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ABSTRACT

Built upon a companion study [1] on the load carrying capacity of cold-formed steel wall panels, the stress/strain distributions in each constituent of a panel – middle and side studs, top and bottom tracks, boards, and screws – are examined in detail with extensive use of strain gauges. These are subsequently synthesized to analyse the structural performance of the panel as a whole. Panels with 1-side sheathing and one middle stud were tested under vertical compressive loading. The main variables considered are screw spacing (300 mm, 400 mm, or 600 mm) in the middle stud, board type (oriented strand board – OSB, cement particle board – CPB, or calcium silicate board – CSB), board number (no sheathing, one-side sheathing, or two-side sheathing), and loading type (1 or 3-point loading).

The test results show that, at a given cross-section of the stud, the strains and stresses experienced by the flanges are significantly different from those in the web. Along the vertical direction, the stresses in the stud are not uniform, decreasing as the bottom track is approached. Screw connections between stud and board not only restrain the lateral displacement of the stud, but also support and re-distribute a portion of the machine load to the board and then to the bottom track. The axial forces experienced by the screws are negligibly small during the initial stage of loading, increasing slowly as the load is further increased until substantial stud buckling occurs. Buckling drastically increases the forces acting on a screw, often resulting in its pulling-out from the board and studs/tracks. The results also show that the role of board in a partition wall panel is multi-fold. It acts as a shearing member to steady the whole structure, as a supporting member to enhance the overall and local buckling performance of middle and side studs, and as a structural member to support part of the machine load. It is important account for the contributions of load-sharing boards (via screw connections) when designing cold-formed steel wall panels against minimum weight.

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1 INTRODUCTION

Partition wall panels composed of cold-formed steel frame lined with one- or two-side sheathing have been widely used in building constructions since 1940s [2]. The panels are commonly made by first connecting studs and tracks with rivets to form the frame, and then connecting sheathing boards to the frame with screws. These panels can be easily assembled to construct load-bearing as well as non-load-bearing partition walls. For load-bearing walls, cold-formed steel studs are traditionally considered as the main structural member.

Wall stud design in United Kingdom is based on the BS 5950:5:1998 [3]. The load carrying capacity of a stud is calculated from the flexural buckling load and the short strut load capacity. The actually used flexural buckling load is the smallest amongst overall flexural buckling loads about principal axes of the stud cross-section and torsional-flexural buckling load. Local buckling is considered in calculating the short strut capacity by using an effective width. BS 5950:5 does not consider the effect of boards on stud load capacity in a panel. The resulting design is conservative, often with a large portion of the full stud capacity unexploited [1].

The Australian Standard for Cold-formed Steel Structures, AS 4600 [4], considers the lateral and rotational supports provided by the lining material to the studs/tracks in the plane of the wall. The AISI specifications [5] include even more factors in calculating the stud load capacity for two-side sheathed panels: column buckling between wall board fasteners, overall buckling (flexural and flexural-torsional buckling) with shear diaphragm bracing, and shear failure of the sheathing. At present no recommendation exists in the open literature for the load capacity of a 1-side sheathed panel.

Research effort on cold-formed steel structures has continued to increase, and so is their market share, especially in countries where the use of timber is restricted. Rondal [6] reviewed the recent progresses on cold-formed steel members and structures, with special emphasis placed on distortional buckling and the development of new types of joint. Recent research activities at University of Missouri-Rolla on steel members and truss assemblies are reviewed by Yu and LaBoube [7, 8]. The practical utilization of cold-formed sections in building construction has focused on three mutually-related subjects, namely, high strength materials, calculation models incorporating practical applications and design procedures, and design codes [9]. The latest trend is to move from simplified design models to design procedures based on "whole section" analysis, and to focus on the system design of whole panels or whole structures. The subsequent increase in the complexity and sophistication of design procedures requires a deeper understanding of the structural behaviour of cold-formed steel members and assemblies.

Experimentally, Telue and Mahendran [10] studied performance of cold-formed steel wall frames lined with plasterboards. Miller and Pekoz [11] conducted individual long column tests to study the interaction of local buckling and overall buckling, flat-ended column tests to estimate loading eccentricities for wall studs and tracks, and wall stud assembly tests to observe the behaviour of overall system including the effects of commonly used bracing elements. They also looked into the behaviour of gypsum-sheathed cold-formed steel wall studs [12]. In all these research, only the general response of studs or panel system was reported; no information on stress/strain distributions in individual members was given.

