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MEMBRANE ACTION IN PROFILED STEEL SHEETING DRY BOARD (PSSDB) FLOOR SLAB SYSTEM

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Abstract

Profiled steel sheeting dry board (PSSDB) system is a lightweight composite structural system that made of the profiled steel sheeting (PSS) connected to the dry board (DB) by self-drilling and self-tapping screws. The objective of this paper is to study the effect of membrane action in improving the flexural capacities of the PSSDB system. According to the literatures, common failure of the PSSDB floor is due to local buckling in the top flanges of steel sheeting at the centre of a simply supported slab. Restraining the horizontal movement at supports may develop the membrane action (MA) in the slab that can remarkably enhance the flexural rigidities of the floor. Experimental tests were conducted along with developing nonlinear finite element model to explore the effect of MA in the PSSDB floor. Experimental results of the PSSDB panel with simply end support were exploited to verify the nonlinear finite element results. The developed finite element model was then modified by restraining the horizontal movement of the slab at the supports. The obtained results disclosed that the developed compressive membrane action enhanced the stiffness of the slab at serviceability load by about 240%.

Keywords: Membrane action, Horizontal movement, Flexural capacity,
Experimental work, Support condition.

1. Introduction

Profiled Steel Sheeting Dry Board known as PSSDB floor system was first proposed by Wright et al. 1989 [1]. The primary intention of this system was to be an alternative to the traditionally timber joist floor system. There were many reasons behind this strategy which can be briefly mentioned as: insect attacks, rot, and misuse by occupants of using timber joist system. These effects considerably reduce the life span of most floors.

The PSSDB system (Fig. 1) is a composite system and comprises of two main components, namely, profiled steel sheeting (PSS) and dry board (DB), which are supposed to carry the tensile and compressive stress respectively. In addition, normal or light-weight concrete is usually used as an infill material and takes the responsibility of carrying some compressive stress in the system. The required interaction between two main components is provided by some self-drilling and self-tapping screws. Due to the deficiency of the screws to transmit the entire horizontal shear forces, the system is treated as a partial interaction system. Besides, as the fasteners are deformable, therefore the slip between the profiled steel sheeting and dry board is inevitable.

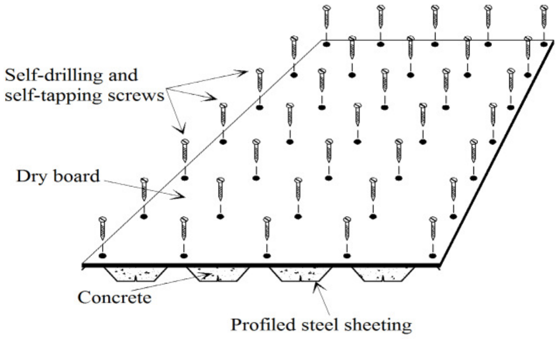


Fig. 1. Typical PSSDB Floor System.

The first issue to consider when discussing the failure of the PSSDB system is that steel sheeting has high strength and low stiffness. This characteristic makes the PSSDB structure more vulnerable to fail as a result of deformation and local buckling of the steel rather than reaching the ultimate strength. Therefore, the local instability usually dominates the design. In spite of the long lists of experiments and analytical studies conducted by previous researchers [2-8] on the PSSDB system, the effect of the membrane action in the system to improve the stiffness and the flexural capacity has not so far been considered.

1.1. Finite element method

The linear elastic finite element method overestimates the stiffness of PSSDB panel at all load levels [4]. Furthermore, the appearance of local buckling in the top flange of the profiled steel sheeting raises the nonlinear behaviour of the model. Accordingly, the nonlinear finite element approach is considered in this study.

1.2. Membrane action

Membrane action may be developed in the slab into two stages, namely, compressive membrane action and tensile membrane action (Fig. 2). Restraining the boundaries of the slab, with strong enough boundary elements, develops the compressive membrane action in the plane of the slab. This phenomenon happens due to the deformation geometry of the slab and tendency of the slab ends to move outward. As the slab deflection increases, the slab ends tend to move inward. The restrained boundary of the slab, leads to the development of the tensile membrane action at this stage [9, 10]. Study of the membrane action can be tracked back in the early 1920s by Westergaard and Slater [11]. In spite of almost one century of research, owing to some vague points in this theory, most of the codes do not consider the potential of the compressive membrane action to enhance the stiffness and the ultimate strength of the slab [12].

