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COMPARISON OF TESTS OF PURLINS WITH AND WITHOUT CLEATS

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SUMMARY

The paper describes a series of tests on Z-section purlins lapped over three spans and subject to wind uplift loading. The purlins were not attached to the rafters by cleats. Sheeting was screw-fastened to the purlins and a range of bridging (bracing) members was used to prevent lateral deflection and twisting. The results of the tests are compared with earlier tests with the same configurations but including cleats at the supports.

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1 INTRODUCTION

In Australia, it is customary to use cleats at support points to connect purlins to the rafters of frames. The cleats provide both lateral and torsional restraints at the supports as well as acting as web stiffeners to prevent web crippling. Substantial test series on purlins with cleats have been performed in the vacuum test rig at the University of Sydney and were reported in the 10th, 11th and 12th Specialty Conferences on Cold-Formed Steel Structures in St Louis (Hancock et al, 1990, Hancock et al 1992, Hancock et al, 1994) However, cleats are expensive items to attach to the rafters of frames and so a research project to investigate cleatless systems has been undertaken recently.

As part of this project, a further test series has been performed on cleatless purlin systems under simulated wind uplift using the same purlin sizes, sheeting configuration and bridging systems as the earlier tests of purlin systems with cleats to allow direct comparison. The paper describes the cleatless purlin tests and compares the results with the earlier tests described in Hancock et al (1990). The forces in the bridging systems were found to be substantial and are compared with design formulae specified in the AISI Specification, Clause D3.2.1.

2 TEST RIG

The test rig consists of a vacuum chamber of length 21 metres (68 ft 10.5 in), of height 4 metres (13 ft 1.5 in) and of width approximately 1 metre (39.3 in). The front and back planes (21 m x 4 m) consist of purlin and sheeting roofing systems sealed with plastic sheeting located between the purlins and metal roof sheeting. Cross-sections of the rig are shown in Fig. 1.(a) (Tests CP1, CP2 and CP3) and Fig. 1.(b) (Tests CP4 and CP5). The top, bottom and end planes consist of stiffened steel plating with the stiffeners external to the vacuum chamber. The plastic sheeting is attached to the top, bottom and end planes in such a way so as not to constrain the roofing system under test.

Transverse support frames, as shown in Fig. 1.(a) and 1.(b), support vertical I-section steel members. The vertical members simulate rafters in prototype structures. The purlins are directly attached to the vertical members with bolted connections. The purlins and sheeting are not attached to the vacuum chamber or support frames at any other point other than through the bridging members described in Section 3.4.

Air is sucked from the chamber using a Nucon Exhauster with capacity 3600 m^3 (127133 ft^3) per hour. The pressure in the chamber is controlled by an adjustable flap at the northern end which provides a controlled leak. The pressure difference between the inside and outside of the chamber is measured using two pressure transducers, one at either end of the rig.

3 TEST SPECIMENS

3.1 Overall Geometry

Two different test setup configurations were used in this test program. The span dimensions of the three span lapped test specimens were 7 metres (22 ft 11.5 in) long by 4 metres (13 ft 1.5 in) high, as shown in Fig. 2.(a) (Tests CP1, CP2 and CP3) and Fig. 2.(b) (Tests CP4 and CP5). Tests CP1, CP2 and CP3 had four lines of purlins equally spaced at 1200 mm (47.2 in), with the line of the screws of the two outer purlins located approximately 200 mm (7.9 in) from the top and bottom of the sheeting. Tests CP4 and CP5 had three lines of purlins equally spaced at 1400 mm (55.1 in), with the line of the screws of the two outer purlins located approximately 600 mm (23.6 in) from the top and bottom of the sheeting. The test specimens were attached to the I-section rafters at 7000 mm (22 ft 11.6 in) centres. The ribs of the sheeting were located vertically.

3.2 Purlin Types and Dimensions

Two Z-sections purlin types were used for the testing. Section Z20015, used in Tests CP1, CP2 and CP4, was nominally 200 mm (7.87 in) deep with 1.5 mm (0.059 in) nominal thickness. Section Z15019, used in Tests CP3 and CP5, was nominally 150 mm (5.91 in) deep with 1.9 mm (0.075 in) nominal thickness.

In all tests, the purlins were oriented in such a way that the end spans had the narrow flange unsheeted and the centre span had the wide flange unsheeted.

The dimensions and geometry of both sections are detailed in Figs 3(a) and 3(b).

3.3 Sheeting Types and Screw Fastenings

BHP Building Products TRIMDEK HI-TEN ZINCALUME sheeting was used in all three test spans for all tests. The nominal sheeting thickness was 0.42 mm (0.017 in) (0.47 mm (0.019 in) including coating).

In all tests, No. 12 x 45 hex head self-tapping screws with a washer under the head of each were fastened at every crest. In Tests CP1, CP2 and CP3, neoprene washers were used, but in Tests CP4 and CP5 cyclone washers were used due to the 600 mm (23.6 in) long cantilever spans at the top and bottom of the sheeting.

3.4 Bridging

Bridging was used in all tests, except Test CP2. The bridging consisted of unlipped channels bolted at each end to the webs of the purlins. One row of bridging in each span was used. The bridging in the CENTRE span was located at the purlin midspan as shown in Figs 2(a) and 2(b). The bridging in the end spans (NORTH and SOUTH) was located at points close to the point of maximum deflection for a three span continuous beam.

Two sizes of bridging were used for the tests. In Tests CP1 and CP3 (4 rows of purlins), 1200 mm (47.2 in) long 75 mm (2.95 in) x 32.5 mm (1.28 in) x 1.25 mm (0.05 in) channel bridging was used. In Tests CP4 and CP5 (3 rows of purlins), 1400 mm (55.1 in) long 75 mm (2.95 in) x 32.5 mm (1.28 in) x 1.0 mm (0.039 in) channel bridging was used. The bridging in Tests CP1 and CP3 only spanned between the purlins and was not connected to external supports. The bridging designated 1-1-1 in Table 1 refers to one row of bridging in each span. The positions of the rows of bridging are shown for each test specimen in Figs 2(a) and 2(b).

