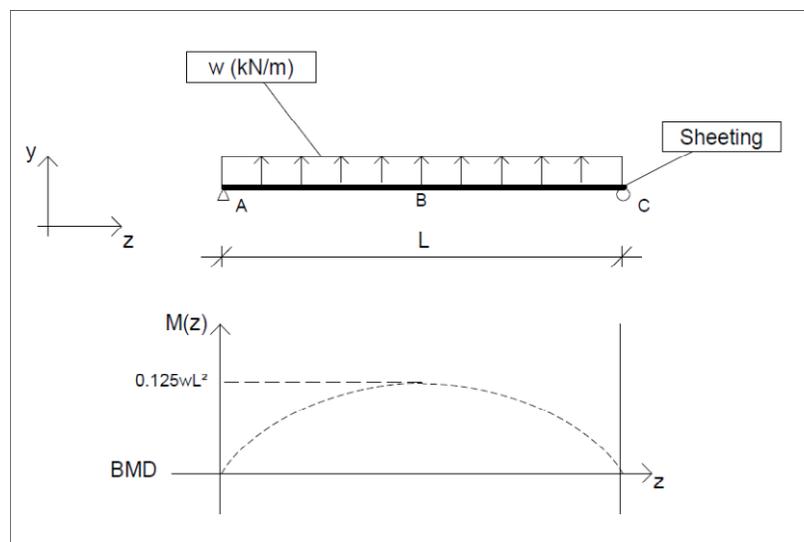
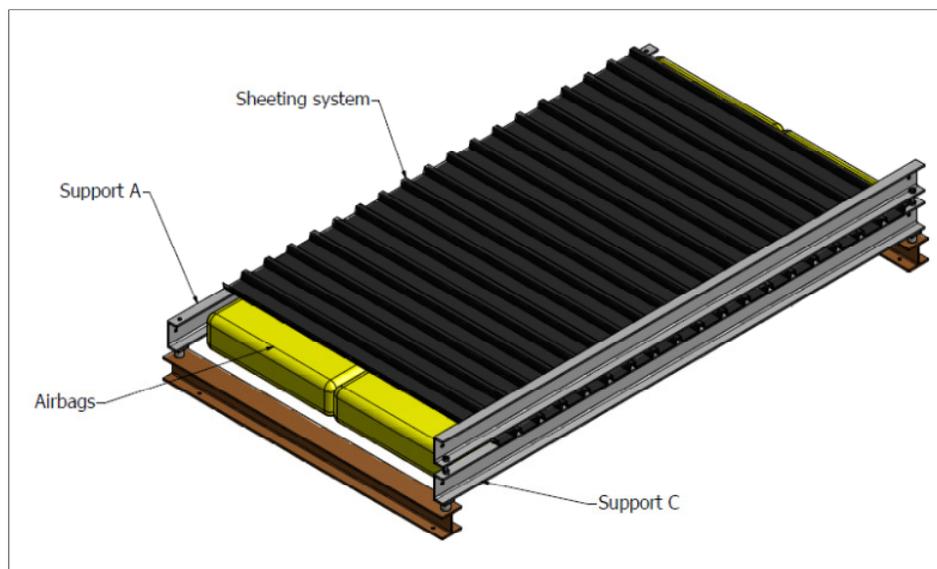


Figure 32: Maximum bending moment at midspan

As shown in Figure 32 above, the support conditions used are a hinged support at A, and a roller support at C. To eliminate any membrane action, the support at C was deliberately chosen a roller type of support. A hinged support at C would limit the maximum curvature at midspan (B) by limiting the lateral translational movement, and hence causing the membrane action. Membrane action would increase the true bending capacity of the profile and is therefore eliminated as discussed earlier.

Figure 33 below shows the practical implementation of Configuration 2 of the experimental test set-up detailed in Figure 32 above. Note that in Figure 33, the Support A corresponds to the point A stipulated in Figure 32. To simulate a hinged support as schematized, the sheeting is fastened with the conventional fastening system as the supplier of the roof covering prescribes. Support C is a roller type support, which only limits the translation in the y-direction. The sheeting is free to move in the x- and z-direction as specified.

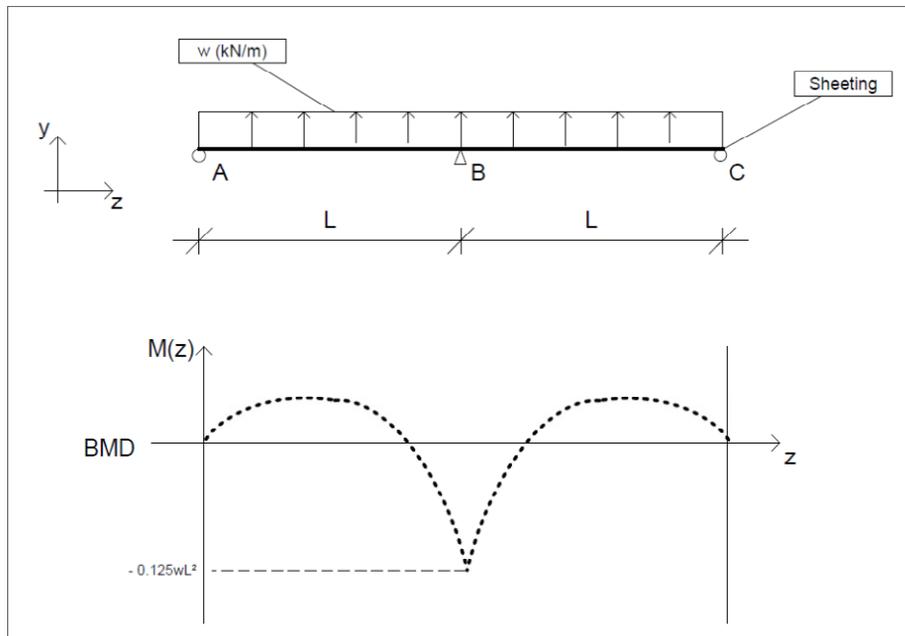


**Figure 33: Experimental test set-up: Configuration 2**

The distance from centre to centre between Support A and Support C is 2100mm. Two airbags are fitted as shown to fit between the supports A and C. The airbags are inflated to exert a uniform load to the underside of the sheeting system. More on the load application in Section 5.6.

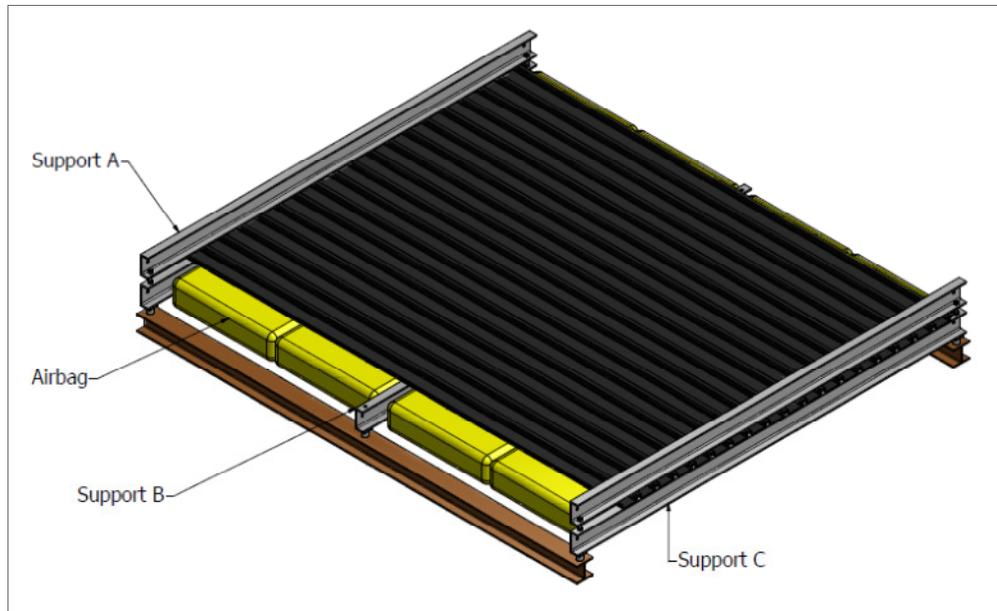
### 5.4.2.2 Configuration 3: Bending moment at an internal support ( $M_{A2}$ )

The maximum applied negative bending moment ( $M_{A2}$ ) will occur at the interior support (B) of a double-span sheeting set-up. Figure 34 below shows a double span continuous sheeting set-up with a Bending Moment Diagram (BMD). The sheeting is loaded with a uniform loading  $w$  and has a span length  $L$ . At point B, where  $z = L$ , the maximum negative bending moment is equal to  $-0.125wL^2$  as shown.



**Figure 34: Maximum bending moment at an internal support**

As shown in Figure 34 above, the support conditions used for the double-span set-up are a roller support at A and C, whereas point B has a hinged support. Figure 35 below shows the practical implementation of Configuration 3 of the experimental test set-up detailed in Figure 34 above.

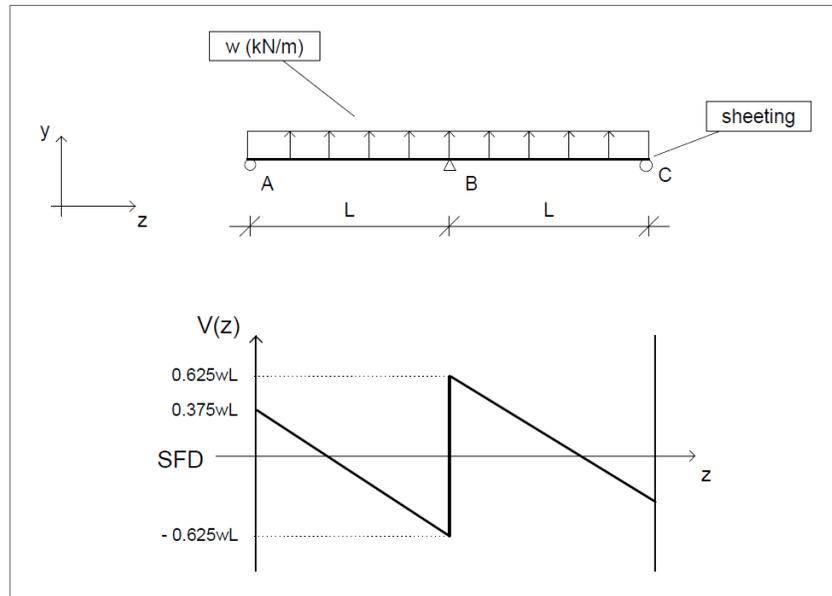


**Figure 35: Experimental test set-up: Configuration 3**

The distance from centre to centre between Support A and Support B is 2100mm. Four airbags are fitted as shown to fit between the supports A, B and C. The airbags are inflated to exert a uniform load to the underside of the sheeting system. More information on the means of load application is discussed in Section 5.6.

#### 5.4.3 Configuration 4: Capacity of the fastening system

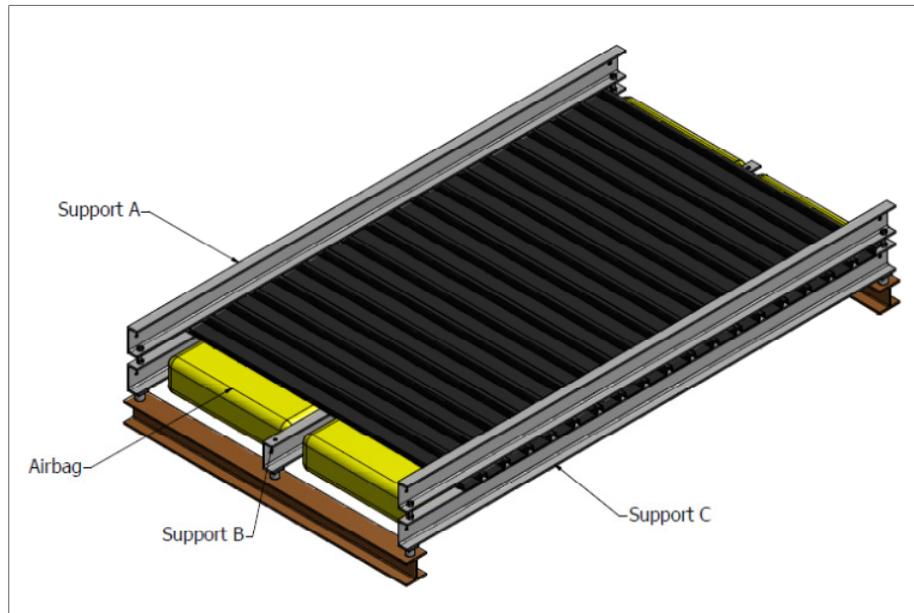
The maximum reaction that the fastening system is able to withstand can be measured by also using a double-span continuous sheeting set-up. Figure 36 shows a double span continuous sheeting set-up with three supports, A, B and C as shown. The sheeting is loaded with a uniform loading  $w$  and has a span length  $L$ . The Shear Force Diagram (SFD) is a graph that computes the external reactions that are the result of the load  $w$ . The SFD shows the maximum reaction at point B of the structure to be  $R_B = 0.625wL + 0.625wL = 1.25wL$ . To test the capacity of the fastening system, the sheeting is fixed using the conventional fastening system at the point of highest reaction. Therefore, the sheeting is supported at point B by means of a hinged support as shown in Figure 36.



**Figure 36: Maximum reaction to fastening system**

To ensure that failure occurs in the fastening system rather than by exceeding the bending capacity of the sheeting, shorter span-lengths were chosen. The span lengths used in Configuration 3 are 2100mm, whereas the span lengths used in Configuration 4 are 1050mm. The applied bending moment at an internal support of a double span continuous beam is  $M = -0.125wL^2$ , which is proportional to the square of the span length. The reaction at an internal support is  $R = 1.25wL$ , which is directly, and not quadratically, proportional to the span length. Therefore, when decreasing the span length ( $L$ ) by a factor of two the reaction is decreased by a factor of two and the applied bending moment is increased by a factor of four. For the determination of the carrying capacity of the fastening system the shortest possible span length is therefore chosen in order to prevent bending failure.

Figure 37 below shows the practical implementation of the configuration schematized in Figure 36.



**Figure 37: Experimental test set-up: Configuration 4**

#### **5.4.4 Bending stiffness**

The bending stiffness of the sheeting is a structural parameter that determines how rigid the sheeting is against loading. A higher deformed loaded state of the sheeting implies a lower stiffness. The maximum vertical deflection ( $u$ ) of the sheeting is measured using the same schematization and configuration used and described in Section 5.4.2.1. The maximum deflection is obtained by measuring the displacement of the sheeting at point B (Figure 32) on the set-up. The bending stiffness of the sheeting can then be calculated using the deflection measured at midspan.

#### **5.4.5 Summary**

To test and evaluate the resistance of roof coverings against wind actions, an experimental test set-up was developed and discussed. Four different configurations are needed to determine the resistance. The theoretic schematization and practical implementation of these four different test configurations were examined. They each differ from one another in order to test a certain structural design parameter. The details on the experimental test set-up is discussed in the following section.

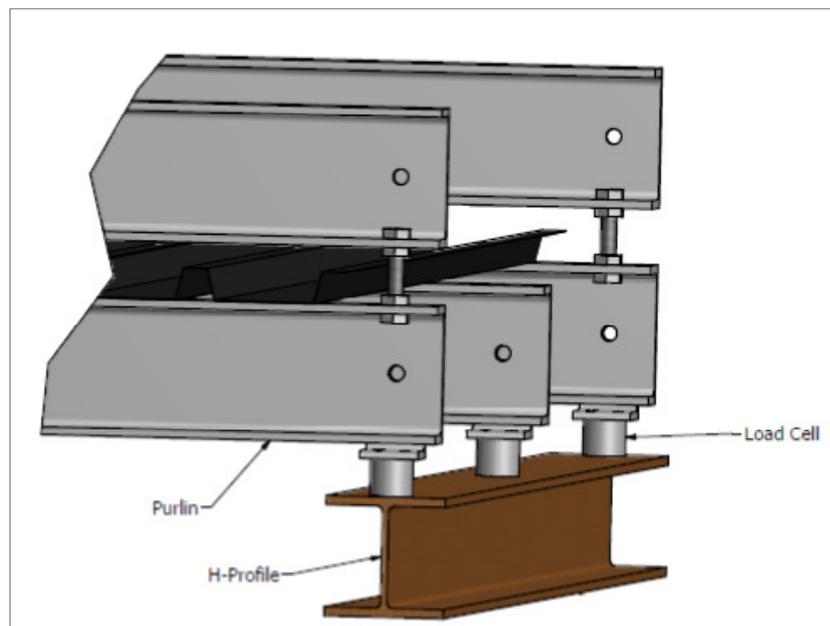
## 5.5 Experimental test set-up components

A number of components and parts make up the experimental test set-up as schematized in the previous section. The experimental test set-up roughly consists of a supporting structure and the roof covering system. How exactly they are fitted and arranged in the experimental set-up is discussed.

### 5.5.1 Supporting structure

The supporting structure of the experimental test set-up is designed to withstand loads that correspond to the highest possible wind actions. The stressed behaviour of the roof covering system is aimed to be tested and not the strength of the structural support.

The whole supporting structure rests on two main beams. The beams are H-profiles (152x152x37) as shown in Figure 38. The beams are secured to the laboratory floor providing a fixed support for the purlins. The connection to each purlin accommodates a load transducer to record the reaction force on each purlin. The measurement apparatus is discussed in Section 5.7.

