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Full Length Research Paper

Development of profiled steel sheeting dry board roof panel system in school classroom modules

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This paper describes the latest development, application, finite element modelling and testing of a full-scale composite roof panel system which was applied as an alternative to traditional forms of roof construction. The system known as the Profiled Sheeting Steel Dry Board (PSSDB) system consists of profiled steel sheeting connected to dry board using simple mechanical connectors. Compared to traditional roofing systems and materials, the PSSDB roofing system eliminates the roof trusses in buildings. Besides, the proposed system has many advantages such as it is lightweight, requires a shorter construction time, optimises the utilisation of materials and provides greater safety for residence (is theft-proof). A full-scale school classroom module was built and tested. A theoretical model of the roof system based on the finite element method (FEM) was proposed. Comparison of deflections between the FEM and the full-scale real roof system showed a safe underestimation by the FEM of the roof stiffness by about 5.8%.

Key words: Profiled steel sheeting, dry board, composite structure, roofing system.

INTRODUCTION

Rapid growth and development in the construction industry has resulted in increasing demands for more effective and innovative construction systems and techniques. Construction is becoming less and less dependent on traditional methods of construction which normally would involve natural materials such as reinforced concrete and timber systems. New concepts of construction technology such as those involving steel building systems, composite systems, modular systems such as lightweight panels, hollow blocks and other similar industrialised building systems (IBS) are now becoming more acceptable (Awang and Badaruzzaman, 2009).

IBS has been introduced into the construction industry in order to enhance the efficiency of construction processes, thus allowing higher productivity and quality, time and cost saving. The IBS is a methodology whereby the construction industry is driven and encouraged towards the production and utilisation of pre-fabricated and mass produced building components off-sites in factories or in a controlled environment, to be transported and installed rapidly at the sites (Rahmadi, 2002).

An innovative load-bearing panel system known as the profiled steel sheeting dry board (PSSDB) system which was first introduced by Wright and Evans (1986) as a replacement to existing timber joist floor is being innovated by researchers at Universiti Kebangsaan Malaysia (UKM) to extend its application not only as flooring as originally envisaged, but now as walling and roofing systems, and this is very much in line with the IBS concept. The PSSDB system is a lightweight composite system consisting of profiled steel sheeting connected to dry boards by simple mechanical connectors. The connectors play an important role in transferring horizontal shear between the boarding and the profiled steel sheeting. Some previous research works on the PSSDB as floor, wall and roof and IBS systems are reported (Ahmed, 1999; Ahmed and Wan Badaruzzaman, 2005; Ahmed et al., 2000; Akhand, 2001; Awang, 2008; Awang and Wan Badaruzzaman, 2009; Wan Badaruzzaman et al., 2003a, 2003b). Figure 1

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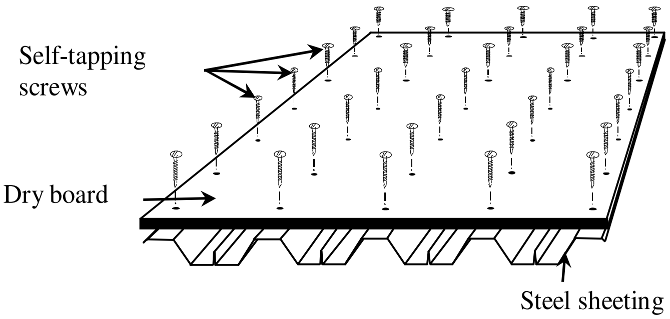

Figure 1. A typical PSSDB system.

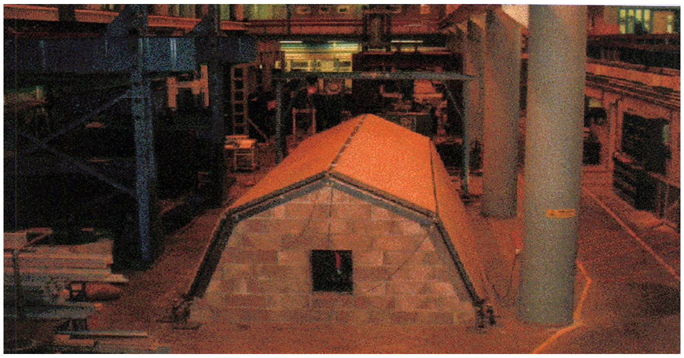

Figure 2. PSSDB folded roof structure tested by Wan Badaruzzaman.

Figure 3. The PSSDB folded roof structure that was tested by Ahmed.

shows a typical composition of a single-skinned PSSDB system.

Based on the original concept of the system as a flooring system, the application of the PSSDB system has been extended to form a new concept of roofing system which is the main focus of this paper. The new approach of applying the PSSDB system as a roof structure will eliminate the roof trusses normally required in traditional roof structure. 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. As a result of composite panel action, the PSSDB roof panel system gained higher rigidities and strength compared to the traditional roof system. Some of the advantages of the PSSDB system over traditional solutions are thus listed:

1. The structure of the roof that would normally involve a considerable number of internal elements that would impinge on the roof space and reduce its effective use is no longer an issue would no more be required.
2. The considerable numbers of connections between elements that is normally required in the skeletal framing, and which are often difficult to form while adding to the cost of roofing is eliminated.
3. The difficulty of providing overall stability of the roof structure by used of cross bracing and allowances for wind uplift would now be removed.
4. Insect attack and rotting of roof timbers; a problem that is not always resolved with preservatives and treatments would no longer be a threat.