To prevent the whole system moving vertically during loading in Tests CP4 and CP5, a wheel system attached to the bridging was used during testing. The system consisted of steel wheels located at the bottom of the rig and were allowed to move inwards during loading. The vertical post fixed to the wheels was connected to the underside of the bottom purlin at the position of the bridging and prevented the purlins from moving up at the bridging point. In this case, the member supporting the wheel was subject to a tensile force. The wheel system is shown diagrammatically in Fig. 4. From the figures, it can be seen that the wheels bore upon two telescopic horizontal arms which acted as a guide for the wheels. The telescopic arms consisted of two steel channels which slid over two standard RHS (Rectangular Hollow Section). The RHS were connected to a very stiff SHS (Square Hollow Section), which was mounted on the laboratory strong floor. The top RHS and the steel angles bolted to the vertical post were used to transfer the load from the wheels to the portable jack whilst the two steel channels were adjusted during testing. This was carried out to enable the steel channels to slide over the RHS without requiring force to overcome the wheel loads. The extension of the arms allowed the wheel to move further inwards until the end of the test. The locations of the wheel system are shown in Fig 2.(b).

3.5 Laps and Bolts

BHP Building Products M12 Grade 8.8 (ASTM A325 0.5 in), 30 (1.18 in) mm long bolts were used for all bolt connections on test specimens. All bolts were torqued to 40 ft.lbs. (54 Nm). Two bolts at 80 mm (3.15 in) spacing were used to attach the flange to the rafters at the mid supports and one bolt was used at the end supports to bolt the flange onto the rafter. The ends of the purlin laps were each connected with two bolts by placing one of them at the unsheeted flange and the other at the web, closer to the sheeting.

3.6 Measured Proof Stresses of Purlins

The proof stress and tensile strength were determined by carrying out tensile coupon tests in accordance with AS 1391-1991 "Methods for tensile testing of metals". One coupon was cut from the centre of the web of the purlins from Row 2 for each test. The average proof stress and tensile strength determined from these coupon tests are 529 MPa (76.7 ksi) and 555 MPa (80.5 ksi) respectively for the Z20015 Section and 511 MPa (74.1 ksi) and 542 MPa (76.0 ksi) respectively for the Z15019 Section.

4 TEST PROCEDURE AND INSTRUMENTATION

4.1 Instrumentation

4.1.1 Displacement and Pressure Transducers

The tests were instrumented to electronically measure displacements and pressures. The positions of the displacement transducers are shown in Fig. 5.(a). Each purlin had a transducer attached to its midspan point at the outside corner between the flange and the web of the purlin to measure horizontal deflections. These transducers were connected to the test specimen with long wires, as shown in Fig. 5.(b), so that displacements normal to the direction being measured did not produce a significant alteration in the readings. Each purlin in Row 2 had at its midspan an additional pair of transducers to measure vertical deflections of the front (unsheeted) and back (sheeted) flange. Due to the complex setup for measurement of vertical deflections, these readings had to be adjusted for inward displacements of the purlin. Each support of the northern span of Row 2 had a pair of transducers used to measure the distortional deformation of the unsheeted flange by measuring deformation of the flange-web junction parallel with the web, and the vertical deformation of the sheeted flange by measuring the vertical deformation web of the purlin at a distance approximately equal to the lip depth from the sheeting. The positions of these transducers are shown in Fig. 5.(b).

Two pressure transducers were used, one at each end of the vacuum rig. The pressure applied to the test specimen was a pressure difference between the outside air and the air inside the chamber. The instrumentation was connected to a data logger which consisted of a SPECTRA automatic data acquisition system interfacing to an IBM compatible computer.

4.1.2 Strain Gauges

To determine the force restraining the bridging members during loading in Tests CP4 and CP5, strain gauges were attached at the sides of the vertical post holding the wheels at each span. Four gauges were attached on two opposite sides with two on each side, and were positioned near the mid height of the vertical post, as shown in Fig. 4.

4.2 TEST PROCEDURE

The pressure was generally increased in 0.1 kPa (2.1 psf) increments until the vicinity of failure where the increment was reduced to approximately 0.05 kPa (1.04 psf). Readings of pressure and displacement were taken at all increments. Readings were normally taken after unloading to determine the permanent deformation in the structure.

5 TEST RESULTS

5.1 Measured Failure Pressures

A complete summary of the measured pressure differences at failure is given in Table 1. The range varied from 1.90 kPa (39.7 psf) for the Z15019 purlin in three rows with bridging and wheel supports (Test CP5) to a value of 2.58 kPa (53.9 psf) for the Z20015 purlin in four rows with bridging but without wheel supports (Test CP1).

5.2 Failure Modes

In all tests, failure occurred in the end spans (NORTH or SOUTH) at the points of maximum deflection. In Tests CP1, CP2 and CP3 (four rows of purlins, no wheel supports) failure occurred in the two middle rows of purlins (Rows 2 and 3). In Tests CP4 and CP5 (three rows of purlins and wheel supports) failure initially occurred in either of the two lower rows of purlins (Rows 1 and 2) followed by the failure in the other rows.

In Test CP1, the end supports failed at an applied pressure of 2.15 kPa (44.9 psf) by the bolt pulling through the purlin flange. The test was stopped and continued after placing a 5 mm (0.2 in) thick 50 mm (1.97 in) x 50 mm (1.97 in) washer between each bolt head and the flange at the end supports. To eliminate the problem of bolts pulling through the flanges, the same washers were used for all further tests. After reloading, Test CP1 failed in Rows 2 and 3 of southern span by flange-web local buckling at the point of bridging and by distortional buckling next to it. Test CP2 failed in Rows 2 and 3 of the northern span by flange-web local buckling at the point of maximum deflection. The direction of the buckle was opposite in the purlins in Rows 2 and 3. Prior to failure, the purlins showed the intention to twist with local buckles along the flange and web. Test CP3 failed in Rows 2 and 3 of the southern span by flexural-torsional buckling and distortional buckling near the bridging. This failure was followed by distortional buckling at the point of bridging in Rows 2 and 3 of the northern span. Although the first failure occurred at 2.45 kPa (51.2 psf), due to catenary action, the system was able to sustain higher load.

The loading was stopped after applying a pressure of 2.55 kPa (53.2 psf).

