Journal of Engineering Science and Technology
Vol. 6, No. 6 (2011) 695 - 708
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EVALUATION OF NATURAL FREQUENCY AND DAMPING OF PROFILED STEEL SHEET DRY BOARD COMPOSITE PANEL

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Abstract

This paper evaluates the natural frequency and damping coefficient of Profiled Steel Sheet Dry Board (PSSDB) composite flooring panel system. The PSSDB composite flooring panel consists of dry board attached to the top surface of profiled steel sheet by self-drilling and self-tapping screws. This PSSDB composite panel has been used successfully as flooring system in few construction projects within Malaysia. As a lightweight flooring system, human induced vibration is becoming increasingly vital serviceability and safety issues for such panel when it is covering relatively longer span or area. Therefore, it is important to evaluate the factors affecting the serviceability performance and hence, to consider the effects of vibration in building such flooring system. This research is focused mainly on the fundamental frequency and damping coefficient of such floor panel. The influence of span length, board thickness, and connectors spacing on fundamental frequency are evaluated. It is shown that for the panels considered in this paper; up to the span length of 3.5 m the fundamental frequency is above the limiting minimum value of 8Hz and hence, it can be concluded that such composite floor panel with practical span length will be comfortable to the occupants of building in terms of human induced vibration.

Keywords: Profiled steel sheet, Dry board, Vibration, Natural frequency,
Flexural rigidity.

1. Introduction

Profiled steel sheet dry board system is one type of the composite panel that can be used successfully as flooring system in building construction [1]. Profiled steel sheet dry board (PSSDB) system consists of profiled steel sheeting that compositely

Nomenclatures

A_b	Area of board section, mm^2
A_n	Amplitude of peak after ‘n’ cycles, m/s^2
A_o	Initial amplitude from time-acceleration plot, m/s^2
A_s	Area of steel section, mm^2
C_B	Coefficient for end conditions
D_{xc}	Orthotropic flexural rigidity of composite section, kN-m^2/m
E	Modulus of elasticity of composite section (kN/m^2 or N/m^2)
E_b	Modulus of elasticity of board, N/m^2
E_s	Modulus of elasticity of steel sheet, N/m^2
f	Frequency, Hz
f_n	Natural frequency, Hz
I	Second moment of area of composite section, m^4
I_b	Second moment of inertia of board section, m^4
I_s	Second moment of inertia of steel section, m^4
k	Connector modulus from push out test, N/mm
L	Span of the composite panel, m
l	Span of the beam, mm
m	Mass per unit length (tons/m or kg/m)
n	Number of cycles
s	Spacing of connector, mm
z	Distance between centroid of two individual beam elements, mm
Greek Symbols	
ξ	Damping coefficient

connected to dry board panel using simple mechanical connectors. Over the past few years, the research on the system has been extended further in Malaysia by utilizing locally available materials [2-4]. As a flooring member, PSSDB panels are generally constructed as a single skin member i.e. profiled steel sheeting connected to a single layer of dry board as shown in Fig. 1. The function of the floor is to safely support all possible vertical loads, and transfer them to the foundation via members supporting the floor. Thus, as flooring system the PSSDB panel carries the out of plane bending and shear.

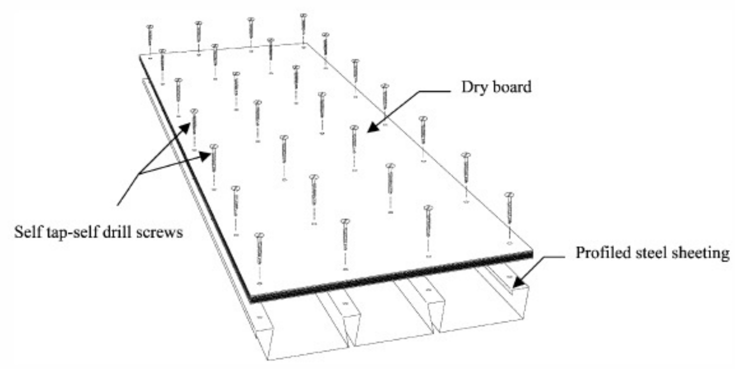


Fig. 1. Profiled Steel Sheet Dry Board Floor Panel.