PREVIOUS RESEARCH WORKS ON PSSDB ROOF

The potential of assembling PSSDB panels to form folded plate roof structures was first studied by Wan Badaruzzaman (1994). Wan Badaruzzaman developed an analytical solution and a computer program to predict the behaviour of both isotropic and orthotropic folded plate structures simply supported on two end diaphragms. The program was successfully verified using full-scale PSSDB folded plate experimental models. This method was extended from theory developed by Evans (1967) and Wright (1988). However, the proposed analytical approach could only be used to solve relatively simple roof structures. Figure 2 shows the model structure tested by Wan Badaruzzaman (1994).

By using the same computer program developed by Wan Badaruzzaman (1994), Nepaul (1994) extended the study to simulate the structural performance of PSSDB roof system under various loading conditions by investigating their potential of use as shelter units.

Ahmed (1999) extended the study of PSSDB systems to a simple pitch folded plate roof. Finite element analyses based on isotropic and orthotropic models were proposed in this work and results show discrepancies between the finite element and experimental models range from 4 to 31.5%. These studies showed that PSSDB folded plate models were structurally satisfactory for use in practice. The use of fixed end support conditions as was done in this work for example reduced the mid-span central ridge deflection by up to 23.7% compared to the deflections for simple support systems. Figure 3 shows the model that was developed by Ahmed

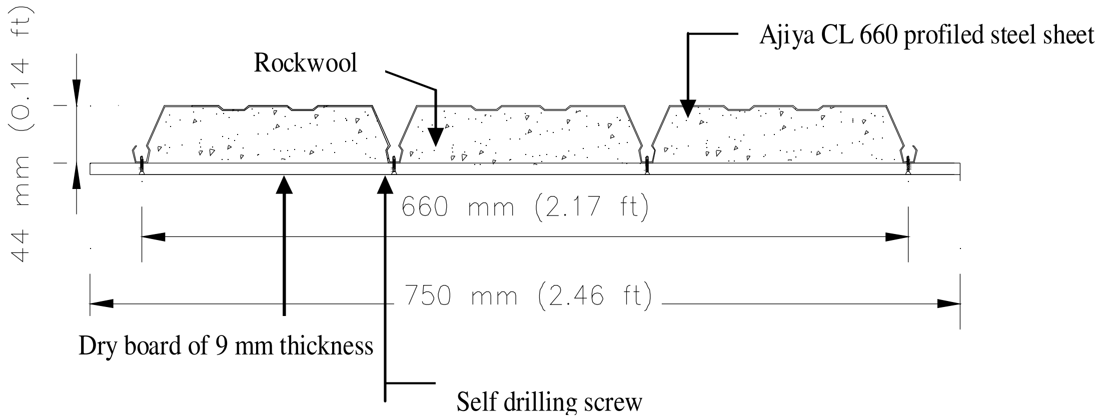

Figure 4. Proposed PSSDB roof panel in the reversed position.

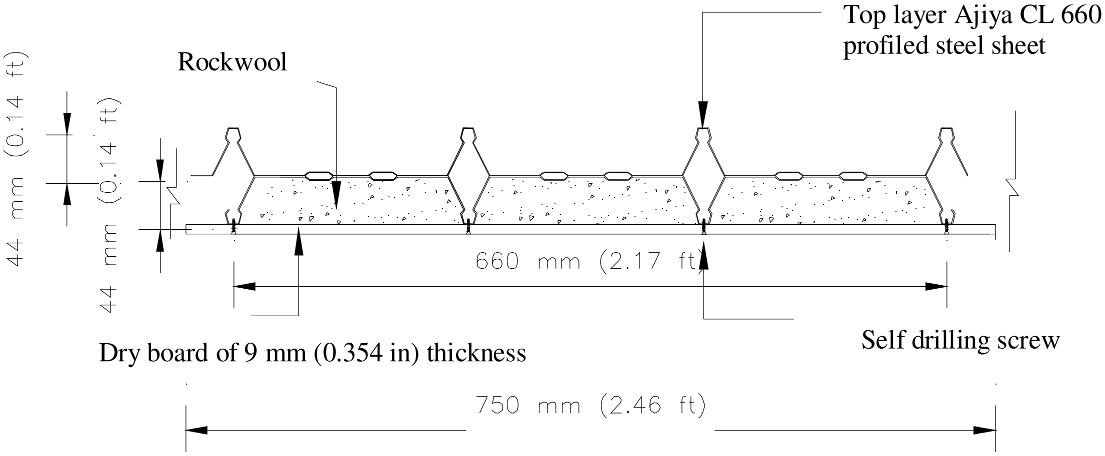

Figure 5. Final configuration of the proposed PSSDB roof panel.

et al. (1999). The work of Ahmed and Wan Badaruzzaman (2003, 2005) contains reports of further studies conducted on PSSDB. The papers discussed on the analytical development in the determination of rigidity properties for the PSSDB as equivalent orthotropic plate.