Test CP4 failed in Row 1 of the southern span by distortional buckling near the wheel support. This failure was followed by local and distortional buckling of all three purlins of the northern span in vicinity of the bridging. Test CP5 failed in Row 2 of the northern span by distortional buckling at the point of bridging, followed by the failure of all other purlins in Rows 1 and 2, near the wheel supports.

5.3 Load-Deflection Response

Test CP1 exhibited vertical deflections of the unsheeted and sheeted flanges on Row 2 of the order of 40 mm (1.57 in) for both at failure. The load deflection response was linear until failure. Test CP2 exhibited vertical deflections of the unsheeted and sheeted flanges on Row 2 of the order of 80 mm (3.15 in) and 40 mm (1.57 in) respectively. The load-deflection response was nonlinear elastic. Test CP3 had a response and vertical deflections very similar to Test CP1 although the horizontal (inwards) deflections were much greater due to the smaller size of the purlins. The smaller vertical deflections of the unsheated flanges of Tests CP1 and CP3 compared with Test CP2 are a result of the torsional restraint provided by the bridging which reduced the transverse bending of the unsheated flange and distortion of the purlin web along its length.

Tests CP4 and CP5 exhibited vertical deflections of the unsheeted and sheeted flanges of the order of 10-20 mm (0.4-0.8 in) for both at failure. These are considerably smaller than Tests CP1 and CP3 due to the restraint provided by the wheel support.

In Tests CP1, CP2 and CP3 (4 rows of purlins), the horizontal displacements of the two middle purlins (Rows 2 and 3) were much higher than the displacements of the other two purlins (Rows 1 and 4). In Tests CP4 and CP5 (3 rows of purlins), the horizontal displacements of all three rows of purlins were very similar with slightly lower deflections of the bottom purlin (Row 1).

5.4 Loads On Top, Centre And Bottom Purlins

The line loads on the purlins may be computed from the average line loads on the assumption that the relative deflections are a result of the relative loads. The apparent flexibilities were computed from the horizontal deflections of the four rows of purlins. The values of flexibility were based on the deflections at 1.0 kPa (20.9 psf), 1.5 kPa (31.3 psf) and 2.0 kPa (41.8 psf) (1.9 kPa (39.7 psf) for Test CP5) and not those at ultimate. There may be a redistribution of loads between the purlins as the ultimate load of the system is approached. The computed values of the load factors and hence line loads on the purlins are set out in Table 2.

In tests with four rows of purlins (Tests CP1, CP2 and CP3), the two middle purlins (Rows 2 and 3) had a load factor on the inner purlins in the range 1.23-1.30 and failure occurred in those purlins. In tests with three rows of purlins (Tests CP4 and CP5), the purlins (Rows 2 and 3) had a load ratio slightly higher than the bottom purlin.

5.5 Strain Gauges Measuring Forces In Bridging

The measured strains in the instrumented vertical RHS of the wheel system were used to calculate the force in the RHS during loading for both Tests CP4 and CP5. The force in the RHS was calculated using $E_{steel} = 200{,}000$ MPa (29000 ksi), the average measured strains in microstrain and the nominal cross section area of the RHS section of $A = 616\ mm^2$ ($0.95\ in^2$). The resultant forces in the bridging system during the loading and unloading procedures are shown in Figs 6 and 7 respectively.

For both tests, the forces in the bridging system at the northern span were slightly lower than for the others, probably due to the initial clearance between the wheels and the two telescopic horizontal arms.

6 COMPARISON OF TEST RESULTS WITH CLEATED TESTS

The failure pressures, average line loads per purlin, computed load factors and line loads on the inner purlins for Tests CP1, CP2 and CP3, and for the top two purlins for Tests CP4 and CP5 are given in Table 2. The load factor of 1.30 for Test CP2 may be slightly high due to nonlinearity in the load deflection response of this test. The equivalent cleated test nomenclature from Series 1 (Hancock et al, 1990) is given along with the failure loads of the equivalent cleated tests. The final column in Table 2 contains the ratios of the cleatless to cleated test failure loads. The ratios range from 0.98 to 1.15 and indicate that the cleatless purlins are generally as strong as the cleated systems provided the bolts do not pull through the flanges where the purlins attach to the rafters. The only test where the ratio was less than 1.00 is CP4 which is a slender Z20015 section with bridging tied back to a rigid support which produced localised stress and failure at the restraint point. The tests without cleats and without the bridging being tied back to rigid supports have an increase in load capacity on average of approximately 10 percent over the cleated purlins.

7 COMPARISON OF BRIDGING FORCES WITH SPECIFICATION VALUES

In Section D of the AISI Specification, Clause D3.2.1, design rules are given for the anchorage of Z-section purlins with sheeting attached to one flange and subjected to gravity load. Equation D3.2.1-6 gives design forces for multi-span systems with midspan restraints. The design rules are based on a first order elastic stiffness model by Murray and Elhouar (1985) and Murray and Seshappa (1986). As such, they are equally applicable for wind uplift or gravity load except that the direction of the brace force is reversed. They have been applied to the test specimens CP4 and CP5 to compare the test values with the design values. The test values are given in Figs 6 and 7 for Tests CP4 and CP5 respectively. At a test value of 2.0 kPa (41.8 psf), the bridging forces are in the range 5.5 - 7.5 kN (1.23 - 1.68 kips) for Test CP4 and approximately 7 kN (1.58 kips) for Test CP5 (ignoring the northern gauge).

Using Eq. D3.2.1-6 of the AISI Specification, the corresponding force values are 17.2 kN (3.86 kips) and 17.8 kN (3.99 kips) for Tests CP4 and CP5 respectively. The experimental values are much less than the theoretical values indicating that the resistance to lateral movement in the test specimens is provided by greater torsional restraint from the sheeting than has been assumed in the design model. The experimental values are of the order of 30-40 percent of the theoretical values.

8 CONCLUSIONS

Results of tests on the three span lapped Z-purlins without cleats are set out in this paper. The test rig appears to have functioned satisfactorily with no apparent difficulties in controlling the applied pressure. No restraint was applied to the purlins and sheeting other than that of the flanges supported on the rafters, the attachment of the bridging between purlins and the wheel supports in Tests CP4 and CP5.