In this work, built upon a companion study [1] on the load capacity of sheathed partition panels, the stress/strain distributions in each component of the panel – middle and side studs, top and bottom tracks, boards, and screws – are examined in detail through the use of strain gauges. These are subsequently synthesized to analyse the structural performance of the panel as a whole. Panels with 1-side sheathing and one middle stud were tested under vertical compression. For panels, the main variables considered are screw spacing, board type, sheathing type, and loading type. The contribution of sheathing to stud load capacity is examined in detail.

2 EXPERIMENTAL PROCEDURES

2.1 Configuration of panels

Panels with 1-side sheathing and one middle stud were tested. A 1-side sheathed panel is made of frame having size 2.45 m by 1.25 m (Fig. 1) and a board. Four tracks of C-channel section (93×67×1.2 mm) without lips, shown in Fig. 2b, are connected together at each end by 4 rivets (2 for each flange) to form the circumference of the frame. A stud of C-channel section with lips (90×39/42×7.8×1.5 mm), Fig. 2a, is fixed onto the tracks by 6 rivets (3 for each flange) at each end. All stud and tracks are made of a high yield strength steel, with yield strength of 350 MPa, Young's modulus of 205 Gpa and Poisson's ratio of 0.3.

Three kinds of boards were used for panel construction: calcium silicate board (CSB), cement particle board (CPB) and oriented strand board (OSB). A board is attached to the frame by self-driving screws. For all panels, screw spacing on side tracks is fixed at 300 mm, whereas screw spacing on the middle stud is varied from 300, 400 to 600 mm for different panels. Details of panel fabrication are summarized in Table 1. The panels in this paper are numbered in the same way as that in [1, 13], with each panel specified by board type, screw spacing and loading points (see Table 1). Apart from strain measurement (via strain gauges) for studs and tracks, load versus displacement curves of the panel and strain distributions on the sheathing board were also measured and will be reported separately [13].

2.2 Test installation

Panels under vertical compression

Panel tests were carried out on a 500-Ton Amsler hydraulic machine. The bottom of a test panel was fixed onto a wood beam laid on the machine base to simulate the situation in building construction. Vertical compressive load was applied to the top of the panel in two different ways. With 3-point loading (Fig. 3a), the load was applied by the machine via three calibrated load cells onto three loading blocks placed separately on top of the middle stud and the side tracks. With 1-point loading (Fig. 3b), the load was applied through one calibrated load cell on top of the middle stud only. During each test, vertical displacement of the panel and lateral displacement of the middle stud were measured by displacement transducers. The arrangement of load cells and transducers is shown in Fig. 3.

Uniaxial strain gauges, type EA-06-120LZ-120, were used throughout the test, and their locations on the middle stud, side studs and top track are shown in Fig. 1. On the top track, strain gauges at sites G and H (Fig. 1) measure strains along the horizontal direction. There are three strain gauges at each site, one located at the middle of web and the remaining two at the edge of each flange. Strain gauges at sites A to F (Fig. 1) measure strains along the vertical direction of side and middle studs. Again, 3 strain gauges are used at each site to measure strains on the web and flanges. At the connection between the middle/side stud and top track, two groups of strain gauges (I & J) are used to measure the local strains, as shown in Fig. 1. The arrangement of strain gauges for each panel is summarized in Table 1, with each strain gauge oriented along the axial direction of the middle stud, side stud or track. The purpose of each group of strain gauges is:

- G and H — measure strain on the top track
- A, B and D — measure strain on the upper part of columns. These strain gauges are positioned slightly below the first screw on each column.
- C — measure strain on the lower half of the middle stud. This group is positioned slightly above the last screw on the middle stud.
- E and F — measure strain between locations B and C on the middle stud.
- I — measure strain on the track near the top connection.
- J — measure strain on the middle stud near the top connection.

Based on the measured strains at the above locations for each column, the load sustained by the column at each location can be estimated. The difference between the loads measured by load cells on the top of the panel and the loads calculated according to the measured strains at, say, A, B and D cross-sections is the load supported by the board through the connecting screws above these cross-sections. Similarly, the difference amongst the loads measured at locations B, E, F, and C on the middle stud is the load passed successively to the sheathing board through screws. The number of screws between B and C of the middle stud is listed in Table 2 for different screw spacings.