Although only moments and shear forces are considered at the yield lines in the proposed yield line theory for slab by Johansen [13], the theory gives good prediction of the ultimate load when the membrane forces are not developed in the yield line pattern. However, the effect of membrane action is not considered in this theory whereas the membrane forces are normally induced in the slab due to the boundary condition and the deformation geometry of the slab [9]. The most important difference between compressive membrane theory and yield line theory is the developed compressive thrust from boundary to boundary of the restrained slab [14]. According to the literatures [11, 14-23], by taking the compressive membrane forces into account, the ultimate capacity of both one-way slab and two-way slab is considerably enhanced far above the predicted value by yield line theory.

Fig. **2** demonstrates the load-deflection relationship for a one-way slab with restrain ends under the uniform load. As the load increases from A to B, after development of the yield line pattern, the ultimate load of the slab improves to point B due to the existence of the compressive membrane action. The developed compressive membrane forces are the result of the produced arch from boundary to boundary. Further increase of the deflection beyond point B, the load rapidly decreases (transition region) to bring the system to the tensile membrane action with the starting point of C.

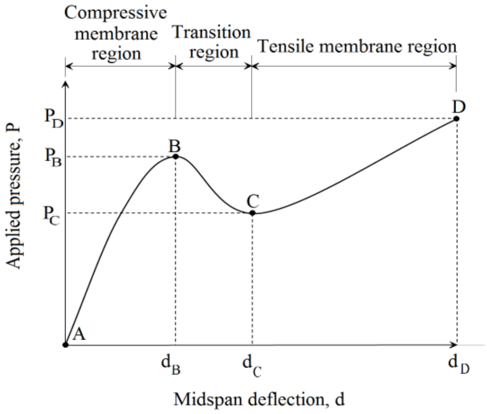


Fig. 2. Load-Deflection Relationship for a One-Way Slab with Restrained Ends.

In the reinforced concrete slab, when the modulus of crack of the concrete is exceeded, the developed cracks, in the tension zone of slabs subjected to flexure, remarkably reduce the flexural stiffness of the slab (Fig. 3). The presence of compressive membrane action strengthens the slab not to experience sudden reduction of the stiffness.

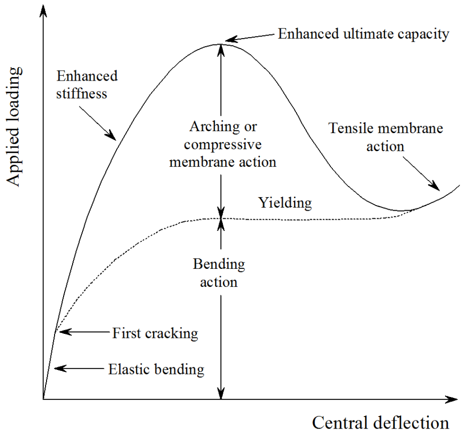


Fig. 3. Load-Deflection Relationship for Reinforced Concrete Slabs with Restrained Ends.

2. Models

In order to investigate the effect of the compressive membrane action in improving the performance of the PSSDB floor, three one-bay models presented in Table 1, are considered is this study. The models dimensions are 1730×795 mm.

Table 2 demonstrates the specification of the model and materials used. It is worth mentioning that the properties of the material are based on manufacturers' literatures.

Table 1. Models.

Model	Dimensions	Supports condition	Method
Model A	1730×795	Simply supported	Experimental
Model B	1730×795	Simply supported	Finite element
Model C	1730×795	Pinned supported	Finite element

Table 2. Details of the Specimen.