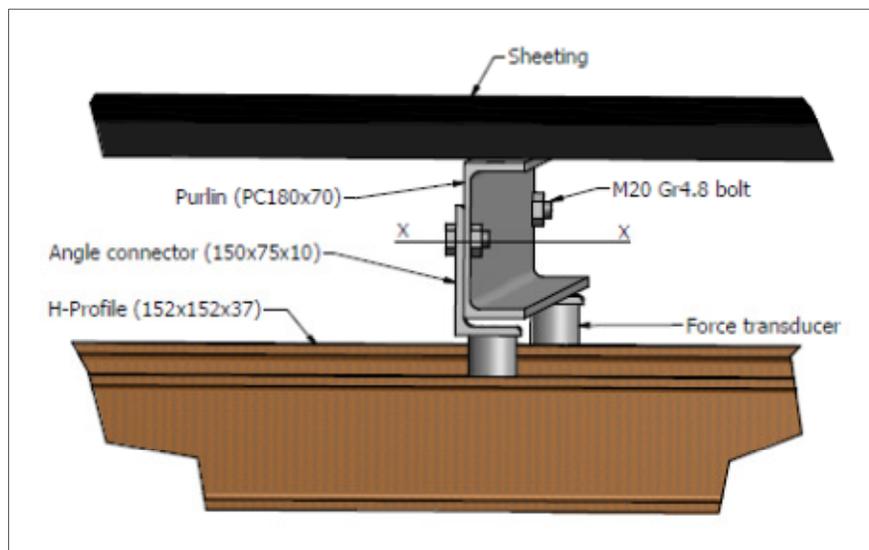


**Figure 38: Detail to H-profile**

*Note: detail to all components in the experimental test set-up can be referred to in Appendix C.*

For the purlins hot-rolled channel profiles (PC180x70) were chosen. In contrary to common roofing practice, the customary use of cold formed lipped channels is replaced by the use of hot rolled channel profiles for purlins in the experimental test set-up. The capacity of cold formed lipped channels is insufficient due to high bending moments created by the potentially high experimental test loads. Depending on the roofing system tested, failure of the supporting structure may occur before any of the roofing components reaches its capacity. According to the draft code of practice *SANS 10237 – Metal roof and side cladding* (SANS 10237:201X, 201X), the supporting structure may be strengthened as long as the strengthening does not affect the performance of the cladding or change its mode of failure.

An angle profile with dimensions of 150x75x10 was used to connect the force transducers to the purlins. A single M20 bolt is used to connect the purlin with the angle profile as to create a simple support that allows rotation about the local x-axis of the purlin. Refer to Figure 39 for all details of the layout.

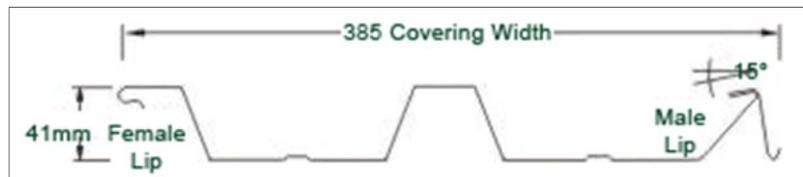


**Figure 39: Detail to purlin connection**

On Figure 39, the line X-X demarks the local x-axis of the channel profile. The connection shown provides a hinged support for the purlin. In this case, the schematization of a hinged support allows the rotational Degree Of Freedom (DOF) about the x-axis to be free and a the translational DOF in all directions to be fixed.

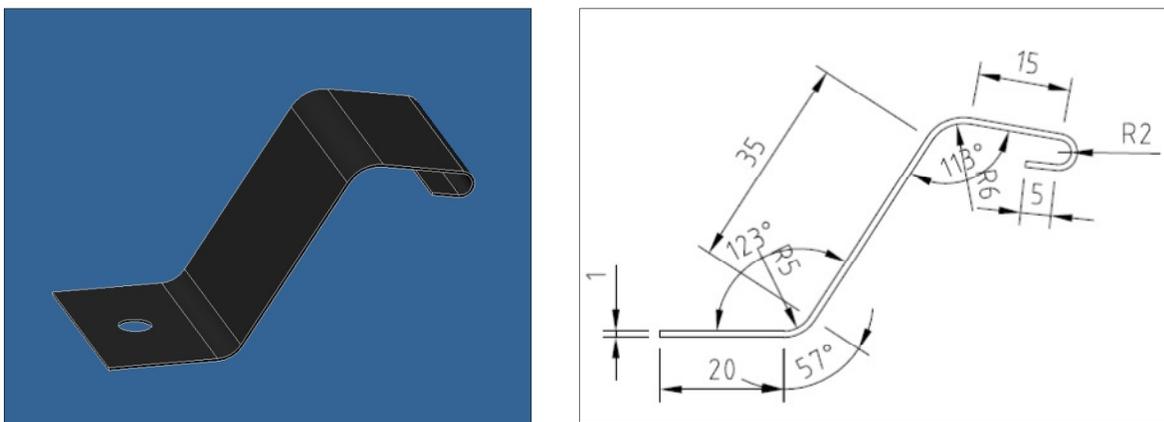
## 5.5.2 Roof covering system

The roofing system, which consists of the sheeting and the fastening system, is to be fitted to the supporting structure as the respective roof sheeting supplier prescribes. Clotan Steel (Pty) Ltd supplied a roof covering system. The coverings system is referred to as Craft-Lock, and it makes use of a non-positive fixing method. Craft-Lock sheeting is of galvanized steel with 550MPa yield strength and a total coated thickness of 0,58mm. The section profile of a single sheet is shown in Figure 40 below.



**Figure 40: Craft-Lock sheeting profile (Clotan Steel (Pty) Ltd.)**

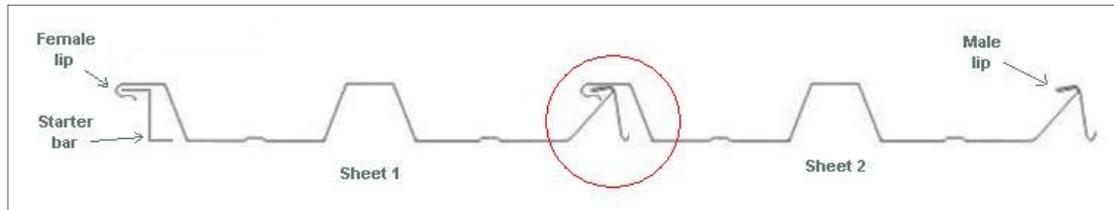
Nine roof sheets, with a total covering width of 3465mm were fitted to the purlins using fastening brackets (refer to Figure 41 below) as supplied. The brackets are 39mm wide and the material has a yield strength of 550MPa. The brackets, also referred to as cleats, were fixed to the purlins using M6 Grade 4.8 bolts with nuts. To fix the cleats to purlins, self-tapping screws are generally used in practice. However, self-tapping screws are only used as fasteners in conjunction with cold-formed sections as purlins. Hot-rolled purlins, as used in the experimental test set-up, were considered unsuitable for self-tapping screws since the flange thickness of 10.9mm is simply too thick for the self-tapping screw threads.



**Figure 41: Detail of fastening bracket (cleat)**

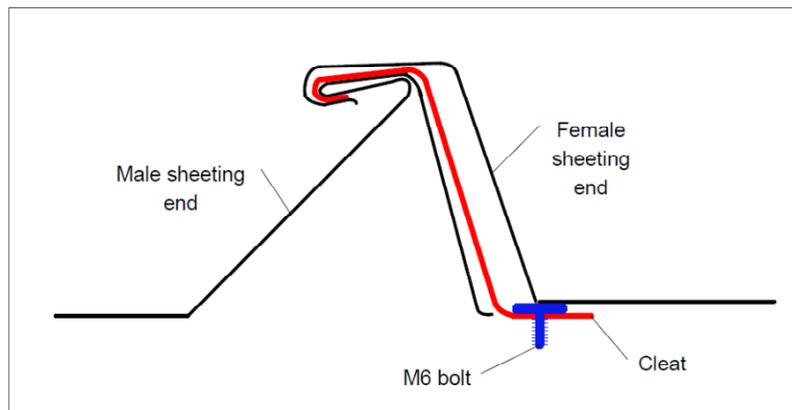
The procedure of fixing the sheeting is presented in Figure 42 and Figure 43 below. The first sheet of the roof set-up is fixed to a starter bar. The female lip folds over the top leg of the

starter bar, where the lower leg of the starter bar is positively fixed to the purlins. The lip of a fastening bracket, or cleat, is used to fold over the male lip of the first sheet. The lower end, with the hole (see Figure 41 above), is positively fixed to a purlin support by a M6 bolt. The female lip of the second sheet is then folded over the male lip (and fastening bracket) of the first sheet. Figure 42 below shows the female and male lip of two sheets interlocked in the middle. The interlocking seam is indicated in red in Figure 42 below and illustrated in detail in Figure 43.



**Figure 42: Interlocking of Craft-Lock sheets**

The encircled (red) at the point where the sheeting system is fixed to a purlin support is illustrated in detail in Figure 43 below.



**Figure 43: Interlocking seam with cleat**

## 5.6 Load application

The loading scheme, which entails the sequence of loading steps and the type of actuator used on the various structural elements, are described in detail in the following section.

### 5.6.1 Concentrated load

Point-load tests represent the actions induced on roofing systems that are incidental to maintenance purposes. The objective of testing the resistance to concentrated loads, using a point-load test, is to assess the vulnerability of the sheeting to local buckling failure.

A hydraulic jack was used to apply a point load to the centre rib, or crest, of the sheeting. A rubber pad inserted between the sheeting crest and the hydraulic jack prevents local stress concentrations as prescribed by the *SANS 10237* (SANS 10237:201X, 201X). A force transducer was fitted to measure the magnitude of the load application. Refer to Section 5.4.1 and Appendix C for a clearer overview of the set-up and layout.

The load is increased from zero to 500N and fully removed again. Thereafter, the load is increased again until ultimate failure is observed. Refer to Section 6.2 for a more detailed definition of the failure criteria.

### 5.6.2 Uniformly Distributed Load (UDL)

As already discussed in Section 2.2.2, the most popular means of applying a UDL is the use of sandbags, mostly because of the simplicity of use. There are three main alternatives to sandbags considered for applying a UDL. The alternatives are a wind tunnel, using water as a load actuator or the use of inflatable airbags. A wind tunnel is regarded unsuitable, because the tunnel would need to be unrealistically large to be able to test the capacity of a full-scale roof covering system. A scaled model of a sheeting and fastening system would not be manufactured by the same company that intends to have their systems tested. Therefore, it would not be a true representation of their respective product in the market. Also, regarding the fastening system of certain concealed fixing methods, it would be very challenging to build such fine detail as well as to accurately observe the true interaction of the fastening brackets within the sheeting set-up.

A further alternative set-up is one that is capable of accommodating water as a load actuator. The advantage of applying a force using water is the fact that it is a near perfectly uniformly distributed force, provided the surface it rests on is flat. However, as soon as extensive deflections occur within the sheeting system ponding occurs. Ponding concentrates more water to higher deflected areas which implies that a higher force is applied to the regions of higher deflections. Since roof sheeting profiles are generally of very thin material, being less than 1mm in thickness, large deflections are likely. Therefore, water can not be used as a realistic means of simulating wind actions.

The third mentioned option of simulating a UDL is the use of inflatable airbags. Airbags can be shaped depending on the size and configuration of the specimen to be tested. Depending on the inlet and outlet control of the airbags the inflation and deflation (i.e. loading and unloading of the roof sheeting) process can be closely monitored and controlled. Comparing the loading resolution to the one that sandbags provide, airbags can be an adequate solution to simulating wind actions. The use of airbags for the testing of roof structures is discussed further in sections to follow.

Considering the pro's and con's of alternative loading techniques, airbags were chosen to be used in this study. To simulate wind actions onto the cladding system specially fabricated airbags were arranged between the floor and the sheeting. The airbags were sized appropriately in order to apply the distributed load to the sheeting only. The purlins were thereby not subjected to any externally applied loads from the airbags, enabling the exclusive testing of the roof sheeting and fastening systems. The Airbags are inter-connected via a "manifold-type" air duct. This allows an even inflation amongst the bags, and thereby a concurrent application of the load to the sheeting.

Each airbag was equipped with two valves, one for the inflation and a second one to accommodate an electronic pressure gauge. This enabled the observation of the pressure build-up within the airbags very accurately. A simultaneous and uniformly distributed load application by the airbags was required. The airbags are inflated at a near-constant rate until the respective failure mode was recorded. The various failure modes and criteria are discussed further in Section 6.2.

The loading rate and the response of the test specimen was measured and recorded using a number of different electronic transducers and measurement equipment. This is discussed in the next section.

## **5.7 Measuring equipment and data acquisition**

All stresses, forces and deflections are intended to be recorded for post-testing data processing and evaluations. The types of measuring apparatus being used to attain readings and to document them are discussed.

### 5.7.1 Reaction measurement

HBM U93 (50kN) force transducers, shown in Figure 44 below, were used to measure the reactions between the H-profiled beam and the purlins (refer to Figure 38 and Figure 39). Appendix B details all specifications of the force transducer used.



**Figure 44: U93 Force Transducer (50kN)**

The force transducers, also referred to as load cells, were fitted on both sides of each purlin in each of the respective configurations. The readings are used to measure the reaction force that each of the purlins are subjected to during the loading of the test specimen. The readings are therefore used to calculate the equivalent UDL.

For Configuration 1, discussed in Section 5.4.1, an additional force transducer was fitted at the point of load application as discussed in Section 5.4.1 and shown in the technical drawings in Appendix C.

### 5.7.2 Pressure transducers

Each airbag is equipped with an electronic pressure transducer via an exclusive valve. The measuring range of the transducers is 40kPa. The pressure measurement serves as a check to monitor the inflation of the airbags. It is of high importance that the airbags are all inflated simultaneously.



Figure 45: Pressure transducer S-10 (40kPa)

### 5.7.3 Deflection measurement

Linear Variable Differential Transformer's (LVDT's) are used to measure the deflections of the test specimen. LVDT's are placed at the point where maximum deflections are expected according to elastic beam theory in each of the respective configurations. The recorded deflections are used for post-testing analysis of the data.

### 5.7.4 Data acquisition system

All apparatus and measuring equipment is electronically linked to a central data acquisition system referred to as Spider8. The Spider8 is an analogue-digital interface that is used to store all measurements from the pressure transducers, force transducers and LVDT's on a computer. The data can then be processed for the interpretation of the test results.

## 5.8 Summary

The experimental test set-up consists of four different configurations as discussed. Each of the configurations are used to individually determine and evaluate the core strength-defining characteristics of roof covering systems referred to as structural design parameters. The configurations differ from each other by the choice of applicable combinations of boundary conditions where each has a particular purpose in testing and determining the respective structural parameter.

How the experimental test set-up is used, including the loading procedure and the pre- and post testing analysis, is discussed and follows. The failure modes for each of the configurations are elaborated.

## 6. Experimental Test Procedure

The experimental test set-up consists of four different configurations, as discussed. Each component of the set-up serves a particular purpose in evaluating the carrying capacity of roof covering systems that are subjected to wind actions. With the test apparatus in place, the detailed procedures of testing is discussed. Testing starts with fixing the test specimen, in this case the sheeting system, and ends at the point when a respective failure mode is observed.

For each of the different configurations, a distinctive failure mode can be identified that determines the capacity of the respective structural design parameters of the covering system. The criteria that determine a respective failure mode is discussed in Section 6.2.

After failure is observed, the recorded data is analyzed. The measurements of all transducers is arranged to outline the relationship between chosen characteristics. These relationships are eventually used to determine each of the structural design parameters discussed in Section 6.3.

### 6.1 Pre-testing procedures

The procedures to be done before testing include the correct installation of the cladding system, the final check if all transducers are operative, and the load actuator is in place.

The cladding system is fastened to the purlins as prescribed by the supplier of the roof covering system. The cladding system should be fastened by skilled labourers from the respective supplier. It is essential to fasten the sheeting system correctly as prescribed. This is to minimize the doubt of the legitimacy of test results, which may be initiated by any discrepancies of flawed installation procedures. Section 5.5.2 specifies the detailed proceedings on how to install the Craft-Lock roof covering system supplied by Clotan Steel (Pty) Ltd (Clotan Steel (Pty) Ltd.). The purlins are each 3680mm long, which accommodates nine Craft-Lock sheets to be fastened as specified.

After the sheeting is installed to the suppliers' satisfaction, the airbags are inserted beneath the sheeting set-up. The airbags are not inserted before the erection of the sheeting system, since drill shavings from the fastening procedures may puncture the airbags under pressure. All

transducers and measurement apparatus as discussed in Section 5.7 should be checked before starting the inflation of the airbags.

The testing process consists of two inflation phases. The first is referred to a pre-loading phase, which is used to get all the airbags in the right shape. The airbags are initially pillow-shaped, and need a full box-shape to apply the load uniformly to the specimen. The pre-loading phase inflates the airbags to the right shape while care is taken that the load applied to the specimen is negligible. During the first inflation phase, the pressure within the airbags is not allowed beyond 0.2kPa.

Once all airbags reached a box-shaped state and the pressure within all airbags is in equilibrium the second inflation phase can commence. The second inflation phase entails the opening of the airflow to allow a uniform inflation amongst all airbags. The inflation process is only stopped once the respective failure mode has been observed and sufficient data has been recorded to perform all post-testing data analysis. More information on failure criteria for each configuration is referred to in the next section.

## 6.2 Failure modes

The definition of failure is considered critical, as this determines how strong each tested element is. Each individual test set-up has its own criterion that is considered as failure to either ULS or SLS depending on the type of test performed.

### 6.2.1 Configuration 1: Concentrated load test

Refer to Section 5.4.1 for the schematization of the test set-up to be considered in this section. The load was applied at midspan to the centre rib of a single sheet. Failure is reached as soon as local buckling and permanent deformations of the sheeting can be observed. Buckling of a structural member causes the element to be stressed beyond the elastic limit of the material and therefore results in permanent deformations.