Several observations regarding the behaviour of specific purlins can be made. These are:

a) The single bolt end support cleatless connection has a very low capacity due to the bolt pulling through the flange and prying action resulting from twisting. The design has to be modified or a washer similar to the one used for the tests has to be used if the load capacity of the connection is to be equal to the load capacity of the purlin.

b) The Z20015 purlin with no bridging twisted more than that with bridging and produced a more nonlinear response especially for deflections normal to the plane of the wall. As a consequence, the Z20015 purlin with bridging was stiffer in bending in its plane than that with no bridging. The failure load for the Z20015 purlin with bridging but no wheel support (Test CP1 3.23 kN/m (18.5 lbs/in) was 5 percent greater than that for the same section with no bridging (Test CP2 3.07 kN/m (17.6 lbs/in), and 11.8 percent greater than that for the same section with bridging and a wheel support (Test CP4 2.89 kN/m (16.5 lbs/in)). The failure load for the Z15019 purlin with bridging and no wheel support (Test CP3 3.05 kN/m (17.4 lbs/in)) was 16.4 percent greater than that for the same section with bridging and a wheel support (Test CP5 2.62 kN/m (15.0 lbs/in)). It is clear that restraint from the bridging being tied back to a wheel support lowers the load capacity, probably as a result of local and distortional failure in the vicinity of the bridging.

c) The vertical deflections (40 mm (1.57 in)) of the sheeted flange of the purlins with bridging but no wheel support (Tests CP1 and CP3) are considerably greater than those deflections (10 - 20 mm (0.4 - 0.8 in)) of the purlins with bridging and a wheel support (Test CP4 and CP5). The magnitude of the deflections for the purlins whose bridging is not tied back to a rigid support are probably unacceptable in practice.

d) The ratios of the failure loads of the cleatless tests to those of the cleated tests range from 0.98 to 1.15 and indicate that the cleatless purlins are generally as strong as the cleated systems provided the bolts do not pull through the flanges where the purlins attach to the rafters.

e) The forces in the bridging are of the order of 30 - 40 percent of those predicted by Clause D3.2.1 of the AISI Specification.

9 REFERENCES

1. Hancock, GJ, et al, (1990), 'Tests of Purlins with Screw Fastened Sheeting under Wind Uplift'. *Tenth International Specialty Conference on Cold-Formed Steel Structures*, St Louis, Missouri, pp 393-419.

2. Hancock, GJ, Celeban, M and Healy, C, (1992), 'Tests of Continuous Purlins under Downwards Loading', *Eleventh International Specialty Conference on Cold-Formed Steel Structures*, pp 155-179.

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Test	Purlin	Number of Spans	Rows of Purlins	Bridging	Wheel Supports	Failure Pressure (kPa)
CP1	Z20015	3	4	1 - 1 - 1	No	2.58
CP2	Z20015	3	4	No	No	2.30
CP3	Z15019	3	4	1 - 1 - 1	No	2.45
CP4	Z20015	3	3	1 - 1 - 1	Yes	2.05
CP5	Z15019	3	3	1 - 1 - 1	Yes	1.90

(1 kPa = 20.88 psf)

Table 1: Test Setup and Failure Pressures

Test Number	Failure Pressure (kPa)	Average Line Load per Portion (kN/m)	Computed Load Factor on Inner Purlins	Computed Line Load on Inner Purlins (kN/m)	Equivalent Cleated Test Number	Computed Line Load on Cleated Test (kN/m)	Cleatless / Cleated Load Ratio
CP1	2.58	2.58	1.23	3.17	S1T5	2.94	1.08
CP2	2.30	2.30	1.30	2.98	S1T4	2.58	1.16
CP3	2.45	2.45	1.23	3.01	S1T2	2.63	1.14
CP4	2.05	2.73	1.05*	2.87	S1T5	2.94	0.98
CP5	1.90	2.53	1.04*	2.63	S1T2	2.63	1.00

* Top two purlins of the three purlins

(1 kPa = 20.88 psf)
1 kN/m = 5.72 lbs/in)

