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BRACING STRENGTH OF CORRUGATED STEEL ROOFING

L.M. Nash *

G.N. Boughton **

SUMMARY

The capacity of a roof to carry lateral loads on walls to bracing walls was investigated using panel testing and a theoretical approach. The mechanism of failure was found to be ductile, but it is important for the continued servicability of the roof that tearing of the roof sheeting does not commence.

Sheet tearing can be initiated by cyclic uplift loading, or by the in-plane-of-roof loads detailed in this work. The interaction of these two effects necessitates the use of a large load factor for lateral loads on domestic buildings when considering in-plane-of-roof forces.

The bracing action of corrugated steel roofing is accompanied by small deflections. Thus where separate bracing is used to carry in-plane-of-roof loads, it should be capable of carrying the load required with less than 5 mm central deflection. This will ensure that the separate bracing carries its share of the lateral loads. In cases where distances between bracing walls are small or lateral loads are small, separate bracing may not even be required.

* Lecturer, Department of Civil Engineering, S.A.I.T., Adelaide.

** Research Fellow, Cyclone Structural Testing Station, Townsville.

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1. INTRODUCTION

The behaviour of roofing under wind loading is very complex. Considering a simple domestic dwelling, the roof experiences uplift forces and the outside walls experience lateral pressure. This lateral pressure is usually carried to the top and bottom wall plates by the wall studs.

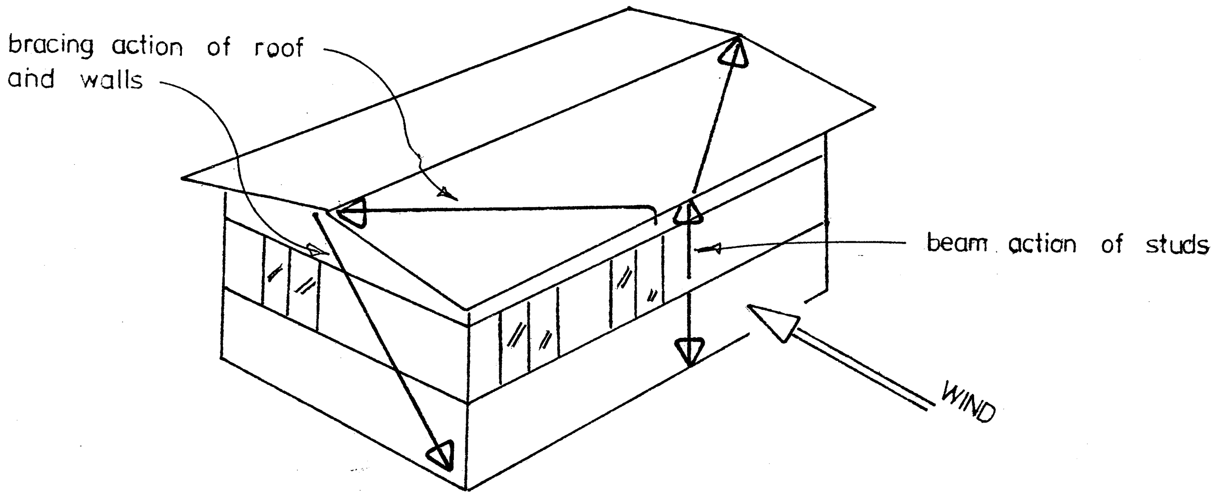


FIGURE 1 Horizontal Force Flow through House

The bottom wall plates are securely fixed to the foundation using details outlined in previous publications. The load from the top wall plates is generally carried to bracing walls in the structure by diaphragm action of the ceilings, diaphragm action of the roof sheeting or in-plane-of-roof cross bracing. It is then carried to the foundations by the bracing walls.

This paper examines the bracing strength of corrugated steel roof sheeting and gives an indication of the effectiveness of the diaphragm action of the roof sheeting.

1.1 Shear Forces on the Roof Sheeting

The shear forces in the roof structure increase from the centre of the roof panel towards the bracing walls. This is due to the summing of the point loads transferred by the wall studs to the roof and gives a maximum shear force in roof system at the bracing walls.

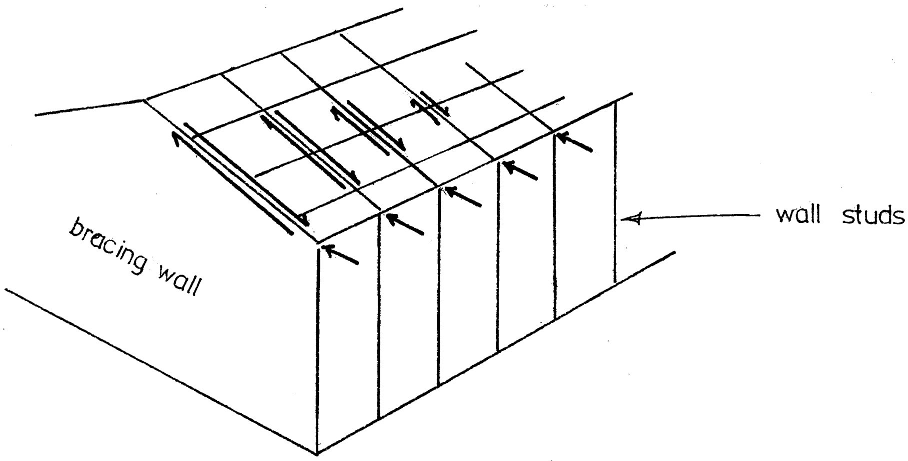


FIGURE 2 Shear Force in Roof

The roofing system modelled in this study consisted of Zincalume coated high tensile corrugated steel decking fixed to timber battens with screws at every second corrugation.

1.2 Properties of Corrugated Steel Sheeting

Corrugated steel sheeting is orthotropic (that is the properties of the sheeting differ according to the direction of application of stress).

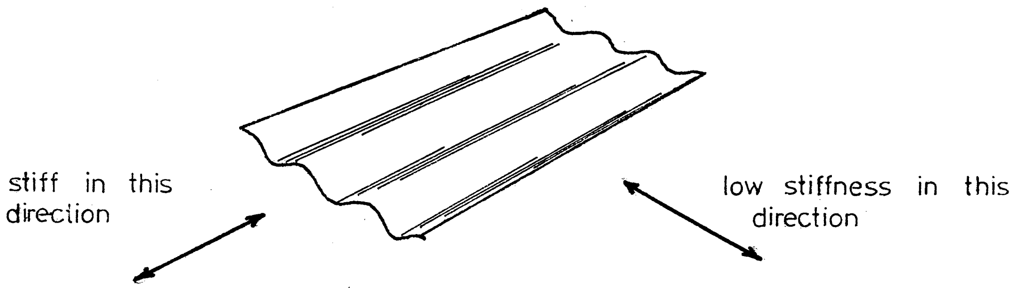


FIGURE 3 Orthotropy in Corrugated Steel Roofing

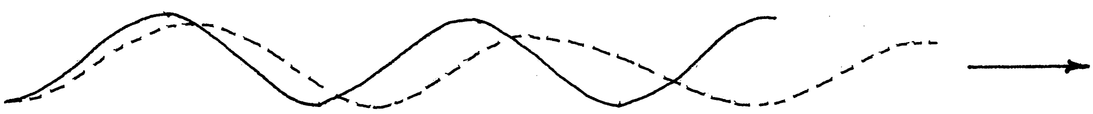


FIGURE 4 Stretching of Roofing across Corrugations

Stretching across the corrugations deforms the profile with little resistance, but stretching parallel to the corrugations stresses the sheeting and the high elasticity of the steel itself is mobilised. This greatly simplifies the analysis of shear in the sheeting, as only the shear carried parallel to the crests is of significance.

Whilst shear can, and must be carried in both directions, for the small deflections encountered in the sheeting, significant tension or compression cannot be carried across the corrugations. Therefore most tension and compression across corrugations is transmitted to the fasteners and out of the sheeting. This ensures that corrugations remain parallel to the rafters while the sheeting is subjected to shear deformation.

1.3 Crest Fixed Sheeting

In conventional 'stressed skin design' due allowance is made for the bracing strength of the roof sheeting, but this requires the roof sheeting to be valley fixed (Bryan, 1973). The practice in Australian domestic construction has been to crest fix the roof sheeting to minimise leakage problems. This changes the bracing strength of the roofing significantly. The sheeting-to-batten fixing behaves in a complex manner and influences the failure mechanism of the roof. It was therefore necessary to test the strength of the crest fixed joint, develop a new theory for the bracing action of the roof and perform full scale tests on the sheeting.

2. THE MECHANISM OF FAILURE OF CORRUGATED STEEL ROOFING IN SHEAR

The mechanism of failure must be examined on the small scale (fixing details) and the large scale (whole roof performance).

2.1 Ultimate Load Development of the Sheeting-to-Batten Fasteners

As can be seen in Figure 5, there are two modes of failure (i) bending and possible breaking of the fastener (ii) tearing of the sheeting. Both of these mechanisms are characterised by large deflections at failure and irreparable damage to the roofing system. The bending of the fastener had a maximum possible deflection which is approximately the depth of one corrugation, (16 mm), but the tearing of the roof sheeting had no limit to the deflection.

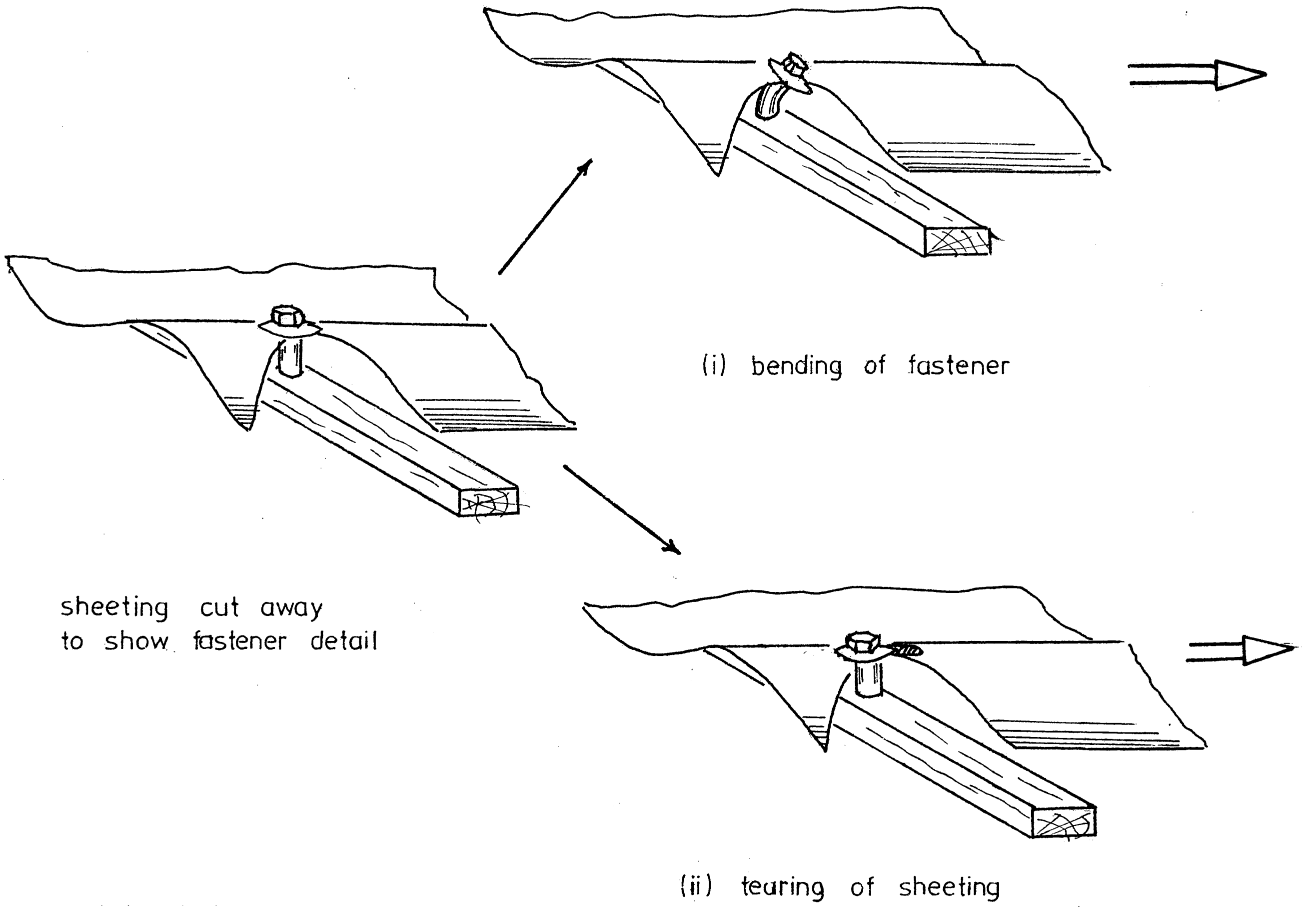
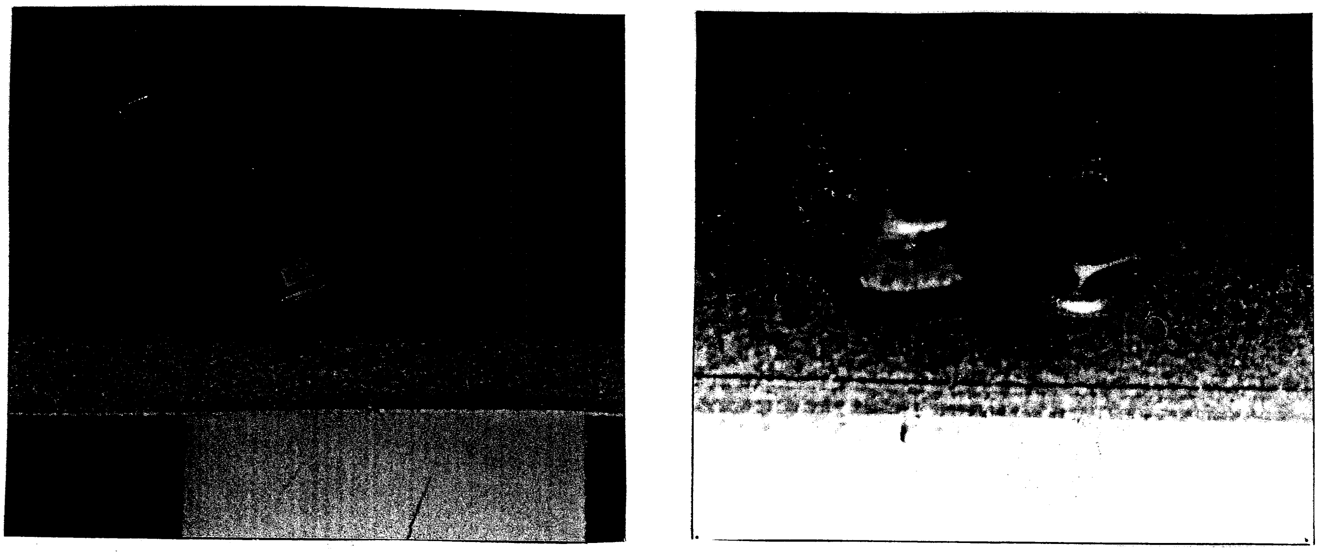


