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The Bending Behaviour of a 'Reversed' Profiled Steel Sheet Dry Board (PSSDB) Panel for Application in a Roofing System

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Abstract: Finite element modelling and experimental study of the structural behaviour involving the stiffness and strength of an innovative composite panel system known as the Profiled Steel Sheet Dry Board (PSSDB) system, to be applied as roofing units in buildings, is investigated in this paper. The system consists of profiled steel sheeting connected to dry board by self-drilling and self-tapping screws. This study considered the behaviour of the PSSDB panel under an out-of plane uniform load to understand the behaviour of the PSSDB panel when it is positioned in a 'reversed' position in order to make it more practical and applicable. In addition, the effect of introducing side timber strips along the edge side of the panel system is also studied. It is found that the timber strips increased the stiffness value from 57.6 kNm^2 m^{-1} to 78.2 kNm^2 m^{-1}, i.e., an increase of 35.8% compared to panels without timber jointing strips. In fact, the maximum load that can be sustained by the connected panels was increased from 3.47 kN m^{-1} to 6 kN m^{-1}. The finite element model developed has shown accuracy within 5% to 11% compared to experimental results in predicting the deflection of the PSSDB panel.

Keywords: Finite element modelling, Profiled steel sheet, Dry board, Timber strips, Out-of plane bending

INTRODUCTION

Technological development in the construction industry has resulted in increasing demands for more effective and innovative construction systems and techniques. Construction is no longer solely dependent on the traditional concepts of construction, which normallyinvolve timber system, but more on dynamic materials and systems. Newer concepts in construction technology, such as lightweight panels, hollow blocks and other similar Industrialised Building Systems (IBS), are becoming more acceptable to the construction industry.

The Composite Systems (also called Mixed or Hybrid Systems) have seen widespread use in recent decades because of the benefits of combining two construction

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materials. The Profiled Steel Sheeting Dry Board (PSSDB) system, a thin-walled, lightweight composite structure, is proposed in order to meet the above requirement. The PSSDB system consists of a profiled steel sheet connected to dry boards by self-drilling, self-tapping connectors. The connectors play an important role in transferring horizontal shear between the boarding and the profiled steel sheeting, while the board plays a dual role, firstly providing a flat surface for roofing and secondly, enhancing the stiffness and strength of the system through composite action. The typical composition of a PSSDB system is shown in Figure 1. A practical application can be seen in Figure 2.

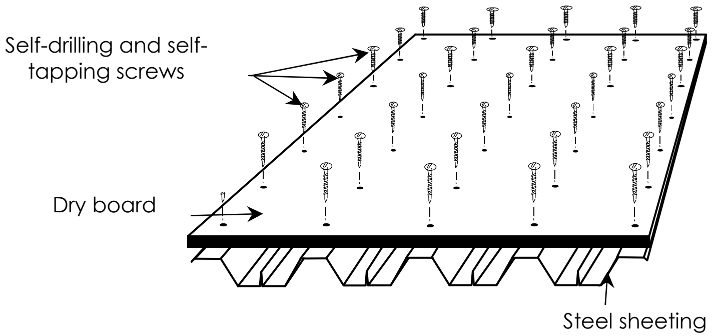


Figure 1. Typical PSSDB System

Figure 2. PSSDB Roof Panels

The idea of using the PSSDB system as a structural component was first introduced by Wright and Evans (1986) as a replacement for existing timber joist floors. The idea was then extended and studied in-depth by researchers not only for floor applications but also for wall and roof systems. Some previous studies of the behaviour of PSSDB floor, wall and roof systems was reported by Ahmed (1996, 1999), Ahmed and Wan Badaruzzaman (2003, 2005), Ahmed et al., (1999a, 1999b, 2000), Akhand (2001), Benayoune and Wan Badaruzzaman (2000), Shodiq

(2004), Wan Badaruzzaman (1994), Wan Badaruzzaman et al., (1996), Wan Badaruzzaman et al., (2003), Wan Badaruzzaman and Wright (1998), Wright et al., (1989), and Wright (1988). These studies included the structural and nonstructural performance of the system.