Table 2: Failure Pressures and Loads

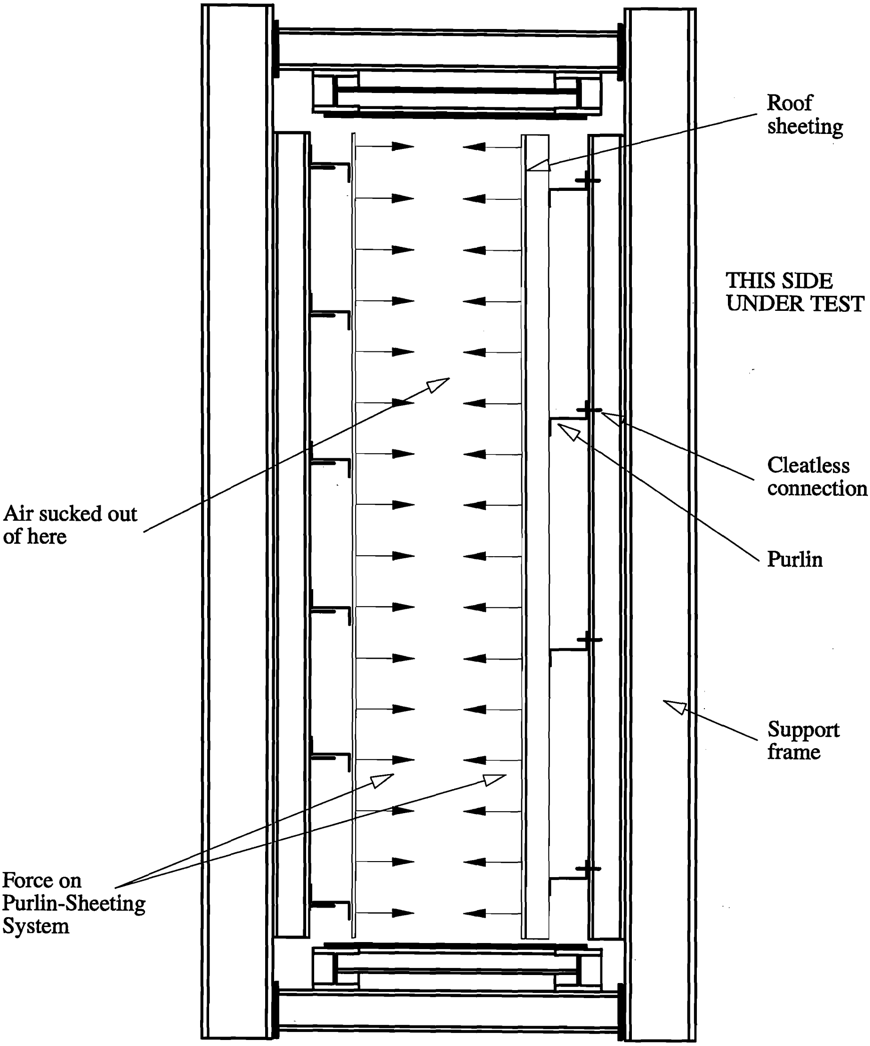


Fig. 1(a) Section of Vacuum Type Purlin Test Rig for Tests CP1, CP2 and CP3 (4 Rows of Purlins)

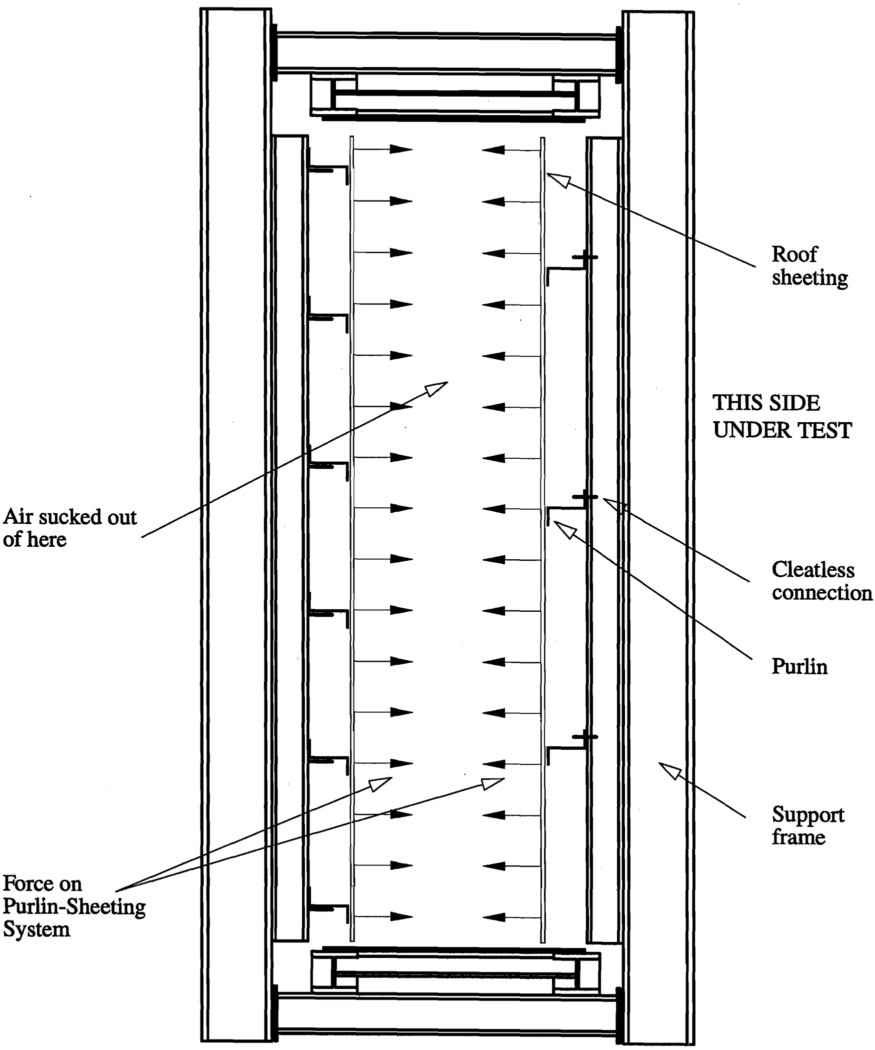


Fig. 1(b) Section of Vacuum Type Purlin Test Rig for Tests CP4 and CP5 (3 Rows of Purlins)