Failure of the roofing system due to concentrated loads is considered an Ultimate Limit State (ULS) failure.

### 6.2.2 Configuration 2: Bending moment at midspan

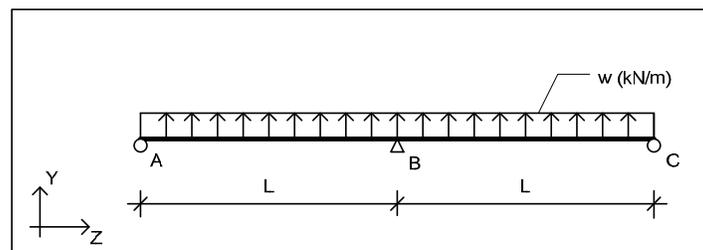
Refer to Section 5.4.2.1 for the schematization of the test set-up to be considered in this section. The single span configuration tests the bending moment capacity of the sheeting system at midspan. A UDL is applied to the underside of the sheeting simulating wind-uplifting forces. Failure is reached once any of the fastened sheets buckled at midspan causing yielding and permanent deformations of the material.

Failure of the roofing system due to exceeding the bending capacity at midspan is considered an Ultimate Limit State (ULS) failure.

### 6.2.3 Configuration 3: Bending moment at an internal support

Refer to Section 5.4.2.2 for the schematization of the test set-up to be considered in this section. The long double span configuration tests the bending moment capacity of the sheeting system at the internal (central) support. A UDL is applied to the underside of the sheeting simulating wind-uplifting forces.

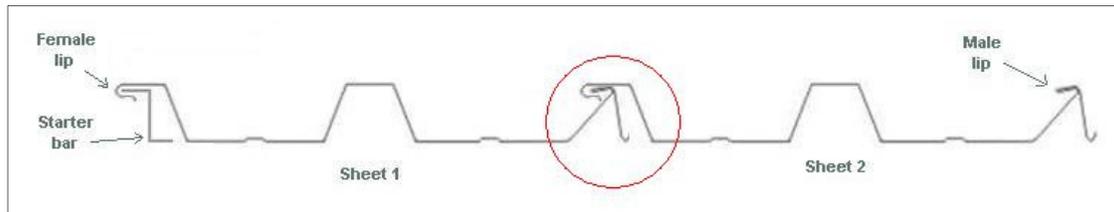
According to ideal elastic-plastic beam theory, failure is expected in the form of global buckling at the internal support (B) of a multi-span continuous beam set-up as shown in Figure 46 below.



**Figure 46: Theoretical schematization of a double-span continuous beam**

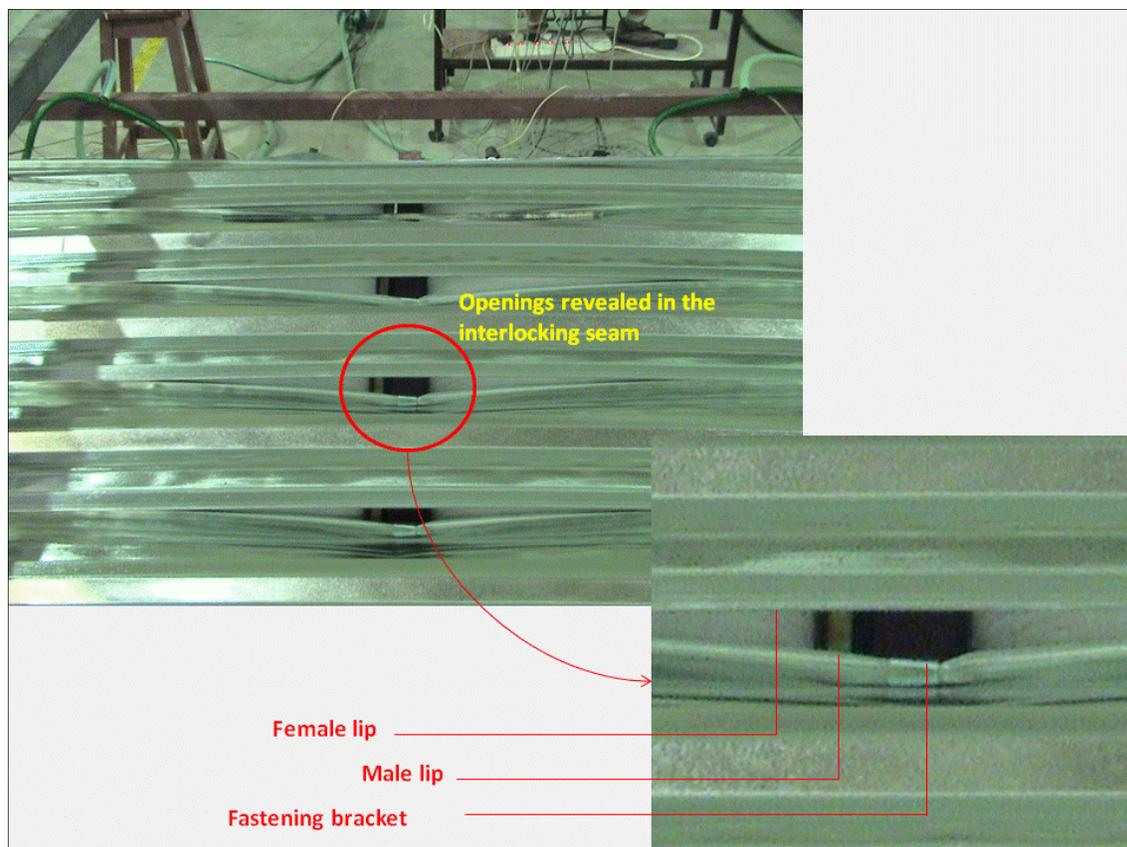
However, for determining the bending capacity of the sheeting system at the internal support, the Craft-Lock cladding system can not be compared to an ideal elastic-plastic beam. Failure due to global buckling is not observed in the sheeting system. To understand failure in the system, the interlocking seam between the sheets are observed. By loading the test specimen, the male lip buckles locally as expected in theory at point B (Figure 46). The female lip (folding over the male lip) however does not buckle but slips out and reveals an opening to the inside of the structure. The interlocking seam is indicated in Figure 47 below. The material is not

stressed beyond its elastic limit at the point where the female lip reveals the opening i.e. the buckling of the male lip has not yet caused any plastic deformations.



**Figure 47: Interlocking seam (female lip folding over male lip between Sheet 1 and Sheet 2)**

The openings revealed at the point of failure, shown in Figure 48 below, occur as a result of the male lip buckling elastically. Failure in bending was therefore considered only when the male lip has undergone plastic deformation by buckling. As soon as the material has deformed plastically, the female lip is unable to slip back into its original unloaded position upon removing the applied load.



**Figure 48: Opening revealed at internal Support B**

Failure of the roofing system due to exceeding the bending capacity at an internal support is considered an Ultimate Limit State (ULS) failure.

#### **6.2.4 Configuration 4: Capacity of the fastening system**

Refer to Section 5.4.3 for the schematization of the test set-up to be considered in this section. The short double span configuration was aimed to test the capacity fastening system of a roof covering structure. A UDL is applied to the underside of the sheeting simulating wind-uplifting forces. Failure is reached once any of the sheets lost its fastened state i.e. the connection between the sheeting and the supporting structure is no longer functional.

Failure of the roofing system due to exceeding the fastening capacity is considered an Ultimate Limit State (ULS) failure.

#### **6.2.5 Discussion**

Considering a general roof structure on site, failure is considered as the case when any of the sheeting undergoes permanent deformation and therefore can no longer function as a reliable weather tight cover. The equivalent UDL that causes failure in each of the respective failure modes, as described, is given and discussed in Section 7.

To determine failure, however, the recorded raw data needs to be processed and analyzed. The administration of all data is discussed in the next section.

## 6.3 Post-test data processing

To determine the point of failure for each of the configurations, and ultimately the carrying capacity of the roof covering system, the recordings of the measurement apparatus is used. From the readings of all transducers installed, test data could be gathered and arranged. The data available from the transducers after conducting a test is the following:

- Pressure transducers
- Force transducers
- Deflection meters

Section 5.7 has further details on each of the measurement apparatus and transducers used. The following section describes the processing of the readings that are recorded.

### 6.3.1 Pressure transducers

The readings of the pressure transducers are compared to one another and checked for their correlation to assure an equally applied load onto all sheeting elements. A simultaneous load application is considered crucial.

### 6.3.2 Force transducers

The readings of the force transducers are primarily used to calculate the magnitude of the equivalent UDL that is applied to the sheeting system. The following equation is used:

$$w = \frac{\sum FT}{A_T} \quad \text{Eq.: 3}$$

where  $w$  equivalent Uniformly Distributed Load (UDL) in kN/m<sup>2</sup>

$FT$  the respective force transducer reading in kN

$A_T$  the total projected surface area of the test specimen being loaded m<sup>2</sup>

Each purlin support is fitted with two force transducers, one at each end. Appendix C details the layout of all force transducers in each of the respective configurations. The readings of the two force transducers are averaged to obtain a single reading of the reaction of each respective support of the sheeting system.

### 6.3.3 Deflection meters (LVDT's)

Three LVDT's are fitted at midspan on Configuration 2. The readings are averaged and used to calculate the stiffness of the sheeting system against bending. The following equation is used:

$$EI = \frac{5wl^3}{384u} \quad \text{Eq.: 4}$$

where  $w$  equivalent UDL

$l$  span length

$u$  average deflection at midspan

$EI$  bending stiffness of the sheeting system

The stiffness of the sheeting system determines how rigid it is against loading. A low stiffness would imply large deflections for a certain applied load.

### 6.3.4 Discussion

After all the raw data is processed, the resistance that the roof covering system has against wind actions can be determined. The test results for testing the carrying capacity of the Craft-Lock roofing system is discussed in the following section.

## 7. Test results for Craft-Lock sheeting

Craft-Lock sheeting was installed and loaded using airbags as discussed previously. The test specimen was loaded until failure in each respective configuration. After failure was observed, a new set of roof sheeting was installed and the loading procedure is repeated. In total, five test-specimens were tested on each of the configurations to obtain statistical reliability.

The test results for each of the individual configurations of the experimental test set-up are provided and discussed.

### 7.1 Configuration 1: Resistance to concentrated loads

As discussed in Section 5.4.1, the test set-up consists of a simply supported single sheet and is loaded at the central crest by a point load. Failure, according to Section 6.2.1 is to be considered as soon as local buckling and permanent deformations of the sheeting can be observed.

The maximum concentrated loads ( $P$ ), that caused failure as defined, from the five tests are shown in Table 11 below.

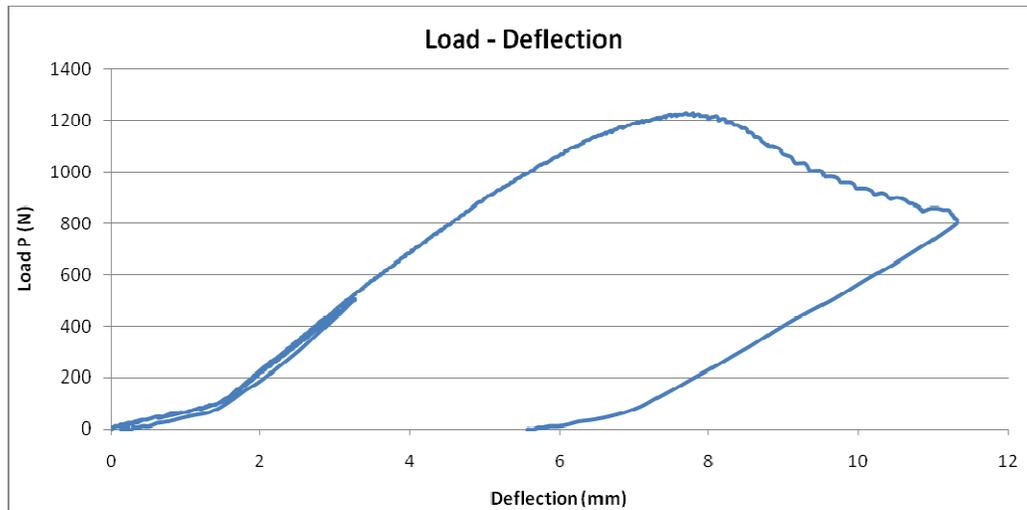
**Table 11: Test results for Configuration 1**

	Load P (N)
<b>Test 1</b>	1230.2
<b>Test 2</b>	1189.0
<b>Test 3</b>	1189.0
<b>Test 4</b>	1177.2
<b>Test 5</b>	1189.0
<b>Ave</b>	1194.9

It can be concluded that the Craft-Lock sheet can resist an average of 1195N before buckling locally and thereby undergoing plastic deformation.

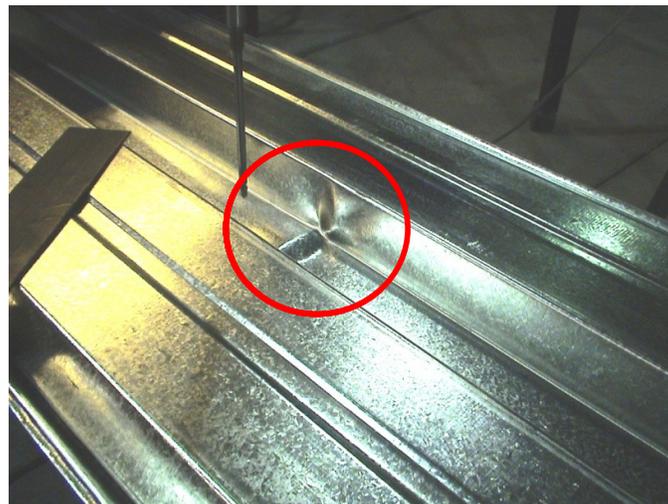
Figure 49 below shows a graph that plots the relationship between deflection measured at the point of load application (midspan at the central rib) and the applied load ( $P$ ) for one of the five tests. As described in Section 5.6.1, the load was increased to 500N and then fully removed. The load was subsequently increased until ultimate failure was reached, as shown in Figure 49. Failure occurred at a recorded load of 1230N, upon which the load is fully removed to record

a permanent set of approximately 6mm. The permanent set is measured using an LVDT (refer to Section 5.7.3) at the point where maximum deflection is expected according to elastic beam theory for the single span schematization under consideration as discussed. As demonstrated in Figure 49, there is no plastic deformation measurable for the pre-loading phase of 500N.



**Figure 49: Load - Deflection for Configuration 1**

Figure 50 below shows the test specimen after it has buckled locally, and plastic deformation is observed at a concentrated load of 1230N. Note that the Craft-Lock sheet is turned upside down, with the crest facing downwards toward the load actuator.



**Figure 50: Local buckling failure in the crest of the sheeting profile due to a concentrated load**

After the sheet has buckled locally, it can not sustain any further loads as illustrated in Figure 49. Therefore, it is considered to have failed in the Ultimate Limit State (ULS).

## 7.2 Configuration 2: Positive bending moment at midspan and bending stiffness

Configuration 2 is used to determine the resistance that the sheeting system has against bending at midspan. As discussed in Sections 5.4.2.1 and 5.4.4, Configuration 2 consists of a single span sheeting system and is loaded by a uniform load to simulate wind uplift. Failure, according to Section 6.2.2 is to be considered as soon as global buckling and permanent deformations of the sheeting can be observed.

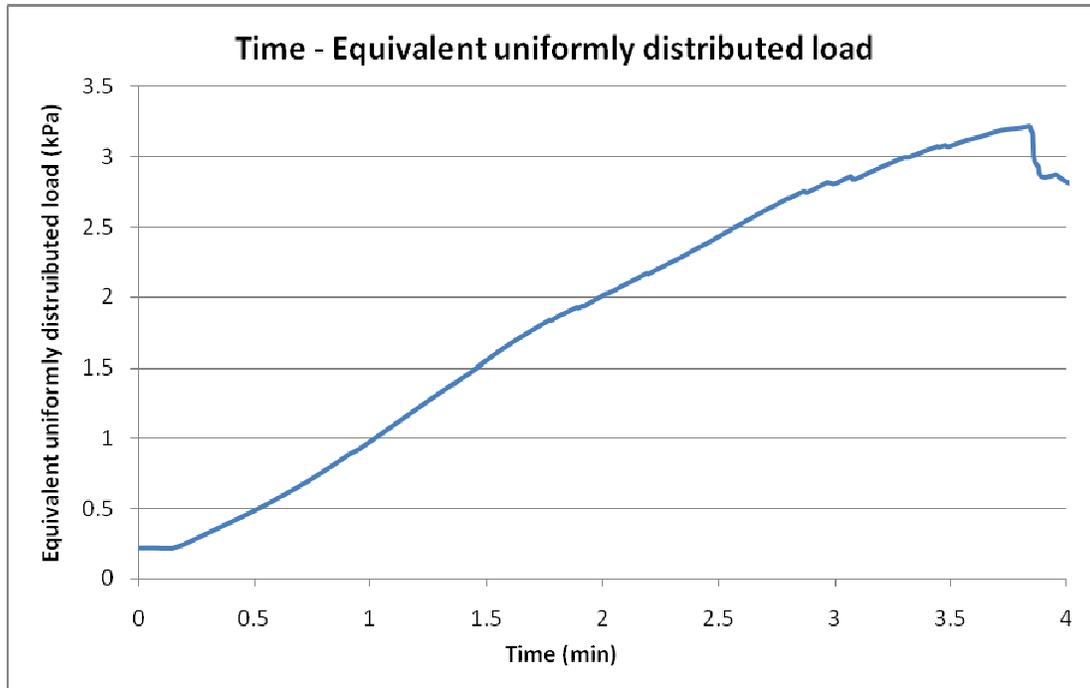
Table 12 below summarizes the test results for each of the five tests. The uniformly distributed load ( $w$ ) listed in Table 12 caused ultimate failure. Table 12 furthermore lists the stiffness of the sheeting system.