	Thickness/ diameter (mm)	Width & Length (mm)	Modulus of Elasticity E, N/mm^2	Ultimate strength N/mm^2	Weight of covered area N/m^2
Profiled steel sheeting (Peva 45)	1.0	795×1730	200×10³	350	130.77
Self- drilling and self-tapping screw	4.2	30.0	----	----	----
Dry board (PRIMA*flex*)	12.0	795×1730	8030	22	172
Concrete grade 30	Infill	Infill	25743	30	598

2.1. Finite element modelling of profiled steel sheeting, dry board, and concrete

The profiled steel sheeting could be assumed as an assembly of the isotropic plate elements and hence the orthotropic behaviour of the corrugated plate is achieved by the geometric shape of the model. Fig. **4** demonstrates the dimensions of Peva

45 cross section, employed as profiled steel sheeting. The dry board could also be modelled as isotropic plates.

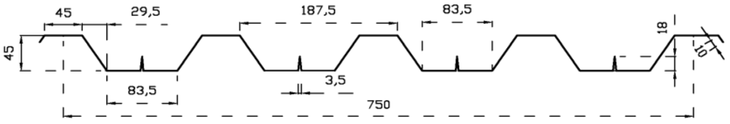
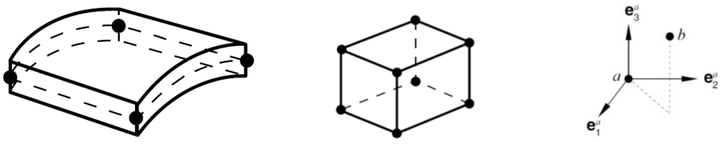


Fig. 4. Cross-Section of Profiled Steel Sheeting, Peva 45. (Note: All dimensions are in mm.)

Implementing the finite element approach requires the proper elements to represent the real behaviour of the system. In fact, the accuracy of this method is highly dependent on the element selections. The essential factors which play the role in the element selection are considered in this study for the sake of reliable results.

Due to the small thickness of the steel sheeting, it must be dealt similar to the thin-walled structures. In-plane and out-of-plane deformation in sheeting must be considered, where shell elements could represent this behaviour properly.

ABAQUS element library includes both thin and thick shell elements. Owing to the development of large strain in the structure, the desirable element is that applicable to both thin and thick shell element. In this study, S4R element is applied to model the profiled steel sheeting and the dry board. S4R is a three-dimensional four-node, doubly curved, general-purpose shell, reduced integration and finite membrane strain, Fig. 5(a). Furthermore, this element has six degrees of freedom per node that uses bilinear interpolation. Since the ABAQUS algorithm does not precisely calculate the normal to the nodes for the coarse mesh, the fine mesh must be applied for doubly curved surface [24].



(a) S4R element **(b) C3D8R element** **(c) Connection type (CARTESIAN)**

Fig. 5. Applied Elements.

Major load in the PSSDB system is carried by Peva 45, profiled steel sheeting [4]. The elastic-perfectly-plastic behaviour was assumed for the property of the steel. PRIMAflex is composite material flat sheet composed of top grade cellulose fibre, Portland cement, and finely ground sand that is produced under the intense pressure. In addition to moisture resistance, higher mechanical properties are achieved in PRIMAflex compared to other available dry boards. The nonlinear material property of the PRIMAflex was assumed based on the manufacturers' documents.

Three-dimensional continuum element (C3D8R element) was chosen to model the concrete infill. It is 8-node linear brick, reduced integration with hourglass control element, Fig. 5(b).

2.1.1. Modelling of connection

Two types of connections are considered in this study, namely, connection between the profiled steel sheeting and the dry board, and the connection between profiled steel sheeting and the infill concrete.

Connector element is applied to model the interaction between profiled steel sheeting and the dry board. This element brings the relative displacements and rotations that are local to the element. In the case of three-dimensional models, connector element uses twelve nodal degrees of freedom to facilitate three displacements and three rotations in element local direction of both end of the element. The isotropic connector element is modelled to represent the biaxial shear deformability of the self-drilling and self-tapping screws. The spaces between connector elements are exactly derived from the space between screws in the experimental specimen. The applied connection type CARTESIAN showed in Fig. 5(c) provides independent behaviour between two nodes in three local Cartesian directions. In addition, the contact interaction is employed to simulate the transmit shear and normal force across the interface between profiled steel sheeting and infill concrete [24]. The required input data for this type of contact interaction is obtained from past study [25].