THE INDIVIDUAL PSSDB PANEL

The PSSDB roof panel was constructed using Ajiya Cliplock CL 660 (profiled steel sheet) (2003) and Prima*flex* (dry board) (2007). The thicknesses of the sheeting and the board were 0.48 mm (0.02 in) and 9 mm (0.35 in), respectively. The sheeting and dry board were screwed together via self-tapping and self-drilling screws spaced at a distance of 100 mm (3.94 in) apart on every rib of the Ajiya CL660 steel sheet. The normal position of the PSSDB panel is shown in Figure 1. However, the roofing panel in this normal PSSDB position could pose durability problems in the long run, as the dry board is exposed directly to the sun, rain, sleet and snow.

In order to solve this problem, the position of the PSSDB panel was reversed (Figure 4). The new position of the board provides for a flat surface on the underside of the roof facing the room. This flat surface eliminates the use of suspended ceiling panels in buildings. In order to provide for some aesthetical value to the top surface of the entire PSSDB panel, an additional top layer of the same profiled steel sheeting was introduced. Figure 5 shows the proposed reversed position of PSSDB roof panel, with the addition layer of profile sheet steel in place.

FULL-SCALE PROTOTYPE STRUCTURE

The proposed PSSDB roof panel previously discussed was for the first time been implemented as a roofing system in two school classroom modules at Sekolah Kebangsaan Telok Mas, Melaka, Malaysia. The total area of the roof for each classroom module was approximately 105 m^2 (1130.25 ft^2). The roof system was designed to cater for a dead load stress of 0.31 MPa (44.96 psi) and an imposed load stress of 0.25 MPa (36.26 psi). Two sizes of panels were used here; 750 mm (29.53 in) wide × 2000 mm (78.74) in length (14 in number) and 750 mm (29.53) wide × 4000 mm (157.48) in length (28 in number), in the arrangement shown in Figure 6. The PSSDB roof panels span across the width of the classroom module and were supported on front and back PSSDB walls at the ends, and on specially designed intermediate inverted-T purlins (2 in number) made of 30 mm (1.18) × 50 (1.97) × 4 mm (0.16) Rectangular Hollow Section (RHS) welded onto 150 (5.91) × 5 mm (0.20) thick mild steel plate (Figure 6). The inverted-T purlins span end to end along the classroom modules supported on the