FIGURE 5 Failure Mode of Sheeting to Batten Fasteners



(i) bending of fasteners

(ii) tearing of sheeting

FIGURE 6 Photographs of Fastener Failures

Both failure modes were observed in the tests although tearing of the sheeting, often in conjunction with bending of the fasteners was most common. From sheeting to batten joint tests (Appendix A) the characteristic ultimate strength of the joint was found to be 1.4 kN per fastener for the system tested.

Another series of tests was performed on a sheeting-to-batten joint that incorporated a lap joint as shown in Figure 7.

In this case the fastener was not subjected to a large bending moment, as the opposing loads were almost co-linear at the fastener. The screw remained straight and failure was through tearing of the sheets. The sheets commenced tearing at approximately 1.4 kN per fastener, but interference between the torn sheets increased the ultimate load to 1.9 kN per fastener.

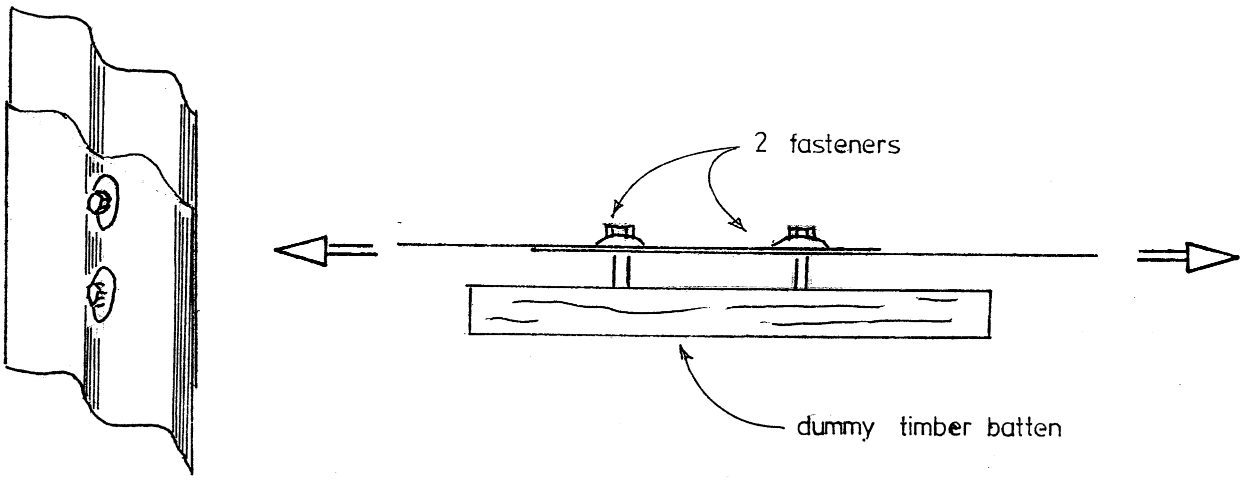


FIGURE 7 Lap Joint Test

2.2 Shear Force Transfer within the Roofing

Shear force is transferred from the battens to the roof sheeting by bearing of the fastener on the edge of the sheeting at the hole. It is then transferred from sheet to sheet by bearing from the edge of the sheet to the fastener and then to the edge of the next sheet by bearing again. The main load transfer system is by bearing on a very small area (the edge of the sheet at the hole). For conventional stressed skin design using valley fixings, high normal loads can be generated in the fasteners giving large friction forces between the batten and the roofing or between sheets at a lap. This more secure fixing system gives ultimate loads of approximately 2 times that obtained using crest fixing.

Use of crest fixing means a much smaller ultimate load can be sustained by the fixing method and so it was expected that failure of the assembled roofing system would be by bending of fasteners and tearing of the roof sheeting.

2.3 Definition of Significant Loads

Three significant loads can be defined.

(i) Yield Load - This load is the highest for which the load deflection curve is linear. It corresponds to the commencement of bending of fasteners for roof panels comprising single sheets and may coincide with the onset of tearing for panels with lap joints.

(ii) Onset of Tearing Load - This is the load at which tearing of the sheeting adjacent to fasteners commences. In panels comprising single sheets, it corresponds to tearing at fasteners closest to corners. In panels with lap joints, tearing commences at fasteners along lap joints.

(iii) Ultimate Load - This is the highest load the roof panel can carry.

2.4 Mechanism of Shear Resistance of Assembled Roofing up to the Onset of Tearing

The relatively low ultimate load of the sheeting-to-batten joint controls the failure load and mechanism for an assembled roof panel acting in shear. The performance of a complete roof is a function of joint properties and the geometry of the roof. Some simple roof panels consisting of no more than two sheets were examined theoretically and tested to determine and confirm performance under shear loads.

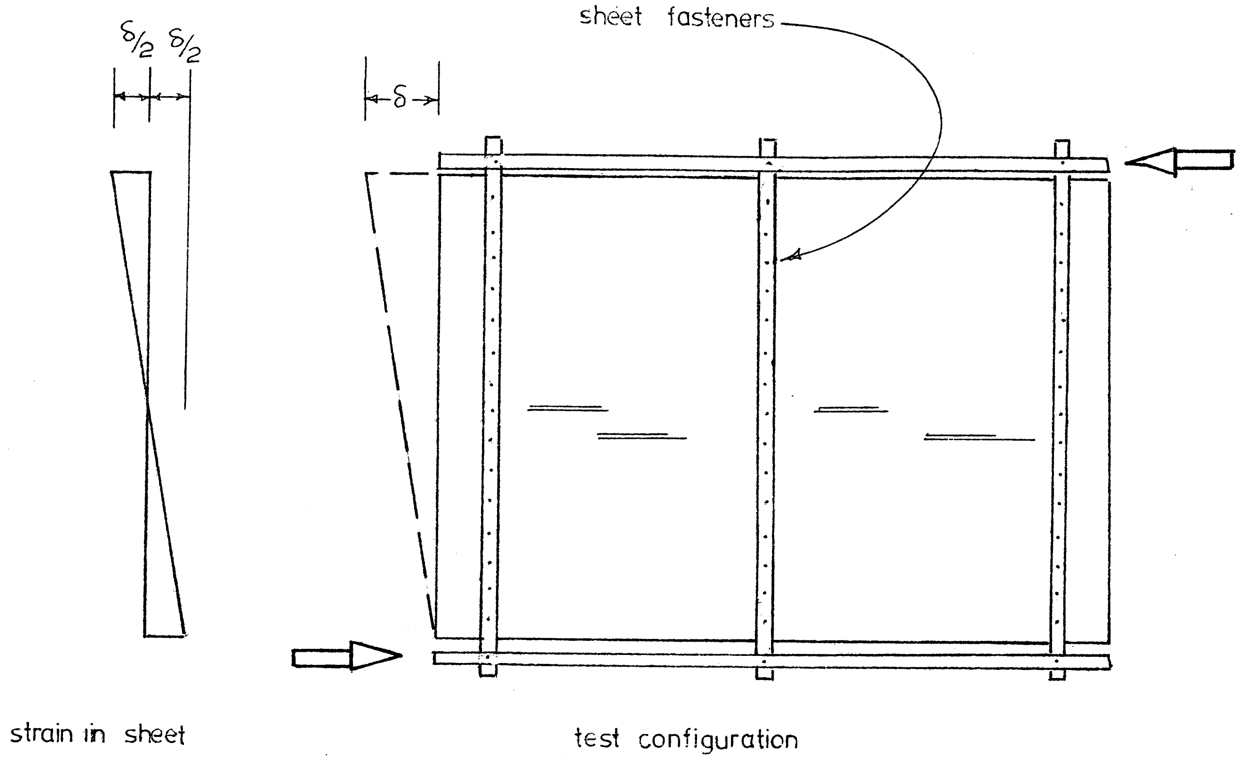


FIGURE 8 Deflected Shape and Strain Pattern in Assembled Roofing Test

Assuming elastic behaviour of sheeting and fasteners at low loads, the load carried by each fastener will be proportional to the deflection of the fastener.

The shear carried by the sheeting can be found by summing the loads carried by the individual fasteners along one batten. This is shown in Figure 9. If there is a lap joint near the centre of the panel as shown in Figure 9, the shear in the sheeting must be transferred from one sheet to the other through the fastening at the lap joint. The roof panel will yield when the shear in the sheeting at the lap joint fastener exceeds the yield load of the lap joint sheeting to batten fastener. Continued loading will cause an increase of shear until the tearing load of the lap joint sheeting-to-batten fastener (1.4 kN) is reached. The sheet will then start to tear allowing large deflection along the lap joint. This condition is designated by the onset of tearing. Further load can be carried by the system, but with increasing load, permanent damage occurs.

For panels without a lap joint, the onset of tearing load is that load at which sheeting first starts to tear at a fastener.

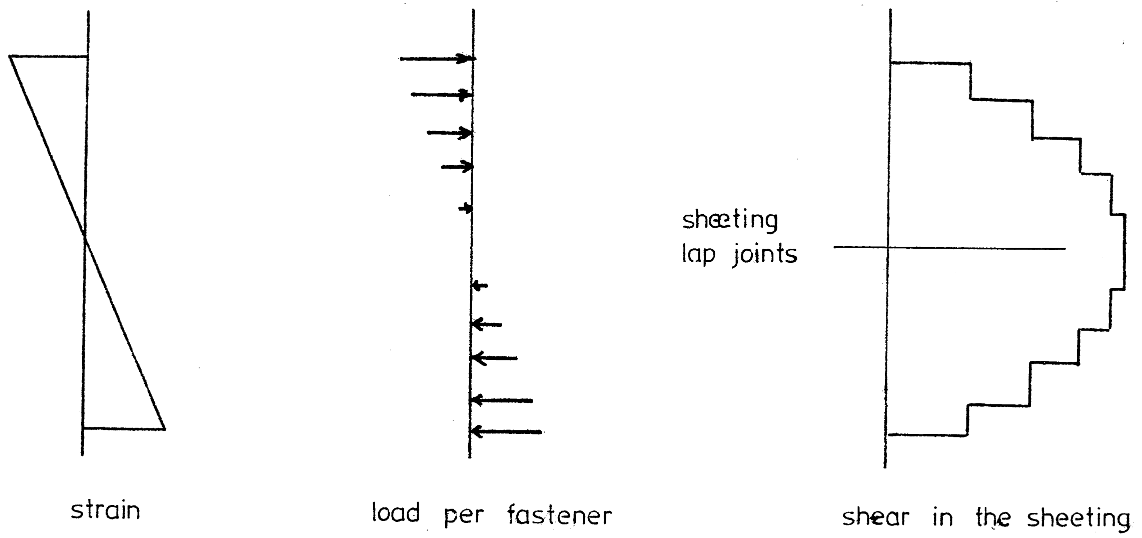


FIGURE 9 Strain, Load per Fastener and Shear in Sheeting

The onset of tearing load can be derived. It depends on the location of the lap joints in relation to the shear carried by the sheeting, and is given by Equation 3 in Appendix C.

It is to be noted that any load applied to the roof structure greater than this load will result in permanent damage to the roof.

2.5 Mechanism of Shear Resistance of the Assembled Roofing up to Ultimate Load

Increasing the load beyond the onset of tearing causes permanent slip along the lap joints closest to the centre of the loaded section. Under further increasing load other lap joints would fail until all lap joints were experiencing significant amounts of slip. By this time, all of the sheets would be behaving independently.

As load is further increased the ultimate load for the sheeting-to-batten connection is reached for the extreme fasteners on every sheet.

These fixing details then fail with further load being carried by fasteners closer to the centre of each sheet. Eventually either all fasteners will attain ultimate load, or the deflection at some fasteners will be such that the fastener breaks or tears loose from the sheeting and failure of the whole assembled roof panel occurs.