Based on the original concept of the system, the application of the PSSDB system has been extended to form a new concept of a roofing system. The new approach will eliminate roof trusses normally required in traditional roof structures. There are many advantages of the PSSDB roof system when compared to traditional forms of pitched roof structures in small- and medium-sized buildings, which normally would involve the use of either a purlin and rafter or a trussed rafter system. These advantages clearly arise due the load bearing capacity of the PSSDB system and due to the fact that it is made of more durable materials. Some of the advantages (Awang and Wan Badaruzzaman, 2007) include the following:

i. Parts of the structure of the roof, which would normally involve a considerable number of internal elements that would impinge on the roof space and minimise its effective use, would no longer be required.
ii. Considerable numbers of connections between elements that are normally required in the skeletal framing, which are often difficult to form and add to the cost, would be eliminated.
iii. The difficulty of providing overall stability of the roof structure, which involves cross bracing and an allowance for wind uplift, would now be removed.
iv. Insect attack and rotting of roof timbers, a problem that is not always resolved with preservatives and treatments, would no longer be a threat.

THE PROPOSED INDIVIDUAL PSSDB PANEL

The PSSDB roof panel was constructed using Ajiya Cliplock CL 660 (profiled steel sheet) and Prima*flex* (dry board). The thicknesses of the sheeting and the board are 0.48 mm and 9 mm, respectively. The sheeting and dry board were screwed together via self-tapping and self-drilling screws at a distance of 100 mm on every rib of Ajiya CL 660. The Ajiya CL 660 has three fluted pans with an effective cover width of 660 mm and rib heights of approximately 44 mm spaced at 221.67 mm between the three fluted pans (see Figure 3). Tables 1 to 4 show the properties of the materials used.

Figure 3. CL 660 Clip 'n' Locking Profiled Steel Sheeting

Table 1. Structural Properties of Clip Lock CL 660

Thickness (mm)	Young Modulus (MPa)	Yield strength (MPa)
0.48	210E03	550

Source: Ajiya, (2003)

Table 2. Structural Properties of Dry Boards (Prima*flex* 9 mm)

Characteristics	Dry	Wet
Modulus of elasticity (MPa)	8000	7000
Shear strength (perpendicular to the plane of the sheet) (MPa)	18	14
Compressive strength (MPa)		
- In plane of the sheet	20	15
- Perpendicular to the plane	> 50 MPa	> 50
Flexural strength (mean)	≥ 16 MPa	≥ 10

Source: Hume Cemboard, 2007

Table 3. Properties of 14DX-RW Screw Connectors

Properties	
Material	Carbon steel
Surface coating	10 -15 mm Zinc Chromate
Length	25 mm
Diameter of thread	4.2 mm
Tensile breaking load	6.3 kN
Shear breaking load	4.35 kN
Twist-off torque	4.7 Nm
Pull-out load from 0.8 mm steel plate	0.75 kN

Source: Powerdrive, 1991

Table 4. Structural Properties of Timber Strips

Size (mm)	Young Modulus (MPa)	Average Poisson's ratio
40 x 45	7E03	0.2

The normal position of the PSSDB panel is shown in Figure 1 above. However, the roofing panel in the normal PSSDB position could pose durability problems in the long run, as the dry board is exposed to the environment. In order to solve this problem, the position of the PSSDB panel is reversed (see Figure 4). The new position of the board will provide for a flat surface on the underside of the roof facing into the room. This flat surface will eliminate the use of suspended ceiling panels in buildings. The PSSDB panels resist the in- and out-of-plane external wind and other loads in addition to carrying the relatively low self-weight, transferring the load to the purlins and rafters, after which the loads are transferred to the foundation via a PSSDB load bearing wall system. Therefore, the currently proposed system is rather unconventional, as suspended ceilings are normally not designed to carry any loads other than self-weight.