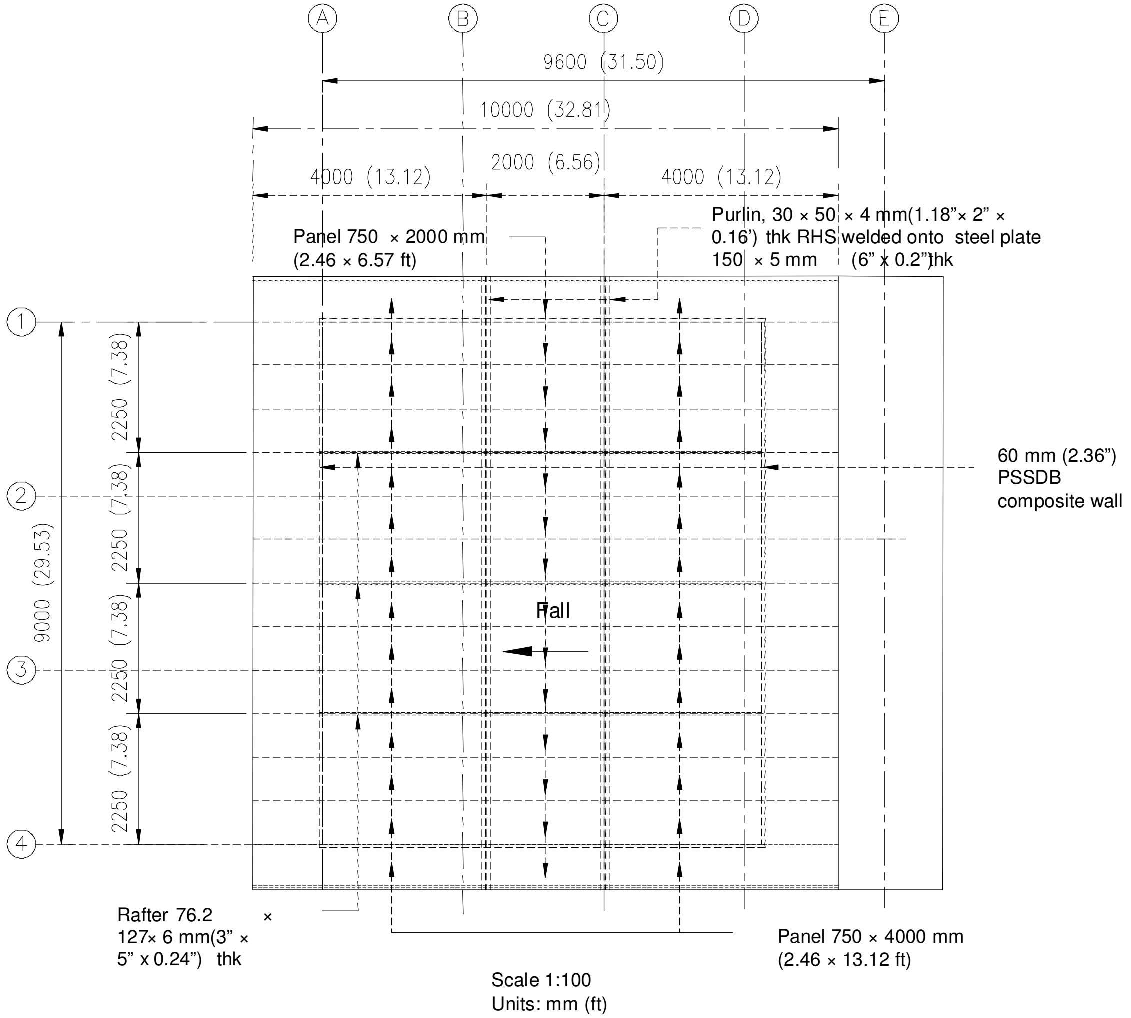

Figure 6. The arrangement of the PSSDB roof panels on a plan view.

two side PSSDB walls and intermediate mild steel rafters made of RHS 76.2 (3) × 120 (4.72) × 6 mm (0.24). All roofing connections were simple screwed connections. The panels were finally connected together and covered by an additional top layer of profiled steel sheet which acted as a cladding, while at the same time adding to the aesthetic of the roofing system. The rafters played an important role in transferring load from the purlins onto the load bearing PSSDB walls. The elevations of the school cabin on which this roofing was installed are shown in Figures 7(a to c).

FINITE ELEMENT MODELLING

The roof structure of the school classroom modules discussed in the foregoing literature was used to undertake theoretical analysis based on linear elastic finite element method (FEM), employing LUSAS-FE finite element software (2003).

Modelling of profiled steel sheeting and dry board

The PSSDB composite panel is normally composed of elements that satisfy the requirements of thin plate theory (the ratio between the length of a side and the thickness of the materials, falling between the values of 8 and 80 (Ventsel and Krauthammer, 2001)). Therefore, the two main components of the PSSDB roof panels, that is, the profiled steel sheet (Clip Lock CL 660) and dry board (Prima*flex*) were modelled as isotropic thin shell elements. QSI4 thin shell element from the LUSAS-FE element library was chosen for this purpose. QSI4 element has four nodes and six degrees of freedom per node. The input properties into the finite element model such as the geometry and dimensions of the components (Figure 4), and the Young's modulus were derived from the manufacturers' details.

Tables 1 and 2 show the structural properties of Clip Lock CL 660 and Prima*flex.*

The Poisson's ratios are assumed to be 0.35 and 0.2 for the Clip Lock CL 660 profiled steel sheet and Prima*flex* dry board respectively.

Modelling of supporting members

The supporting members aforementioned and shown in Figure 6, the purlins and rafters were modelled as isotropic thin shell elements for the very same reason aforementioned. The input


06/08/2007
06/08/2007

(a) Front elevation (b) Side elevation


06/08/2007

(c) Rear elevation

Figure 7. Plan and elevations of the school cabin module roofed with PSSDB roof in the present work.

Table 1. Structural properties of clip lock (CL) 660 profiled steel sheeting.

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

Source: Ajiya (2003).

Table 2. Structural properties of dry board type Prima*flex* of 9 mm thickness.

Characteristic	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 (2007).

material properties to the finite element model in this case were the Young's modulus = 210E03 MPa) and Poisson's ratio = 0.35. The yield strength of the materials is 550 MPa.

Modelling of connections

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 closely as possible to represent the action of shear connection. The compatible joint spring element, JSH4 was chosen for this purpose, from the LUSAS-FE element library (2003). In the numerical model, the JSH4 spring elements were used to connect the board and sheeting at the finite element nodes at discrete screw locations (every 100 mm on every rib of the Clip Lock CL 660), known as 'active' spring elements. In addition, JSH4 spring elements were also introduced at 50 mm distance from the 'active' spring element locations, known as the 'dummy' joint spring elements. This is to model the contact plane between the profiled steel sheet and dry board in between screw locations to avoid them from behaving independently of each other. The values of spring stiffnesses were assumed to be the same for both the 'active' and 'dummy' spring elements, except for the stiffness along the contact plane, which in the case of the 'dummy' spring element is assumed to be very small.

For the actual screws, the value of the stiffness in the shear directions (the global *X*- and *Z*-directions) for the 'active' joint spring elements were derived from actual value obtained experimental push-out test results (345 N/mm) conducted by the authors. The third value of the stiffness, in the direction of the screw, the *Y*-direction was assigned a very large value of stiffness (2.9×10^6 N/mm predicted value from Shodiq (2004)). This is to represent the real situation during the experiment where no vertical separation was observed between the Clip Lock CL 660 profiled steel sheet and the Prima*flex* dry board.