<u>Screw pulling-out</u>

The panel tests reported in [1] show that many panels failed just before or immediately after some fixing screws (especially those on the middle stud and bottom track) are pulled out from the board, or from thin gauge stud and tracks with small wall thickness (0.7 or 0.9 mm). In order to investigate the screw pulling force as a function of panel load, two screws (screws 1 and 2) in the central portion of the middle stud were removed from the panel shown in Fig. 4. Two 6 mm bolts were then inserted into the cavities, each connected to a U-shaped transducer (Fig. 5). The transducers were connected to a data logger and the recordings were subsequently analysed to obtain the pulling force acting on the bolts (screws).

3 TEST RESULTS

The maximum panel displacement and the maximum machine load for all panels are listed in Table 3. The distribution of strains measured for various constituting members of a panel is reported below.

3.1 Strain on top track

The strains on the top track for Panel 4 (CPB400-1, Table 1) with one-point load are plotted as functions of panel vertical displacement in Fig. 6a. Fig. 6b presents similar results for the strains on the top track of Panle 15 (CSB600-3, Tabel 1) subjected to 3-point loading. These strains are all measured along the axial direction of the track. In each case, the top track made of 1.2 mm gauge steel deforms under bending, and hence tensile and compressive strains co-exist in the track (Fig. 6). In addition to bending, the board attached to the top track restricts its displacements on one side: torsion of the track may be induced by this asymmetrical loading. Therefore, as a result of sheathing, the top track is working at a complex stress/strain state. The difference between strains at different sites increases as loading is increased.

3.2 Strain on sidetracks

Strains measured at cross-sections A and D on the sidetracks of Panel 6 (OSB400-1) subjected to 1-point loading are presented in Fig 7a. Panel OSB400-1 is a frame sheathed with oriented strand board, and the screw spacing on the middle stud is 400 mm. Because there was no load acted directly on top of the sidetracks, load was transmitted to the sidetracks from the board through screw connections and from the top track. From Fig. 7a, it is seen that both sidetracks bend outwards, inducing tension on their webs (A1 and D1) and compression on their flanges (A2, A3, D2 and D3, all along the principal axes). Strains on the left sidetrack (A1, A2 and A3) exhibit similar trend as those on the right sidetrack, but they are different in magnitude. Although the majority of load is supported by the middle stud, the load passed to the sidetracks through the top track and board is sufficient to cause local buckling at the flanges of the sidetracks. This local buckling, together with inaccurate panel assembly, may cause the unsymmetrical strain/stress distribution in the sidetracks.

Fig. 7b presents the strains at cross-sections A and D on the sidetracks of Panel 10 (OSB400-

3) subjected to 3-point loading. The composition of Panel 10 is identical to that of Panel 6. The only difference between the two panel tests is the loading type (1-point versus 3-point loading). In comparison with the sidetracks of Panel 6 where bending occurs, the strains on the sidetracks of Panel 10 are all compressive and are significantly larger. However, the big difference of strains on web and flanges in Fig. 7b indicates that certain amount of bending exists in these columns. Test results on 3-point loaded panels with different screw spacings and lining boards exhibit similar trends, and hence will not be shown below. As the side tracks are not stiffened on the web, they undergo local buckling and distortion when the panel vertical displacement is increased to about 1 mm, corresponding to a load level of about 7 to 10 kN on each track. Subsequently, the compressive strains on the side track increase approximately linearly with load (Fig. 7b). At panel failure, most of strains on the sidetracks are smaller than one third of the steel yield strain.

3.3 Strain on middle stud

Strains measured at cross-sections C and B of the middle stud in Panel 6 (OSB400-1) are shown in Fig. 8a. Cross-section B is located beneath the first screw (counted from the top) whereas C is above the last screw on the middle stud. There are 5 additional screws between B and C. It is seen from Fig. 8a that the strains increase stably as the load is increased, with maximum strains reached at the outside flange (B2 and C2, not attached to board) and minimum strains at the web (B1, C1). The strains at cross-section C exhibit similar trend as those at B, but are significantly smaller, implying that the load carried by the middle stud at cross-section C is much less than that at B. The difference in load between the two cross-sections is taken up by the 5 screws (and hence the board) in between. It is noticed that the difference between the flange strains at C2 and C3 is small, in contrast with those between B2 and B3. At panel failure, the maximum strain in the middle stud is less than half of the yield strain of steel.

In Fig. 8b, similar results for Panel 10 (OSB400-3) are presented. Compared with Panel 6 under 1-point loading (Fig. 8a), the web strain measured at C1 is now bigger than that at B1, and the difference between the strains on both flanges measured at different cross-sections (B and C) is small. This may be attributed to the much more uniform distribution of strain across the board of Panel 10 under 3-point loading than that under 1-point loading.