Vibration problems in floor systems caused by human activities have long been a serviceability concern to engineers as mentioned by Murray [5]. Although, these floor vibrations are not a threat to the structural integrity of the floor system, they can be so uncomfortable to the occupants that the floor system may be rendered useless. Therefore, to avoid a vibration related problem with the lightweight flooring system having lesser depth and longer span, it is desirable to get a proper understanding on its dynamic behavior and to consider it in the design.

Previous research on PSSDB panel has concentrated mainly on the structural performances of such panel. It was shown structurally efficient under the associated bending [1-2] and also for axial compressive loading [6-7]. Furthermore, performance of such panels in the form of folded plate configuration for roof structure has also been studied [8-9].

The current design method of PSSDB floor panel is primarily based on the serviceability and ultimate limit state design philosophy. Both the partial interaction analysis based on simple beam theory [2] and folded plate methods of analyses [9] have been successfully used to the structural design of various practical floors [3-4]. However, systematic approach to evaluate serviceability vibration performances of such flooring panel is limited in literatures.

Two parameters such as natural frequency and damping are considered very important in vibration related problem. Natural frequency is the frequency at which the structure will vibrate when displaced and quickly released. All structures, although posses many natural frequencies; the lowest or the 'fundamental' frequency is the most concern. Damping of structure is important in mitigating its excessive vibration response. Until recently, damping in floor systems is generally determined from the decay of vibration following an impact. Vibration characteristics can be improved by increasing the amount of damping of the floor system. In general, the objects within the structure, for example use of partitions, presence of stationary humans etc. will provide additional damping to the structure. From the decay of vibration, the damping coefficient is reported to vary between 4 to 12 % for typical office buildings [10]. In general, damping of bare steel deck composite floors is reported to be between 1.5% and 1.8% [11]. Murray [5] used damping of 3% for an office without permanent partition.

In this paper, the theoretical and experimental bending rigidity of the panels are used to evaluate the dynamic design parameters such as natural frequency of the panels. Impact heel test [12] on selected panel is also carried out to determine the experimental natural frequency and to evaluate inherent damping of the PSSDB panel. Based on theoretical and experimental study, the factors that affect the natural frequency of PSSDB panel system; such as span length, dry board thickness and connectors' spacing are highlighted and finally, their effects are indicated in this paper.

2. Experimental Specimen and Material Properties

Two different types of tests were conducted in the laboratory in order to investigate the vibration performance of PSSDB flooring system. The flexural test was performed to obtain the load deflection graph, which facilitated the experimental stiffness values of the composite panel. These stiffness values of the test panels were then used to determine the natural frequency of the panels.

Impact heel tests were performed to measure the experimental natural frequency and the damping coefficient of the floor system. The test specimens were constructed by using locally available Bondek II profiled steel sheeting, connected compositely to 12-24 mm thick cement board by self-drill, self-tapping screws. Table 1 shows the details of the experimental specimens.

Table 1. Experimental Specimens Detail.

Test panel	Span (mm)	Sheet type and thickness	Board type and thickness	Connector spacing
1	1500	Bondek-II, 1 mm thick	Cement board 12 mm	200 mm centers in each rib
2	2200	Bondek-II, 1 mm thick	Cement board 16 mm	50 mm centers in each rib
3	2200	Bondek-II, 1 mm thick	Cement board 16 mm	100 mm centers in each rib
4	2200	Bondek-II, 1 mm thick	Cement board 16 mm	200 mm centers in each rib
5	2200	Bondek-II, 1 mm thick	Cement board 24 mm	200 mm centers in each rib
6	2200	Bondek-II, 1 mm thick	Cement board 12 mm	200 mm centers in each rib

The first panel having a relatively shorter span of 1.5 m was used for the heel impact test. The rest five specimens; with a span length of 2.2 m, were used in bending test to evaluate the flexural rigidity of the panels. The test parameters considered were the effect of connector spacing and thicknesses of the board. Before conducting flexural and vibration test, material properties for each of the components of PSSDB system; namely profiled steel sheet, dry board and screw connectors, were determined in the laboratory. Figure 2 shows the cross sectional dimensions of Bondek II profiled steel sheet used in the experimental study.