**Table 12: Test results for Configuration 2**

Test nr	Equivalent uniformly distributed load $w$ (kPa)	Stiffness $EI$ $10^9$ (Nmm <sup>2</sup> )
1	3.22	9.015
2	3.15	9.445
3	3.15	8.610
4	3.22	9.344
5	3.21	9.040
<b>Avg</b>	3.19	9.091

### 7.2.1 Bending at midspan

According to the results listed in Table 12, it can be concluded that the Craft-Lock roof covering system can resist an average UDL of 3.19kPa before buckling globally at midspan and thereby undergoing plastic deformation. The values of the UDL  $w$  listed in Table 12 are obtained by a graph that plots the relationship between Time and the Equivalent UDL as shown in Figure 51 below. Note, that the equivalent UDL  $w$  is calculated by dividing the sum of the reactions by the total projected area subjected to loading (refer to Section 6.3.2).



**Figure 51: Time - Load graph indicating failure for Configuration 2**

Global buckling of the sheeting system causes permanent deformation or yielding of the material. Yielding results in the loss of resistance to loading which is clearly shown Figure 51. Failure in the sheeting system occurs at an equivalent UDL of 3.22kPa, as indicated by the sudden decrease in the uniform load. Local buckling occurs in the valleys (compression elements) of the sheeting system as indicated by slight irregularities in the graph at an approximate uniform load of 3kPa. These irregularities are the first signs of local buckling failure that initiate local plastic deformation. Ultimate failure is however only considered when the sheeting system undergoes global buckling. Global buckling is illustrated in Figure 52 and Figure 53 below.



**Figure 52: Failure due to global buckling in the sheeting system for Configuration 2**



**Figure 53: Failure due to global buckling in the sheeting system for Configuration 2**

After the sheet has buckled, it can not sustain any further loads as illustrated in Figure 51. Therefore, it is considered to have failed in the Ultimate Limit State (ULS).

### 7.2.2 Bending stiffness

The average flexural bending stiffness that the sheeting system has is  $9.1 \times 10^9$  Nmm<sup>2</sup> as shown in Table 12. The bending stiffness is calculated using the deflections that are measured while the test specimen is loaded in its elastic range. As previously mentioned, the deflection of the sheeting system is measured at the point where maximum deflection is expected. The bending stiffness ( $EI$ ) is calculated using the equation detailed in Section 6.3.3.

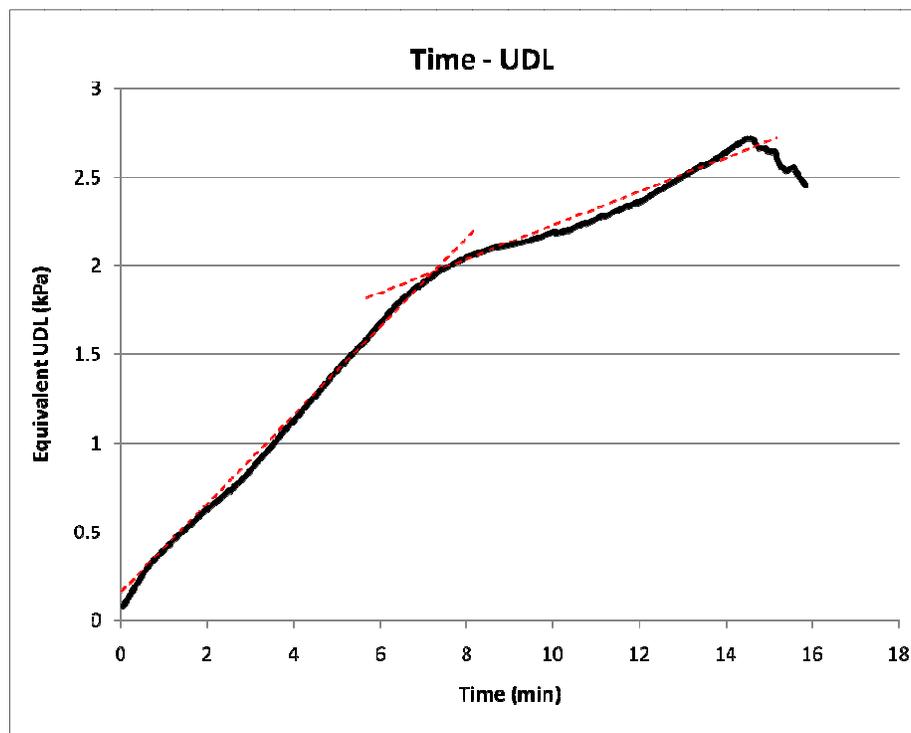
## 7.3 Configuration 3: Bending moment at an internal support

Configuration 3 is used to determine the resistance that the sheeting system has against bending at an internal support. As discussed in Section 5.4.2.2, Configuration 3 consists of a long double span sheeting system and is loaded by a uniform load to simulate wind uplift. Failure, according to Section 6.2.3 is to be considered as soon as the male lip has buckled locally and caused yielding of the material. The plastically deformed male lip causes the female

lip to open up to such an extent that it is incapable of returning to its original state upon removal of the load.

To determine failure, the recorded data is used and analysed. When the female lip opens up, the sheeting displaces away from the purlin support by revealing the opening. The opening therefore causes the pressure in the airbags to reduce because of the increase in volume under the sheeting. At a constant rate of inflation, the equivalent UDL that is applied to the test specimen is expected to decrease.

A graph that computes the rate of increase of the applied UDL is shown in Figure 54. Two distinct gradients are observed for a constant inflation rate. The point where the two gradients dissect is considered the point where the male lip buckles locally, causing plastic deformation and yielding and thereby failure.



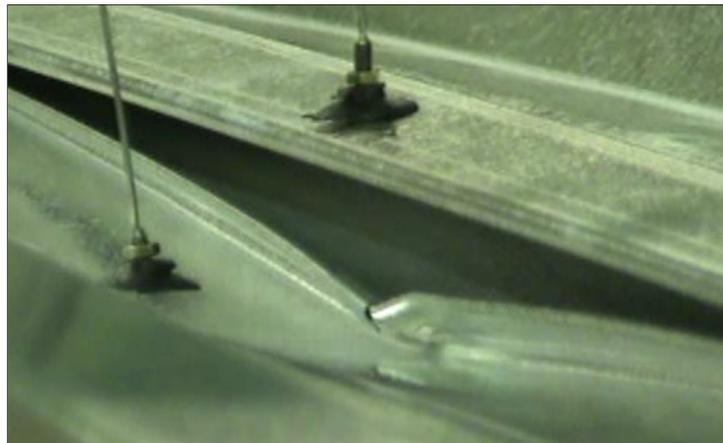
**Figure 54: Time - UDL**

At the inflection point in Figure 54, the sheeting system buckles and thereby reveals an opening large enough to be certain that the sheeting system will not return to its original normal closed state. The local buckling of the male lip is indicated in Figure 55 and Figure 56 below.



**Figure 55: Local buckling at the fastening point indicated in red**

*Note: the local buckling in the valleys of the sheeting in Figure 55 are a result of high compressive stresses and are found to be in the elastic range. They are not visible once the load is removed. This phenomenon is known as oil-canning.*



**Figure 56: Local buckling of male lip at the cleat**

The equivalent UDL ( $w$ ) that causes failure in bending at an internal support is detailed in Table 13 below. This load is the inflection point indicated in red in Figure 54.

**Table 13: Test results for Configuration 3**

Test nr	w (kPa)
1	1.95
2	1.93
3	1.97
4	1.91
5	1.97
<b>Avg</b>	1.94

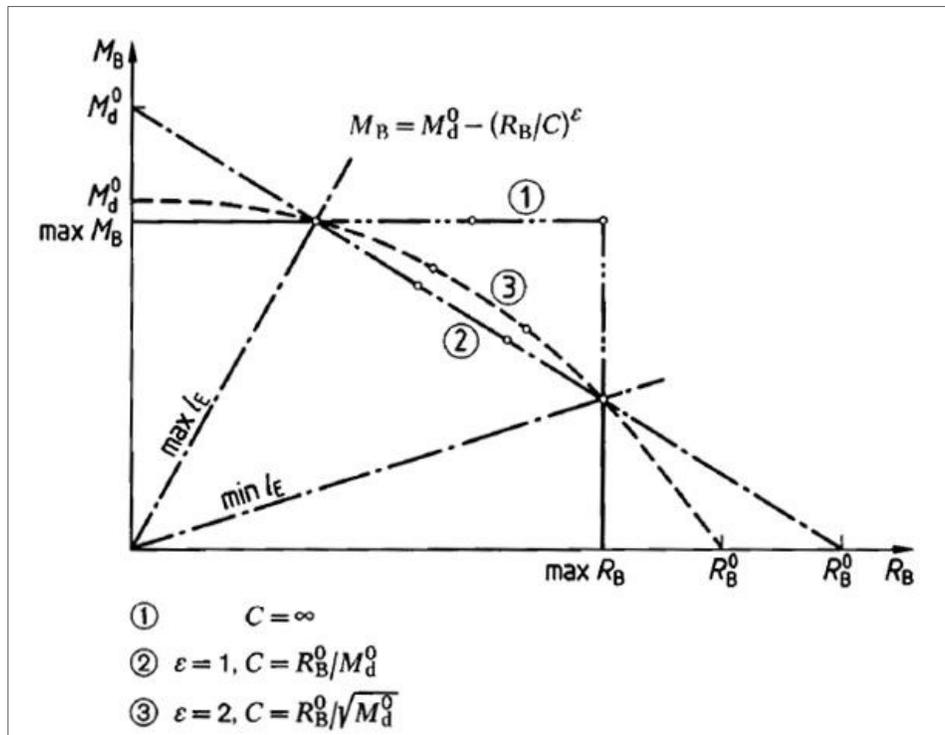
It can be concluded that the values listed as failure in Table 13 above are the loads that cause local buckling. However, it is unclear if the female lip is able to return to its initial unloaded state upon removal of the load once local buckling has occurred. To be certain an iterative loading approach is required. The specimen should have been loaded and unloaded increasing the applied load iteratively until it can be observed that the female lip does in fact not return to its closed state. Therefore, the values listed as failure in Table 13 introduce some degree of uncertainty. Alternative methods of determining the point of failure in bending were therefore considered.

The German code of practice *DIN 18807.2* (DIN 18807-2, 1987) defines failure in bending at an internal support by the use of an interaction diagram. The claim is that the bending capacity of the sheeting at an internal support depends on the magnitude of the reaction of the internal support. An interaction can be computed between the bending moment and the reaction at the internal purlin to obtain the resisting capacity of the sheeting system in bending. More detail is discussed in the next section and the results of the German standard are compared to the values listed in Table 13.

### **7.3.1 Failure according to *DIN 18807.2***

The *DIN 18807.2* (DIN 18807-2, 1987) details specifications to test the capacity of covering systems in the form of sheeting. Amongst others, as discussed in Section 3.2, guidelines are listed on the analysis of the recorded test data. An interaction diagram that computes the relationship between the reaction and the bending moment at the internal support of a multi-span continuous sheeting set-up is discussed. Using the interaction diagram and the principles it relies on, a corresponding bending moment can be calculated for every reaction measured.

For a double span continuous sheeting set-up as for Configuration 3, it can be considered that the reaction at Support B acts as a point load applied to the sheeting system. The resistance of the sheeting at B ultimately depends on the magnitude of the reaction force as well as the magnitude of the bending moment applied. There is an interaction between the reaction ( $R_B$ ) and the bending moment ( $M_B$ ) at point B of the set-up. The *DIN 18807.2* considers the interaction according to the graph shown in Figure 57 below.



**Figure 57: Interaction between  $M_B$  and  $R_B$  in *DIN 18807-2* (Bild 12.) (DIN 18807-2, 1987)**

The graph curves 1 and 3 are not used for the purpose of this discussion. Considering the straight line (shown as 2 in Figure 57 above), the line plots the relationship between the bending moment ( $M_B$ ) and the reaction ( $R_B$ ) by the equation shown below:

$$M_B = - \left( \frac{M_d^0}{R_B^0} \right) R_B + M_d^0 \tag{Eq.: 5}$$

The value of the two parameters that define the gradient of the interaction between the bending moment ( $M_B$ ) and the reaction at B ( $R_B$ ) are:

$M_d^0$  the bending moment of the sheeting system if there is no reaction force

$R_B^0$  the reaction force of the sheeting if there is no bending moment

When the above two parameters are defined, the relationship between the bending moment and the reaction force at an internal support can be computed using Equation 1 from above.

The bending moment capacity of the sheeting system of a double span continuous sheeting set-up where the reaction of Support B is zero is:

$$M_d^0 = \frac{\sigma I}{y} \quad \text{Eq.: 6}$$

where  $\sigma$  the yield stress of the material

$I$  the effective moment of inertia of the section of the profile

$y$  the distance from the neutral axis of the section of the sheeting profile to the crest of the sheeting

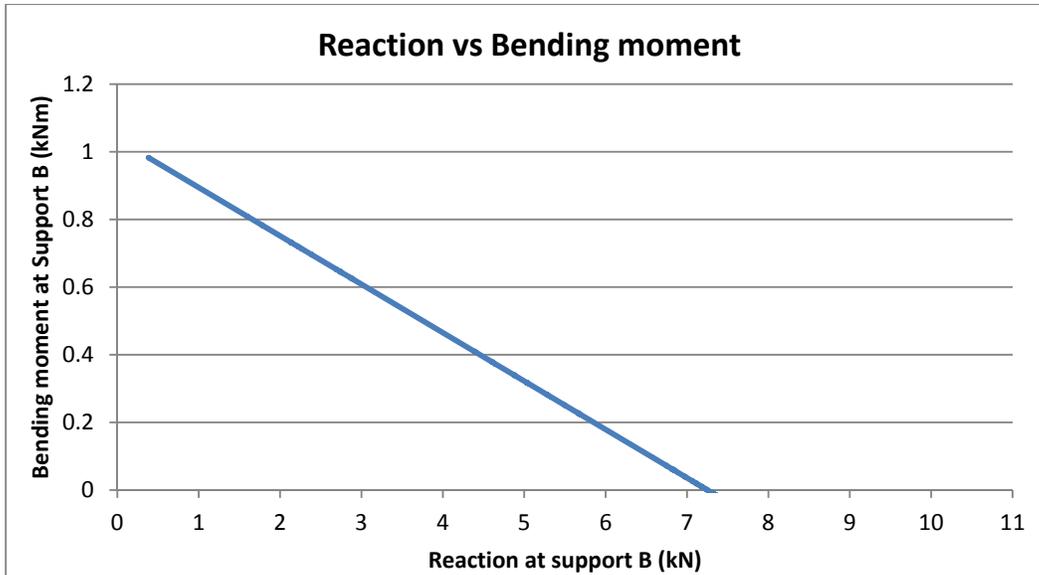
Note that this computes the bending resistance where the crests of the sheeting are in compression. Refer to Equation 2 as discussed in Section 5.2.1.2 for resistance of sheeting systems in bending.

To obtain the boundary value of the maximum reaction ( $R_B^0$ ), where there is no applied bending moment at B, the carrying capacity of the fastening system is used. The test results for the fastening system are discussed in the Section 7.4 to follow.

Populating Eq.:5, leads to Eq.: 7:

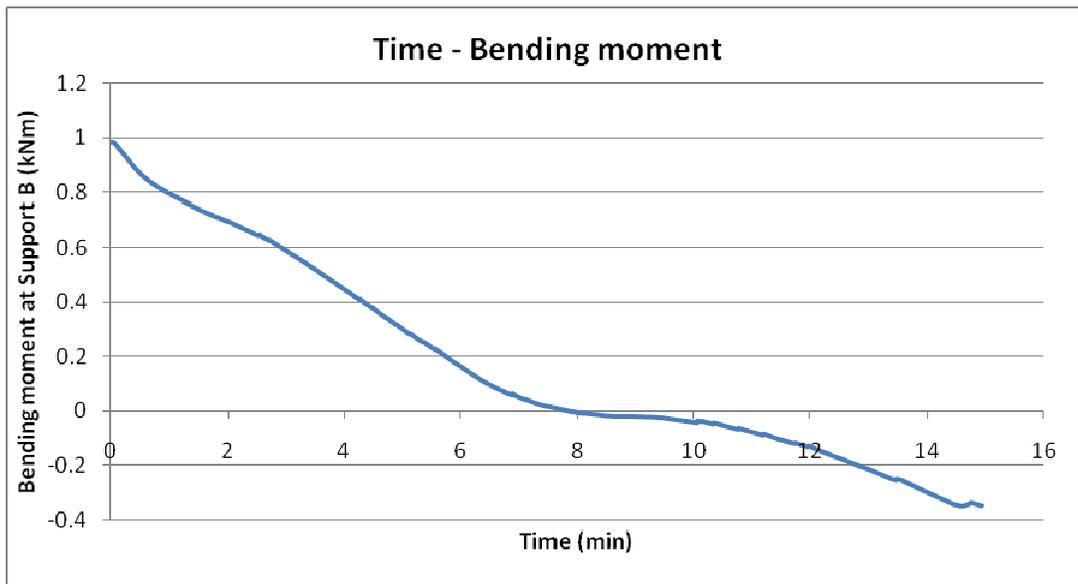
$$M_B = (-0.143)R_B + 1.04 \quad \text{Eq.: 7}$$

For each reaction measured the corresponding bending moment is calculated. The graph Figure 58 below shows the interaction between the  $M_B$  and  $R_B$  as determined using the guidelines in *DIN 18807.2* as described above.