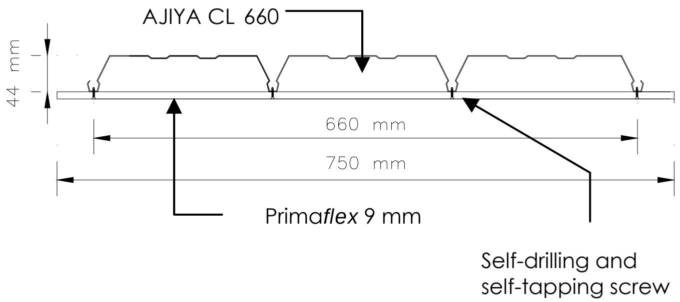


Figure 4. Cross Section of Sample 1

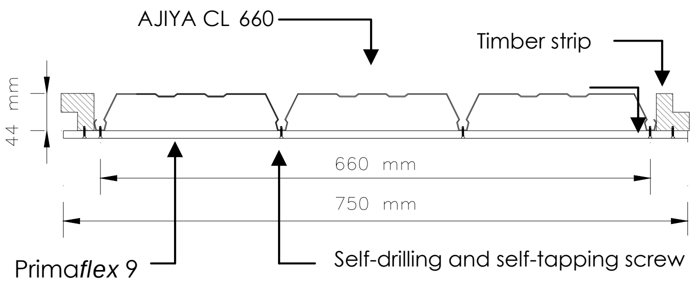


Figure 5. Cross Section of Sample 2

THE AIMS OF THE STUDY AND THE MODELS

Two different test cases were adopted for this study. The study is aimed at developing finite element models that can reasonably predict the structural behaviour of the PSSDB roof panels under a static bending load. Figures 4 and 5 shown the cross-sections of Models 1 and 2, respectively. Model 1 is the model without timber strips, while Model 2 is the one with side timber strips. The test panel length is 2000 mm. The models were simply supported. The study involved both experimental and theoretical models. From the results obtained experimentally, which showed reasonable reliability thes two model are considered sufficient and cost saving. This verified the accuracy of the finite element modelling technique. However, the comparisons were limited to comparing maximum deflection values within the linear elastic range between the experimental and Finite element Analysis (FEA) models. In addition, the study also aimed to find a method that can improve the stiffness and strength of the PSSDB roof panels in the present 'reversed' configuration. This is achieved by comparing results of maximum deflections and ultimate loads between Models 1 and 2 (without and with timber strips) obtained experimentally. In the future, more FEA parametric studies (including extended to non-linear models) will be conducted based on the currently verified FEA models. In this manner, the PSSDB roof panels could be enhanced further to achieve improved stiffness and strength.

EXPERIMENTAL MODELS

The models described above were constructed and tested in the laboratory. The test programme consisted of two series of full scale tests, as given in Table 5. The models were tested on a simple span via a whiffed tree loading to simulate a uniformly distributed load. The load was applied through four steel loading beams to the samples. The deflection values were measured using displacement transducers. The transducers were located at the middle and quarter span along the mid span line. The transducers were also located at both ends of the mid width line to detect any unintentional unsymmetrical eccentricity of loading.

Table 5. Models for the Flexural Tests

Model	Profiled steel sheet (PSS)	Dry Board (DB)	Screws	Timber strips
1	CL660 0.48 mm thick	Prima*flex* 9 mm thick	DX-RW 25 mm length at 100 mm c/c on each bottom PSS flange	N/A
2	CL660 0.48 mm thick	Prima*flex* 9 mm thick	DX-RW 25 mm length at 100 mm c/c on each bottom PSS flange	40 mm x 45 mm timber strips screwed with DX-RW 25 mm length at 100 mm c/c along the mid width.

EXPERIMENTAL TEST RESULTS AND DISCUSSIONS

Table 6 and Figure 6 show the maximum load, flexural stiffness and load-deflection behaviour of the test models based on the mid-span, mid-width deflection values for the various load intervals. The load-deflection curves obtained from the experiment exhibit similar characteristics. At the initial stage, the curves show a linear elastic relationship. This linear elastic response continues until a non-linear stage and a plastic stage are reached before failure of the models.

From the results, the model with timber strips (Model 2) obviously performs much better than model without timber strips (Model 1). As predicted, the timber strips in the PSSDB roof panel increase the stiffness and strength of the models. Model 2 recorded a higher stiffness and maximum load values.