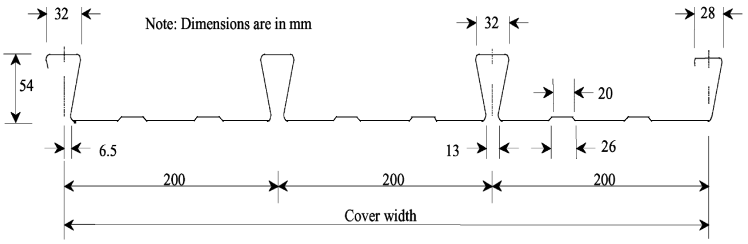


Fig. 2. Cross-sectional Dimension of Bondek II Sheet.

Table 2 shows the necessary properties of Bondek II profiled steel sheets that were either obtained from the manufacturer manual or calculated from the cross-sectional dimension of the sheet.

Table 2. Properties of Profiled Steel Sheeting.

Nominal thickness (mm)	Depth of profile (mm)	Mass (kg/m^2)	Height to neutral axis (mm)	Area of steel (mm^2/m)	Moment of Inertia (cm^4/m)	Moment capacity (kNm/m)
Bondek II, 1.0 mm thick	54	13.6	14.43	1633.5	63.68	8.2

To determine the material properties for the cement board, three-point bending test was conducted in the laboratory as shown in Fig. 3. Table 3 tabulates the properties of typical 16 mm thick cement board used in this study.

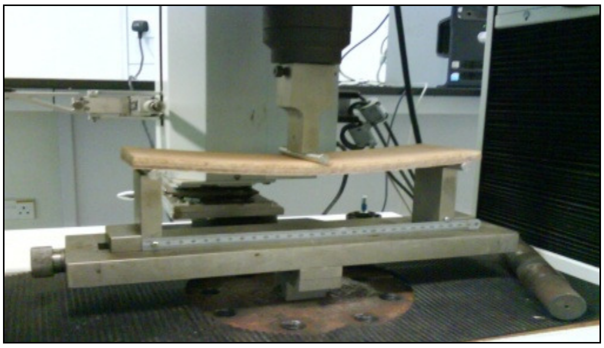


Fig. 3. Three Point Bending Test of Board.

Table 3. Properties of Cement Board.

Type	Density (kg/m^3)	Young's modulus (MPa)	Bending strength (MPa)
16 mm cement board	1250	5250	8.4

The capacity of screw connection was expressed by its shear modulus, which is the amount of shear force transferred per unit length of shear displacement. The shear modulus and total shear capacity of the screw connections determined by push out test (refer to Fig. 4) are shown in Table 4.

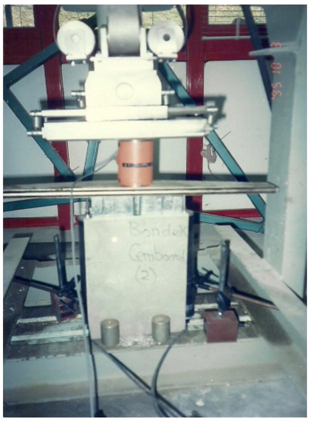


Fig. 4. Push-out Test of Connectors.

Table 4. Connector Stiffness and Capacity from Push-out Test.