The distribution of strains in the middle stud of panels with different board materials or different screw spacings is found to be similar to that shown in Fig. 8, with maximum strains always reached at the outside flanges. Furthermore, the difference between the strains measured at B and C becomes smaller when the screw spacing is reduced (and hence the number between these two cross-sections).

3.4 Screw pulling force

The measured pulling force on screws 1 and 2 in Panel 10 is plotted in Fig. 9 as a function of the load applied on its middle stud. Before the load on the middle stud reached about 35 kN, both the screws mainly supported shear load with negligible puling force in the axial direction (Fig. 9), and the vertical members in the panel remained in compression. Afterwards, transverse disturbances due to buckling (local buckling, flexural buckling, and torsion-flexural buckling) and inaccurate assembly or balances started to show effects. When the load on the middle stud reached about 80% of its loading capacity, it started to fail due to overall buckling, and the screw pulling force started to increase sharply. The pulling-out behaviour of the two screws is nearly identical except in the final stage.

The maximum pulling force a screw can sustain is dependent upon stud/track wall thickness as well as board type and board thickness. Consequently, screw pulling-out should be an integral part of any optimal design of a structural panel.

4 ANALYSIS

The strains measured at different panel locations can used to estimate the load carried by stud, board, and screws, as illustrated below. Throughout the analysis, averaged stresses on the cross-sectional area of individual members (stud/tracks and board) are used to calculate the load carried by each member.

4.1 Load carried by stud

During 3-point loading, loads P_L, P_M and P_R are applied to each column (stud and tracks) through loading blocks as shown in Fig. 10, where P_L is the load on the left sidetrack, P_M is the load on the middle stud, and P_R is the load on the right sidetrack. The total machine load, P_{sum}, is the sum of these three loads:

$$P_{sum} = P_L + P_M + P_R \tag{1}$$

For 1-point loading, $P_L = P_R = 0$, and hence $P_{sum} = P_M$.

A typical cross-section of panel from A to D is shown in Fig. 10. By equilibrium, the total machine load, P_{sum}, is given by:

$$P_{sum} = P_{stud} + P_{board} \tag{2}$$

where $P_{stud} = P_A + P_B + P_D$ is the total load carried by the left track (A), middle stud (B) and right track (D), and P_{board} is the average force acting on the board (Fig. 10). Supporting forces provided by the columns, P_A, P_B and P_D, can be calculated from the strains measured at each site, whereas the supporting force provided by the board, P_{board}, is the difference between the machine load P_{sum} and P_{stud}.

Fig. 11a compare the total machine load, P_{sum} with the stud load, P_{stud} for Panel 6 (OSB400-1). Because the panel was subjected to 1-point loading, the load taken up by the two sidetracks was negligibly small. The stud load, P_{stud} was approximately 20% smaller than the machine load, P_{sum} during the whole test (Fig. 11a), indicating that about 20% of the total load was supported by the board (via the screw connections and the top track). Fig. 11b shows similar results for Panel 10 (OSB400-3), which was identical to Panel 6 except for the 3-point loading applied. The total machine load, P_{sum}, is now about 5 to 10% higher than the stud load, P_{stud}, indicating that only a small portion of the load was passed onto the board. The load carried by the middle stud is about twice that carried by each sidetrack. In the final stage of the test, because of heavy buckling and distortion of the stud and sidetracks, the load carried by each member cannot be measured accurately through the use of strain gauges.

4.2 Load carried by screws on the middle stud

During a panel test, focus has been placed on measuring the strains at different cross sections of the middle stud. These strains were subsequently used to calculate the distribution of load at each cross section, from which the load transmitted to the board by screws above this cross section was obtained.

Figs. 12a and b plot the load on the middle stud as a function of panel displacement for Panel 6 (OSB400-1) and Panel 9 (OSB600-3), respectively. Here, P_M is the machine load applied on top of the middle stud, whereas P_B and P_C are separately the load calculated based on the measured strains at cross-sections B and C. Since a portion of P_M is also transmitted to the board through the screws, P_B and P_C are always smaller than P_M. Furthermore, P_B is in general bigger than P_C: the difference between P_B and P_C, defined here as P_{BC}, is the load supported by the screws in between.

The results of Fig. 12a correspond to 1-point loading and with 400 mm screw spacing (Panel 6), whereas those of Fig. 12b refer to 3-point loading and 600 mm screw spacing (Panel 9); otherwise the two panels are identical. Consequently, the maximum load level reached in the middle stud of Panel 6 is about 40% higher than that reached in the middle stud of Panel 9. Correspondingly, the load P_{BC} carried by the screws in Panel 6 is significantly higher than that in Panel 9.