On the other hand, for the 'dummy' joint spring elements, the global *X*- and *Z*-direction springs were assigned assumed very small values of spring stiffness (1 N/mm) to represent the natural friction in between the Clip Lock CL 660 and the Prima*flex*, which is

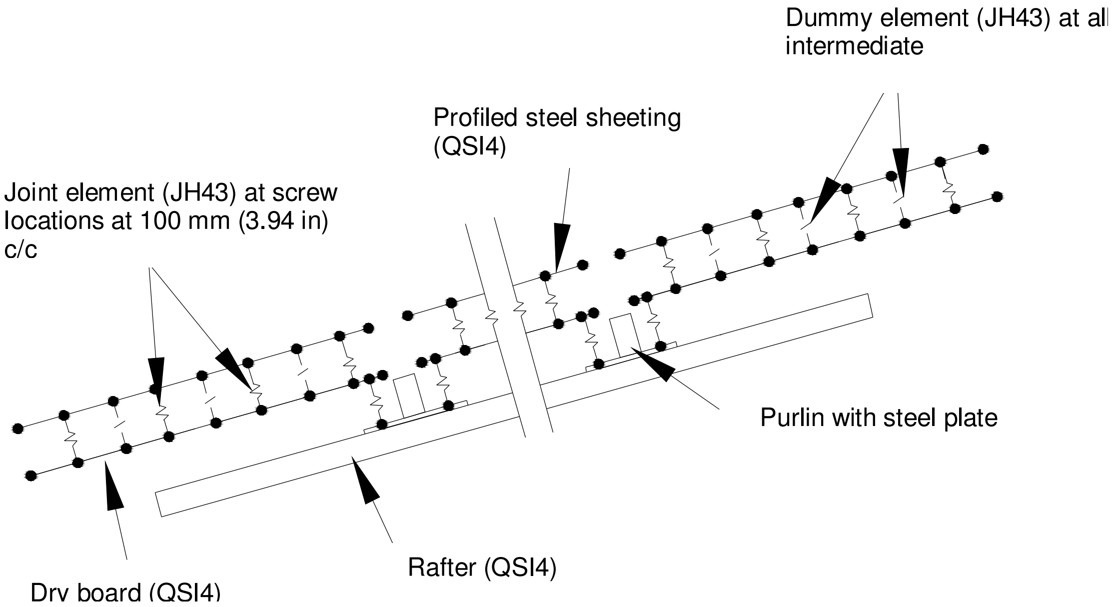

Figure 8. Finite element idealisation of the roof model used in the present work.

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

very nominal in reality. Again, the spring in the *Y*-direction in these joints was assigned the same value as used in the 'active' joints (2.9×10^6 N/mm). The input properties of the components, Young's modulus and Poisson's ratio of the individual materials, and connection modulus were derived from either the manufacturers' details. Table 3 shows the properties of screw connectors used.

The finite element model developed here took 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. The cross-section for the FEM model for the roof developed in this work is shown in Figure 8.

TESTS ON THE ROOFING STRUCTURE PROTOTYPE DEVELOPED

An experimental study was conducted on a full-scale roof of the school classroom module developed in this work to gain an understanding of its behaviour. Sand was placed on the roof top to provide a uniformly distributed loading acting on the top of the roof. The sand was contained in a plywood box. The area of loading covered was only 4 m (13.12 ft) × 4.5 m (14.76 ft), due to the limited testing equipment. The location chosen for the loading and instrumentation (deflection transducers) was within the centre-most interior panel and its surrounding roof area. This is the position where deflection is predicted to be the largest. Prior to the test, all equipment (data logger, deflection transducers and load cells) were calibrated to ensure accuracy of results, and transducers used were those that are suitable for detecting small values of deflections (as predicted by the finite element analysis) to avoid errors due to the wrong choice of transducers.

The locations of transducers on the roof are shown in Figure 9. The transducers were placed to measure the mid-span deflection at the centre of the selected interior panels as well as at two locations under the purlins. Figure 10 (a) and (b) shows the set up of the instrumentation. The loading was applied in six increments from 0.058 MPa (8.411 psi) until 0.272 MPa (39.45 psi).

The value of the maximum load applied to the roof was chosen to represent the actual dead and possibly applied loading on the roof. For every load increment, the displacement was recorded directly by an electronic data logger. After the maximum load was applied and the deflection measurement recorded, the load was released until the load dropped to zero. It was observed that the final readings of the transducers were close to their initial unloaded readings. This indicated that the roof structure has not been loaded beyond its elastic range as expected for the kind of magnitude of maximum load applied onto the structure.

OBSERVATIONS AND DISCUSSION OF RESULTS

Here, we first check the results from the actual test for symmetry, hence will be limited to comparing the gradients of the plotted curves. The deflections recorded at symmetrical positions on either side of centre line (TP1 and TP8, and TP3 and TP7) were observed to be identical and hence symmetrical. Comparing the gradients of the two supposedly identical curves, the variation in gradients is 2.1%. This is considerably small, as seen from Figures 11 and 12. The slight deviation at higher loads is quite common for a full scale test