The stiffness of the screwed connections is the essential parameter to model the partial interaction in the system. Although some experimental test has been conducted by previous researchers on PSSDB system interaction, none of them has studied the interaction between Peva 45 and PRIMAflex. The derived stiffness of the used screws from the push-out test conducted by the authors is applied in the analytical model.

2.1.2. Convergence

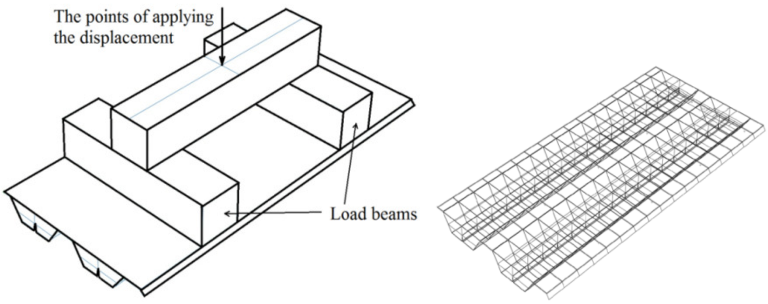
As mentioned earlier, increasing the number of elements in spite of boosting the accuracy of the results makes the computation time longer. The ideal is to minimise the number of elements without affecting the accuracy of results. Hence, the aspect ratio of the elements is an important factor. Since the generated model is expected to predict the local buckling and stress distribution in the system, therefore the actual distribution of the mesh is important, which could be obtained by convergence history and result. The reliable results are determined only by a trial-and-error approach [4].

2.1.3. Modelling of boundary conditions

Behaviour of the profiled steel sheeting in the simply supported specimen subjected to vertical loading in boundary area is unknown. That means the lower flange of the profiled steel sheeting tends to move upward in some area while the PSSDB system undergoes the vertical load. Avoiding the upward movement of the specimen boundaries in the model may affect the reliability of the results, because the generated model does not properly simulate the behaviour of real structure. To overcome this problem, the contact feature in the ABAQUS is applied in boundaries so that in spite of restricting the downward movement of the specimen ends, they are free in upward movement.

2.1.4. Modelling of loading

For the purpose of modelling the load, two methods are applied in literatures, namely, load control and displacement control methods. In order to have the falling branch of the load-deflection curve, the displacement control is applied in this study. The displacement control is normally used for the concentrated load; hence this method could not be exploited straight away in this study as the distributed load is considered. To take this fact into account, the loading beams, as weightless rigid parts, are applied in a similar way of the experimental test with the same dimensions. The desirable control displacement is then applied exactly at the place of load cell in the real test. Fig. **6**(a) demonstrates the way of applying displacement control in the developed quarter-scale model.



Dimensions of load beams section: 100 mm×100 mm

(a) Point of applying the displacement control **(b) Finite element idealisation of the model**

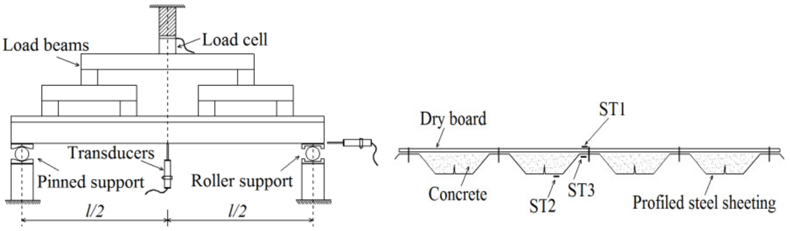
Fig. 6. The Quarter-Scale Model.

2.2. Experimental model`

The experimental test is conducted on three specimens in order to explore the effect of the membrane action in the PSSDB floor subjected to the vertical loading. The specimens are one-bay PSSDB floor composed of Peva 45, PRIMA*flex*, concrete infill, and the self-drilling and self-tapping screws.