<u>Relative load supported by screws</u>

For convenience, non-dimensional displacement parameter $d/d_{\max}$ and non-dimensional load parameter P_{BC}/P_M are introduced, where d is the vertical displacement of the panel and $d_{\max}$ is its maximum.

Fig. 13a plots P_{BC}/P_M as a function of $d/d_{\max}$ for Panel 13 (OSB300-3) and Panel 9 (OSB600-3), both sheathed with an OSB board and both subjected to 3-point loading. The percentage of load P_{BC} / P_M carried by screws is nearly identical for both panels, except for the early stage of loading ($d / d_{max} < 40\%$) where the ratio P_{BC} / P_M is larger for Panel 9 with 600 mm screw spacing than that for Panel 6 with 300 mm screw spacing.

Fig. 13b shows the results of two identical panels, Panels 7 and 9, except that Panel 7 is subjected to 1-point loading and Panel 9 to 3-point loading. These results clearly show that the amount of load carried by screws relative to the total machine load carried by the middle stud is sensitive to the loading condition. The ratio P_{BC} / P_M for Panel 7 is more than twice that for Panel 9 throughout the loading.

Fig. 14 depicts the load ratio P_{BC} / P_M as a function of d / d_{max} for Panel 11 (CPB300-3), Panel 13 (OSB30000-3) and Panel 14 (CSB300-3). Except for the sheathing board, the three panels are identical: 3-point loading and 300 mm screw spacing. Note that, because of the uncertainty of strain measurements in the early and final stages of loading, the meaningful results for P_{BC} / P_M are in the range of $30\% < d / d_{max} < 85\%$. Generally speaking, the magnitude P_{BC} / P_M increases as the board stiffness is increased (CSB stiffest and OSB softest). However, when $65\% < d / d_{max} < 85\%$, the ranking between CPB and CSB boards changes for reasons yet to be clear.

5 CONCLUDING REMARKS

The main purpose of this paper is to experimentally characterise the structural function of each component in a 1-side sheathed panel and then synthesize the test data to analyse the structural performance of the panel as a whole. The following conclusions are obtained:

1. The top track of a panel is in a complex stress/strain state because the sheathed board and connecting screws redistribute the loads from the load cells via the top track.

2. Side tracks experience a combination of compression and bending. Although local buckling is visible early during loading, they normally fail due to overall flexural buckling.

3. There is large difference amongst the strains measured on the web, front flange (not attached to the board) and back flange (attached with the board). The front flange experiences the largest stressing.

4. The sheathing board not only provides support for stud/tracks and acts as shear diaphragms, but also withstands vertical load.

5. Because overall buckling is the main mechanism of panel failure which causes the pulling-out of screws from the board and/or studs, the screw pulling-out strength and its dependence on steel thickness and board properties need to be properly addressed in panel design.

6. The load capacity of a panel increases with decreasing screw spacing, but the gain is

small for relatively small (and more expensive) screw spacings.

Future work is needed to quantify the effect of board properties such as stiffness and strength on panel design. Inaccurate panel fabrication can lead to significant knock-down of overall panel strength. It is yet unclear what should be the economic tolerance for manufacturing and assembly accuracy. The pulling-out of screws from boards and studs/tracks needs to be modelled and its influence on panel design established.

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Table 1. Specifications of test panels

Panel No[1]	Panel Type[2]	Screw spacing on middle stud	Sheathing	Loading points	No. of strain gages	Strain gage locations
1	Frame	n.a.	No	3	n.a.	n.a.
2	Frame	n.a.	No	1	n.a.	n.a.
3	CPB400-3	400	One side	3	15	A, B, D, G, H
4	CPB400-1	400	One side	1	15	A, B, D, G, H
5	CPB600-1	600	One side	1	12	A, B, C, D
6	OSB400-1	400	One side	1	12	A, B, C, D
7	OSB600-1	600	One side	1	12	A, B, C, D
8	CSB400-1	400	One side	3	12	A, B, C, D
9	OSB600-3	600	One side	3	12	A, B, C, D
10	OSB400-3	400	One side	3	12	A, B, C, D
11	CPB300-3	300	One side	3	18	A, B, C, D, E, F
12	CPB600-3	600	One side	3	18	A, B, C, D, E, F
13	OSB300-3	300	One side	3	18	A, B, C, D, E, F
14	CSB300-3	300	One side	3	12	A, B, C, D
15	CSB600-3	600	One side	3	18	A,B,C,D,G,H
19	CSB400-3	400	One side	3	20	A,B,C,D,I,J

[1]The numbering of panels is identical to that in Tian et al. [1].