Board type	Steel sheet Type	Connectors' stiffness (N/mm)	Connectors' capacity (kN)
16 mm cement board	Bondek II, 1 mm thick	625	3.0

3. Determination of Natural Frequency

3.1. Determination of natural frequency using impact heel test

To investigate the natural frequency of the PSSDB panel due to vibration, standard impact heel test was carried out in the laboratory on test panel 1. Pulse vibration analyzer available in the Mechanical Engineering laboratory of UNIMAS was used to conduct this test. In this test, a heel drop excitation was exerted on the floor panel. An average person stood-up at the mid span on the test floor, raised his heel to about 50 mm and produced a sudden impact on the floor. The resulting acceleration time history was measured by the accelerometer placed near the feet of the test person. The impact heel test result was interpreted using acceleration versus time graph. Figure 5 shows the typical heel impact acceleration response at the mid location of the panel. To get reliable result, four heel impact tests were carried out on the selected floor panel. To determine the fundamental frequency of PSSDB system, the acceleration versus time response was converted to frequency versus magnitude values using Fourier analysis. Figure 6 shows the typical Fourier amplitude spectrum analysis of the test panel.

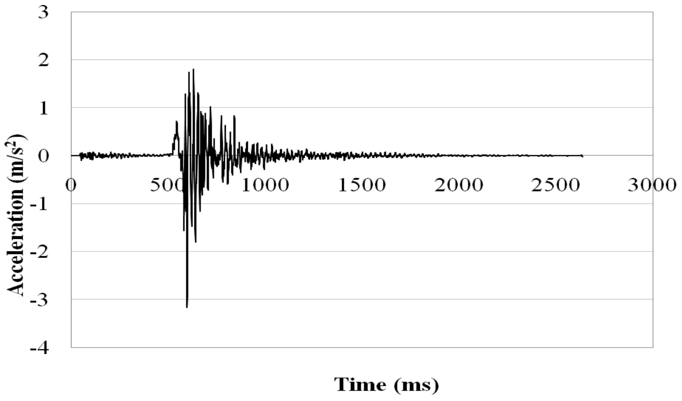


Fig. 5. Typical Acceleration Responses at Mid-span.

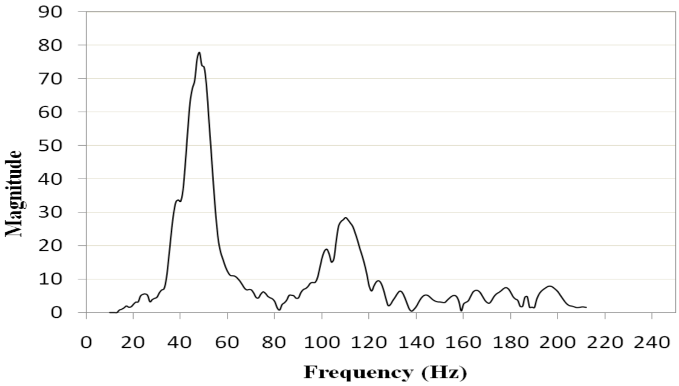


Fig. 6. Fourier Amplitude Spectrum Analysis of the Test Panel.

From the time-acceleration plots in Fig. 5, the damping coefficients were also calculated using Eq. (1) as presented by Ellis [13]:

$$\xi = \frac{1}{2n\pi} \log_e \frac{A_o}{A_n} \tag{1}$$

In the above equation, A_o is the initial amplitude and A_n is the amplitude of peak after “n” cycles of the acceleration–time response plot. Damping obtained from the equation mentioned above was “Log decrement damping’. Murray [5] stated that modal damping is one-half to two thirds of the value of the log decrement damping. In this study, five initial successive peaks were used to determine average damping coefficient of the test panel.