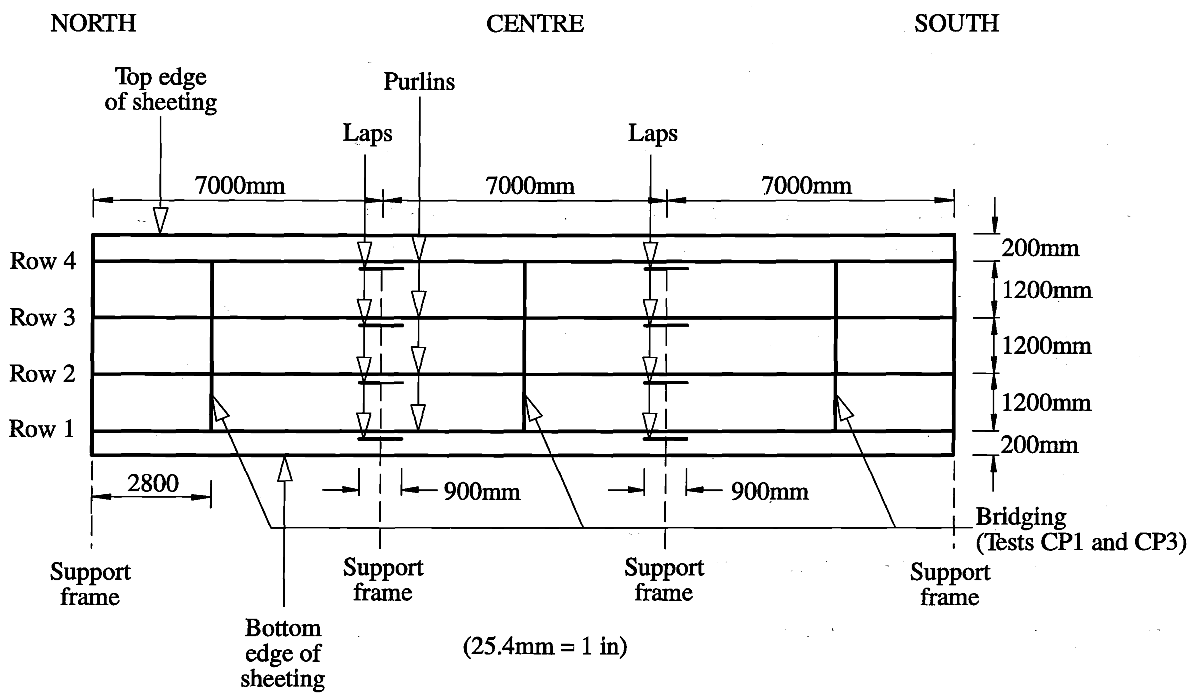


Fig. 2(a) Test Specimen Dimensions for Tests CP1, CP2 and CP3 (4 Rows of Purlins)

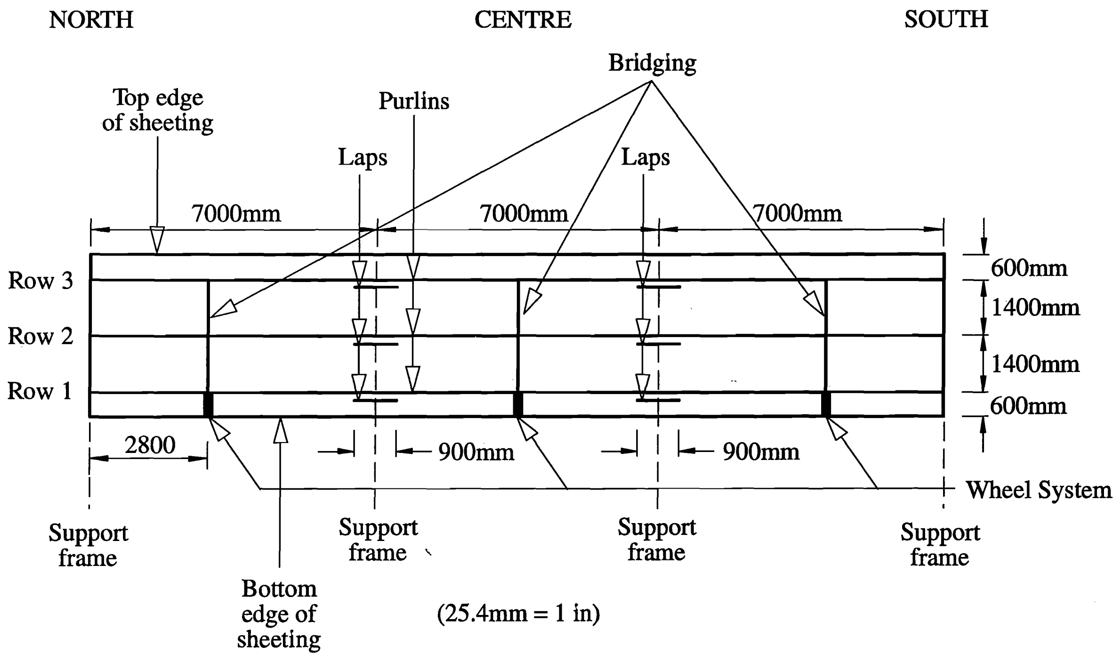
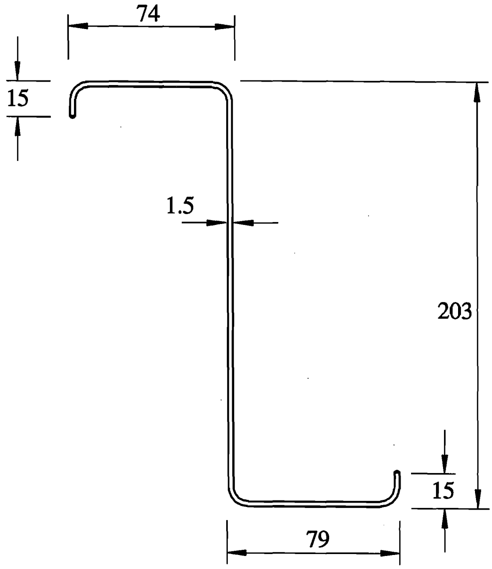
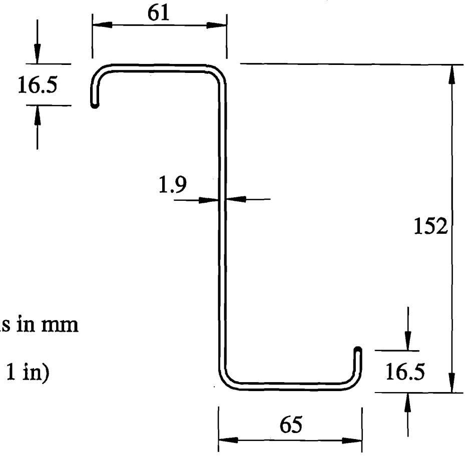


Fig. 2(b) Test Specimen Dimensions for Tests CP4 and CP5 (3 Rows of Purlins)



(a) Z20015



All dimensions in mm

(25.4mm = 1 in)