[2]Panel type specifies board type, screw spacing and loading points.

Table 2. Characteristics of screws

Screw Spacing (mm)	Number of screws between cross-sections B and C
300	7
400	5
600	3

Table 3. Maximum panel displacement and maximum machine load[1]

Panel No	Board	Screw spacing on middle stud	Maximum panel displacement (mm)	Maximum machine load (kN)
1	n.a.	n.a.	6.292	46.8
2	n.a.	n.a.	6.264	30.4
3	CPB	400	n.a.	111.4
4	CPB	400	6.818	54.9
5	CPB	600	5.387	53.4
6	OSB	400	7.285	58.2
7	OSB	600	3.256	53.2
8	CSB	400	3.382	61.6
9	OSB	600	8.113	76.9
10	OSB	400	8.218	83.8
11	CPB	300	6.617	97.2
12	CPB	600	8.166	78.4
13	OSB	300	5.376	84.7
14	CSB	300	10.279	87.2

[1]The maximum machine load was reached when the middle stud failed, whereas the maximum panel displacement was the vertical displacement of panel at maximum machine load.

Table 4. Maximum load on each stud and the corresponding failure mode

Panel No	Panel type	Loading points	Maximum load (kN)				Failure mode
			Left	Middle	Right	Total	
1*	Frame	3	n.a.	n.a.	n.a.	46.8	FB
2	Frame	1	n.a.	30.4	n.a.	n.a.	FB
3	CPB400	3	28.8	56.1	29.5	111.4	FTB
4	CPB400	1	n.a.	54.9	n.a.	n.a.	FTB
5	CPB600	1	n.a.	53.4	n.a.	n.a.	FTB
6	OSB400	1	n.a.	58.2	n.a.	n.a.	FTB
7	OSB600	1	n.a.	53.2	n.a.	n.a.	FTB
8	CSB400	3	20.8	35.6	20.4	67.1	FTB
9	OSB600	3	21.4	43.2	20.7	77.4	FTB
10	OSB400	3	25.8	44.3	23.9	83.9	FTB
11	CPB300	3	24.7	58.5	25.0	98.0	FTB
12	CPB600	3	23.9	48.5	22.2	78.4	FTB
13	OSB300	3	21.4	49.5	19.9	85.0	FTB
14	CSB300	3	18.5	56.2	18.4	89.5	FTB
15	CSB600	3	22.2	28.9	20.7	62.6	FTB
19	CSB400	3	25.3	28.4	23.3	60.4	FTB

[1]The maximum machine load was reached when the middle stud failed, whereas the maximum panel displacement was the vertical displacement of panel at maximum machine load.

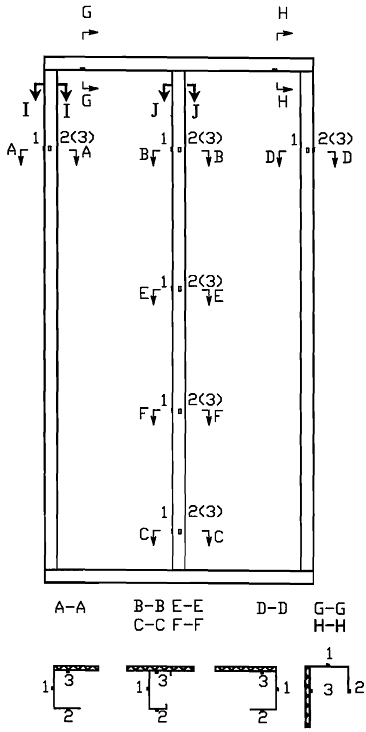
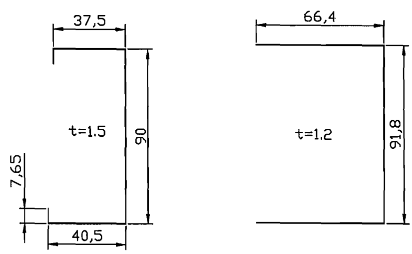


Fig. 1 Strain gauge locations.



(a) (b)

Fig. 2 Cross-section of: (a) middle stud; (b) track.