**Figure 58: Interaction between  $M_B$  and  $R_B$**

For comparison purposes, the bending moment can be calculated from the measured reaction force using Equation 7 and plotted on the same time scale as used in Figure 54.



**Figure 59: Time - Bending moment at the internal support**

The point where  $M=0$ , where there is no bending moment resistance, occurs at a testing time of 7.8min. At 7.8min the equivalent UDL was 2.02kPa. According to Table 13, the average UDL that caused failure is 1.94kPa, as discussed in the previous section. The interaction diagram as specified in the German *DIN 18807.2* therefore confirms that if the point of inflection is used to determine failure in Figure 54 a viable failure definition is obtained.

The principle of interaction is applied using the test data of Configuration 2 and Configuration 4 for the two constants  $M_d^0$  and  $R_B^0$  respectively. The outcome of the interaction is therefore biased by the test results of other experimental test set-up configurations. A third concept is considered to be used to determine the UDL that causes failure in bending at the internal support. The concept relies on the fact that once the sheeting system has buckled, forming a plastic hinge at the internal support, the reactions and moments are being redistributed accordingly. More on this follows in the next section.

### 7.3.2 Failure according to reaction redistribution

Theoretical models can predict all reactions that result from the loads that are being applied on a structure. Theoretical models, however, initially rely on elastic behaviour. As soon as plastic deformation occurs in a structural element, the theoretical predictions are no longer applicable. After plastic deformation has occurred, the initial theoretical reactions are being redistributed. By observing the redistribution of reactions, the point where failure in bending i.e. local buckling has occurred can therefore be determined.

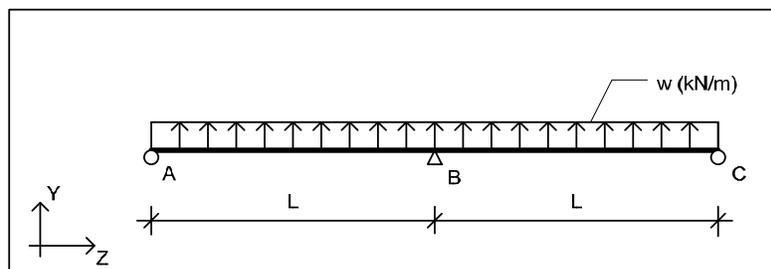
Assuming free rotational supports A, B and C, in Figure 60 below, the reactions at A and C can be calculated according to elastic theory by:

$$R_A = R_C = 0.375wL \quad \text{Eq.: 8}$$

where as the reaction at point B is calculated as:

$$R_B = 1.25wL \quad \text{Eq.: 9}$$

for a given UDL ( $w$ ) and a span length ( $L$ ).



**Figure 60: Theoretical schematization of long double span configuration**

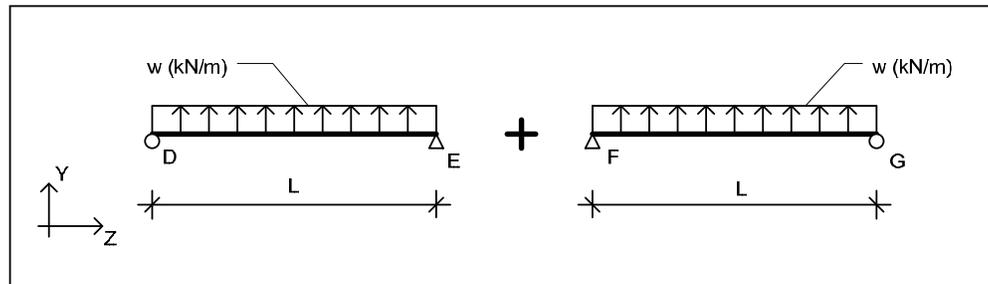
When buckling occurs, the material is forced to yield and deform plastically. The bending stiffness at the central support (B) is lost. As a result of the loss in stiffness the reactions of the supports A, B and C are redistributed to form the two equivalent simply supported

configurations as shown in Figure 61 below. The reactions at D and E (or F and G) can be calculated as:

$$R_A = R_C = 0.5wL \quad \text{Eq.: 9}$$

whereas the reaction at point B is calculated as:

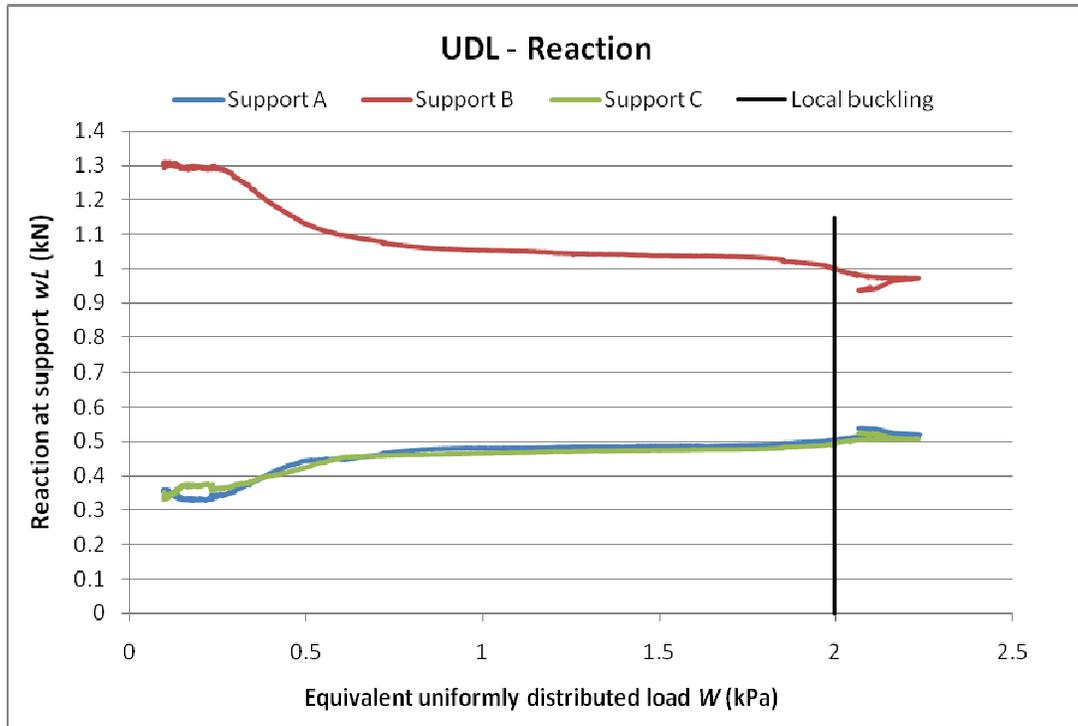
$$R_B = 1.0wL \quad \text{Eq.: 10}$$



**Figure 61: Theoretical schematization of two simply supported configurations**

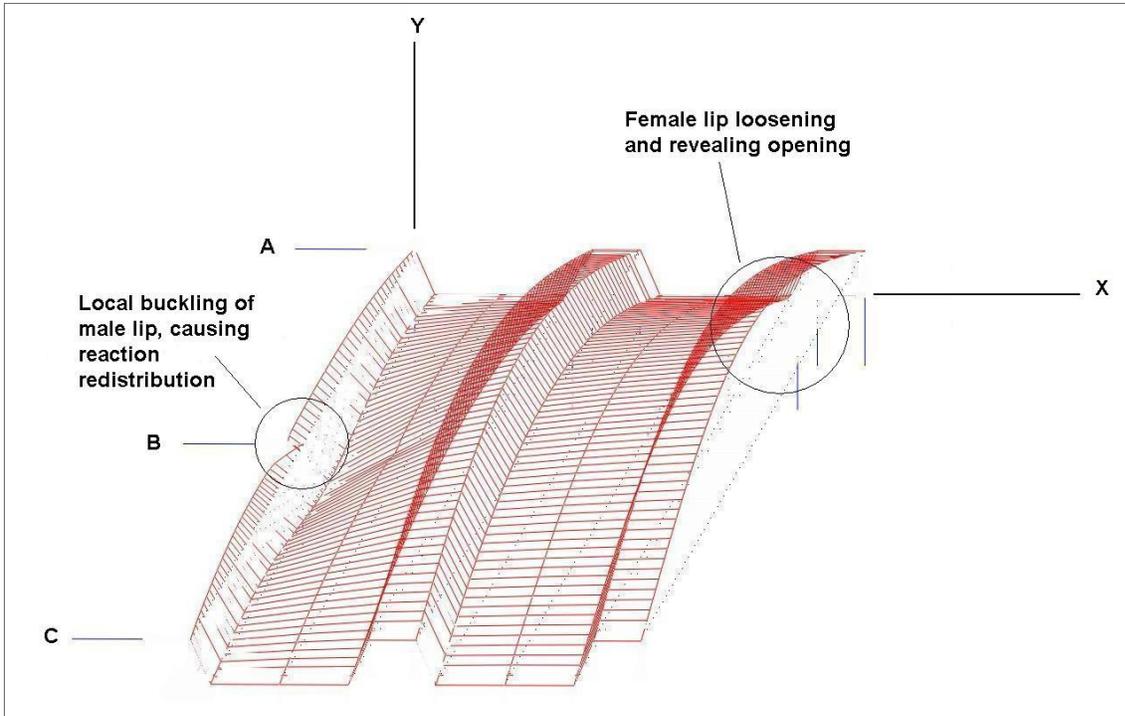
In other words, as the loading is increased the reaction at A ( $0.375wL$ ) in Figure 60, is redistributed to the reaction at D ( $0.5wL$ ) in Figure 61, as soon as the sheeting fails in bending due to buckling and deforms permanently. Consequently, the reaction at B ( $1.25wL$ ) is redistributed to both the reactions E and F ( $0.5wL + 0.5wL = 1.0wL$ ). This reaction redistribution between the elastic and buckled configuration (Figure 60 and Figure 61 respectively) is measured in the experimental test set-up and is used to determine when there is failure in the form of buckling due to negative bending moment at Support B.

The graph in Figure 62 below shows the relationship between the applied equivalent UDL and the reaction ratios of the double span set-up. As shown, the reactions are initially  $0.375 : 1.25 : 0.375$  as theoretically predicted and then redistributed toward  $0.5 : 1.0 : 0.5$  for the supports A:B:C respectively. The point where local buckling occurs, coincides with the point where the reaction of the internal Support B is redistributed to values of lower than  $1.0wL$  as indicated by the black line in Figure 62 below.



**Figure 62: Reaction redistribution for the supports A, B and C**

According to theory, as discussed above and illustrated in Figure 60 and Figure 61, it is practically not possible for the reaction at Support B to decrease below the value of  $1.0wL$  assuming that all support conditions at A, B and C allow a free rotation. To explain why the redistribution below  $1.0wL$  was in fact recorded, the stressed behaviour of the Craft-Lock cladding system is considered. There are two reasons explaining the redistribution shown in Figure 62. The first, and the most obvious is local buckling occurring in the sheeting and forming a plastic hinge at the internal support. However, to form a fully developed plastic hinge at Support B, the sheeting system is required to buckle globally. Local buckling would therefore only contribute to part of the redistribution. The fact that the female lip of the sheeting loses its grip after buckling has occurred, explains that the reactions are redistributed as shown in Figure 62. Figure 63 below illustrates the effect of the loosening female lip on the redistribution of reactions.



**Figure 63: Deformed single metal sheet**

Figure 63 shows the extreme deformed state of a single sheet with supports at A, B and C and principle axes X and Y. As shown, the female lip loosens from the male lip to reveal an opening. This means that on the opened end the sheet has lost the contact to Support B. The reactions measured at Support B before the loosening of the female lip, are now redistributed to the Supports A and C. In other words the initial theoretical distribution of 0.375 : 1.25 : 0.375 is redistributed to 1.0 : 0 : 1.0 once female lip openings are introduced. In other words, each single sheet within the cladding system finds itself subjected to the reaction redistribution combination of the following:

$$\begin{aligned} \text{Male end: } R_A &= 0.5wL \\ R_B &= 1.0wL \\ R_C &= 0.5wL, \end{aligned}$$

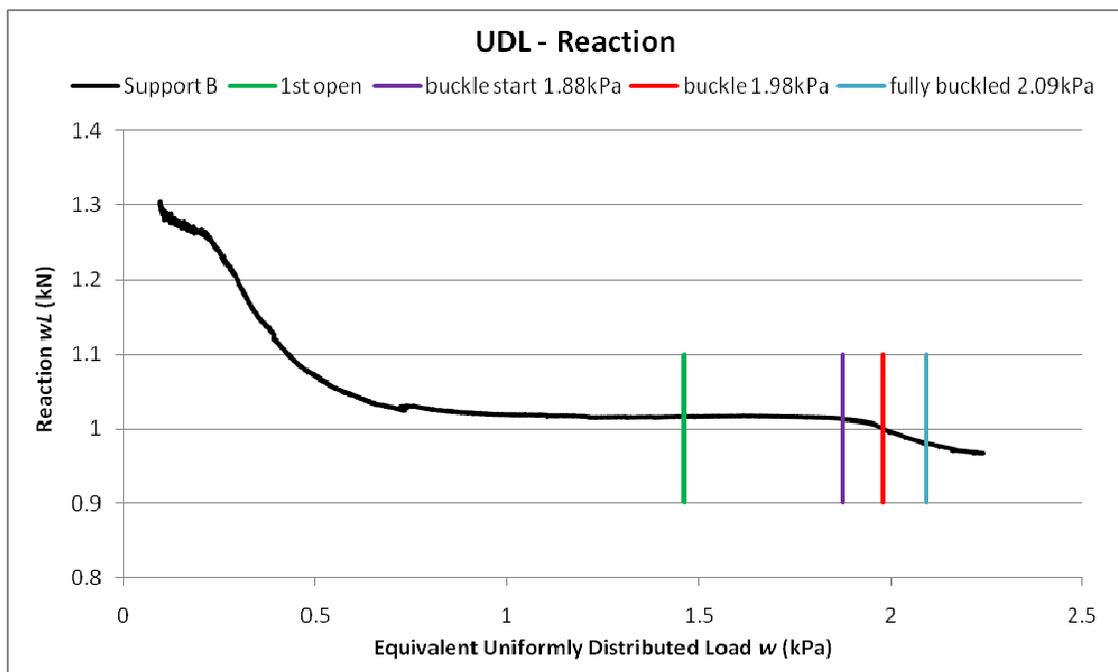
which are the result of buckling and plastic deformation in the male lip of each sheet.

$$\begin{aligned} \text{Female end: } R_A &= 1.0wL \\ R_B &= 0 \\ R_C &= 1.0wL \end{aligned}$$

which are the result of the opening created by the female lip losing its grip and contact to the internal support (B). Refer to Figure 40 as a reference on the male and female end, which

correspond to male and female lip respectively. Depending on the weighted contribution of either of the of the above mentioned reactions (at the male and female end), the redistribution of the reactions at the supports that progress beyond the 0.5 and 1.0 limits, as shown in Figure 62, can thereby be explained.

Figure 64 below shows a graph of the reaction redistribution of the internal Support B. Detailed analysis showed that the average UDL where the sheeting system buckles locally at the male lip was 1.98kPa, which is when the reaction at Support B is redistributed below 1.0  $wL$  as indicated in red in Figure 64 below.

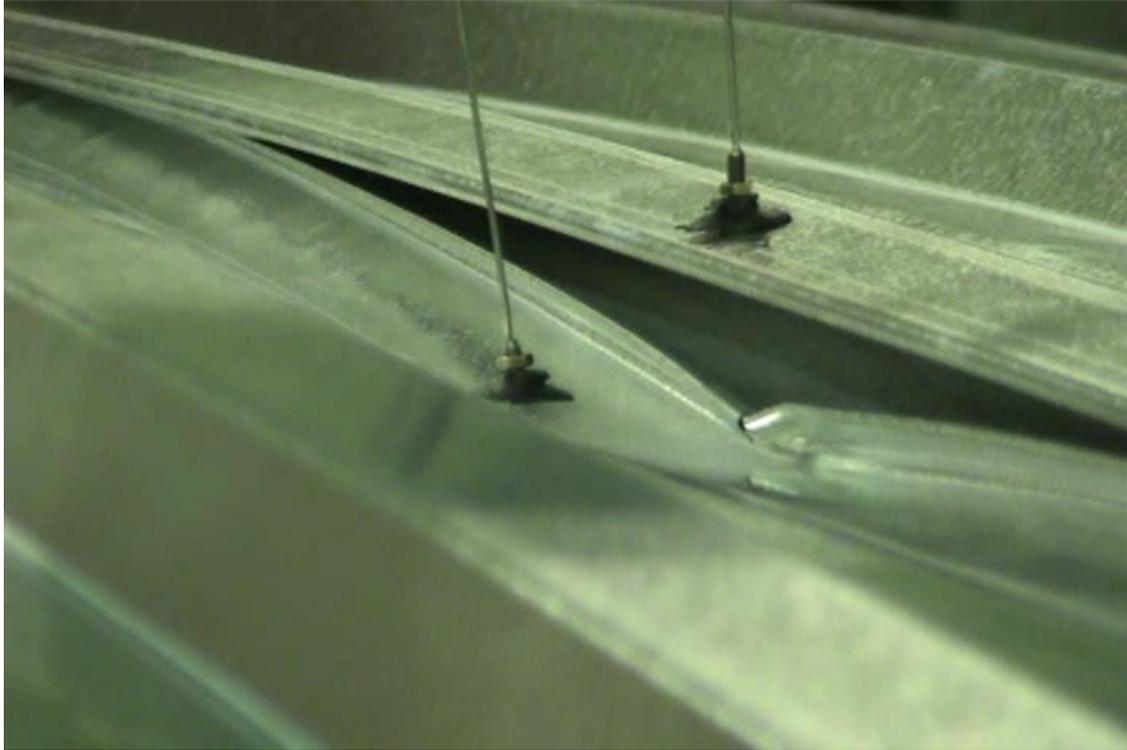


**Figure 64: Failure according to the redistribution of reactions as measured at the internal Support B**

The green line denotes the point where the female lip is starting to slip out by loosening its grip to the male lip. The purple line denotes the equivalent UDL causing the first signs of local buckling as shown in Figure 65 below, and the blue line is represents the point when the male lip has buckled locally as shown in Figure 66.