3.2. Theoretical determination of natural frequency

To assess the floor response to dynamic loads, an accurate calculation of the first natural frequency is important to use in the design criteria against floor vibrations. Research done by Wyatt [14], Williams et al. [15], Bachmann and Pretlove [16] and, Brand and Murray [17] yielded various method to estimate natural frequencies of floors. In this paper, fundamental natural frequency of the test floor panel was obtained from the generally used analytical solution given in Design Guide on Vibration of Floors [14]. This analytical solution for fundamental natural frequency is given as:

$$f_{Analytical} = C_B \left(\frac{EI}{mL^4} \right)^{1/2} \tag{2}$$

where m is the mass per unit length (unit in tons/m if EI is expressed in kNm^2, or kg/m if EI is expressed in Nm^2), L is the span in meters, E is the modulus of elasticity (kN/m^2 or N/m^2), and I is the second moment of area (m^4) of the composite section. The values of C_B for various end conditions are 1.57 for the pinned supports (simply supported), 2.45 for fixed/pinned supports, 3.56 for fixed both ends and 0.56 is for fixed/free (cantilever) ends.

To get the fundamental frequency from the equation mentioned above, it is necessary to calculate the actual value of *EI* of the composite panel. In this paper, the *EI* values of the test panels were determined from the full scale flexural experimentations. Also, partial interaction analysis based on beam theory was used in evaluating the *EI* value of the test panels.

3.2.1. Experimental determination of bending stiffness

To determine the experimental bending stiffness of the composite PSSDB panel system, full-scale flexural tests were carried out in the laboratory. Figure 7 shows the typical specimen and the instrumentation detail for the flexural test. The test procedure followed was that of conventional bending test and it was similar to that of DIN 18807 Part 2 [18].

The panels were tested over a simple span as mentioned in Table 1 and instrumented for the measurement of quarter and mid-span deflections. Linear displacement transducers were used to measure the deflection of the beam.

Portable electronic data logger was used to record the reading of deflections. Loads were applied by hydraulic jack, which were attached to the pressure gauge that facilitated in getting the load readings. After a regular increase of loading, the loading values and the corresponding deflections were recorded. The load and the corresponding deflections taken at mid-width and mid-span location were then used to obtain the EI values of the composite panel. The quarter span transducers were used mainly to check the symmetrical nature of the loaded panel.

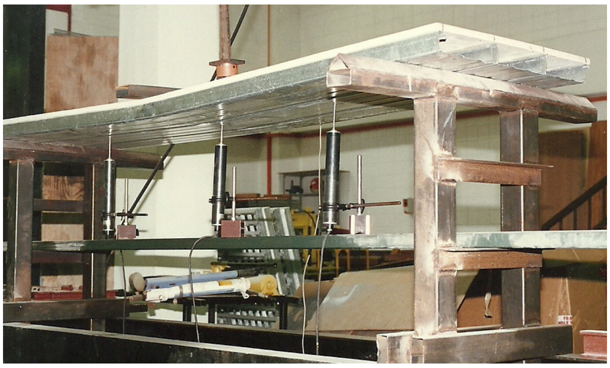


Fig. 7. Test Arrangement and Instrumentation Detail.

Figures 8 and 9 show the load-deflection behavior of panel 2-4 and panel 4-6 respectively at mid-width, mid-span location. It is observed from the graphs that the initial load-deflection response is linear and elastic and this elastic response continue until just before failure. The final failure of the panels occurred when the upper flanges of the steel sheeting buckled. The slope of the load deflection graphs for the elastic portion was the input into the simple beam theory to obtain the EI value of the composite panel.