Table 6. Stiffness of Composite Panels with Application of Timber Strips

Model	Maximum load, (kNm^{-2})	Mid-span, mid-width deflection at maximum load (mm)	Flexural stiffness, EI ($kNm^2\ m^{-2}$)
1	3.5	23.1	57.6
2	6.0	39.7	79.3

The flexural stiffness of the panel without timber strips was found to be 57.6 $kNm^2\ m^{-2}$, whereas that for panels using timber strips was 79.3 $kN\ m^2\ m^{-2}$. Comparison of the stiffness values shows that there was a 35.8% increase in the stiffness of the panel when using timber strips. In fact, the maximum load that can be sustained by the connected panels increased from 3.5 $kN\ m^{-2}$ to 6 $kN\ m^{-2}$. It can also be seen that the curve of the panel with timber strips gives a smoother load deflection curve compared to the panel without timber strips. This indicates that the presence of the timber strips helped maintain the stability of the cross-sectional dimensions of the very flexible PSSDB panels (due to the very thin profile steel sheet adopted). Therefore, for the above mentioned reasons and practical considerations, PSSDB roof panels with the timber strips are strongly recommended.

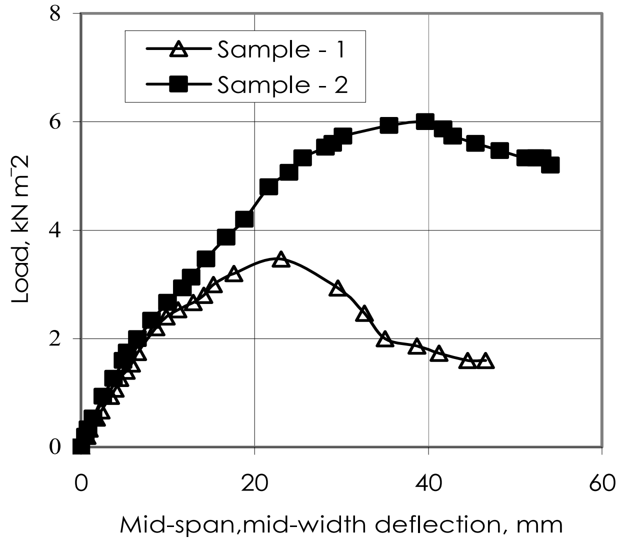


Figure 6. Flexural Load-Deflection Behaviour of PSSDB Panels

THE FEA MODELS

The theoretical analysis was based on FEA using Landon University stress Analysis System (LUSAS) finite element software (LUSAS 2003). The QSL8 thin shell element was chosen to model the **thin** profiled steel sheet and dry board, as this is more affordable in terms of computer memory, space and time. The semi-loof shell element (QSL8) is a quadrilateral thin, doubly curved, iso-parametric element formed by applying Kirchoff constraints at discrete points to a three-dimensional degenerate thick shell element. Figure 7 shows the QSL8 element. The formulation of the element takes into account both membrane and flexural deformations. However, as required by thin shell theory, transverse shearing deformations are excluded.

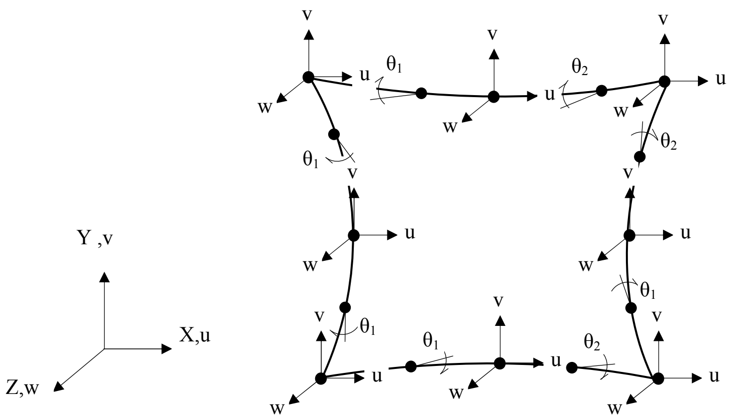


Figure 7. Nodal configuration for QSL8 element in LUSAS, (2003)

A compatible volume element, HX20, was chosen to model the **solid** timber strips. Figure 8 shows the element of HX20. HX20 is a solid continuum element, which has 20 nodes and 3 degrees of freedom per node.