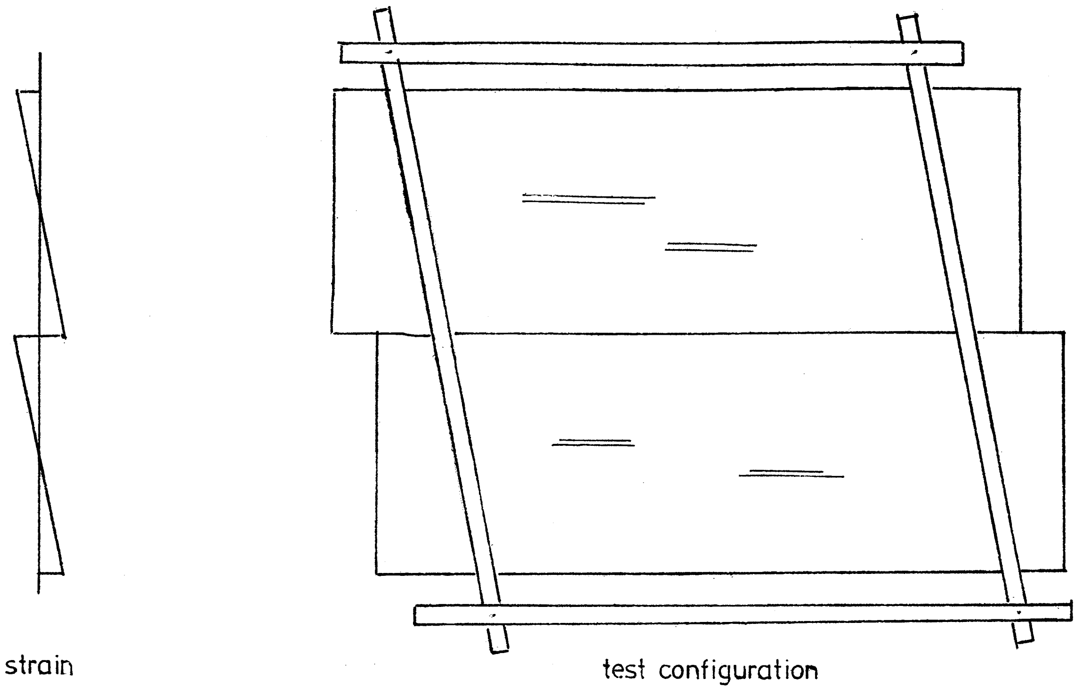


FIGURE 10 Strain in Sheet and Test Configuration of an Assembled Roof Panel after Onset of Tearing.

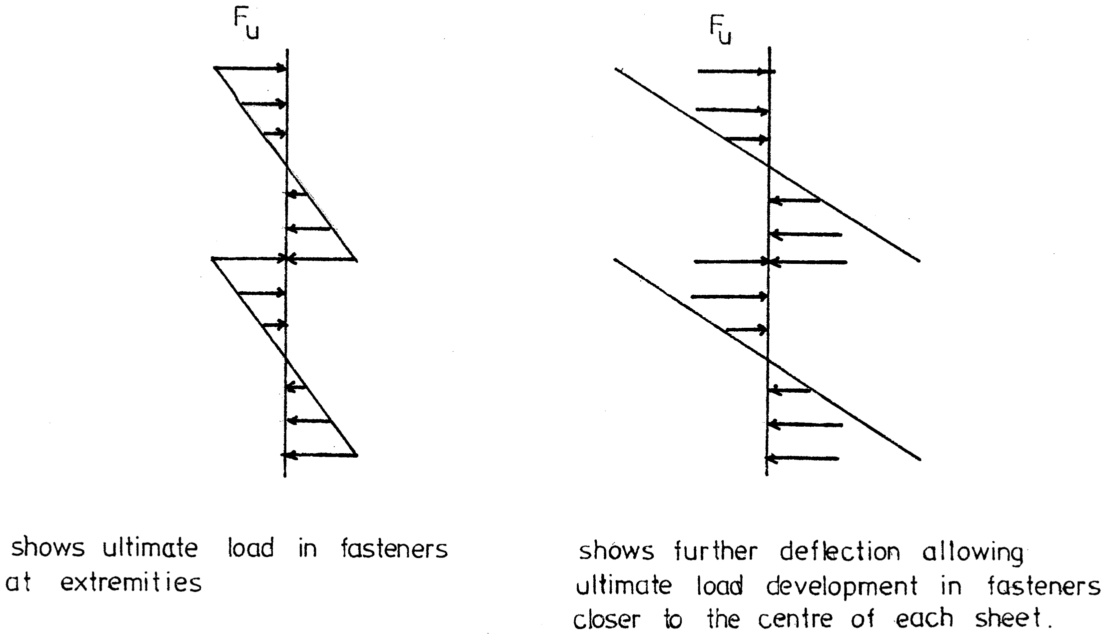


FIGURE 11 Elastic Deflection and Load in Fasteners superimposed during Development of Ultimate Load of an Assembled Roof Panel with a Lap Joint.

The mechanism described above gives rise to a formula for the prediction of ultimate loads of a simply loaded shear panel (equation 5 derived in Appendix C). The mechanism was confirmed with a model testing program.

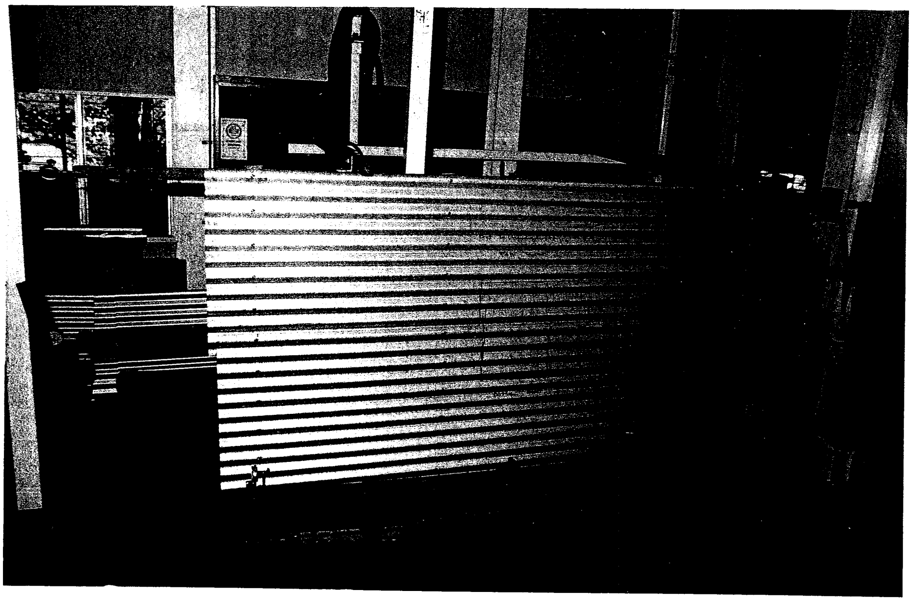


FIGURE 12 Failure of Assembled Roof Panel Test Piece

3. ROOF PANEL TESTING PROGRAM

3.1 Test Panels

Six test panels were fabricated as shown in Figure 13. All panels were placed upright in the orientation shown.

The load, P, was applied at the top rafter, and reactions, R, were provided at the bottom rafter and end battens. As can be seen, combinations of 2, 3 or 4 battens and one or two sheets were tested. All panels were loaded parallel to the crests and troughs of the sheeting.

Lysaght Custom Orb was fastened to timber battens with Deutsher Type 17 screws. A more detailed description of individual components can be found in Appendix A. A 1½ corrugation lap was used on panels 1, 2 and 3 and the fasteners at the lap passed through both sheets into batten.

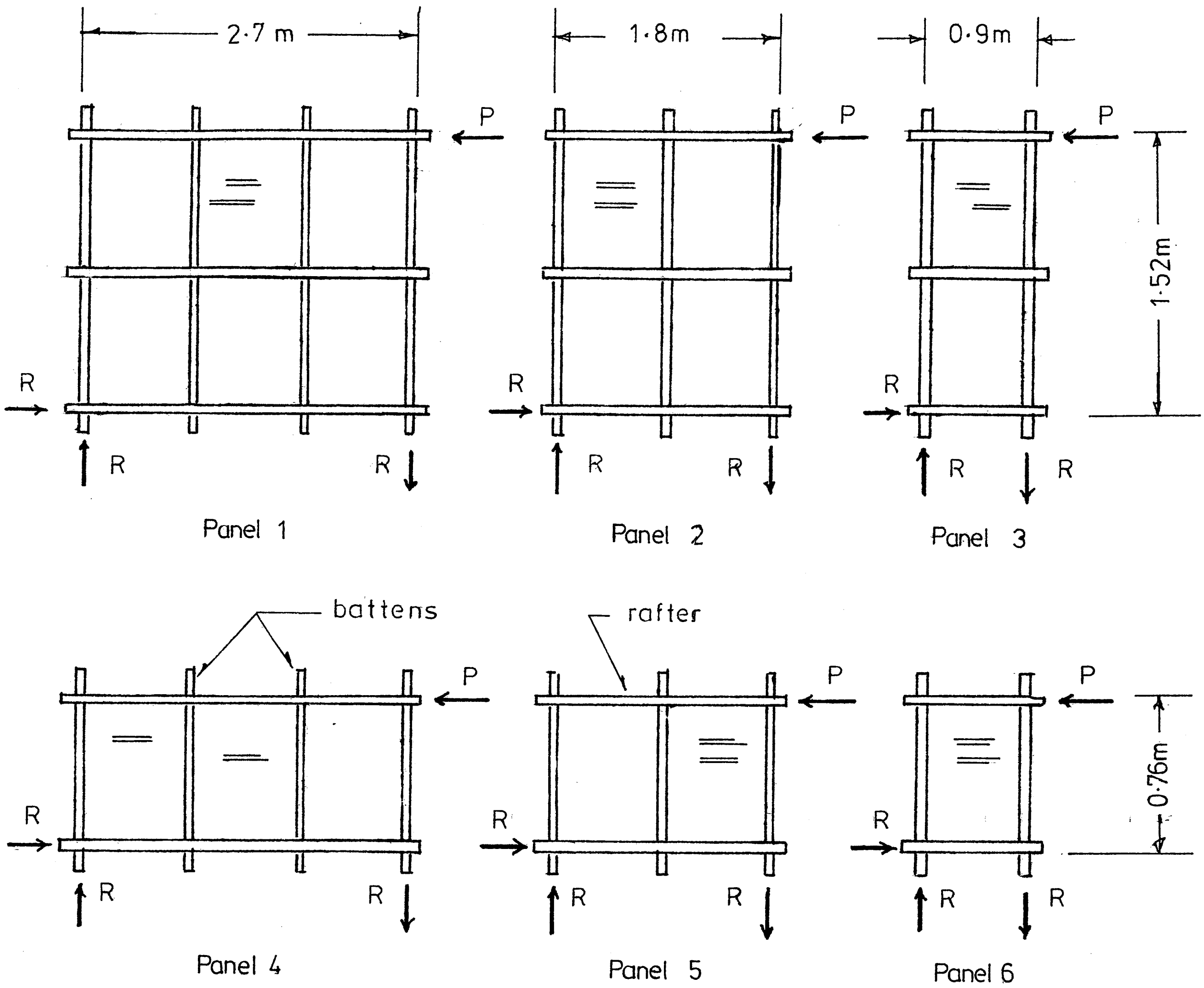


FIGURE 13 Configuration of Test Panels

Eleven fasteners per batten were used on panels 1, 2 and 3 and six fasteners per batten were used on sheets 4, 5 and 6. The battens were connected to rafters with single screws at each joint. This enabled rotation of the battens with the only resistance provided by the sheeting.

3.2 Test Results

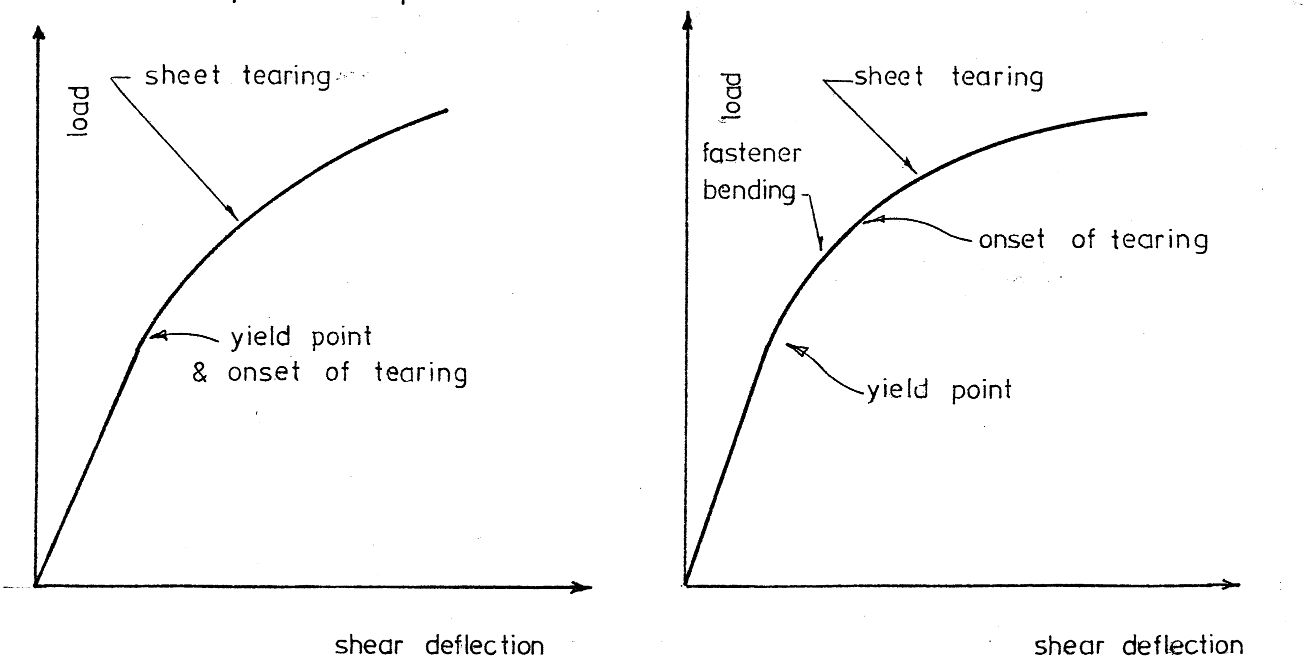
The applied load (P) was recorded and the response of the panel was measured to show deflection of the top rafter and distortion of the frame. The true shear deflection could then be calculated.