(a) Z15019

Fig. 3 Purlin Geometry and Dimensions

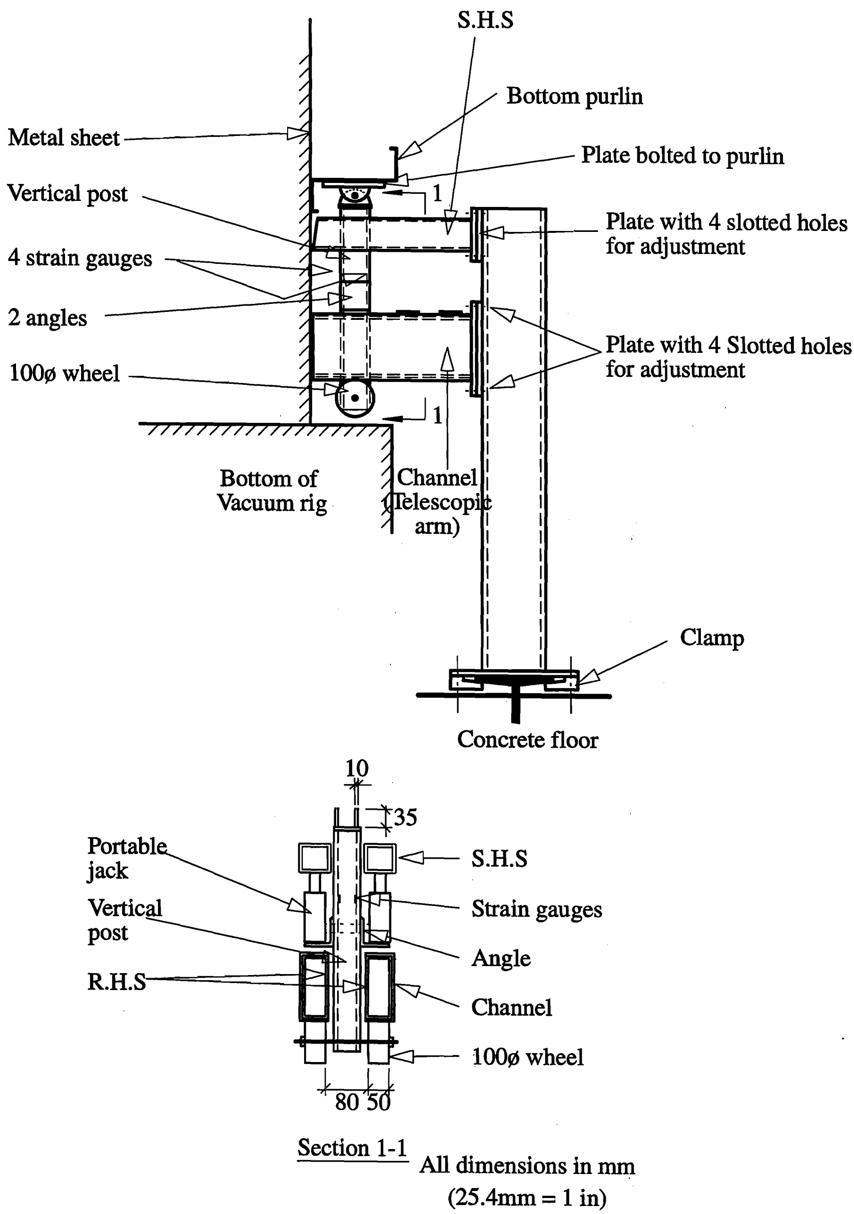
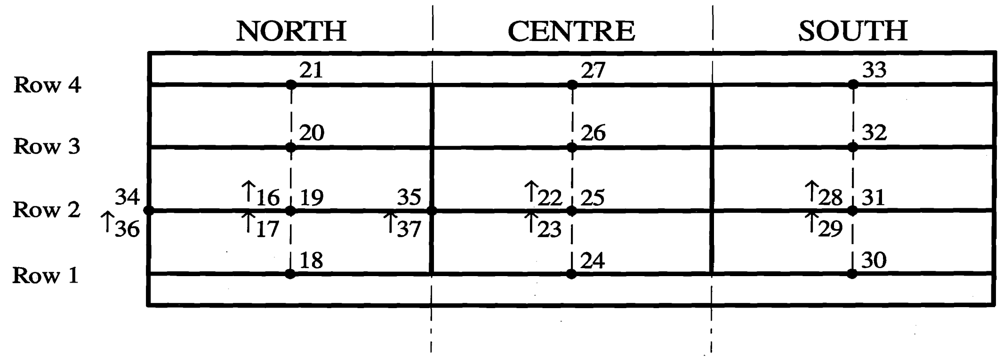


Fig. 4 Wheel System Setup for Tests CP4 and CP5



- Horizontal deflections positive inwards

↑ Vertical deflections positive upwards

Note: Tests CP4 and CP5 had 3 rows of purlins so row 4 and its corresponding transducers 21, 27 and 33 did not exist