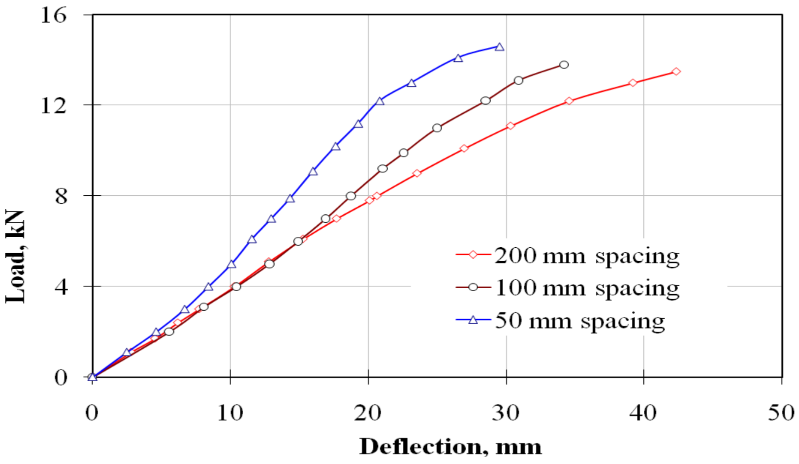


Fig. 8. Load-deflection Behavior of Test Panel 2-4.

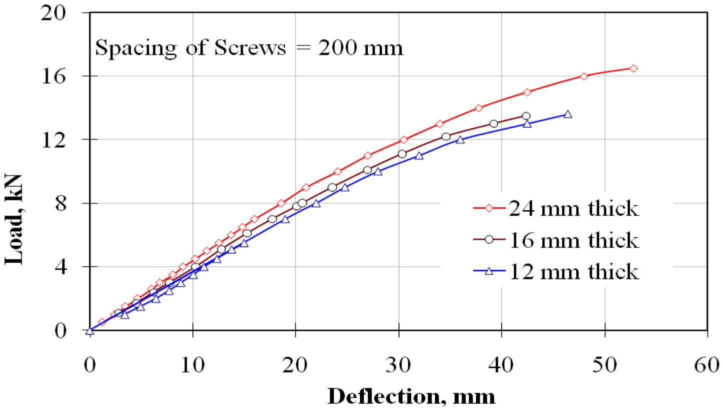
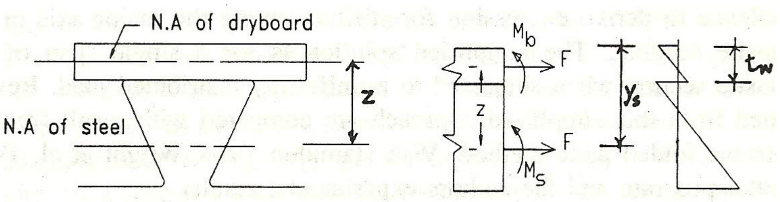


Fig. 9. Load-deflection Behavior of Test Panel 4-6.

3.2.2. Analytical determination of composite stiffness

To determine the theoretical composite stiffness of the PSSDB system, classical partial interaction analysis was carried out on the composite panel system. One repeating section of the composite panel was considered as a beam; the upper layer was the dry board whereas the lower layer was corrugated steel sheet. In the analysis, two elastic members (board and profiled steel sheet) were considered to be connected by linearly elastic connection. The analysis included the flexibility of the connection medium in predicting the stiffness of the panel. Figure 10 shows the cross section and strain distribution for the repeating section of the panel.



(a) Cross-section (b) Internal Forces (c) Strain Distribution
Fig. 10. Composite Beam with Imperfect Interaction.

The governing differential equation for the composite beam section was derived to get the general expression for deflections. Finally, method of elastic equivalence was applied to get the final expressions for bending stiffness.

The final expression for the stiffness of a simply supported panel of this type is given below:

$$\frac{1}{D_{xc}}=\frac{1}{\sum EI}\left(1-z^2\frac{\overline{EA}}{\overline{EI}}\right)+\frac{384}{5l^4}\left[z^2\left(\frac{\overline{EA}}{\overline{EI}}\right)\frac{l^2 s}{8k}+z^2\left(\frac{\overline{EA}}{\overline{EI}}\right)^3\frac{\sum EI}{\left(\frac{k}{s}\right)^2}\left\{\sec\mathrm{h}\left(\sqrt{c_1 l/2}\right)-1\right\}\right] \quad (3)$$

where, l is the span of the beam, s is spacing of the connector, z is the distance between centroids of two individual beam element, D_{xc} is orthotropic flexural rigidity of composite section, and k is the connector modulus from push out test.