Numerical results and plots of shear deflection against load applied are shown in Appendix B. The general form of the plot is shown in Figure 14.

For panels 1, 2 and 3 a linear elastic portion of the curve corresponded to the elastic resistance of the fastener and the increasing shear in the sheeting. At the point at which failure at the lap commenced (detailed in section 2.3) the yield point was reached and tearing of the sheeting commenced. At this point all the fasteners were still straight. Further loading tore the sheet further and bent fasteners until the ultimate load was attained.

For panels 4, 5 and 6, yield occurred when the fasteners first started to bend. Further load was sustained until the roof sheeting started to tear. This was the onset of tearing. Further load was sustained until the ultimate load was obtained.

The overall mode of failure was ductile. All sheets tore extensively at the fasteners, although some fasteners broke. At laps, the fasteners remained straight, but ripping of the sheeting was the most severe. After development of the ultimate load it could be sustained with increasing deflection. Load drop off was very slow, giving a very ductile failure and subsequent collapse.



(i) lapped sheets (panels 1, 2 & 3) (ii) single sheets (panels 4, 5 & 6)

FIGURE 14 Shape of Force vs Shear Deflection Plots

3.3 Comparison of Test Results with the Theory

The theory developed in Appendix C can be used to predict onset of tearing and the ultimate load the sheets sustained. This is shown in Table 1.

TABLE 1

Comparison of Test Load Results in Theory

Panel	Onset of Tearing Load (kN)		Ultimate Load (kN)	
	Test	Theory	Test	Theory
1	4.0	4.1	10.9	10.1
2	3.4	3.1	8.1	7.6
3	2.6	2.1	5.4	5.1
4	8	7.8	10.9	10.1
5	6	5.8	7.9	7.6
6	3.5	3.9	5.3	5.3

This shows that the theory accurately predicts the onset of tearing and the ultimate loads.

The deflection results can also be compared with the theory and this is shown in Table 2.

TABLE 2

Comparison of Test Deflection Results with Theory

Panel	Yield Deflection (mm)		
	Test	Theory	
1	4.8	5.2	onset of tearing
2	6.7	5.2	onset of tearing
3	8.1	7.1	onset of tearing
4	4.4	4.8	yield
5	5.9	5.7	yield
6	6.7	5.8	yield

Bearing in mind the difficulties often encountered in predicting deflections, the test results and theory are in close agreement.

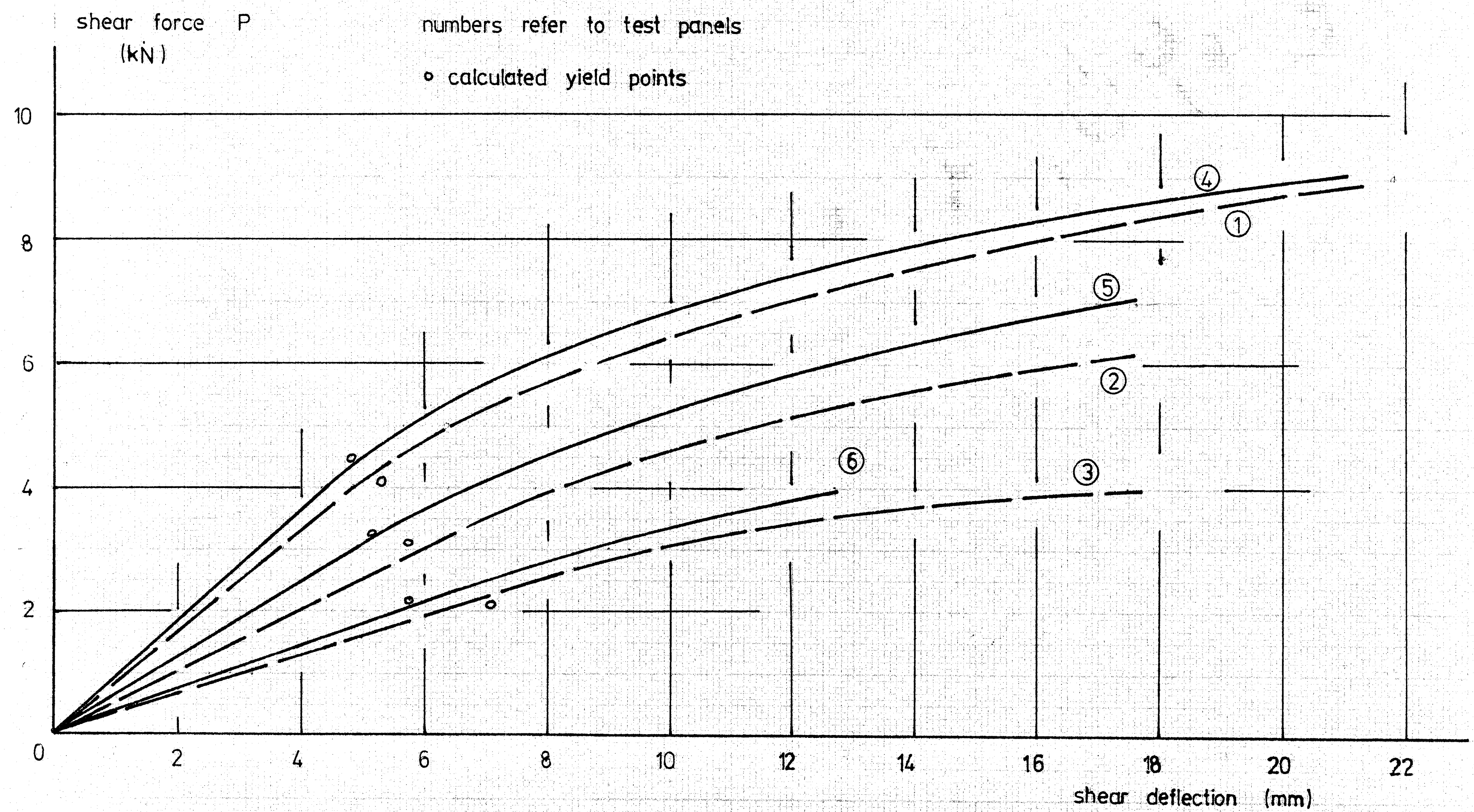


FIGURE 15 Graphed Results of Roof Panel Tests

Errors in the yield load estimation are also reflected in the deflection estimation. The results have been plotted in Figure 15 and it can be seen that the predicted yield points in each case lie very close to the curves.

It can be concluded that the theory accounts for the observed behaviour in the cases tested. This enables extrapolation of the theory to estimate the capacity of housing roofs to resist shear loadings.

4. IMPLICATIONS FOR THE BUILDING INDUSTRY

4.1 Mode of Failure

The lateral forces that give rise to shear stressing of the roofing are only part of the complex loading on a building during high winds. At the same time, the sheeting can be subjected to violent and repeated uplift forces. The fasteners and the sheeting are required to remain intact to resist these uplift forces, so it is important that no tearing of the sheeting occurs.

Both uplift forces and in-plane-of-roof forces give rise to tearing of the sheeting, starting at the holes drilled for the fasteners and propagating radially outwards. The stresses induced by uplift forces and in-plane-of-roof forces will therefore combine to give early tearing under combined loading. The bracing action of the roof sheeting therefore reduces the factor of safety against failure of the sheeting in uplift by pulling over the fastener heads.

4.2 Load Factors

For fasteners designed for an uplift load factor of 1.6 under cyclic loading, the factor of safety against failure of the fastener-sheeting system is nominally 1.6. If a load factor of 2.5 is applied to in-plane-of-roof forces the overall factor of safety of the fastener-sheeting system could be as low as 1.03.

$$\frac{1}{\text{F.S.}} = \frac{1}{2.5} + \frac{1}{1.6} = \frac{1}{1.03}$$

Hence a minimum load factor of 2.5 should be used for in-plane-of-roof forces. This allows little room for errors or poor installation practices. As the strengths have been obtained for static loadings, the load factor of 2.5 may be further increased when the effects of cyclic loading are taken into account in cyclone-prone areas. The diaphragm action of ceilings and bracing action of the building frame will attract some load, and hence increase the overall factor of safety a little, although this effect is as yet unknown.

As it is necessary to eliminate tearing of the roof sheeting so that the fasteners may still resist uplift loads, the load factor must be applied to the onset of tearing load for the roof. In Appendix C, section C.8, a formula is derived which gives W_{on}, the uniformly distributed load at the top wall plate for onset of tearing with the load applied parallel to corrugations.

$$W_{on} = \frac{2.60\, n\, Fu}{b}$$

n = number of battens

F_n = characteristic tearing strength of the roof sheeting-fastener system

b = distance between bracing walls

The design load, W_d, can be found from

$$L.F.\ W_d < W_{on} \quad \text{with} \quad L.F. > 2.5$$

W_d = design uniformly distributed load normal to top wall plate

4.3 Loads on a Domestic Building

A check on a simple domestic building was performed to determine the wind speed for which the bracing action of the roof sheeting is effective. The house was a small low-set house as shown in Figure 16, and loadings were taken from AS 1170 - II 1981. Wind direction was parallel to the sheeting's corrugations.

John Lysaght's current recommendations for terrain category 3 in cyclone-prone areas and for "average conditions" in non-cyclonic areas are for 900 mm between outside battens and 1200 mm between internal battens. In

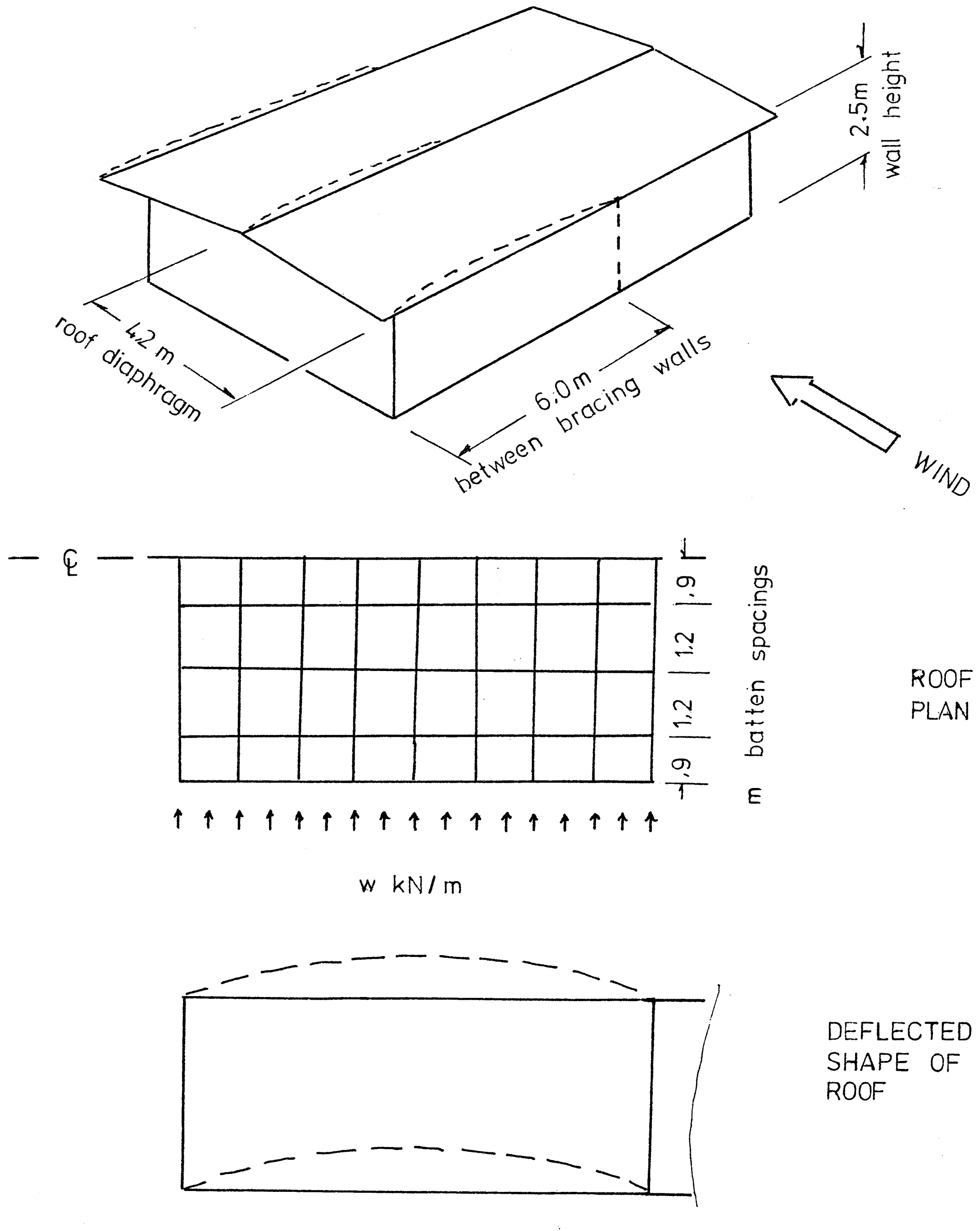


FIGURE 16 Geometry and Loads in Example

cyclonic areas the Deutscher Type 17 No. 14 screw in recommended for fixing. As this has not been tested for in-plane-of-roof forces associated with this paper, the data obtained for No. 12 screws will be used. This may be conservative for cyclone-prone areas.

$$W_{on} = \frac{2.60\, n\, Fu}{b} = \frac{2.60 \times 5 \times 1.4}{6} = 3.0 \text{ kN/m}$$

As W_{on} is independent of spacing of the fasteners along the batten, this figure is applicable for 5 fasteners per sheet (terrain category 3 cyclonic-areas) or 3 fasteners per sheet (non-cylconic areas).