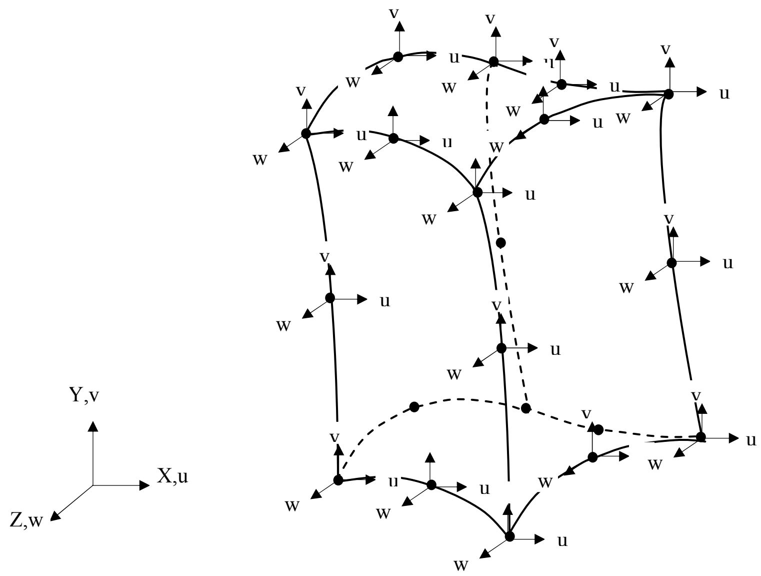


Figure 8. Nodal Configuration for HX20 Element in LUSAS, 2003

The discrete screwed connections between the profiled steel sheet and dry board were modelled as spring elements, which have a combination of translational and rotational elastic springs. The connections were modelled as close as possible to represent the actual action of the shear connection. A compatible joint spring element, JL43 (see Figure 9), was chosen for this purpose. The JL43 joint elements connect two nodes by three springs in the local x, y and z – directions.

Only two springs that are parallel to the neutral plane of bending (i.e., springs in global x- and z-directions) are involved in representing the shear behaviour at the screwed connection. The input values for these two springs can be the same. The value of the stiffness for the spring elements is derived from experimental push-out test results (345 N mm^{-1}). The third spring (the spring in the y-direction) was assigned a very large value of stiffness [2.9 x 10^6 N mm^{-1} predicted value from Shodiq (2004)]. The connection stiffness of timber strip to dry board is taken from experimental push-out test results (300 N mm^{-1}). For the 'dummy' joint spring elements, the global x- and z-direction springs are assigned a very small value for the spring stiffness (1 N mm^{-1}). The spring in the y-direction in these joints is assigned the same value as that used in the actual joints (2.9 x 10^6 N mm^{-1}).

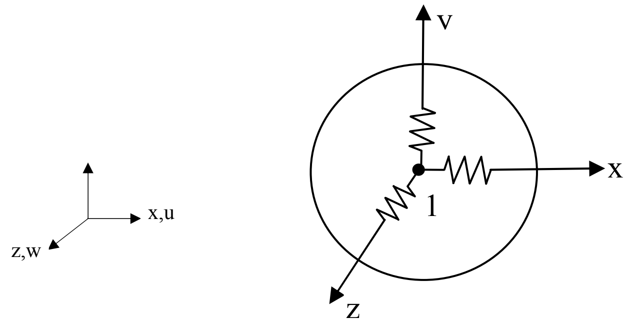
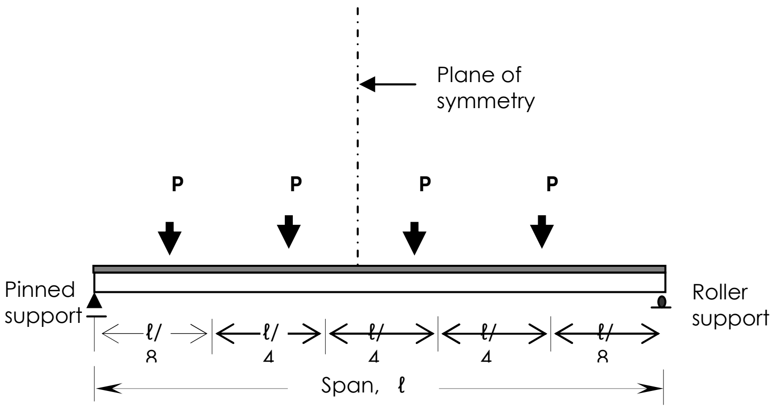
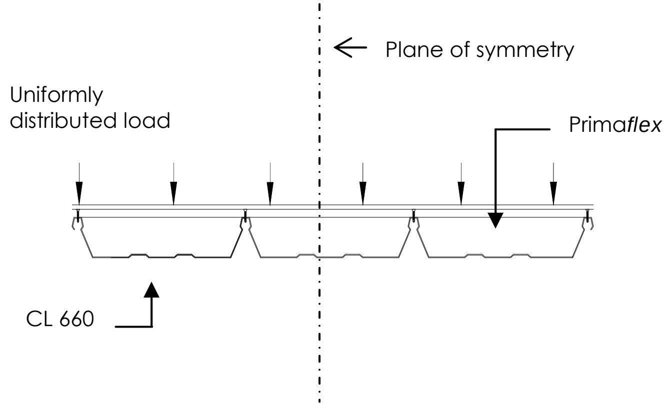