$$\sum EI = E_b I_b + E_s I_s\,,\ \ \overline{EA} = \sum EI + \overline{EA} z^2\,,\ \ \frac{1}{\overline{EA}} = \frac{1}{E_s A_s} + \frac{1}{E_b A_b}\,,\ \ c_1 = \frac{k}{s}\frac{\overline{EI}}{\overline{EA}\sum EI}$$

where A_s and A_b are areas of the board and steel section respectively, E_b and E_s are modulus of elasticities of board and steel sheet respectively, and I_b and I_s are the second moment of areas of board and steel section respectively.

The stiffness of composite panels where fully composite action takes place between the board and steel sheet can be obtained from the simplification of Eq. (3) and is as given below:

$$D_{xc} = \frac{\sum EI}{1 - \dfrac{\overline{EA}}{\overline{EI}} z^2} \tag{4}$$

The derivations leading to these final expressions; Eqs. (3) and (4), are given in detail in [2]. These equations were programmed in a computer to get the theoretical bending stiffness of the composite panel.

4. Results and Discussion

4.1. Impact heel test result

Four sets of tests were conducted on test panel 1 in order to get an accurate average natural frequency for the panel. The test results were analyzed and from the Fourier amplitude spectrum analysis, the average natural frequency for the test panel was determined. Table 5 shows the comparison of fundamental natural frequency obtained from impact heel test and theoretical natural frequency from Eq. (2) using experimental EI value. A very close agreement between these two results indicates the validity of the expression in Eq. (2), in evaluating the natural frequency of such composite panel.

Table 5. Comparison of First Natural Frequency for Test Panel 1.

Natural frequency, f_n Hz	
Experimental fundamental frequency (obtained from Impact heel test)	Analytical (using Eq. (2))
47.0	48.6

Beside the natural frequency, the heel impact test result was used to estimate the damping coefficient of the test panel. Equation (1) was used to evaluate the damping coefficient and it was on average 3% (log decrement damping) for the test panel. Thus, the true damping of the panel was established as 1.5% for tested PSSDB panel, considering the modal damping is 50% of the log decrement damping. However, it should be noted that such flooring panel within the structure will provide additional damping due to the presence of other objects, furniture, and finishing.

After the validation of Eq. (2), the fundamental frequency of all other test panels for a practical span length 2.2 m has been calculated. Column 5 of Table 6 shows the fundamental natural frequency of the test specimens based on experimental EI values, which have the same length-width ratio but different structural mode.

4.2. Effect of connectors' spacing and board thickness on frequency

It is observed from Table 6 (refer to test 2 to 4) that closer connectors spacing very clearly improve the stiffness of the composite panel. The closer the spacing, the higher is the stiffness and hence, the higher is the fundamental frequency. Fundamental frequency becomes smaller with the increase in spacing of connectors. However, it is observed from Table 6 (test 2-4) that the change in natural frequency is not that profound and hence, any spacing between 50-200 mm is considered practical for such flooring panel.

In all cases, it was noted that the test stiffness values (refer to col. 2 of Table 6) are much lesser than the fully composite stiffness values (Col. 4 of Table 6). In fully composite analysis, it was assumed that there is no slip between board and the profiled steel sheeting. However, due to the flexibility of the connectors, partial interaction always takes place between the board and steel sheet in practice. As a result, the actual stiffness of the panel will be different from that of the calculated stiffness based on full interaction. The actual stiffness of the panels depends mainly on the connector modulus and its spacing. If the slip between board and steel sheet can be prevented using very closely spaced highly stiff connectors, then the experimental stiffness value will be closer to that of the calculated theoretical fully composite one.

Table 6. Comparison of Results for the Specimens.