Then using the minimum load factor of 2.5

$$W_d = \text{design load} = \frac{3.0}{2.5} = 1.2 \text{ kN/m} \quad \text{at top plate}$$

for a wall height of 2.5 m => wind pressure $= \frac{1.2}{1.25} = 0.96$ kPa

$C_p$ext windward wall = +0.8
$C_p$ext leeward wall = -0.5

total C_p on the house giving rise to lateral forces in roof = 1.3

assuming that the load is shed 60% to front side of roof
40% to lee side of roof

then C_p for front side is 0.8

$$\Rightarrow q_{3m} = \frac{0.96}{0.8} = 1.2 \text{ kPa}$$

This corresponds to a wind speed at eaves (3 m)

$$V_{3m} = 44.72 \text{ m/s}$$

i.e. at wind velocities of 44.7 m/s at 3 m height the roof can carry lateral loads between bracing walls with a load factor of 2.5.

For Terrain Category 1, this corresponds to

$$V = 44.7 \text{ m/s}$$

i.e. Melbourne, Perth, Hobart, Adelaide, Sydney and others.

For Terrain Category 2, this corresponds to

$$V = 49.6 \text{ m/s}$$

i.e. Melbourne Perth, Hobart, Adelaide, Sydney and others.

For Terrain Category 3, this corresponds to

$$V = 68.77 \text{ m/s}$$

i.e. all Australia including cyclone-prone areas, with the proviso that cyclic load performance of the system acting against in-plane-of-roof forces has not been explored.

4.4 Stiffness of the Roof as a Bracing Element

For the example of the previous section, theoretical elastic deflections of the sheeting at the load considered were

0.6 mm for the 5 fasteners per sheeting fixing
1.0 mm for the 3 fasteners per sheeting fixing

midway between bracing walls.

Allowing for clearances at holes and movement in joints the overall deflection will be approximately 5 mm midway between bracing walls as shown in section C.10. The allowable deflection is almost independent of span, so where separate bracing systems are incorporated in the building frame, they should limit the maximum horizontal deflection midway between bracing walls to less than 5 mm. This will prevent overstressing of the roof sheeting and hence early failure.

4.5 Recommendations

Roof sheeting can be used as a bracing material but the bracing action is at the expense of capacity to resist uplift. It should only be used where a large load factor on uplift forces on fasteners has been used, and then with a minimum load factor on bracing forces of 2.5.

It may be possible to reduce the in-plane-of-roof bracing within the building frame to take advantage of the bracing action of pierce fixed roof sheeting.

In view of the stiffness of the roof sheeting acting as a bracing element, horizontal deflections of the sheeting, midway between the bracing walls should be limited to less than 5 mm where pierce fixed sheeting systems are used. Other roof bracing should be designed to keep deflections less than 5 mm, otherwise it will shed load to the roof sheeting and may result in overstressing and hence failure of the sheeting.

5. CONCLUSIONS

The structural system of roof sheeting, fasteners, battens and rafters acting in shear, has been explored and the following conclusions can be made.

(i) The roof sheeting when acting in shear, forms a stiff elastic membrane. If it is used in conjunction with bracing in the plane of the roof, the bracing should be designed so that it has equivalent stiffness to the roof sheeting. The central deflection of roofing between bracing walls should be less than 5 mm to prevent damage to the roof sheeting.

(ii) The mode of failure of roof sheeting when acting in shear alone is very ductile. However, in the course of failure, the sheeting tears significantly rendering the roof unservicable.

(iii) The onset of failure of the roof sheeting when acting in shear is indicated by cracks or tearing propagating outwards from the fasteners. This is similar to the onset of failure during uplift. Shear forces in the roof sheeting will lower the failure load in uplift. More work is required in this area to quantify this effect.

(iv) The pierce fixed roofing material tested had sufficient strength in shear to resist lateral forces for Terrain Category 3 on domestic type buildings, although it significantly lowered the overall factor of safety on the roof system. For Terrain Categories 1 and 2, bracing walls should be at spacings such that roof is not overstressed, or the roofing should be supplemented with stiff bracing.

(v) As a result of the work performed in this study the action of the roof sheeting in shear has been demonstrated and a theory for it developed and confirmed with test results. Formulae have been derived which can be used to predict the onset of tearing load of the roofing. A load factor of at least 2.5 should be used in conjunction with this analysis.

Elastic deflection of the sheeting fastener system can also be predicted.

For loads on a building parallel to corrugations in roof sheeting

$$W_{on} = \frac{2.6\ n\ Fu}{b} \qquad {}^{*}\delta = \frac{6\ W\ Fu\ s\ f}{n}$$

For loads on a building perpendicular to corrugations of roof sheeting

$$W_{on} = \frac{2.67\ n\ Fu}{d}\left(\frac{b}{d}\right) \qquad {}^{*}\delta = \frac{3}{2}\,\frac{W\ Fu\ s\ f}{n}\,\frac{d^3}{b^3}$$

W_{on} - uniformly distributed load at top plate that gives rise to onset of tearing in roof sheeting.

W - uniformly distributed working load at top plate.

n - number of battens in the stressed section of roof.

b - width of building (measured perpendicular to corrugations).

d - depth of building (measured parallel to corrugations).

Fu - tearing load of a single fastener loaded parallel to the corrugations.

s - spacing of fasteners along a batten.

δ - horizontal deflection at midway between bracing walls due to deformation of the sheeting-fastener system.

f - single fastener flexibility loaded horizontally parallel to the corrugations.

* NOTE - deflections are elastic deflections assuming rigid frame. Actual deflections can be up to 4 mm higher allowing for movement of fasteners within holes and framing elements.

ACKNOWLEDGEMENTS

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(b) Parkside Timber Co. for donating the timber.

(c) Ramset Fasteners (Aust.) Pty. Ltd., for donating the batten-to-rafter screws.

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APPENDIX A
MATERIALS TESTS

A series of tests were performed on the screw fasteners used, to determine their properties, and the properties of the sheeting to batten joints.

Screws - Deutscher Type 17, 12-10, 50 mm long with 5.2 mm shank diameter

Sheeting - Lysaght Custom Orb, Zincalume finsih, overall thickness of sheeting 0.48 mm.

Battens - 75 x 38 Brown Tulip Oak Moisture content 15-19%.

Screws were tightened to compress the neoprene washer against the roof sheeting but not to deform the sheeting.

A.1 Shear Strength and Flexibility of the Sheeting-to-Batten Joint.

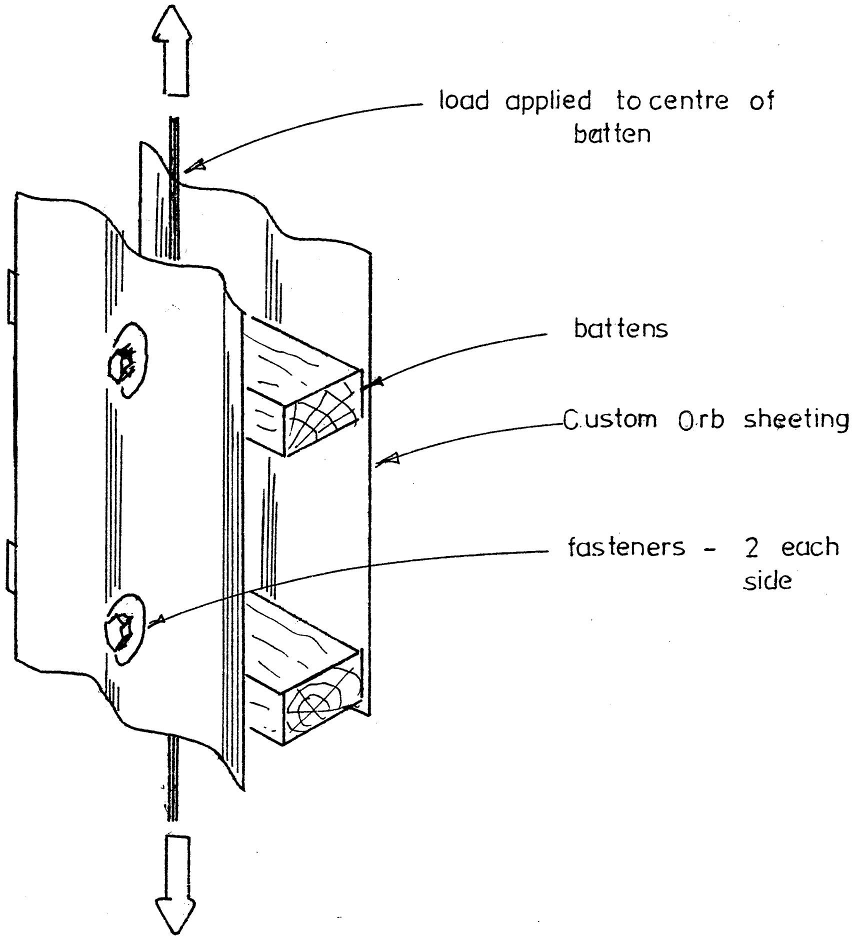


FIGURE A.1 Testing of Sheeting to Batten Fastener

Test specimens were set up as shown in Figure A.1. Each batten carried two fasteners - one on each side, and the load was applied to the centre of the batten. This distributed half the applied load to each fastener and each piece of sheeting.

Results are as follows.

Test	Ultimate load per fastener
1	1.69
2	1.54
3	1.62
4	1.67
5	1.47

Mean ultimate load 1.60 kN standard deviation 0.09 kN. For single sided 95% confidence limit have characterised ultimate strength = 1.6 - 2.13 x 0.09
= 1.4 kN.

The load versus deflection curve is as shown in Figure A.2. An elastic portion can be seen at the bottom of the curve. At approximately 0.4 times the failure load, permanent deformation of the fastener took place. At the failure load, the sheeting started to tear, and this load could be reached again while the fastener tore through the sheeting.

From the elastic portion of the curves, the mean flexibility of the fastener was found to be 2.0 mm/kN.

NOTE - this flexibility included some sheet flexibility but as this amounted to only 0.013 mm/kN it can be ignored.

A.2 Shear Strength and Flexibility of the Sheeting-to-Batten Lapped Joint

Test specimens for this test were set up as shown in Figure A.3. Load was applied to the joint by loading the two pieces of sheeting directly. The load was transferred between the two sheets through two fasteners. The load carried by each fastener then was half the direct load applied.