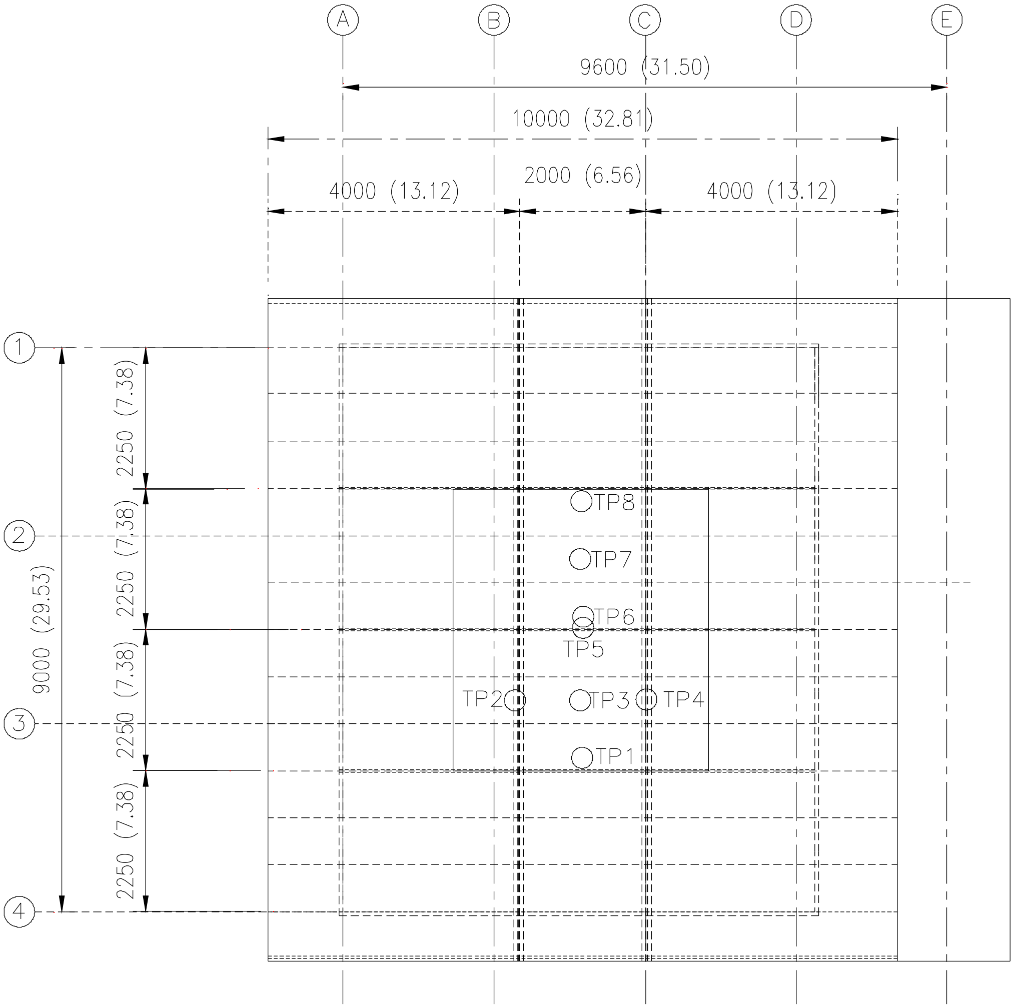

Figure 9. Locations of transducers. TP: transducer.

(a)

(b)

Figure 10. Instrumentation set-up. (a) Transducer placed at the angle plate (b) Locations of transducers.