2.2.1. Construction

Concrete grade 30 was chosen to be applied as an infill material. PRIMA*flex* dry board was attached to the profiled steel sheeting by self-drilling and self-tapping screws with the space of 200 mm. The boundary condition of the test is simply supported at both ends of the specimen. The movements and the strains of sensitive points of the specimen in this study were measured by the properly installed transducers, and the strain gauges. The sensors, especially the strain gauges, were installed cautiously so that obtained results by the data logger are reliable. The uniformly distributed load on the specimen was applied by means of load beams acting as equivalent line load with an equal amount. To measure the applied load, 1000 kN load cell is used, and it is located exactly under the hydraulic jack. More details about the strain gauges, transducers, spreader beams, and position of load cell are demonstrated in **Error! Reference source not found.**.



(a) Location of the Transducers and Load Beams. **(b) Strain Gauges Positions at Mid-span.**

Fig. 7. Test Set-up Details.

2.2.2. Testing process

After calibration and installation of the apparatus for measuring the required data, the electronic data logger was initiated so that the condition can be considered as an initial unloaded state of the model. The loading was then started with the increment of 200 N as a monotonic static load until the amount of load was about the 80% of the predicted ultimate load or the appearance of the first plastic buckling in the profiled steel sheeting; either case happened earlier. Further loading was applied in a way to create around 1.0 mm increase in the mid-span deflection at each increment. The succeeding increments of loading in the inelastic range were applied when the additional movement of specimen deflection is discontinued. The test was carried on until the central deflection hits 90 mm. The testing of a PSSDB floor specimen for the horizontal movement is shown in Fig. 8.

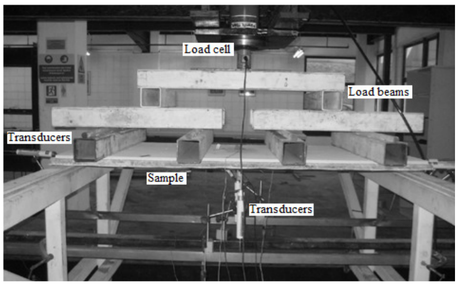


Fig. 8. Testing of a PSSDB Floor Specimen for the Horizontal Movement.

3. Results and Discussion

3.1. Verification of analytical model

The plotted graph in Fig. 9 demonstrates the load-deflection curve for the unrestrained condition (model A and model B) of the experimental test and the finite element results. The ABAQUS prediction for the behaviour of the slab shows good agreement with experimental test in the both elastic and plastic phases of the curve. The evaluated ultimate load carrying capacity by the nonlinear finite element model differs less than 10% from that of experimental results, which is within maximum allowable variation of 15% according to the standards. The main conclusion from the verification against experimental data, obtained from conducted test by authors, is that the developed non-linear finite element model can be used to simulate the pinned support slab.

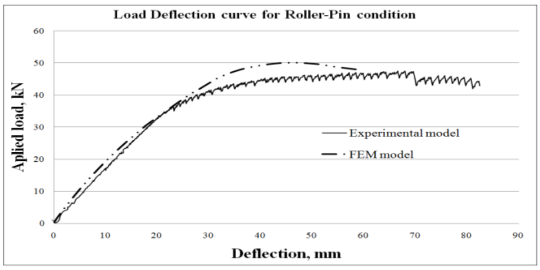


Fig. 9. Load-Deflection Curve for Roller-Pin Condition Model.

3.2. Parametric study

Fig. **10** depicts the load-deflection curves of unrestrained condition model (model A) along with finite element models of unrestrained (model B) and restrained condition (model C). Comparing the experimental and the FE curves of the simply supported model depict the similar behaviour in both elastic and inelastic ranges. The unrestrained condition in the finite element model then was upgraded to the restrained condition in order to restrict the horizontal movement of the specimen ends. The plotted graph in Fig. 10 demonstrates the remarkable improvement in the stiffness of the specimen at serviceability load by about 240%.

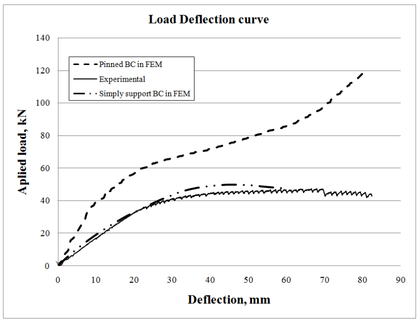


Fig. 10. Load-Deflection Curve for Roller-Pin and Pin-Pin Condition Model.