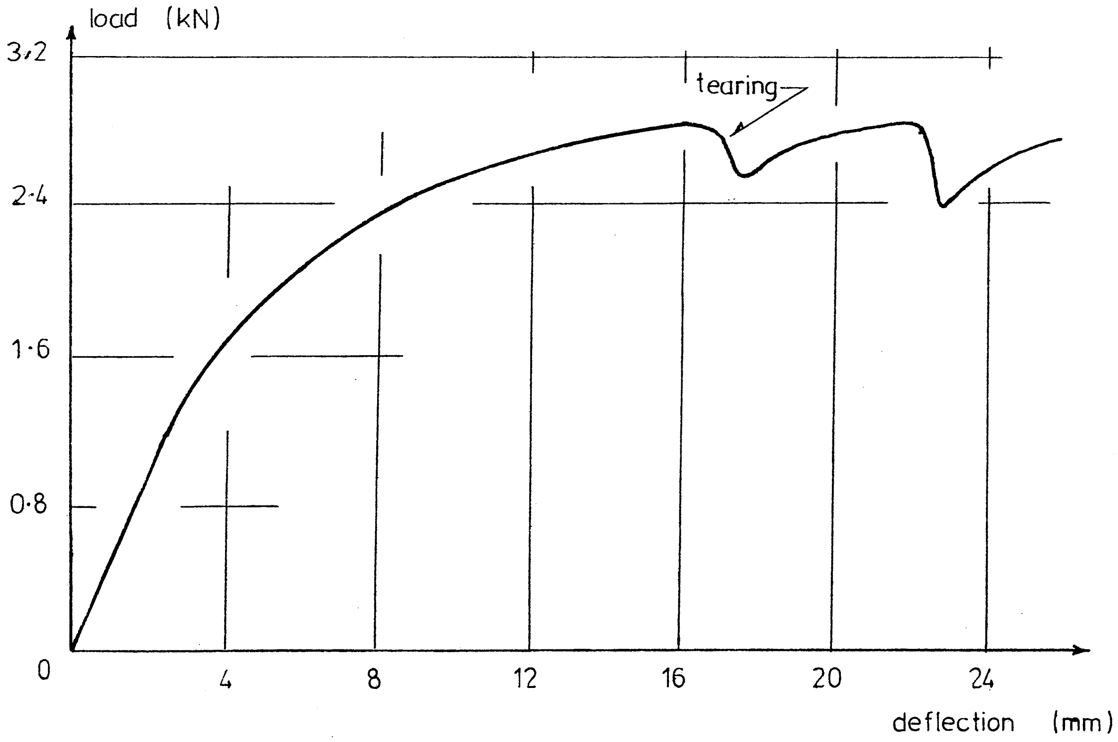


FIGURE A.2 Load Deflection Curve for Sheeting to Batten Joint

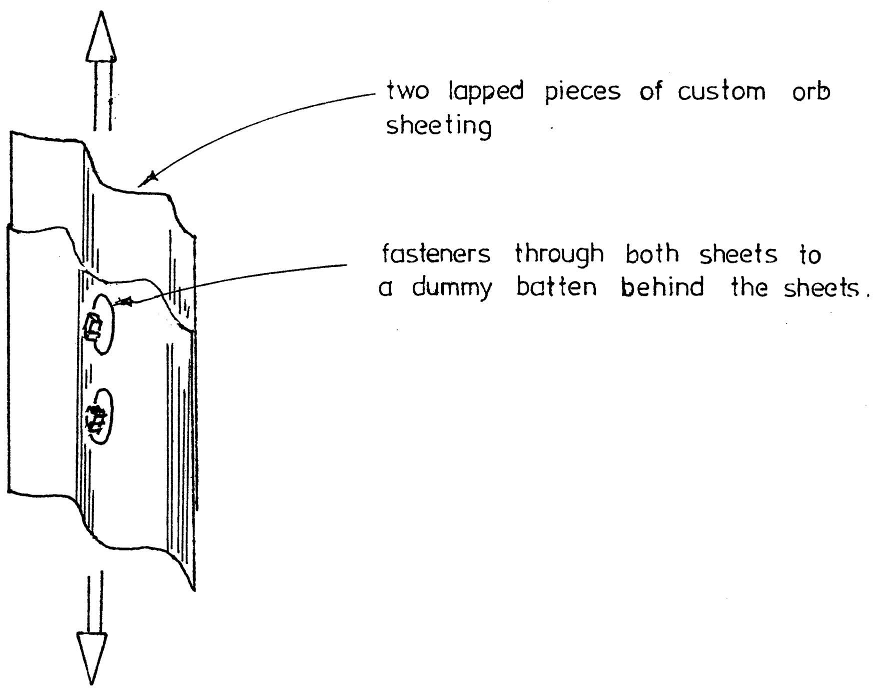


FIGURE A.3 Testing of Sheeting to Batten Fastener with Lap Joint

Results of the tests on sheeting-to-batten fasteners with lap joints are as follows.

Test	Ultimate load per fastener (kN)
1	2.16
2	2.14
3	2.14
4	1.94
5	2.11

Mean ultimate load 2.1 kN, Standard deviation 0.09 kN. For single sided 95% confidence limit have characteristic ultimate strength = 2.1 - 2.13 x 0.09
= 1.9 kN.

The characteristic tearing load was 1.43 kN and the mean flexibility of the fastener was 1.0 mm/kN.

The ultimate strength was comparable with that obtained for the simple sheeting to batten fastener but the flexibility was significantly less. The higher flexibility of the simple sheeting to batten fastener was due to the flexibility of the fastener itself. This was not a factor in the lapped joint test.

In both the lap joint and plain configurations, the sheeting started to tear at about the same load - 1.4 kN. This load was adopted as the value of F_u in this paper.

APPENDIX B
ROOF PANEL TESTS

The test panels were set up as shown in Figure 12. The load was applied by a jack which can be seen in the top right hand corner of the photograph. The different geometries tested can be seen in Figure 13. The spacing between battens was uniform at 900 mm and each sheet had 760 mm between outside fasteners.

B.1 Deflection Analysis

In order to obtain an accurate measure of the shear deflection of the roofing panel it was necessary to account for distortion of the batten to rafter joints and the support system. This was accomplished using the gauge system shown in Figure B.1.

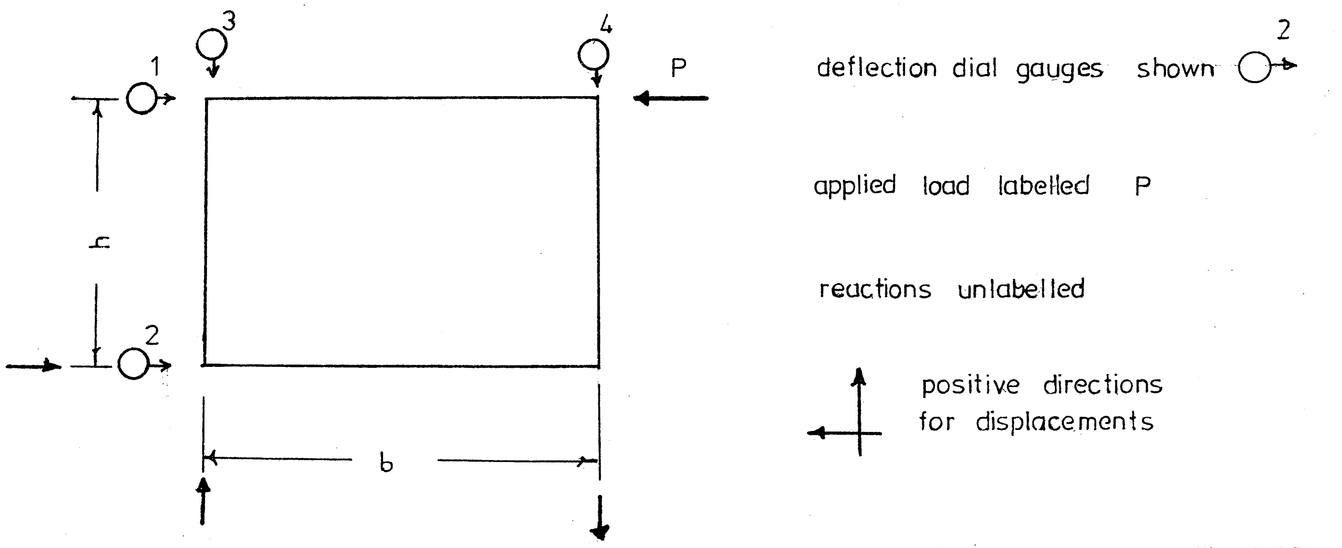


FIGURE B.1 Deflection measurements on test panels

Gauge 1 registered δ_1, the total movement of the top of the rig parallel to the applied load. Gauge 2 registered δ_2, the movement in the reaction support at the base of the frame. Gauges 3 and 4 registered δ_3 and δ_4 respectively - the vertical movement of the tops of the purlins at the end of the test piece. δ_s is the shear deflection.

$$\delta_s = \delta_1 - \delta_2 - (\delta_4 - \delta_3) \times \frac{h}{b}$$

B.2 Results Tabulation

Shear Deflections for Given Loads (mm)

Test Piece	1	2	3	4	5	6
Load kN						
1	1.2	2.5	3.2	1.1	1.5	2.8
2	2.5	4.5	7.9	2.3	3.2	5.6
3	3.7	6.0	9.3	3.3	4.9	9.0
4	4.8	7.8	17.5	4.3	6.4	12.7
5	6.4	10.8		5.7	9.4	
6	8.6	16.7		8.0	12.6	
7	12.2			10.3	17.6	
8	16.0			14.1		
9	21.8			20.1		
10	28.1			27.5		
11						

These results have been plotted in Figure 15

APPENDIX C
DEVELOPMENT OF STRENGTH AND DEFLECTION THEORY

C.1 Assumptions

1. The corrugated roofing cannot transfer tension or compression across the corrugation.

2. Fasteners behave in a linear elastic manner up to the yield point.

3. Lap fasteners yield by tearing of the sheet at the same load that all sheeting to batten fasteners fail by tearing (1.4 kN).

4. Distortion of rafter to batten fixing can be ignored.

5. At ultimate conditions, all fasteners have failed by tearing of the sheeting.

C.2 Notation

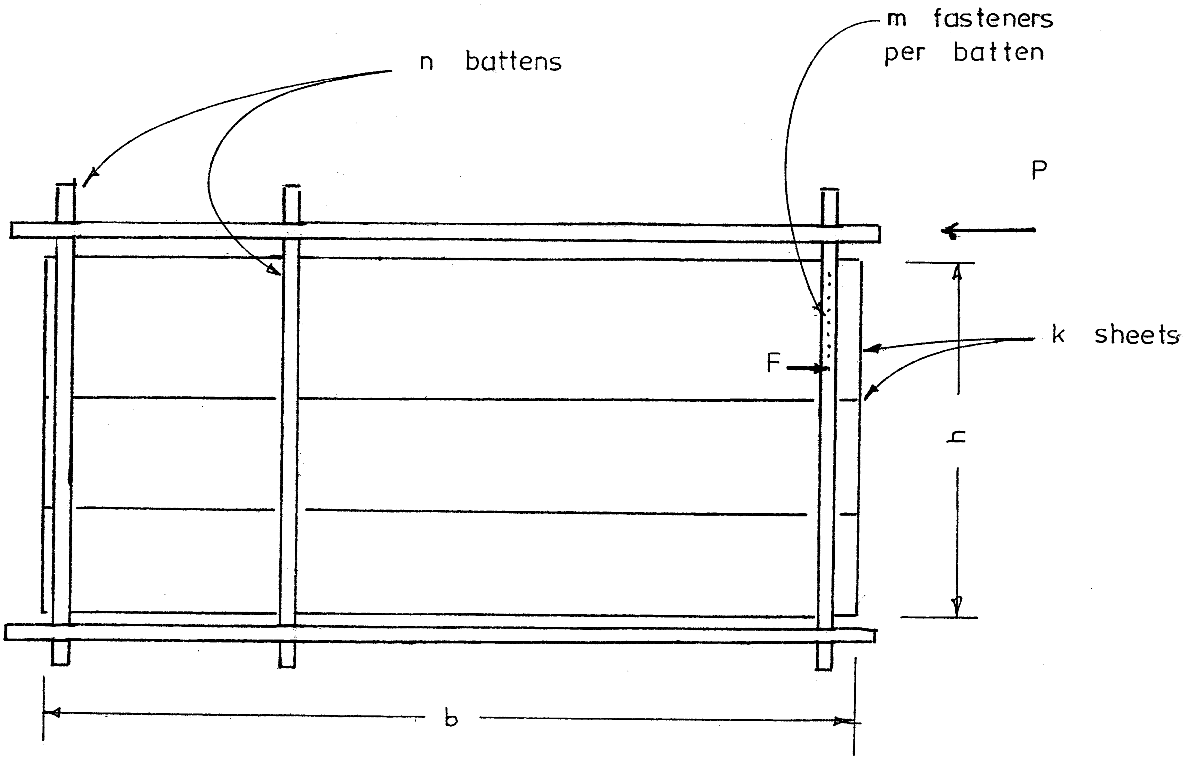


FIGURE C.1 Notation Used

b	length of panel or length of building measured perpendicular to the corrugations
f	flexibility of fasteners mm/kN
F_i	force in the i^{th} fastener
F_o	force on the outside fastener
F_u	characteristic ultimate strength of fastener
h	height of panel
k	number of sheets of corrugated roofing
m	number of fasteners per batten
n	number of battens
p	applied shear force
p_{on}	shear force at onset of tearing
p_{ult}	ultimate shear strength of panel
s	spacing of fasteners along a batten
x_i	distance from neutral axis to i^{th} fastener
δ	total deflection due to shear
δ_f	deflection due to fastener flexibility
δ_j	deflection due to movement of joints.

C.3 Load Distribution

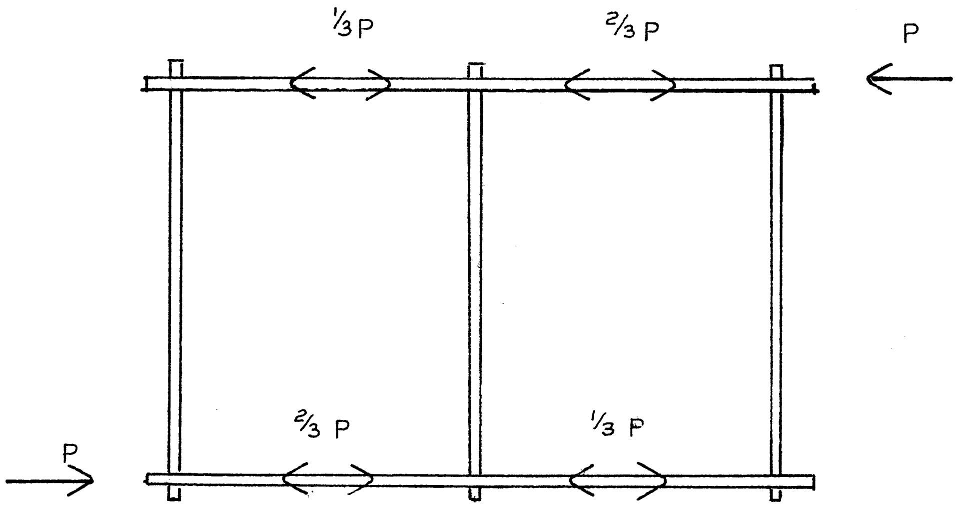


FIGURE C.2 Load Distribution

The shear resistance of the panel is provided by the fasteners on each batten. As each batten undergoes the same deflection, each batten carried the same proportion of the total load.