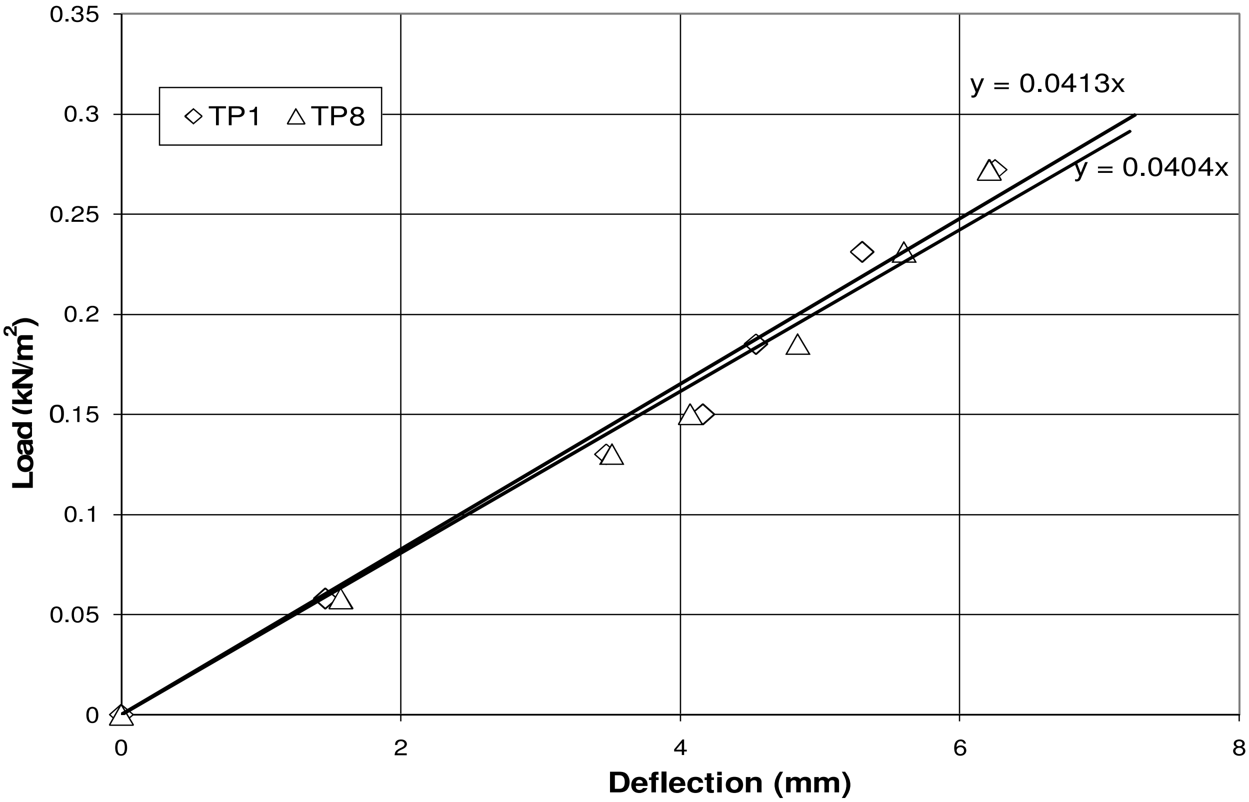

Figure 11. Symmetry between TP1 and TP8.

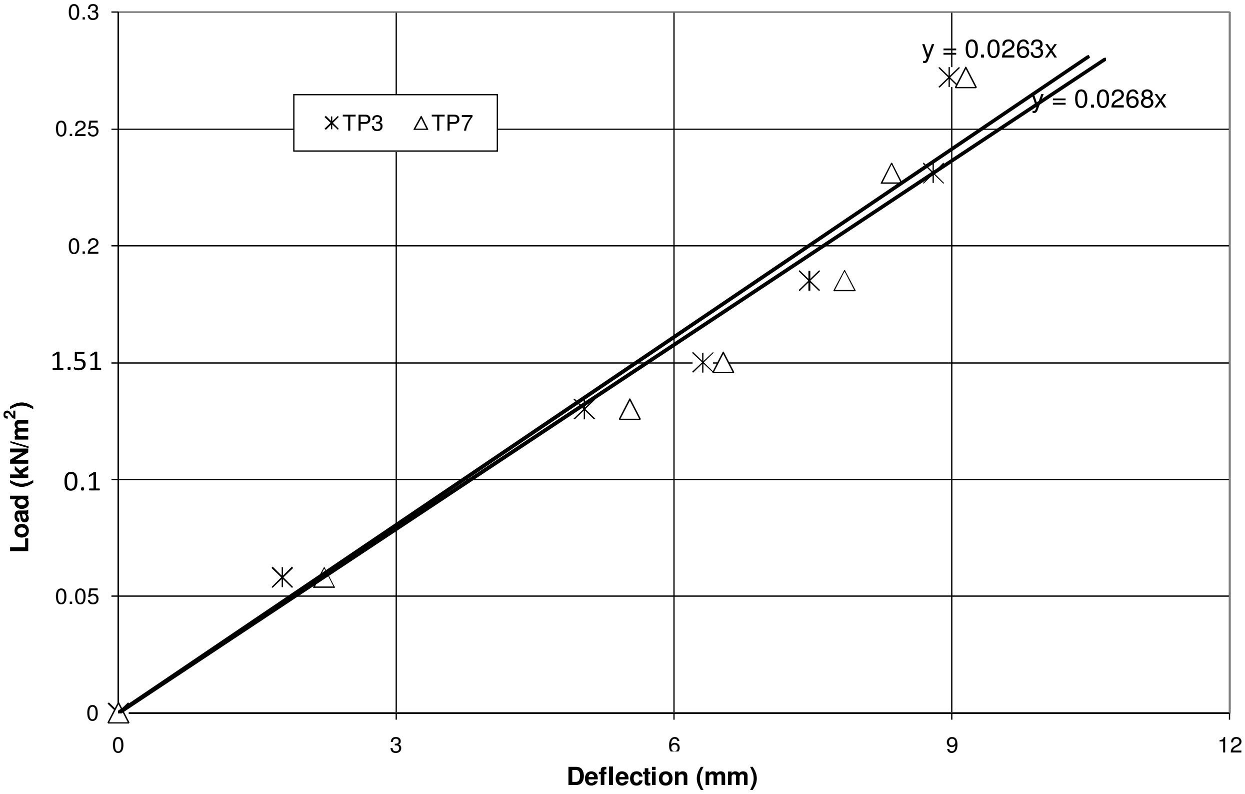

Figure 12. Symmetry between TP3 and TP7.

Table 4. Comparison of roof deflection under an evenly distributed load.