Figure 9. Joint Element, JL 43, (LUSAS 2003)

The model takes advantage of the symmetrical nature of the roofing system, where only half of the roof structure was modelled, employing appropriate boundary conditions at the symmetrical axis and end supports (see Figure 10). From the assumed symmetry, all the longitudinal edges of the sheeting and the boarding were restrained against rotations about the longitudinal axis (i.e., global z-axis). Their translations (in the global x-direction) were also restrained. Figure 11 show the idealised structural symmetry.

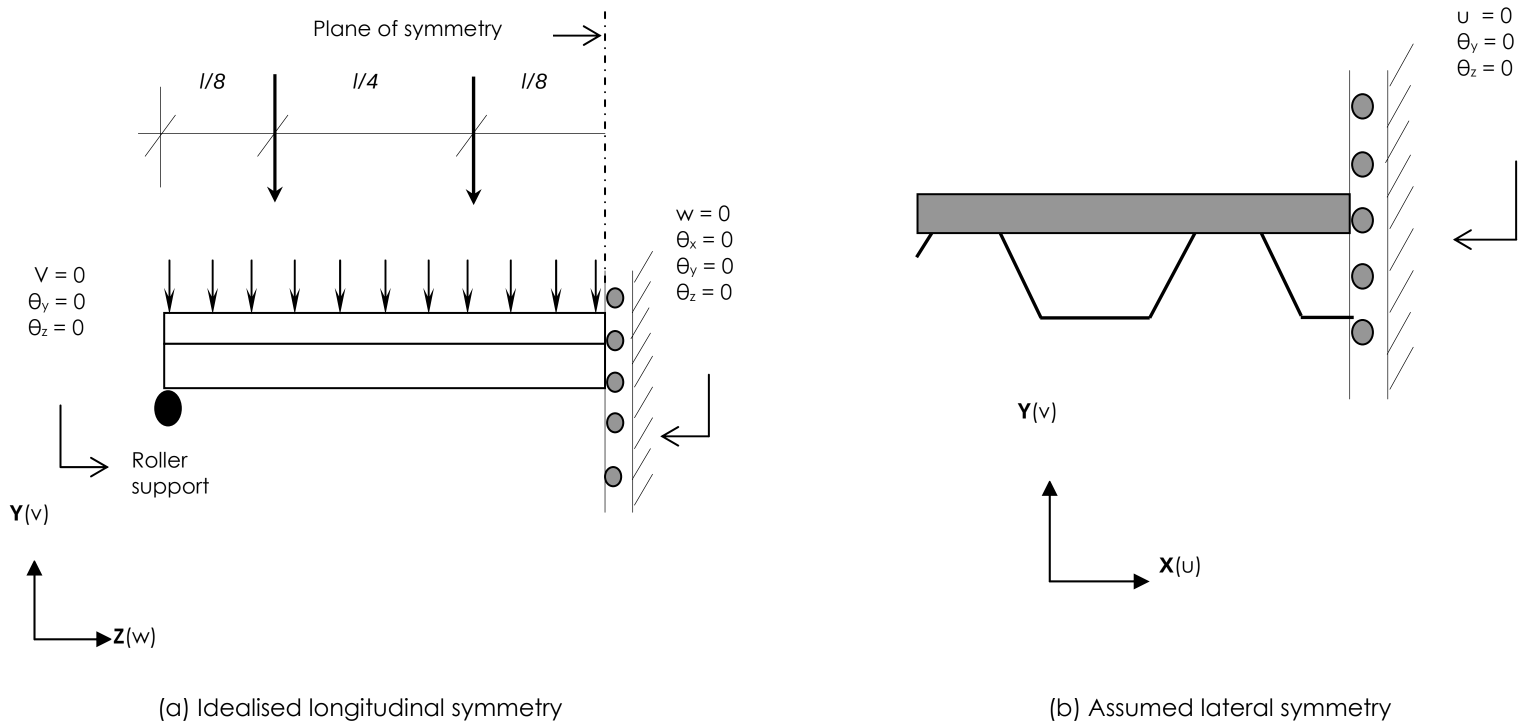


(a) Longitudinal span



(b) Cross-section of a PSSDB panel

Figure 10. Idealised Representation of a Simple Span under Uniform Loading



(a) Idealised longitudinal symmetry

(b) Assumed lateral symmetry

Figure 11. Idealised Structural Symmetry

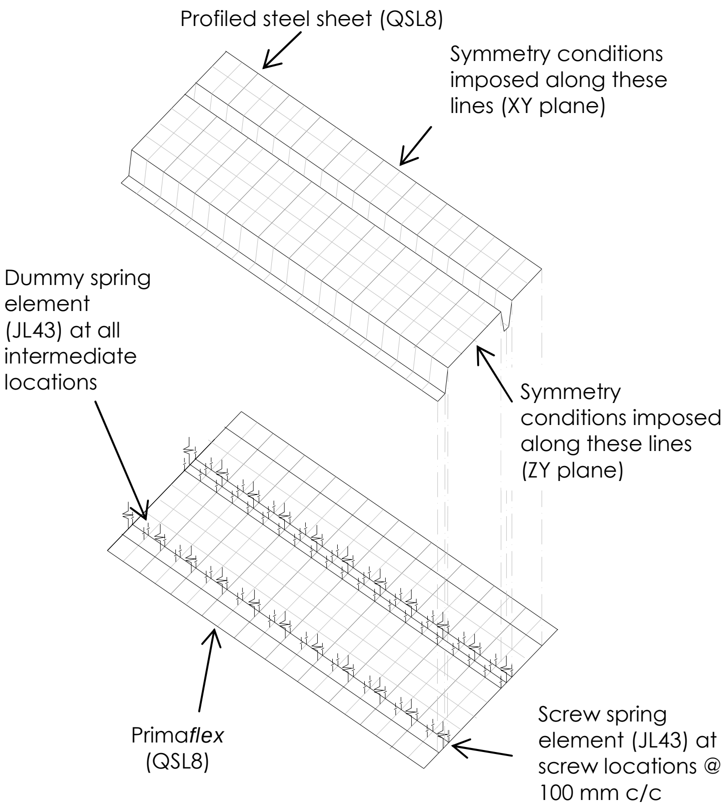


Figure 12. Finite Element Idealisation of Panel without Timber Strips

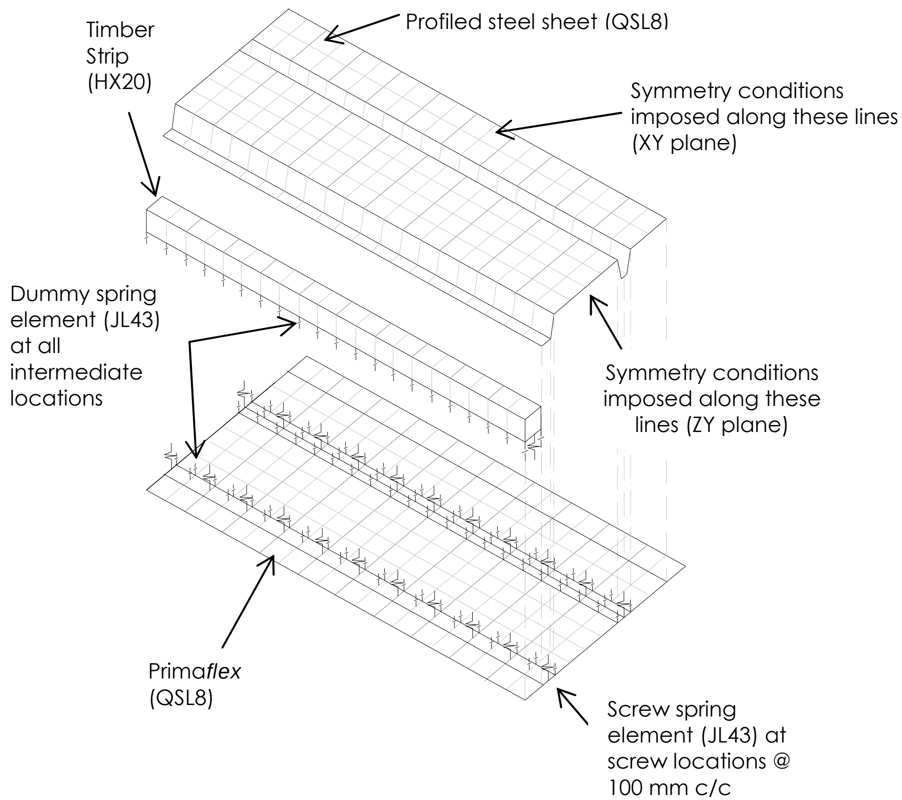


Figure 13. Finite Element Idealisation of Panel with Timber Strips

The input properties, such as the geometry and dimensions of the components, the Young's modulus and Poisson's ratio of the individual materials and the connection modulus, were derived from either the manufacturers' details or determined experimentally. Figures 12 and 13 show the FEA models for both Models 1 and 2.