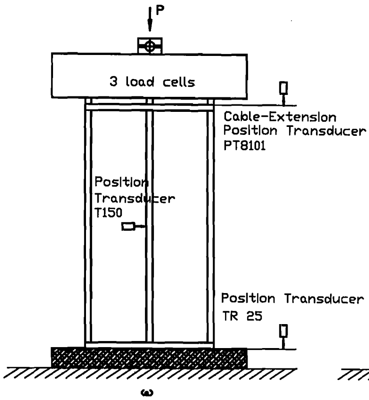


Fig. 3 Load cells and position transducers: (a) 3-point loading; (b) 1-point loading.

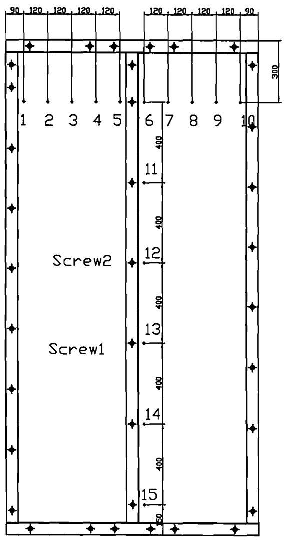


Fig. 4 Positions of screws 1 and 2 on middle stud for pulling-out test.

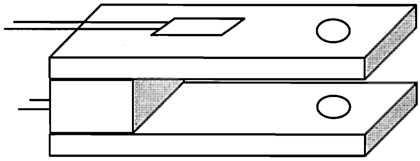


Fig. 5 U-shaped transducer for screw pulling-out force measurement.

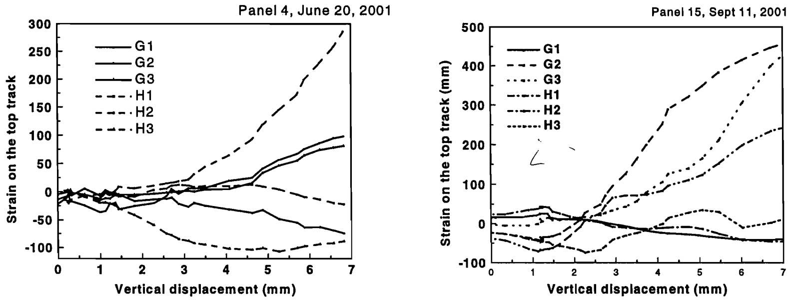


Fig. 6 Strain distributions on top track: (a) Panel 4 (1-point loading); (b) Panel 14 (3-point loading).

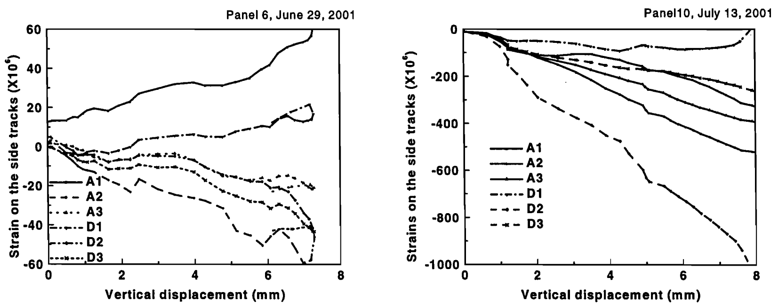


Fig. 7 Strain distributions on side tracks: (a) Panel 6 (1-point loading); (b) Panel 10 (3-point loading).

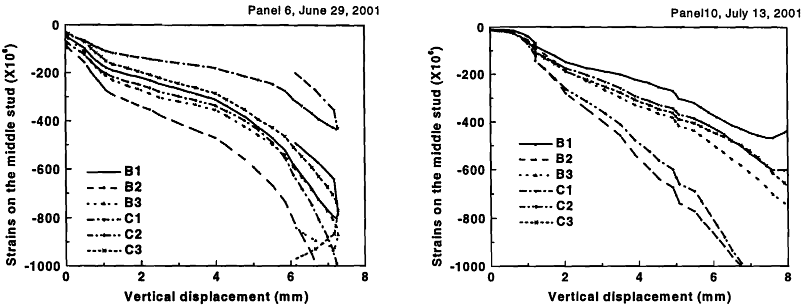


Fig. 8 Strain distributions on middle stud: (a) Panel 6 (1-point loading); (b) Panel 10 (3-point loading).

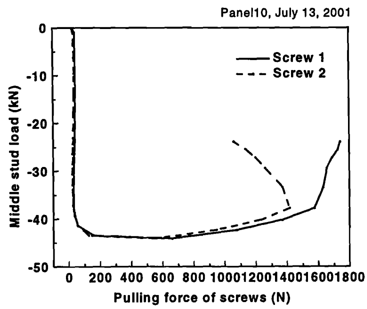


Fig. 9 Screw pulling-out force plotted as a function of middle stud load for Panel 10.