Load (MPa)	Experimental maximum deflection (mm)			FEM prediction	Discrepancy (%)
	TP5	TP6	Average		
0	0	0	0	0	0
0.058	2.51	2.69	2.6	2.98	14.6
0.130	6.99	7.54	7.27	6.68	-8.1
0.150	8.32	8.04	8.18	7.71	-5.7
0.185	9.56	9.26	9.41	9.51	1.06
0.231	11.08	10.58	10.83	11.87	9.6
0.272	11.9	11.94	11.92	13.98	17.2

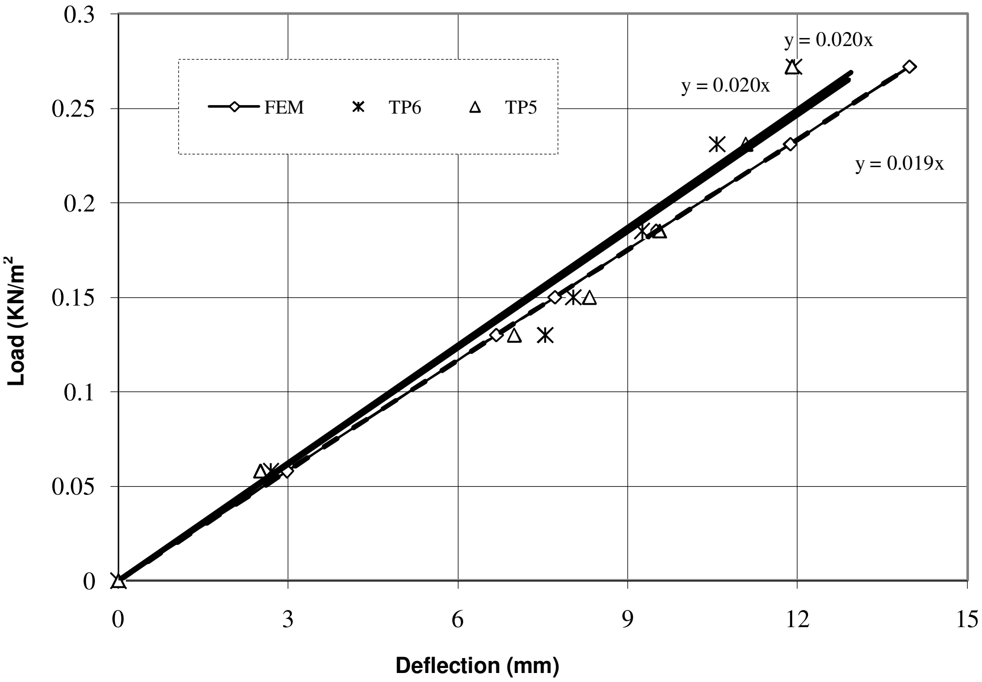

Figure 13. Comparison of deflection curves.

structure.

The deflection values were observed to be slightly higher on one side of the roof, in the case of TP7 and TP8 as compared to the other side of the roof as recorded for TP1 and TP3. This was probably due to some slight imbalance in distribution of the manually placed sand as loads to be contained in the plywood box on top of the roof.

The values of the highest deflections at mid-span (at TP5 and TP6) obtained from the experiment were compared to those predicted by the finite element modeling. Table 4 shows the deflections at TP5 and TP6 and those predicted by FEM. Figure 13 shows the load against deflection curves for TP5, TP6 and FEM. It is observed that if the results were compared, value by value for each load increment, the discrepancies ranges from 8.1 to 17.3%, with the lowest discrepancy of 1.06% when the load is at 0.185 MPa. However, comparing the gradients of the lines of best fit (which could be used to calculate the stiffness value of the PSSDB floor system), the load-deflection curve obtained from the FEM follow closely the experimental graph with a slight underestimation of the roof stiffness (which is safer) by 5.80%, thus predicting a less stiff roof structure than the real roof. This is still within an acceptable discrepancy limit (about 5% target).

PRELIMARY DESIGN

The design of the PSSDB roof system is mainly governed by deflection of the system as was for the PSSDB flooring (Wan Badaruzzaman et al. (1995). Therefore, this paper covers the serviceability aspect of the design of PSSDB roof. A strict deflection limit of span/250 is adopted here. Therefore, for a span of roof of 2 m, the deflection limit is 8.0 mm. In the test conducted, the maximum deflection was found to be 11.94 mm and hence has exceeded the deflection limit. Therefore, the roof system has failed under the deflection criteria; hence stress check could be ignored for now.

Conclusions

This paper has described further development, real application, theoretical modelling and testing of a full-scale PSSDB composite roof panel system which was applied as an alternative to traditional forms of roof construction. The PSSDB panels were applied to form the complete roof of two school modules. The theoretical and experimental investigation of the deformation characteristics of the PSSDB roof panel structure under uniform top load was described in detail. The PSSDB panel system has been brought a step forward in terms of real application as a roofing system as reported in this paper.

The finite element method was used to undertake theoretical modeling in this study. The accuracy of the proposed finite element model was verified by conducting full scale experimental tests on the actual roof system. It was seen by comparing the results from the theoretical model of the roof system based on the finite element method (FEM) and the full-scale real roof system under experimental testing that the accuracy of the former method was reasonable, given the small slight underestimation (which is safer) of the roof stiffness by 5.80%.

However, the full-scale PSSDB roof system was found to exceed the limiting deflection under service load. In order to improve the system, method of improving the system such as employing stiffer profiled steel sheeting, the use of different types of dry boards (or thicker Prima*flex* board), closer screw spacing or reducing the roof span could be considered in future tests of the PSSDB roof system.

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