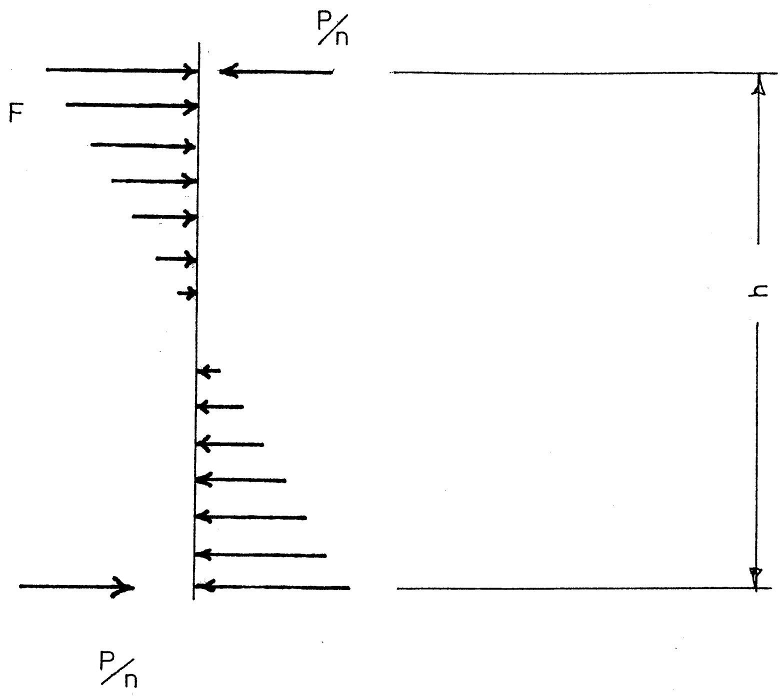


FIGURE C.3 Load on one Batten

Examining the horizontal loads on one batten, the applied forces give a moment of $\frac{Ph}{n}$ which must be resisted by the forces on the fasteners.

C.4 Elastic Conditions and Onset of Tearing

As discussed in section 2.2, the onset of tearing is the point at which the characteristic ultimate strength of the fastener is reached at the critical lap. Figure 9 has been reproduced here to assist the development of a formula to predict onset of tearing load.

For elastic conditions the load per fastener is proportional to the distance from the neutral axis i.e. the centre of the sheet.

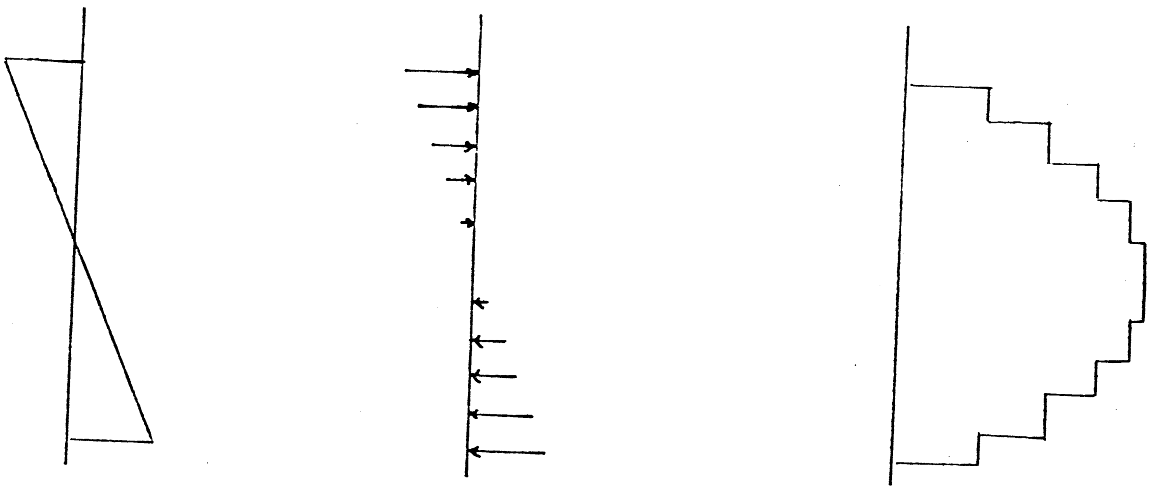


FIGURE C.4 Strain, load per fastener and shear in sheeting for elastic conditions.

i.e.
$$F_i = F_o \frac{x_i}{h/2}$$

$$F_i = \frac{2F_o}{h} x_i$$

i.e. resisting moment $= \Sigma F_i x_i = \frac{2F_o}{h} \Sigma x_i^2$ (1)

Equating resisting moment and applied moment gives

$$F_o = \frac{Ph^2}{2n\Sigma x_i^2} \qquad (2)$$

Now at onset of tearing.

For test pieces $F_u = \Sigma F_j$ j for all fasteners from edge of sheet to critical lap.

where
$$F_j = \frac{2F_o x_j}{h}$$

i.e.
$$F_u = \frac{Ph}{n} \frac{\Sigma x_j}{\Sigma x_i^2}$$ at onset of tearing.

rearranging given $$P_{on} = \frac{n F_u \Sigma x_i^2}{h \Sigma x_j}$$ i for all fasteners/battens
j for fasteners between edge and critical lap (3)

This formula was used to predict onset of tearing load for panels 1, 2 and 3 given in Table 1.

For the simple cases of panels 4, 5 and 6 where there was no lap joint, the onset of failure corresponds to the condition of F_u being reached at the outermost fastener i.e. $F_o = F_u$ in eqn. (2)

i.e. $$P_{on} = \frac{2F_u n \Sigma x_i^2}{h^2}$$ i for all fasteners/batten (4)

This formula was used to predict onset of tearing load for panels 4, 5 and 6 in Table 1.

C.5 Ultimate Load Conditions

As indicated in figure 10, at ultimate conditions, the lap joints have completely failed and the resisting moment of the assembled panel is the sum of each of the individual roof sheets. The failure characteristics are shown in figure 11. At ultimate load of the roof panel F_u will have been developed in all fasteners.

Resisting moment per sheet $= F_u \Sigma x_i$ i is for all the fasteners on that sheet only

then for k sheets of roofing $\frac{Ph}{n} = kF_u \Sigma x_i$

i.e. $$P_{ult} = \frac{nk F_u \Sigma x_i}{h} \qquad (5)$$

i is for all fasteners per batten per sheet of roofing.

C.6 Deflections

The deflections of the panels in pure shear are given by the sum of deflections due to the fasteners + shear deflection of the sheeting + deflection of batten to rafter joints. Deflection of the sheeting was found to be minimal compared to the deflection due to the fasteners and that due to the batten to rafter joints. It was therefore ignored. Thus

$$\delta = \delta_f + \delta_j$$

(i) Deflections due to the fasteners.

From the tests on the fasteners outlined in Appendix A, a linear elastic portion of their response to load can be isolated. The flexibility of the joint can be designated f. For elastic deflection

$$\delta_f = 2fF_o$$

then from equation (2)

$$\delta_f = \left(\frac{fh^2}{n\ \Sigma x_i^2}\right) P \qquad (6)$$

(ii) Deflections due to the batten to rafter joints.

These joints were flexible and gave rise to elastic deformation. The top joints each carried a horizontal force of $\frac{P}{n}$ and the bottom joints also carried a horizontal force of $\frac{P}{n}$. Hence the horizontal deflection due to both of these forces is equal and is eliminated in the calculation of the shear deflections. However the bottom joints were subject to a vertical force of $\frac{Ph}{nb}$.

$$\delta_j = \frac{vh}{nb} P$$ v is a proportionality constant.

i.e. $$\delta = \left(\frac{fh}{\Sigma x_i^2} + \frac{vh}{b}\right) \frac{P}{n} \qquad (7)$$

In this equation, all terms are known except v. At least squares analysis was used to determine the v = 1.5 mm/kN for the panels tested. This gives δ as a function of P and is valid over the elastic range. The upper limit of this range - the yield point has been plotted in Figure 15 for each wall panel tested.

The yield load can be found from equations that have been developed. The fasteners start to bend when the horizontal load per fastener reaches 0.4 Fu.

thus yield load can be found by substituting

$$F_o = 0.4\,Fu \qquad \text{in equation (2)}$$

$$\text{giving yield load} = \frac{0.8\,Fu\,\Sigma x_i^2}{h^2}$$

However in some cases onset of tearing may occur before the outside fasteners start to bend. Thus the yield load is the lesser of

$$P_{on} \quad \text{and} \quad \frac{0.8\,Fu\,\Sigma x_i^2}{h^2}$$

C.7 Onset of Tearing Load for a Roof

This case differs from the pure shear of the simple panels tested as a uniformly distributed load gives rise to a curved deflected shape.

The load on each fastener is proportional to its deflection. Thus for a deflected shape of the quadratic form, the force on each fastener is

$$F_i = a\,x_i^2 + c$$

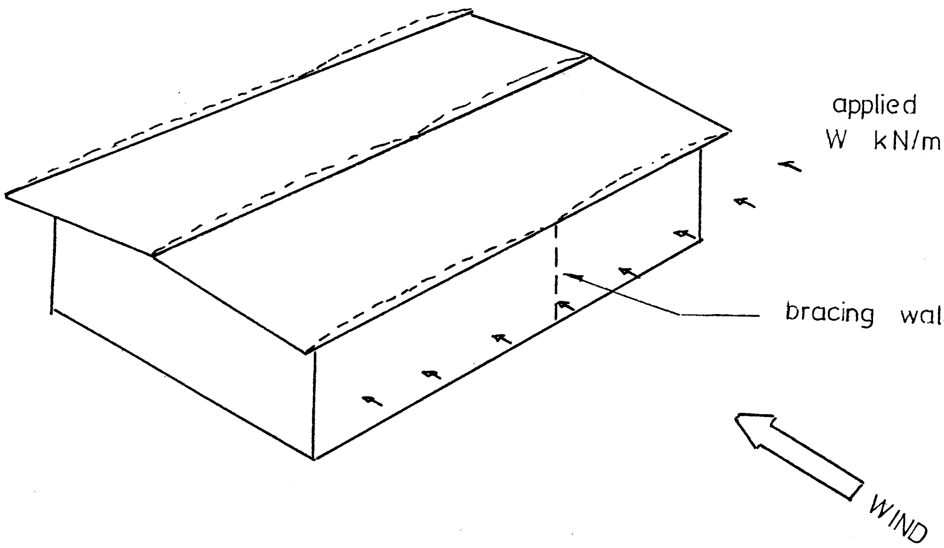
by summing over all fasteners $\Sigma F_i = 0 \qquad i \text{ in}(-\frac{b}{2},\frac{b}{2})$

and moment at centre $= \frac{Wb^2}{8} = \Sigma F_i x_i \qquad i \text{ in}(0,\frac{b}{2})$

$$\Rightarrow \quad C = \frac{Wb^2}{8\left(\Sigma x_i - \frac{m\,\Sigma x_i^3}{\Sigma x_i^2}\right)} \qquad \text{and } a = \frac{-cm}{\Sigma x_i^2}$$

The maximum shear force at a lap in the roof sheeting occurs at

$$x_{max} = \frac{\sqrt{\Sigma x_i^2}}{m}$$



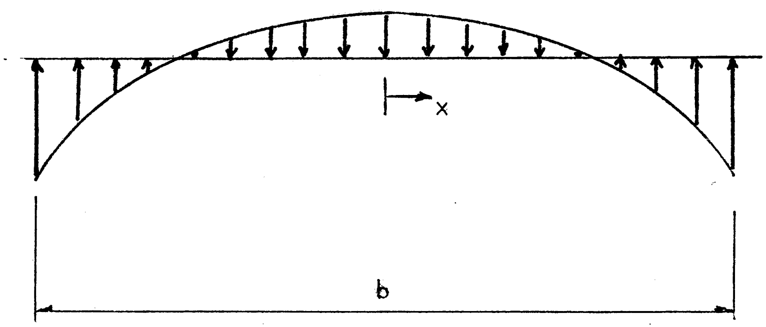


FIGURE C.5 Load and Deflection Shape for Lateral Loading of a Roof Panel

The maximum shear force at a lap is ΣF_i

(i from the edge of the sheet to x_{max}).

i.e. onset of tearing load $= \Sigma(a\ x_i^2 + c)$

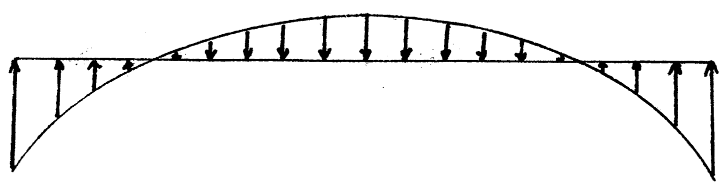
(i from the edge of the sheet to x_{max}).

The maximum deflection can be found from

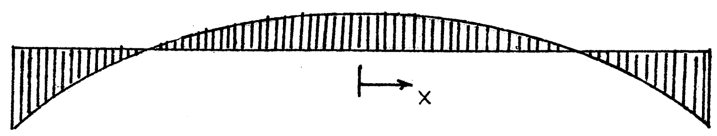
$$f(F_o - c) = \frac{f\ a\ b^2}{4}$$

C.8 Derivation of a Simple Formula for Onset of Failure Conditions in a Roof

The analysis given in C.7 is greatly simplified if it is assumed that the moment at the centre of the panel is resisted by a continuously varying stress field rather than by a number of discrete fasteners.