A sensitivity analysis or convergence test was conducted before the final converged finite element mesh was obtained. The results thus given in this paper are for the already converged finite element mesh.

COMPARISON OF RESULTS

As discussed in the previous section, the values of deflections obtained from the experiments are compared with those predicted by FEA. Table 7 shows the deflection values from the finite element predictions and also from the experimental test results. It can be seen that the deflection values obtained from Finite Element Method (FEM) follow closely the experiment results (within the linear elastic range). Reasonable accuracy was observed with discrepancies varying from 5.6% to 11.2%. Therefore, the finite element prediction with some safety factors can be used to design the PSSDB panel system at the serviceability stage without any loss of accuracy and without being too conservative.

Table 7. Deflection Values: Test Result and Finite Element Prediction

Load kN m^{-2}	Deflection (Sample 1)			Deflection (Sample 2)		
	Test results (mm)	FE model (mm)	Difference (%)	Test results (mm)	FE model (mm)	Difference (%)
0.25	0.94	0.88	6.4	0.72	0.66	8.3
0.50	1.85	1.75	5.4	1.45	1.31	9.7
0.75	2.85	2.63	7.7	2.15	1.96	8.8
1.00	3.75	3.51	6.4	2.90	2.61	10.0
1.25	4.65	4.39	5.6	3.65	3.26	10.7
1.50	5.64	5.26	6.1	4.32	3.91	9.5
1.75	6.52	6.13	5.7	5.14	4.56	11.3
2.00	7.51	7.0	6.7	5.85	5.21	10.9
2.25	8.62	7.87	8.5	6.43	5.86	8.9
		Average	6.5		Average	9.8

CONCLUSION

This paper describes in detail the theoretical and experimental investigations of an innovative PSSDB roof panel system. Results from the experimental have been used to validate the theoretical results obtained from finite element analysis. The PSSDB panel in a 'reversed' position has been shown in this paper to be potentially useful as a load bearing roof panel. Though the FEA results underestimated the real conditions, the discrepancies are still within 5% to 11%. The flexural stiffness of the composite PSSDB roof panel with timber strips was found to increase by 38.5% compared to the panel without timber strips. The timber strips play a very important role in increasing the stiffness and strength of the PSSDB panel system. It can be concluded that the panel with timber strips has great potential to be used as a load-bearing structural roof system.

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