**Figure 65: Local buckling in the male lip of the Craft-Lock sheeting system starting to occur at 1.88kPa (refer to Figure 63)**



**Figure 66: Local buckling in the male lip of the Craft-Lock sheeting system has occurred at 2.09kPa (as in Figure 64)**

It can be concluded that by observing the redistribution of reactions, measured in Configuration 3 of the experimental test set-up, proved a reliable comparison to the failure criteria discussed in previous to Sections 7.3.1 and 7.3.2.

### 7.3.3 Summary

Three different concepts to determine the UDL that causes failure in bending at an internal support of the Craft-Lock sheeting system were discussed. All three concept converge to an average of 2.0kPa as the equivalent UDL.

The Craft-Lock roof covering system is found to be very vulnerable in the resistance to a bending moment at an internal support comparing it to the carrying capacities of bending moment at midspan. The low bending capacity can be explained by the fact that the internal support at point B (with reference to Figure 34) is subjected to the point of highest reaction as well as the highest bending moment in the structural system. The combination of moment and the applied concentrated load of the support causes local buckling in the early loading stage and thereby plastic deformation. The method of fastening Craft-Lock sheeting is in specific very

vulnerable to early local buckling since it causes an opening to be revealed which initiates early serviceability problems. This problem can be strengthened and provided for by simple methods, yet these are not discussed herein.

#### **7.4 Configuration 4: Capacity of the fastening system**

Configuration 4 is used to determine the resistance that the fastening system has against an UDL. As discussed in Section 5.4.3, Configuration 4 consists of a short double span sheeting system and is loaded by a uniform load to simulate wind uplift. Failure, according to Section 6.2.4 is to be considered as soon as once any of the sheets lost its fastened state.

The fastening system consists of a number of components. As described in Section 5.5.2, each sheet has a female and a male lip on either end (Figure 40). These are locked into one another to form an interlocking seam (Figure 42). The interlocking seam forms part of the fastening system, because when the grip between the male and female lip is lost over the whole length of the seam, the sheet has no halt anymore and therefore can no longer function as a weather-tight cover. The sheeting is fixed to purlin supports by the use of fastening brackets, or cleats (Figure 41). If the cleat fails to hold down any of the sheets, failure is reached. The cleat is fixed to the supporting structure by means of M6 bolts. The failure of the bolt is also considered fastening system failure.

Failure of the Craft-Lock cladding system, set up in Configuration 4, was observed in the fastening bracket. The cleat is subjected to tensile forces causing tear-out as illustrated in Figure 67 below. When tear-out was not observed, the fastening bracket failed by bending open as in illustrated in Figure 68 below.



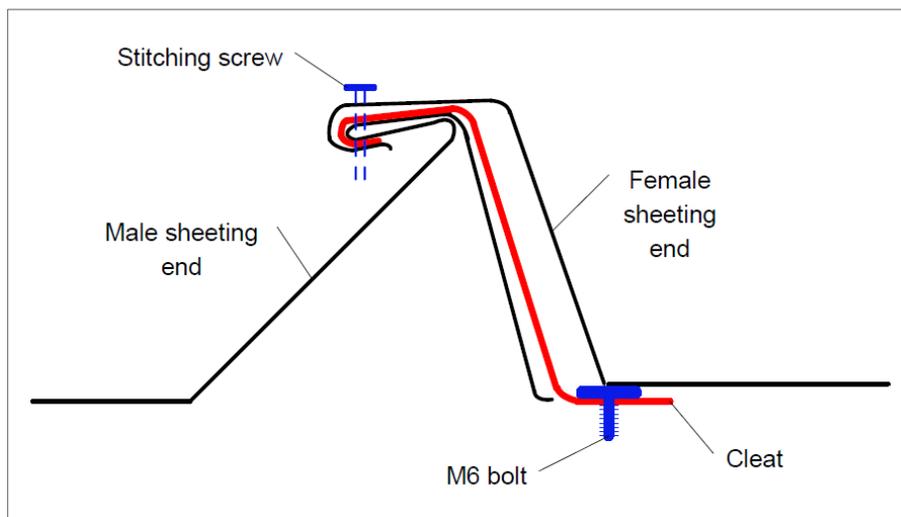
**Figure 67: Fastening system failure due to tear-out**



**Figure 68: Fastening system failure due to cleat bending open**

As mentioned in Section 6, five sets of Craft-Lock sheeting systems are tested to obtain reasonable repeatability of the measured results. For the first three of the total of five tests performed a failure in the form of bending of the sheeting system at the internal support was

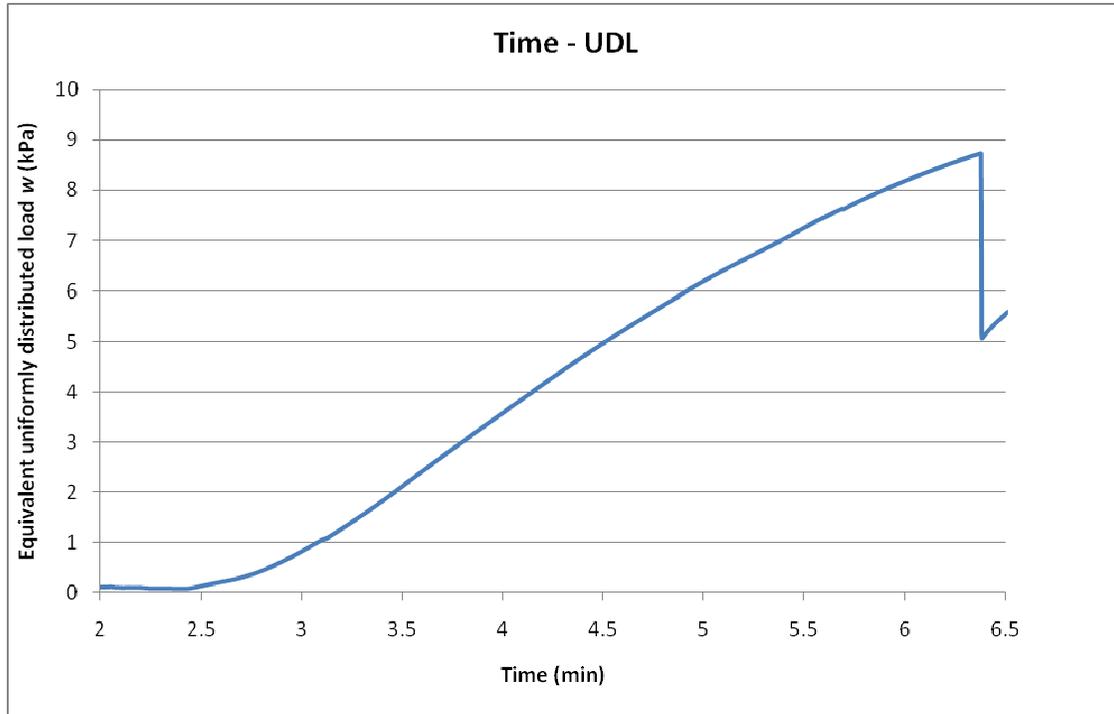
observed. The failure was distinguished by the female lip loosening its grip on the male lip at the interlocking seam (refer to Configuration 3 where failure was distinguished in bending at an internal support as discussed in Section 7.3). Since Configuration 4 intends to test the capacity of the fastening system, the sheeting system was strengthened for the remaining two tests in order to promote failure in the fastening system. To prevent the female lip of opening up by releasing its grip to the male lip, the female lip was fastened to the male lip of the sheeting at the interlocking seam by means of a self-tapping screw (stitching screw). This procedure is referred to as stitching. Refer to Figure 69 below for a clearer understanding of stitching. The self-tapping screw is indicated in blue, fixing the overlying female lip to the male lip. Note that the stitching screw was not fixed through the cleat. In plan, the screw was inserted just next to the cleat.



**Figure 69: Stitching of interlocking seam**

Stitching is an accepted strengthening method. The roof set-up is not considered positively fixed, since the stitching does not introduce perforations in the cladding that allow an opening to the interior of the structure. Also, if the stitching screw is not drilled through the fastening bracket, membrane action is not enhanced which would strengthen the whole cladding system against loading. Expansions or contractions in the sheeting material, due to high temperature fluctuations, are not limited by stitching.

After the sheeting profile was strengthened, to prevent failure in bending, failure in the fastening system was observed. Figure 70 below shows the point of failure of the fastening system, after the sheeting was strengthened by means of stitching, as described.



**Figure 70: Time – UDL indicates failure of the fastening system**

The results for testing the carrying capacity of the fastening system are detailed in Table 14 below.

**Table 14: Failure loads of the fastening system capacity**

Test nr	Wind load
	$w_L$ (kPa)
4	7.98
5	8.69
<b>Avg</b>	8.33

The average load  $w_L = 8.33$  kPa was taken as the maximum equivalent UDL that the fastening system is able to withstand. If the fastening system has failed, the roof structure can not sustain any further wind loads, therefore the cladding system is considered to have failed in the ULS.

## 7.5 Summary

The test results of the experimental test set-up are summarized and discussed. Failure was determined as described in Section 6.2. Considering the data and results available, after all tests have been performed, a set of tables can be drawn up for the purpose of designing roof coverings safely. These tables provide the engineer with structural design parameters which

can be used to design any conventional roof structure that is within the applicable scope of the roofing system under investigation.

Appendix B discusses the detailed proceedings how the test results can be used to develop the structural design parameters and ultimately the design tables.

## 8. Conclusion

Roof coverings in the form of sheeting are subjected to extreme wind actions, which contribute to the most critical loadings combination for roof structures. The design of roof sheeting against wind actions, in South Africa, is however typically neglected or very often implemented only vaguely and as a result of that also not always safe. One of the reasons of the improper designs is that engineers do not have the appropriate design parameters available. Most cladding systems companies in the industry provide a simple design table for their respective products that only details the maximum allowable span length, or the purlin/support spacing for the sheeting system. The spacings are however listed irrespective of any Uniformly Distributed Load (UDL) that the covering needs to resist. How the design tables are produced is typically unknown to the design engineer. To determine the carrying capacity of any cladding system, experimental tests need to be done on the cladding structure.

### 8.1 Experimental testing

In this study the experimental test set-ups that are used in the industry were reviewed, and ample room for improvement was identified. The testing schemes described in the literature consisted of a multi-spanned configuration with fixed span lengths and made use of sandbags as a load actuator. Sandbags were found to be a very simple and straightforward loading means. However, the relatively large load increments and the sequence of the exact position the sandbags are applied appeared to be a problem that needed improvement. The traditional testing scheme described is useful when testing if a certain configuration, with fixed span lengths and a specific layout, holds a predetermined load. However, a more comprehensive testing scheme was required for the development of a generic design table. The design table would consist of the two major variables that determine the carrying capacity of any roof covering system i.e. the UDL ( $w$ ) and the span length ( $L$ ).

To generate a new generation design table, a new experimental test set-up was developed that allows the experimental testing of the structural design parameters of sheeting systems. The parameters are used to determine the carrying capacity of roof structures against UDL's by analytical design calculations as proposed in Appendix B. The new experimental test set-up that was used consists of several configurations, each to determine a respective structural design parameter. Also, the means of simulating a wind uplifting load, previously by using

sandbags, was improved by using airbags that were introduced in the testing scheme. The new experimental test set-up produced superior results as compared to the previous testing techniques and is discussed next.

## 8.2 Experimental conclusions

The loading system that was used was found very accurate as compared to previous testing attempts using sandbags. The airbags can inflate uniformly, applying an evenly distributed load to all sheeting elements and adjacent spans simultaneously. Simultaneous inflation i.e. load application was monitored by the electronic measurement of the air pressure within the airbags.

The pressure measurement equipment that was installed proved very sensitive to the slightest volume changes of the airbags. The high sensitivity allows a detailed observation of events of distortions and deflections within the loaded test specimen. The stressed state, of the test specimen, at failure can be closely monitored by analyzing the post-testing data, since any cladding distortions caused noticeable changes in the recorded data. The observation of the respective mode of failure was therefore considerably enhanced. In addition, the observation of failure was significantly improved by the fact that the load was applied slowly and evenly with no high loading increments as compared to previously mentioned sandbag loading procedures.

The results produced by the experimental tests were found to be very repeatable. Table 15 below summarizes the experimental test results for all of the four experimental configurations. For recapitulation purposes, the role of each of the four configurations are:

- Configuration 1 is used for testing the resistance to concentrated loads
- Configuration 2 is used for testing the bending moment at midspan ( $M_{A1}$ )
- Configuration 3 is used for testing the bending moment at an internal support ( $M_{A2}$ )
- Configuration 3 is used for testing the capacity of the fastening system

The standard deviation is computed and expressed as a percentage of the calculated mean of the measured values. With the exception of Configuration 4, all measured results are

repeatable within 5%, which is considered a significant improvement compared to previous testing attempts.

**Table 15: Overall summary of test results**

	Configuration 1	Configuration 2		Configuration 3	Configuration 4
Test nr	Concentrated load P (N)	UDL w (kPa)	Stiffness $EI \cdot 10^9$ (Nmm <sup>2</sup> )	UDL w (kPa)	UDL w (kPa)
Test 1	1230.2	3.22	9.02	1.95	-
Test 2	1189.0	3.15	9.45	1.93	-
Test 3	1189.0	3.15	8.61	1.97	-
Test 4	1177.2	3.22	9.34	1.91	7.98
Test 5	1189.0	3.21	9.04	1.97	8.69
Ave	1194.9	3.2	9.1	1.9	8.3
% std dev	1.7	1.1	3.6	1.5	6.0

The airbags do however also introduce some disadvantages for testing. The major weakness of applying the load to the underside of the sheeting system is that the contact area of the load application can not be observed. Most cladding systems are of very thin material and therefore are subjected to extensive deflections between fastening points. It is unclear how effective the shape of the airbags adapts to these deflections, and if possible membrane action is introduced within the airbags.

In addition to the inability to observe the area of load application, the airbags lose their pressure once some type of failure occurred that increased the volume under the test specimen. The airbags are all interconnected via an air duct to assure simultaneous inflation amongst all bags by constantly striving to pressure-equilibrium. In the rare case where a defect within the test specimen causes early and unanticipated failure of some kind that creates the slightest yield of sheeting material, a change in volume beneath the test specimen is created. The increase in volume causes the collective decrease in air pressure in all of the airbags, and thereby a decrease in the rate of the applied loading.

To evaluate the test results of the testing scheme proposed and developed in this project, it is crucial that the rate of loading remains constant because for most graphs that were used to determine failure, time was used as a variable. The solution to the problem is a more comprehensive deflection measurement, which would allow producing load-deflection curves. Load-deflection curves are independent of the variable Time and thereby also the rate of

loading. The deflections that were measured in the experimental test set-up were only in the near-elastic range of the test specimen. As soon as ultimate failure was about to happen, the deflection measurement apparatus (LVDT's) were removed to prevent damage to the equipment.

### 8.3 Concluding recommendations

The experimental test set-up proved to be a significant improvement to the approaches currently used in the industry. It is capable of testing the carrying capacity of roof covering systems in the form of sheeting and it conforms to all specifications and requirements in the new draft code of practice *SANS 10237* (SANS 10237:201X, 201X) for the testing of sheeting systems.

To complement the results obtained by practical experimental testing, a theoretical approach is suggested to be considered. Theoretical models based on elastic beam theory proved inadequate since the stressed behaviour of sheeting systems can not be modelled by using elastic beam theory. A finite element membrane model would be required which was outside the scope of this study. It is however recommended to investigate the application of a detailed Finite Element Analysis (FEA) to the test results obtained experimentally.

A concise approach to the design of roof structures is required. Engineers need to rethink and consider proper and accurate designs for cladding systems. These can now be correlated with the test results of the experimental test set-up. A new design approach should also allow for optimizing the structure according to the different loading zones on the surface of a building.

It is strongly recommended that future studies investigate the feasibility of the new design approach. This could lead to safer, more conservative and more accurate designs as the previous approaches. This future study should include the combination of different purlin and support layouts, ranging from high to lower loaded zones and their respective contributing area as a percentage of the whole structure.

The new design tables enable a new design approach of roof systems that is recommended to be enforced. Although the new design approach could be more time consuming, it will lead to more reliable structural cladding systems.

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# Appendix A: Wind Load Calculations

## A.1 Wind loads

The worst scenario of a design wind load is calculated. The standard *SANS 10160.3* (SANS 10160-3, 2008) was used to determine the procedures detailed herein. A typical study is done considering the following values and assumptions:

- Maximum basic wind speed of 36m/s
- Terrain category A
- A topography factor  $c_0(z)$ , which is applicable for unusual topographic characters such as hills and cliffs, was used and calculated according to section 6.3.3 in *SANS 10160-3* (SANS 10160-3, 2008). For the consideration of the topography, refer to Annex A.3 where the most extreme case was considered. Figure A.2 and A.3 reveal the factor  $s = 0.7$  for the worst scenario.  $C_0$  is therefore:

$$c_0(z) = 1 + 2s\phi = 1 + s(0.7)(0.3) = 1.42$$

by equation A.2 and choosing  $\phi=0.3$ .