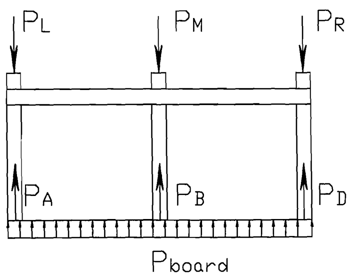


Fig. 10 Force balance on a panel.

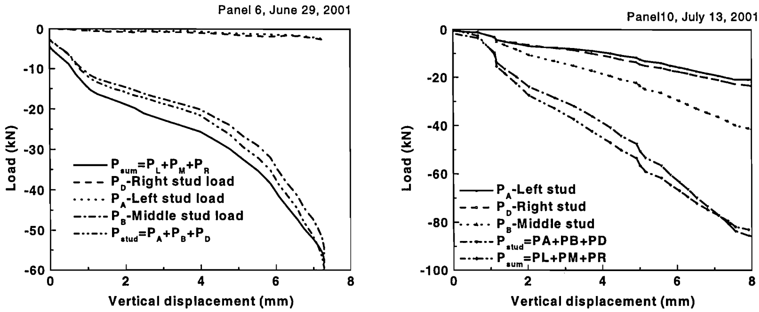


Fig. 11 Comparison between machine load and load supported by studs: (a) Panel 6 (OSB400-1); (b) Panel 10 (OSB400-3).

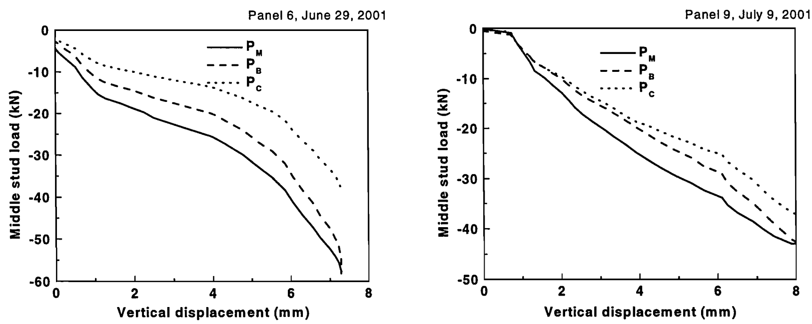


Fig. 12 Load supported by middle stud at different cross-sections: (a) Panel 6 (OSB400-1); (b) Panel 9 (OSB600-3).

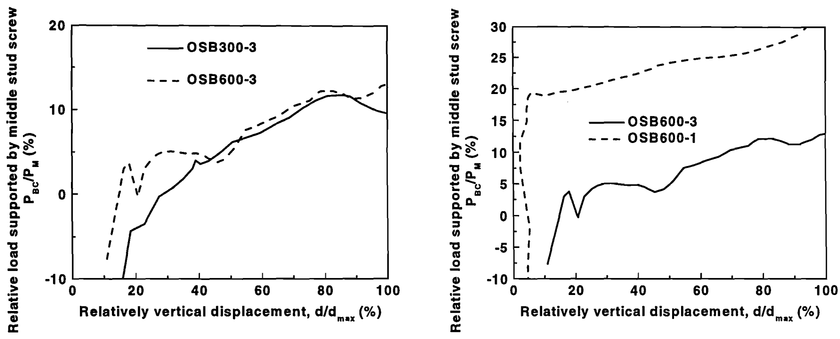


Fig. 13 Load supported by screws between middle-stud sections B and C plotted as a function of panel displacement: (a) Panel 9 (OSB600-3) and Panel 13 (OSB300-3); (b) Panel 7 (OSB600-1) and Panel 9 (OSB600-3).

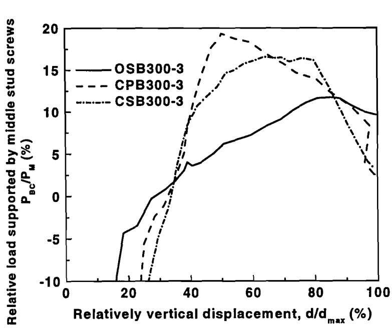


Fig. 14 Load supported by screws between middle-stud sections B and C plotted as a function of panel displacement for Panel 9 (OSB300-3), Panel 11 (CPB300-3) and Panel 14 (CSB300-3).