Fig. 5(a) Displacement Transducer Positions along Purlins

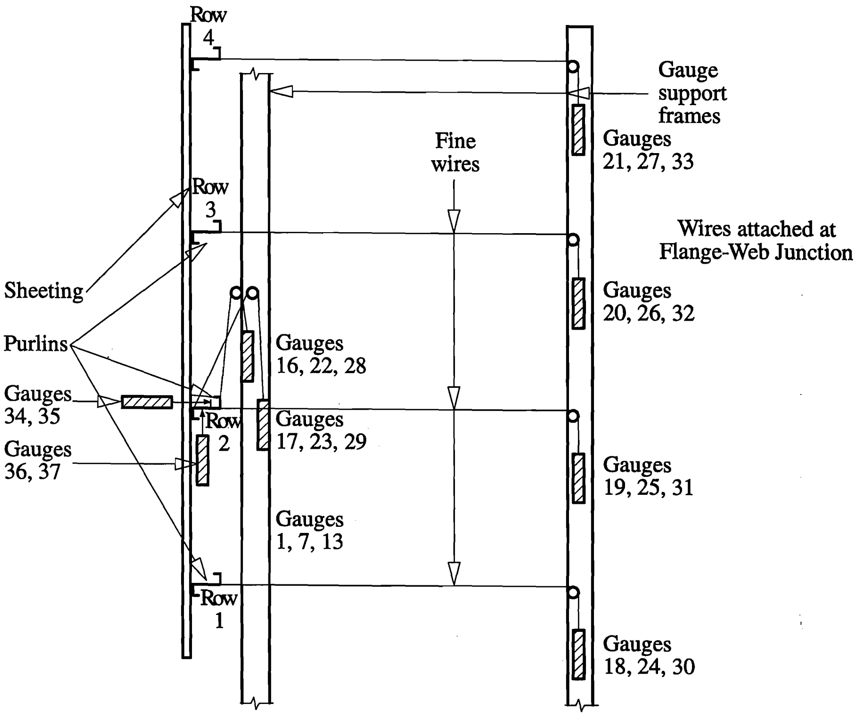


Fig. 5(b) Displacement Transducer Positions at a Section

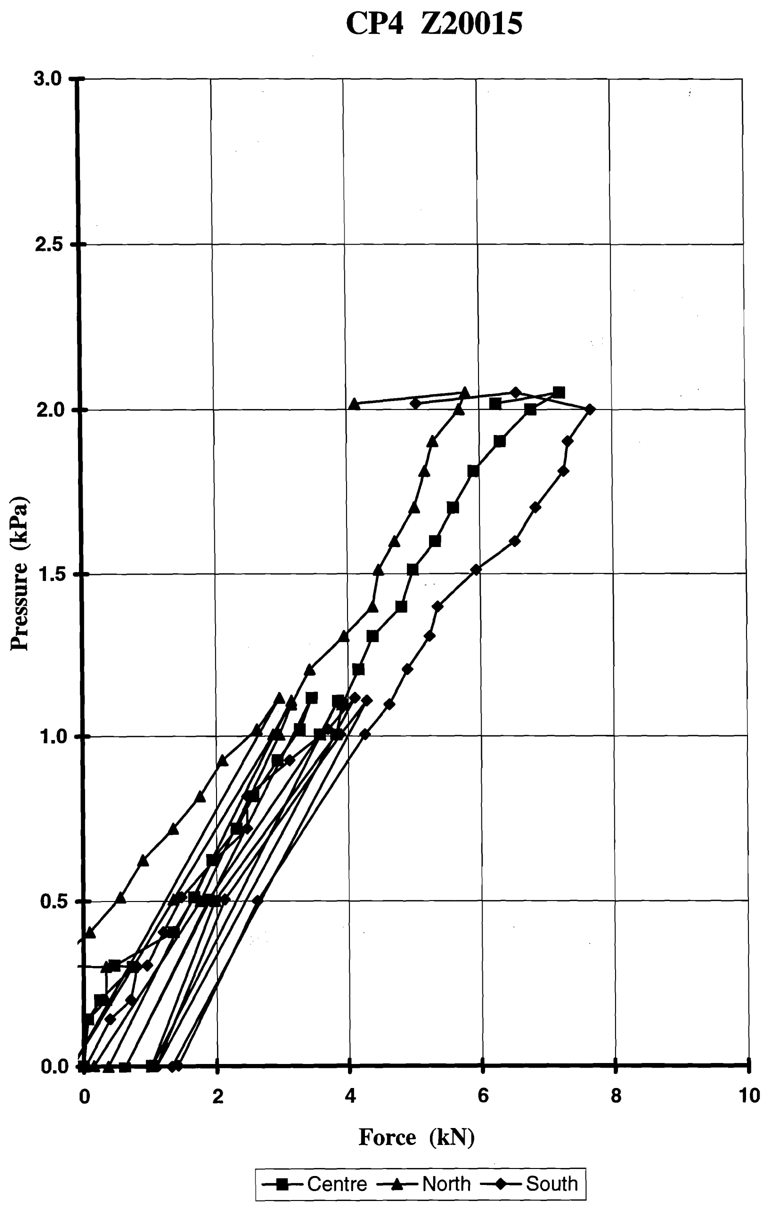


Fig. 6 Forces in Wheel System Test CP4

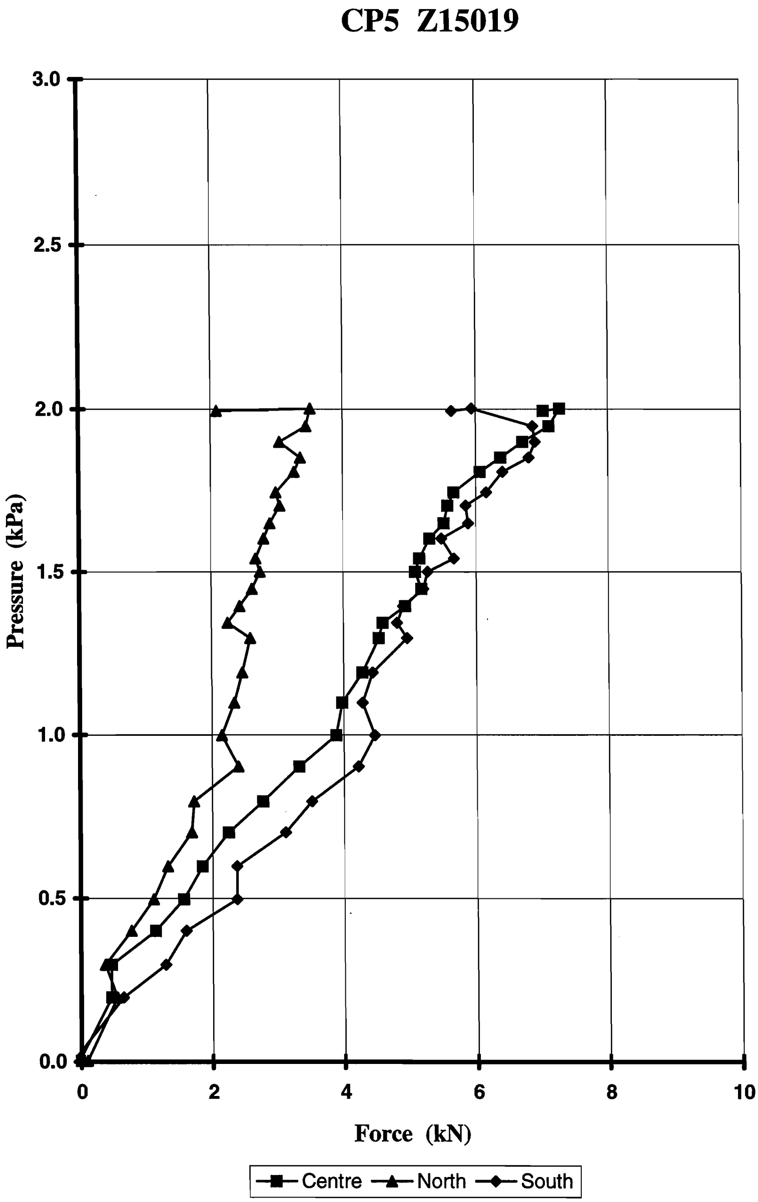


Fig. 7 Forces in Wheel System Test CP5