(i) load resistance by discrete fasteners



(ii) assumed equivalent stress field

FIGURE C.6 Assumed Stress Field along a Batten

Assuming the same shape used in section C.7, and integrating to find the moment at the centre

$$\text{force/unit length} = \frac{24\ W\ x^2}{b} - 2W \qquad (9)$$

integrating between the point with zero force per unit length and the end maximum shear force in roof sheeting

$$= \frac{4}{3\sqrt{12}}\ Wb$$

$$= 0.38\ Wb \qquad \text{and occurs at} \qquad x = 0.29\ b$$

w at onset of tearing by equating $F_u = 0.38\ Wb$

$$W_{on} = \frac{2.60\ n\ F_u}{b}$$

This equation is not very sensitive to the initial assumption of deflected shape. If a linear deflected shape is assumed of the form

$$\text{force/unit length} = \frac{12\ W}{b}\ |x| - 3W$$

(This would correspond to pin joints in wall plates and battens midway between bracing walls).

For this deflected shape

$$W_{on} = \frac{2.67\ n\ Fu}{b}$$

i.e. higher than for quadratic deflected shape.

The difference is not significant and so the relationship recommended is

$$W_{on} = \frac{2.6\ n\ Fu}{b} \qquad (10)$$

By comparing W_{on} from this analysis with that obtained using the techniques indicated in section C.7 shows that the assumption is valid for length of panel/spacing of fasteners greater than 15, and is independent of the spacing of the fasteners.

Maximum deflections can also be obtained from the above analysis.

$$\text{Force on individual fastener} = \text{force/unit length}\ \frac{s}{n}$$

i.e. displacement of an individual fastener $= \frac{fs}{n}\ \left(\frac{24\ W\ x^2}{b} - 2W\right)$

$$\text{Max disp} = \delta(x=0) - \delta(x = \tfrac{b}{2}) = \frac{6\ f\ s\ W}{n} \qquad (11)$$

As can be seen from this relationship, deflection is proportional to the fastener spacing, and the fastener flexibility. Both of these parameters have been decreased in recent years, particularly for cyclone prone areas.

This has a drastic effect on the stiffness of roof panels subjected to in-plane-of-roof forces and will have implications for the building industry. This will be the subject of another Technical Report.

C.9 Roof Bracing for Horizontal Loads Perpendicular to Corrugations

The derivation W_{on} and δ for this case follows closely the method outlined in section C.8. However in this instance the load is applied across the corrugations, and can be replaced by an equivalent load parallel to the corrugations.

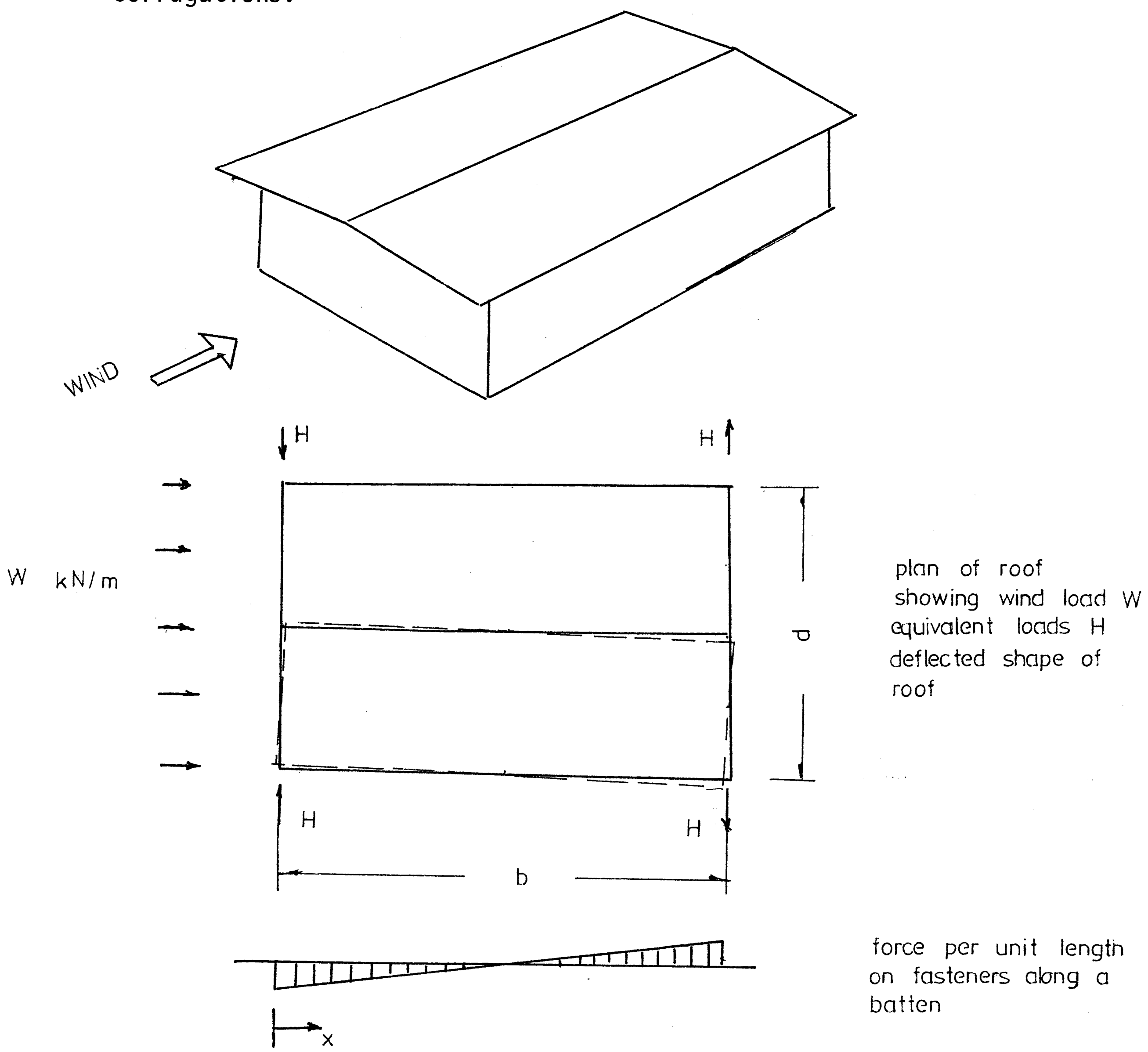


FIGURE C.7 Loads & Deflections of Roof with End-on Wind

The load perpendicular to the corrugations can be replaced with point loads H at each end of the roof panel

$$H = \frac{wd^2}{8b}$$

the deflected shape along each batten then is linear giving

$$\text{force/unit length} = \frac{12\ H\ x}{b^2} - \frac{6H}{b} \qquad (12)$$

by equating forces to zero and moments to Hb on one side of the roof only.

This gives the maximum shear at the centre is $\frac{3H}{2}$.

This can be equated with $\frac{n}{2}$ Fu (only half the battens in the roof have been considered in determining maximum shear).

$$\Rightarrow \quad H_{on} = \frac{n\ Fu}{3}$$

equating with $H = \frac{Wd^2}{8b} \Rightarrow W_{on} = \frac{2.67\ n\ Fu}{d}\left(\frac{b}{d}\right)$ (13)

This has the same basic form as equation (10), but the $(\frac{b}{d})$ term accounts for the fact that battens run parallel to the applied force.

Similarly deflections can be derived from equation (12).

The force on the corner fastener $= \frac{6H}{b} \times \frac{2\ S}{n}$

then deflection of corner fastener

$$= \frac{12\ f\ Hs}{bn}$$

i.e. deflection at ridge $= \delta = \frac{12\ f\ Hs}{bn}\left(\frac{b}{d}\right)$

from $H = \frac{Wd^2}{8b} \Rightarrow \delta = \frac{3}{2}\ f\ \frac{Ws\ d^3}{n\ b^3}$ (14)

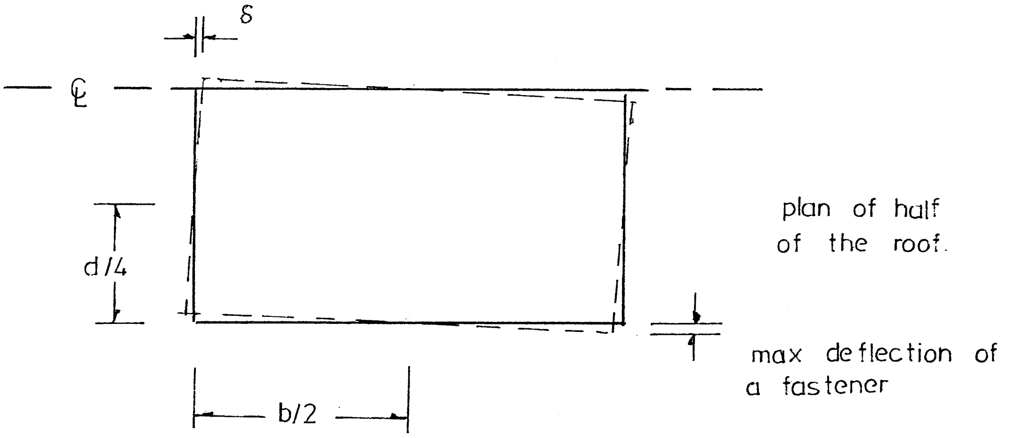


FIGURE C.8 Deflection of Roof Material

Comparing the performance of roof sheeting bracing for forces acting parallel to the corrugations to the performance for forces acting perpendicular to the corrugations significant differences can be seen.

The onset of tearing load for wind perpendicular to the corrugations is $\frac{b}{d}$ times that for wind parallel to the corrugations. For most configurations then, the sheeting will be able to sustain higher loads when wind is normal to a gable. In this direction, the deflections are significantly effective. For houses with $\frac{b}{d} > 1.5$, the bracing action of the roof sheeting can carry wind load for terrain category 3 throughout Australia without additional roof bracing in this direction.

C.10 Deflections of Roof Sheeting at Maximum Design Load

In sections C.8 and C.9, the elastic deflection of the roofing system was found. The total deflection midway between bracing walls will be composed of the elastic deflection of the roofing system + deflection of joints in roof system + free play in roof fasteners.

From equation (7) the deflection of joints in the system can be represented by

$$\text{load} \cdot \frac{v \cdot \text{panel dimension across corrugations}}{n \cdot \text{panel dimension along corrugations}}$$

i.e. $$2W \frac{v\,b^2}{nd}$$

From equation (12) the elastic deflection of the sheeting is

$$\frac{6\,f\,W\,s}{n}$$

free play in roof fasteners is typically 1 mm.

i.e. deflection midway between bracing walls for wind parallel to corrugations

$$\delta = \frac{6\ f\ W\ s}{n} + \frac{2v\ W\ b^2}{nd} + 1\ \text{mm}$$

$$= Wn\ (6\ f\ s + \frac{2v\ b^2}{d}) + 1$$

Now

$$W = \frac{W_{on}}{2.5} = \frac{2.6\ n\ Fu}{2.5\ \ b}$$

$$\Rightarrow \quad \delta = 1.04\ Fu\ (\frac{6\ f\ s}{b} + \frac{2v\ b}{d}) + 1$$

This then gives the maximum allowable deflection of the roofing for the load factor on bracing loads to be larger than 2.5.

Evaluating δ_{max} for different b using

f =	2.0 mm/kN	evaluated from tests
s =	0.152 m	Lysaght recommendations
Fu =	1.4 kN	evaluated from tests
d =	7.2 m	typical
v =	1.5 mm/kN	evaluated from panel tests

$$\delta_{max} = 1.46\ (\frac{1.82}{b} + 0.426) + 1$$

b	2	3	4	5	6	m
δ_{max}	3.54	3.71	4.10	4.57	5.09	mm

Evaluating δ_{max} for different b as indicated above shows little variation in δ_{max} with b. The maximum allowable deflection midway between bracing walls is between 4 and 5 mm. If this value is exceeded, the sheeting will have been overstressed and failure could result.

If the roof framing is to be used to brace the roof, the bracing in the framing must not allow deflections greater than 5 mm midway between bracing walls.

By comparison for wind normal to the gable δ_{max} can be found from

$$\delta_{max} = 1.07\ Fu(1.5 \frac{f\ s\ d}{b^2} + \frac{v}{4}) + 1\ mm$$

for values of f, s, Fu, d and V as above and b = 15 m (the length of a small house)

$$\delta_{max} = 1.6\ mm$$

This is significantly less than the deflection for loads acting in the other direction, and indicates that the roof has greater stiffness and hence will attract nearly all loads acting on the gabled end. Load carrying capacity in this direction is sufficient.

$$W_{on} = 2.67 \frac{n\ Fu}{d} (\frac{b}{d}) = 10.8\ kN/m$$

i.e. $\frac{W_{on}}{2.5}$ = allowable load = 4.32 kN/m with load factor 2.5.

corresponding to a q_z of 3.14 kPa with overall C_p of 0.8 + 0.3 = 1.1
and wall height = 2.5 m

then wind speed at 3 m = 72 m/s

i.e. ample load resistance for wind forces throughout Australia when considering bracing of building for horizontal loads perpendicular to sheeting corrugations.

Bracing action for loads parallel to the corrugations is critical.