3.3. Failure of the specimen

Local buckling in the top flange of the profiled steel sheeting at the central region of the slab is the common failure of the PSSDB system subjected to flexure. Local buckling in the top flange increase as the overall buckling of the slab is growing. On the other hand, the overall buckling of the slab is strictly associated with the horizontal movement of the slab. Restricting the horizontal movement of the slab ends decrease the overall buckling and consequently, the local buckling is delayed in the system.

Early appearance of the local buckling in the simply supported floor results in failure of the specimen while the stress in bottom flange of the profiled steel sheet is far below than its ultimate strength. Delaying of the local buckling as a frequent failure of the PSSDB system paves the road to increase the forces in the bottom flange (tensile membrane action) and accordingly improve the flexural capacity of the system. Fig. **11** illustrates the stresses obtained from finite element model for both pin-roller (model B) and pin-pin (model C) conditions at quarter span position in bottom flange of the profiled steel sheeting. The induced stress in the pin-roller model does not reach the ultimate strength of steel while in the pin-pin model the stress experiences the full strength of the steel.

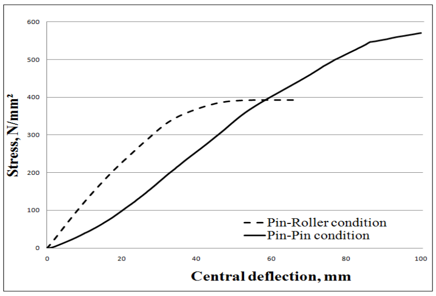


Fig. 11. Stress at Quarter Span Position in Bottom Flange of the Profiled Steel Sheeting.

3.4. Membrane force-deflection curve of pinned model

Fig. **12** reveals the history of the horizontal forces at one end of the pinned supported specimen against the mid-span deflection of the model. First part of the graph proves the developed compressive membrane forces in the model. As discussed earlier, the stiffness of the slab improves thanks to the progressed compressive forces. In addition, stiffness improvement of the slab is apparent in Fig. 10. As the compressive forces decreases at the deflection of 8.3 mm, the stiffness of the slab tends to reduce at that specific deflection. Subsequently, the tensile membrane forces then develop in the slab as the deflection increases.

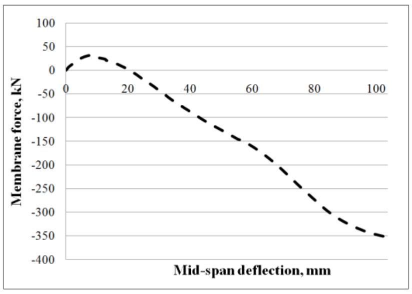


Fig. 12. Membrane Forces at One End of Pinned Supported Specimen against Mid-Span Deflection.

4. Conclusions

The purpose of the current study was to determine the effect of developing the membrane action in the PSSDB floors, by restricting the horizontal movement of the slab ends, on the stiffness and the flexural capacity of the system.

The main conclusion to be drawn from this study was that the mid-span vertical deflection of the floor is remarkably decreased that is the result of considering the role of compressive membrane action in the floor. The obtained results proved the claim that developed compressive membrane action in the floor results in the stiffer behaviour of the system at the serviceability loads. Thus, it is fair to say that applying the compressive membrane action in the PSSDB system conquer the weakness of low stiffness of the profiled steel sheeting. On the other hand, lower mid-span deflection at higher imposed load improves the capability of the system to be applied for different applications.

The second obvious finding to emerge from this study was that the full strength of the profiled steel sheeting came to the picture in the stage of developing the tensile membrane action in the floor. This is despite the fact that the weakness of the steel sheeting in stiffness plays a big role in the failure of the simply supported PSSDB floor.

Further research in this field, regarding the role of fixed boundaries of the floor, would be of the great help in improving the capability of the PSSDB system to be applied for more practical applications.

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