Test No.	Test stiffness (kNm^2/m)	Theoretical stiffness (kNm^2/m)	Fully composite stiffness (kNm^2/m)	Natural frequency (Hz)	Comment (connector spacing in mm)
2	215	148	288	26.2	16 mm board, screw spacing 50,100 and 200 mm
3	166	142	288	22.9	
4	142	139	288	21.3	
5	157	144	385	19.6	24 mm board, screw spacing 200 mm
6	138	138	245	22.7	12 mm board, screw spacing 200 mm

The theoretical results obtained from partial interaction analysis (col. 3) show close agreement and in general gives slightly conservative estimation of the experimental results. Thus, the partial interaction approach can safely be used to evaluate the bending stiffness of the composite panel.

It is observed from Table 6 (refer to test 4-6) that the increase of panel self-weight using thicker board affects the fundamental frequency of the panel. It is observed that with the increase of panel self weight, the fundamental frequency slightly changes in the same constraint condition. However, higher stiffness to mass ratio of the panel can increase the fundamental frequency and thus reduces human induce vibration.

4.3. Effect of span length

In building industries, the span length of composite PSSDB panel will be between 2-3 m for normal office and residential houses. To investigate the effect of span length of PSSDB panel, Eq. (2) can be used to predict the theoretical natural frequency for different span length of the panel. Table 7 shows the natural frequency for PSSDB panel system comprising of 1 mm thick Bondek II sheet with 12 mm thick cement board for different span length. Connector spacing is maintained 200 mm along the rib of the panel. The EI values used are based on theoretical partial interaction analysis of panel.

Table 7. Natural Frequency of PSSDB Panel for Different Span Length.

Span length (m)	Theoretical EI values (kN-m^2/m)	Bondek II- 1 mm with 12 mm cement board
		Natural frequency (Hz)
1.5	135.9	48.6
2.2	137.6	22.7
2.5	138.5	17.6
3.0	140.1	12.3
3.5	142	9.1
4.0	144.1	7.0

Based on this result, it is observed that the change in span length results a significant change in its natural frequency. Smaller span produces larger frequency, while longer span produces smaller frequency. For panel with 2.2 m span, it shows a natural frequency of 22.7 Hz which is well above the limiting value and quite satisfactory for human comfort in terms of vibration. For span length more than 3 m, the natural frequencies obtained are becoming smaller. For 3.5 m span, natural frequency obtained is 9.1 Hz which is closer to the limiting value of 8 Hz [10].

Thus, from this study, it can be concluded that PSSDB panel comprising of 1 mm thick Bondek II with 12 mm thick cement board gives satisfactory performance up to 3.5 m length of span and beyond this span length it causes discomfort to the occupants of the building.

5. Conclusions

Both theoretical and experimental investigations have been carried out to evaluate the vibration performance of PSSDB panels. Based on the study, the following conclusions can be drawn:

- A comparison between analytical and experimental study for the flexural performance revealed that, the theoretical approach that is considering full interaction between dry board and steel sheet overestimated the stiffness value of the PSSDB panel. Thus, it is recommended to calculate the actual stiffness of the panel either from experimentation or from partial interaction analysis to evaluate the first natural frequency of the panel.

- The analytical expression, Eq. (4), given in this paper can effectively evaluate the fundamental frequency of PSSDB panel, provided the actual bending stiffness of the panel is obtained.
- The experimental inherent damping for the PSSDB floor panel is established using the heel-impact test, which is 1.5% for the test panel.
- Material properties such as dry board thicknesses, spacing and rigidity of connectors contribute to the stiffness of the panel system, thus affecting the fundamental frequency of the flooring system using such panel.
- Span length of floor panel should take as a major consideration when designing such floor system. A longer span generates more vibration due to decrease in natural frequency. In this paper, it is shown that the effective and practical span length for PSSDB panel is up to 3.5 m.

Acknowledgement

This research has been conducted in the Structural Engineering laboratory of UKM and Heavy Structure and Mechanical Engineering laboratory of University Malaysia Sarawak. The authors would like to thank the technicians of these laboratories for their contribution in preparing and testing the specimens.

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