- The highest applicable air density was used to be  $\rho = 1.2\text{kg/m}^3$

### A.1.1 Peak wind speed:

The peak wind speed at a height of  $z$  above the ground is calculated by:

$$v_p(z) = c_r(z) \cdot c_0(z) \cdot v_{b,peak} \quad [SANS10160.3 - \text{Section 6.3.1.1}]$$

where  $v_{b,peak} = 1.4(v_b)$

and the factor  $c_r(z)$  shall be determined by:

$$c_r(z) = 1.36 \cdot \left( \frac{z-z_0}{z_g-z_0} \right)^\alpha \quad [SANS10160.3 - \text{Section 6.3.2.1}]$$

where for Terrain category A:

$$z_g = 250,$$

$$z_0 = 0,$$

$$\alpha = 0.07 \text{ and}$$

$$z = \text{the roof height above the NGL}$$

The peak wind speed has been calculated for two scenarios considering the extreme case of an uphill in the one ( $c_0(z) = 1.42$ ) and a normal topography in the other ( $c_0(z) = 1.0$ ).

**A.1.2 Peak wind speed pressure:**

The peak pressure was calculated using both the normal topographic wind speeds as well as the uphill extremes.

$$q_p(z) = 0.5 \cdot \rho \cdot v_p^2 \cdot (z) \quad [\text{SANS10160.3} - \text{Section 6.4}]$$

**A.1.3 Peak wind pressure coefficients:**

Refer to Section 7.3 in *SANS10160.3*.

External pressure coefficient for the walls:

$$c_{pe,max} = +1.0 \text{ from Figure 8 and Table 6.}$$

External pressure coefficient for the roof:

$$\text{Flat roofs: } c_{pe,min} = -1.8 \text{ for sharp eaves (Figure 9 and Table 7)}$$

$$\text{Monopitch: } c_{pe,min} = -2.5 \text{ for the higher end (Figure 10 and Table 8,9)}$$

$$\text{Duo-pitch: } c_{pe,min} = -2.5 \text{ for sagging troughs (Figure 11 and Table 10,11)}$$

$$\text{Hipped: } c_{pe,min} = -1.7 \text{ for the most extreme case (Figure 12 and Table 12)}$$

Internal pressure coefficient for the roof:

$$c_{pi,max} = (0.9) \cdot c_{pe,max} = 0.9 \text{ where } c_{pe} \text{ is the coefficient of the dominant wall.}$$

**A.1.4 Peak wind pressure:**

Finally, the peak wind pressure can be calculated by:

$$w_i = q_p(z) \cdot C_p$$

where  $C_p = c_{pe} + c_{pi}$

A general example was prepared considering a building of ranging height ( $z$ ) between 10 and 100m. The peak wind pressures are listed in Table 16 below. Note, that the pressures do not include partial load factors as specified in *SANS 10160.1* (SANS 10160-1, 2008), but are merely the characteristic maximum wind pressures. The values are obtained using the calculations as discussed in the sections A.1.1 to A.1.4 and based on a 50 year return period.

**Table 16: Characteristic peak wind pressures for a normal topography**

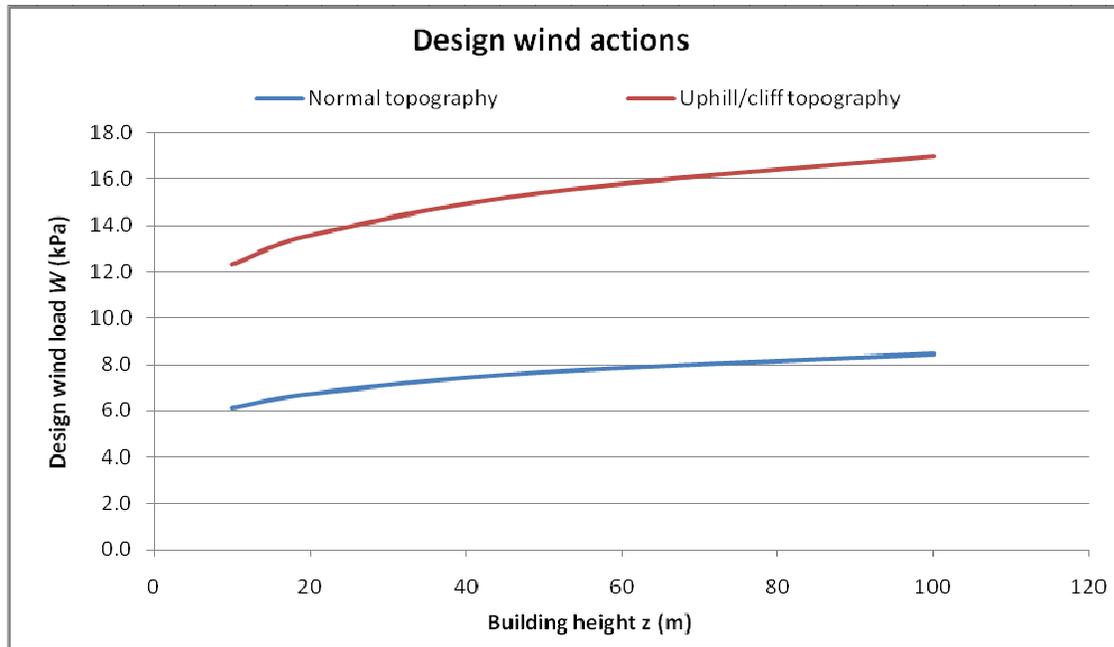
Building height (m)	Roughness factor	Peak wind speed (m/s)	Peak wind speed pressure (kPa)	Wind pressure (kPa)
$z$	$C_r(z)$	$v_p(z)$	$q_p(z)$	$w_i(z)$ in kPa
10	1.1	54.7	1.8	6.1
20	1.1	57.4	2.0	6.7
50	1.2	61.2	2.3	7.7
100	1.3	64.3	2.5	8.4

Table 17 below details the same calculated values for an uphill topography. Wind actions are significantly higher for regions at the edge of a cliff or the tip of a hill. The topography factor  $c_0(z) = 1.42$  was introduced into the calculations as described above.

**Table 17: Characteristic peak wind pressures for an uphill or cliff topography**

Building height (m)	Roughness factor	Peak wind speed (m/s)	Peak wind speed pressure (kPa)	Wind pressure (kPa)
$z$	$C_r(z)$	$v_p(z)$	$q_p(z)$	$w_i(z)$ in kPa
10	1.1	77.7	3.6	12.3
20	1.1	81.6	4.0	13.6
50	1.2	87.0	4.5	15.4
100	1.3	91.3	5.0	17.0

Figure 71 below shows the distribution of the peak wind pressures for the calculated values listed in Table 16 and Table 17.



**Figure 71: Increase of peak wind pressure over increasing building height**

## Appendix B: Design sheet for Craft-Lock

### B.1 Reference

From the results discussed in Section 7, it is possible to calculate design parameters that can be used for the set-up of a design sheet for 0.58mm Z275 Craft-Lock from Clotan Steel Pty (Ltd).

**Error! Reference source not found. Error! Reference source not found.** details the calculated average of the maximum UDL each of the configurations were able to withstand.

**Table 18: Summary of Test results**

Configuration		Symbol		Unit
1	Concentrated load	P	1195	N
2	Bending at midspan	$M_1$	3.19	kPa
	Bending stiffness	EI	9.09	$10^9 \text{ Nmm}^2$
3	Bending at internal support	$M_2$	1.94	kPa
4	Fastening system	R	8.33	kPa

From the values detailed in **Error! Reference source not found.** above, the following calculations were done to obtain the structural design parameters shown in Table 19.

Note that all UDL values are projected onto a purlin length of one unit meter. For example, the UDL causing failure in bending at midspan is  $W = 3.19 \text{ kPa}$  (or  $\text{kN/m}^2$ ). For a purlin of unit length, the distributed load onto the sheeting would therefore be:

$$w = 1.0 \cdot W = 1.0 \cdot (3.19)$$

in  $\text{kN/m}$  per meter purlin length.

### B.2 Bending moment resistance

#### B.2.1 At midspan ( $M_1$ )

The maximum bending moment at midspan exerted onto a roof sheeting system occurs in a single span configuration and can be calculated by:

$$M_1 = \frac{wl^2}{8} = 1.758 \text{ kNm/m}$$

where  $w = 3.19 \text{ kPa/m}$  from **Error! Reference source not found.**

#### B.2.2 At the an internal support ( $M_2$ )

$$M_2 = -\frac{wl^2}{8} = -1.069 \text{ kNm/m}$$

where  $w = 1.94$  kPa/m from **Error! Reference source not found.**

### B.3 Reaction to fastening system

The maximum reaction force exerted on the fastening system of a roof sheeting set-up occurs at the middle support of a double span configuration can be calculated by:

$$R = 0.82869wl = 7.251 \text{ kN/m}$$

where  $w = 8.334$  kPa/m from **Error! Reference source not found.** Note that the factor of 0.82869 was determined experimentally.

**Table 19: Structural Design Parameters**

Symbol		Unit
P	1195	N
$M_1$	1.758	kNm
EI	9.09	$10^9$ Nmm <sup>2</sup>
$M_2$	-1.069	kNm
R	7.251	kN

Section B.4 below details a proposed full design sheet for the 0.58 mm Z275 Craft-Lock.

### B.4 Design table: Craft – Lock Z275 0.58mm

*Note: The design table below is only displayed as an example for demonstration purposes.*

<b>Date</b>	12.01.2011	
<b>Location</b>	Stellenbosch	
<b>Tested by:</b>	FdT Oosthuizen G Kretzschmar	
<b>Company</b>	Clotan Steel Pty (Ltd)	
<b>Roof system details</b>		
<b>Mechanical properties</b>		
<b>Material strength</b>	550 MPa	
<b>Thickness</b>	0.58 mm	
<b>Fastening mechanism</b>	Bolt/screw size	M6 Gr 4.8
	Fastening bracket	550MPa 1mm thick
	Washer/Insulation	N/A
<b>Profile details</b>		
<b>Section properties:</b>		
	Area	342.248 mm <sup>2</sup>
	Y <sub>1</sub>	24.12 mm
	Y <sub>2</sub>	17.799 mm

**Strength capacities**

Experimental	Postive bending moment ( $M_1$ )	1.758	kNm/m
	Negative bending moment ( $M_2$ )	-1.096	kNm/m
	Bending stiffness ( $EI$ ) $10^9$	9.09	Nmm <sup>2</sup>
	Capacity of fastening system ( $R$ )	7.252	kN/m

**Design Tables**

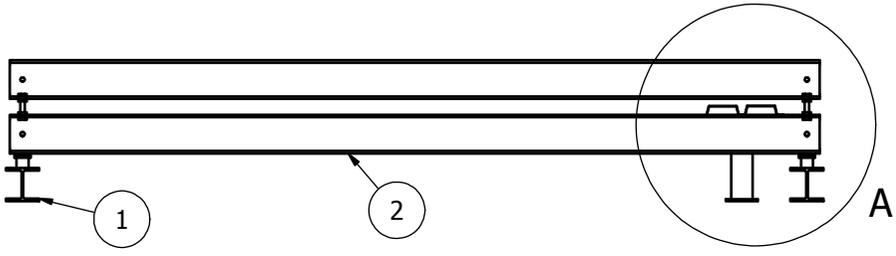
	Span length (m)
Single span	$= \min \left\{ \sqrt{\frac{8M_1}{w}}; \frac{2R}{w} \right\}$
End span	$= \min \left\{ \sqrt{\frac{8M_2}{w}}; \frac{R}{1.25w} \right\}$
Internal span	$= \min \left\{ \sqrt{\frac{M_2}{0.1w}}; \frac{R}{1.1w} \right\}$
Cantilever	$= \min \left\{ \sqrt{\frac{2M_2}{w}}; \frac{R}{w} \right\}$

Remarks: Where w in kPa

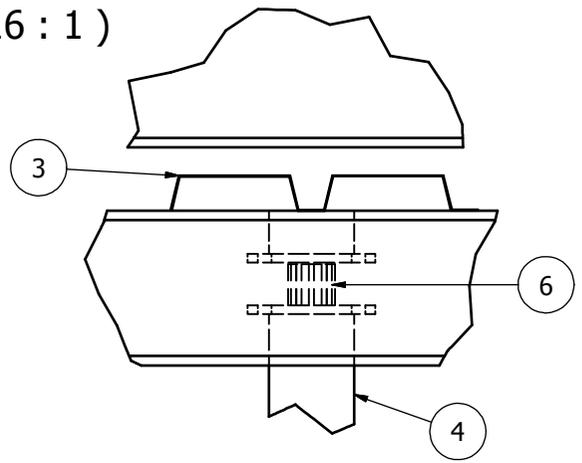
## **Appendix C: Technical drawings and figures**

### **Drawing 1: Configuration 1**

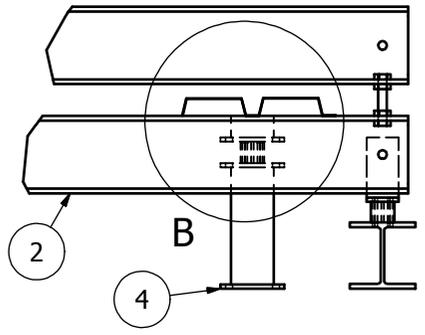
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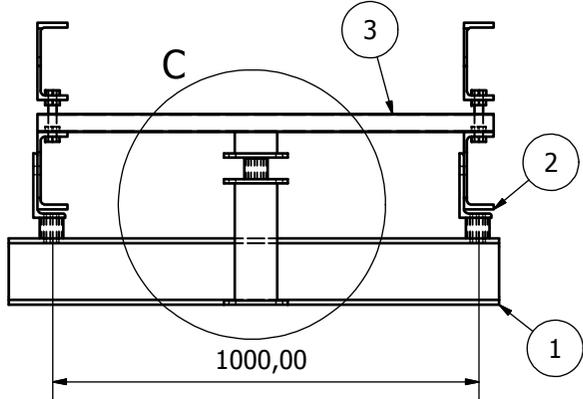
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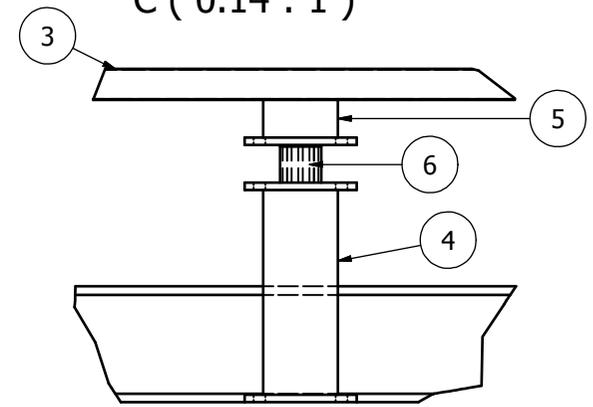
A ( 0.08 : 1 )



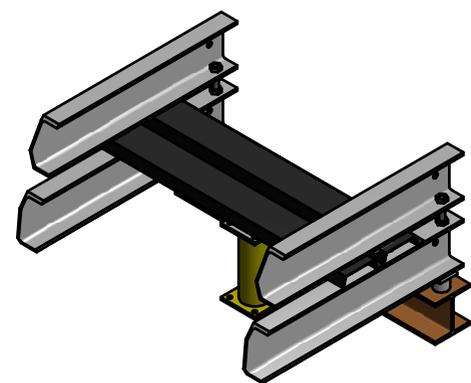
C



C ( 0.14 : 1 )



1000,00



PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION
1	2	152x152x37 H-Section	
2	2	PC180x70 Purlin	
3	1	Roof sheeting	
4	1	Enerpac (Hydraulic jack)	
5	1	Enerpac rubber pad	
6	1	Force Transducer (50kN)	

Designed by G Kretschmar	Checked by	Approved by	Date 2011/09/09
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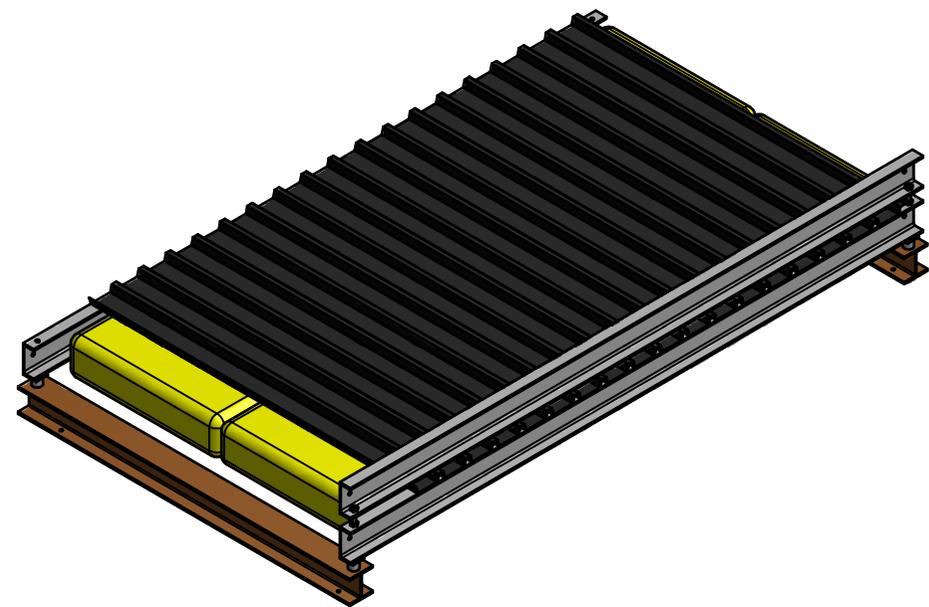
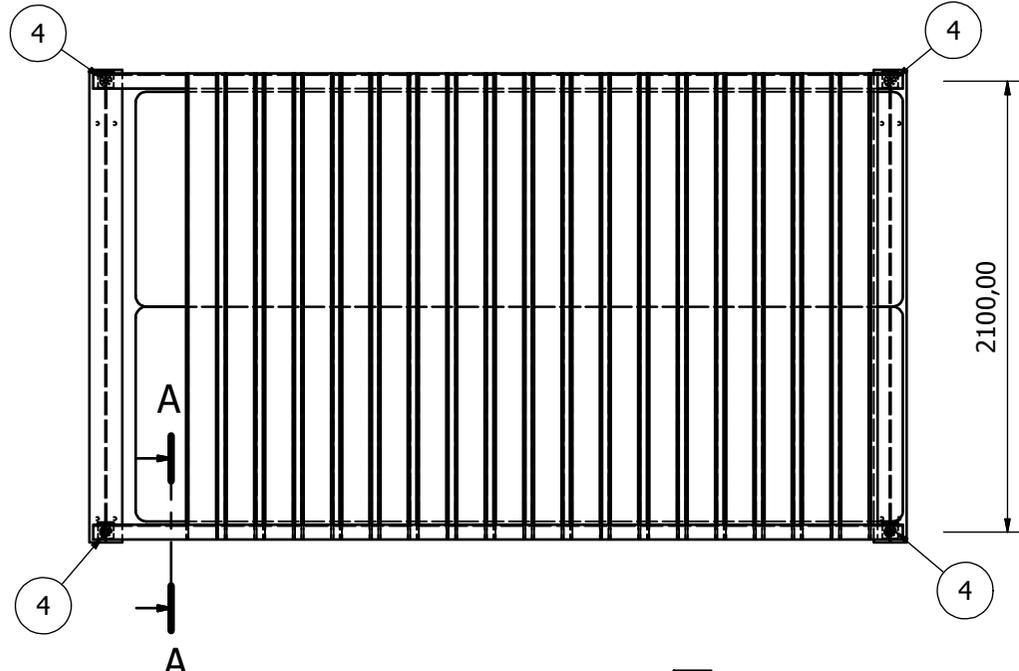
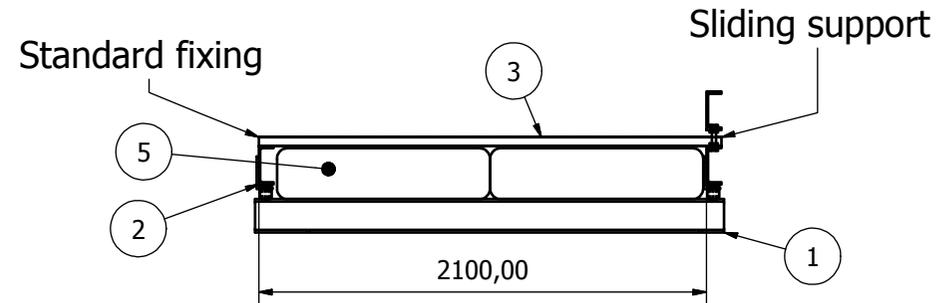
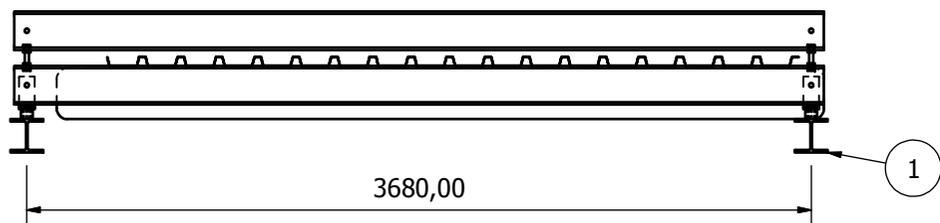
6 5 4 3 2 1

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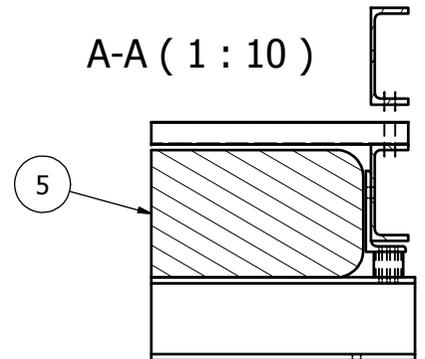
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## **Drawing 2: Configuration 2**

6 5 4 3 2 1



A-A ( 1 : 10 )



Sliding support

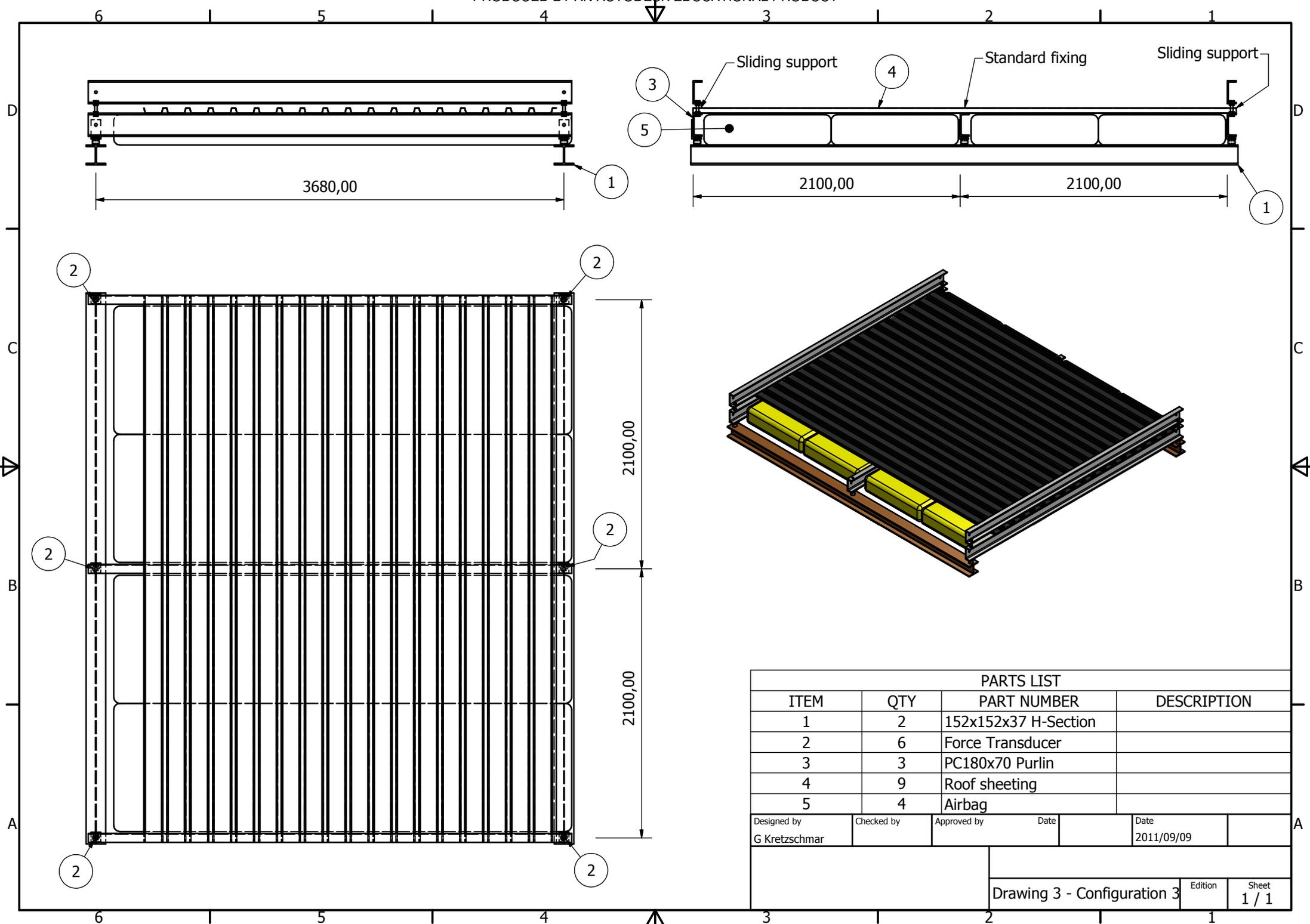
PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	2	152x152x37 H-Section	
2	2	PC180x70 Purlin	
3	9	Roof-sheeting	
4	4	Force Transducer	
5	2	Airbag	
Designed by G Kretzschmar		Checked by	Approved by
		Date	Date 2011/09/09
Drawing 2 - Configuration 2			Edition Sheet 1 / 1

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6 5 4 3 2 1

## **Drawing 3: Configuration 3**



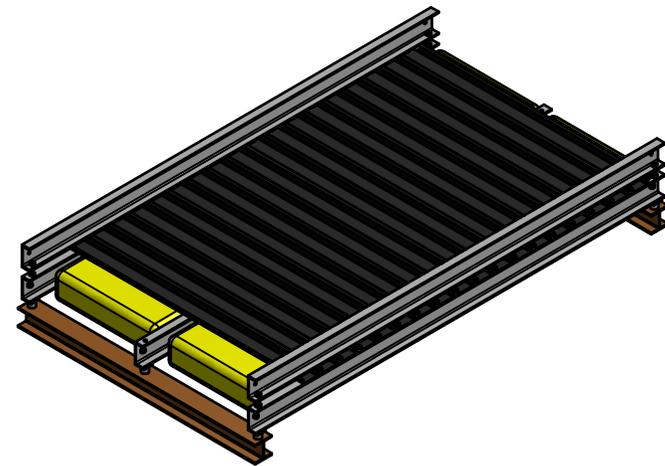
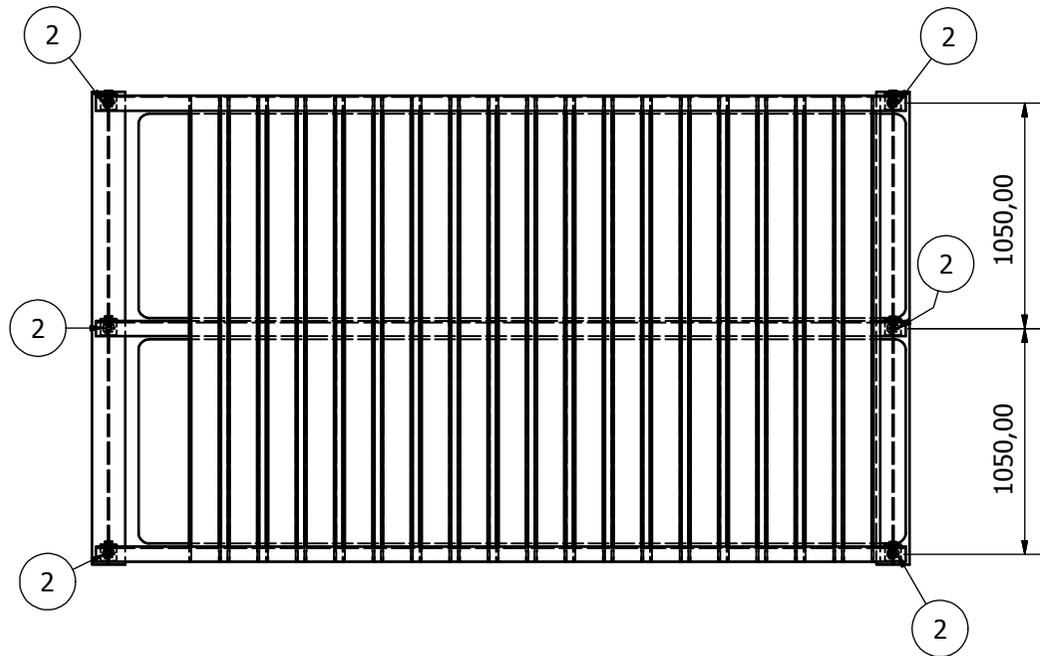
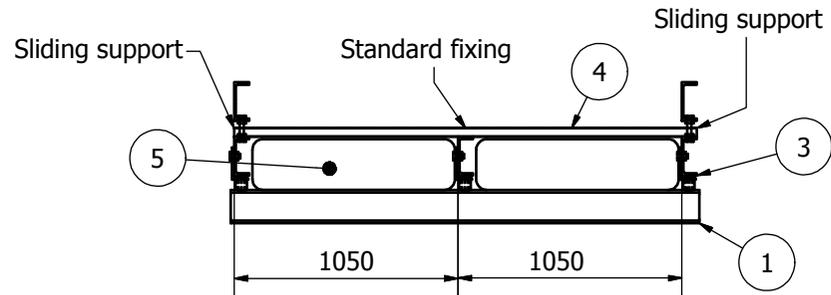
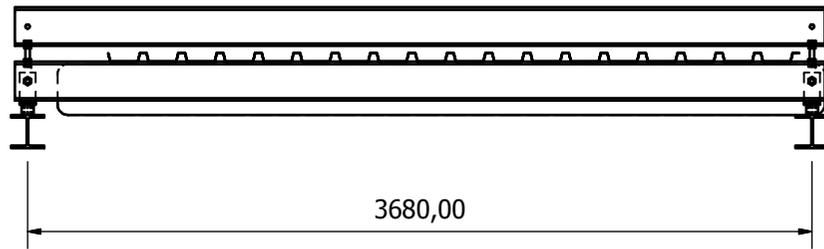
PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	2	152x152x37 H-Section	
2	6	Force Transducer	
3	3	PC180x70 Purlin	
4	9	Roof sheeting	
5	4	Airbag	
Designed by G Kretschmar		Checked by	Approved by
		Date	Date 2011/09/09
Drawing 3 - Configuration 3			Edition 1 / 1

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## **Drawing 4: Configuration 4**

6 5 4 3 2 1



PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION
1	2	152x152x37 H-Section	
2	6	Force Transducer	
3	2	PC180x70 Purlin	
4	9	Roof_sheeting	
5	2	Airbag	

Designed by G Kretschmar	Checked by	Approved by	Date	Date 2011/09/09
			Drawing 4 - Configuration 4	
			Edition	Sheet 1 / 1

6 5 4 3 2 1

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D

D

C

C

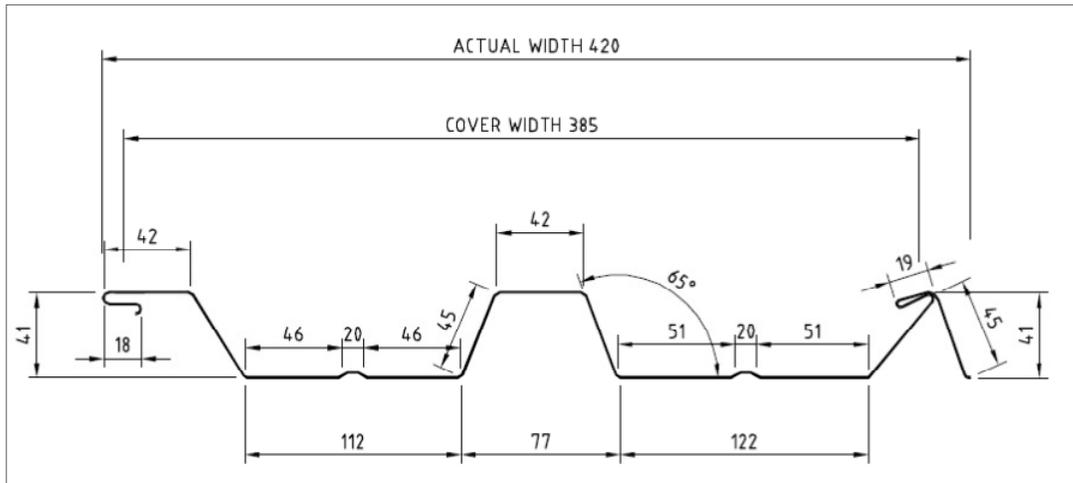
B

B

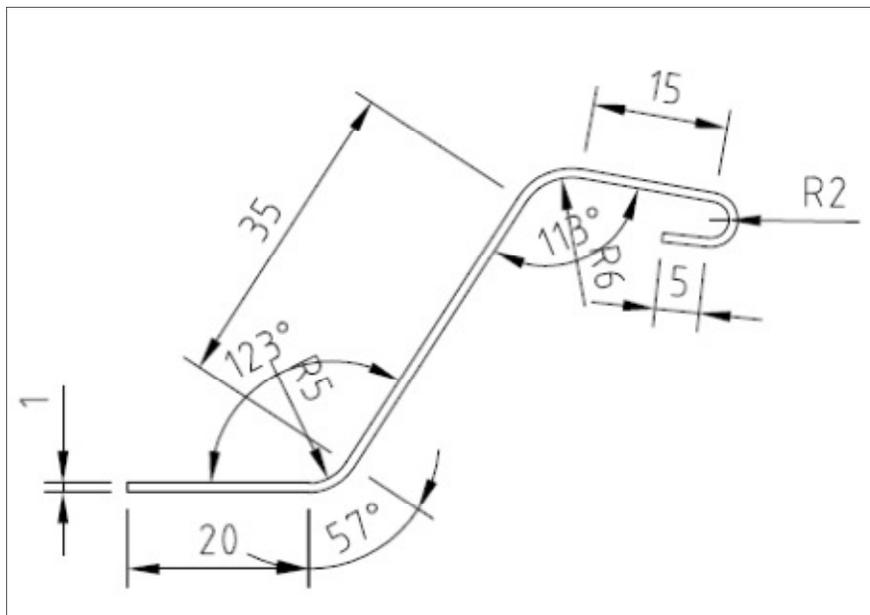
A

A

**Drawing 5: Craft-Lock (0.58mm) roofing system**



**Figure 72: Craft-Lock sheeting profile dimensions (Clotan Steel (Pty) Ltd.)**



**Figure 73: Craft-Lock fastening bracket profile dimensions (Clotan Steel (Pty) Ltd.)**