Performance of Profiled Steel Sheet Dry Board System Under Flexural Bending and Vibration

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Abstract-- This paper describe the experimental performance of Profiled Steel Sheet Dry Board system (PSSDB) against out-of plane bending and vibration. The PSSDB panel consists of plywood attached to the top surface of profiled steel sheet by self-drilling and self-tapping screws. Profiled steel sheet dry board 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 structural performance and also to consider the effects of vibration in building such flooring system. This paper will focus on theoretical and experimental procedures to determine the overall performance of PSSDB system due to flexural bending and vibration. Each parameter that effect the performance of PSSDB system against vibration and flexural will be discussed in this paper. It is found that PSSDB panel with a practical span length have a natural frequency well above of 8Hz and hence, considered comfortable to the occupants of building in terms of vibration.

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

I. INTRODUCTION

Profiled steel sheeting dry board system or PSSDB is one type of the composite slab that had been used as flooring system in construction. Profiled steel sheet dry board (PSSDB) system consists of profiled steel sheeting that compositely 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. 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 Figure 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.

Vibration problems in floor systems caused by human activities have long been a serviceability concern to engineers as mentioned by Murray [1]. 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.

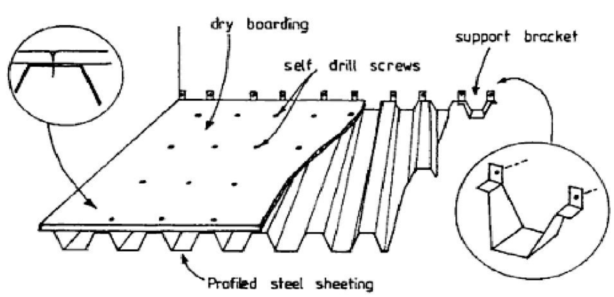

Figure 1: Profiled steel sheet dry board floor panel

In this paper, flexural test is carried out to investigate flexural rigidity of PSSDB floor panel. This test result is then used to evaluate the dynamic design parameters such as natural frequency of the panel. Impact heel test is also carried out to determine the experimental natural frequency and to evaluate inherent damping of the PSSDB panel. The factors that affect the performance of PSSDB system against flexural and vibration such as span length, material properties, board types etc. are highlighted and their effects are also indicated in this paper.

II. EXPERIMENTAL SPECIMEN AND MATERIAL PROPERTIES

Two different tests are conducted in the laboratory in order to investigate the flexural and vibration performance of PSSDB flooring system. The flexural test is performed to obtain the load deflection graph, which facilitated the experimental stiffness values of the composite panel. Impact heel tests are performed to measure the experimental natural frequency and the damping coefficient of the floor system. The test specimens are constructed by using locally available SDP-51 profiled steel sheeting, connected compositely to 12 mm thick plywood by self-drill, self-tapping screws. The following table shows the typical experimental specimen detail:

Table 1: Experimental specimen detail

Panel	Span (mm)	Width (mm)	Sheet type and thickness	Board type and thickness	Connector spacing
1	1400	1000	SDP-51, 1mm thick	Plywood,12mm	200mm centers in each rib

Before conducting flexural and vibration test, material properties for each of the two main components; namely profiled steel sheet and dry board, need to be determined in the laboratory. Figure 2 shows the cross sectional dimensions of SDP-51profiled steel sheet used in the experimental study. For SDP-51 profiled steel sheet, the necessary properties are either obtained from the manufacturer manual or calculated from the cross-sectional dimensions and are shown in Table 2.

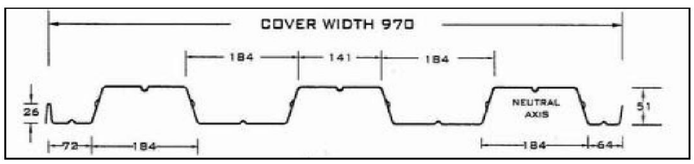

Figure 2: Cross sectional dimension of SDP-51 Sheet

Table 2: Properties of profiled steel sheeting

Nominal thickness(mm)	Depth of profile (mm)	Weight (Kg/m^2)	Height to neutral axis (mm)	Area of steel (mm^2/m)	Moment of Inertia (cm^4/m)	Moment capacity (kNm/m)
SDP-51 1.0mm	51	10.56	25.5	1178	61.36	6.12

To determine the material properties for the plywood, three-point bending test is conducted in the laboratory using Testometric machine as shown in Figure 3. Table 3 tabulates the properties of the plywood board used in this study.

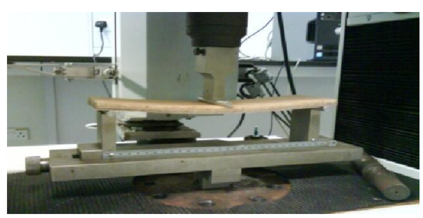

Figure 3: Three point bending test using Testometric machine

Table 3: Properties of Ply-wood board

Type	Density (kg/m^3)	Young's modulus (MPa), parallel to grain	Bending strength (MPa), parallel to grain
12 mm ply board	700	5277	45

III. EXPERIMENTAL STUDY

(a) Determination of bending stiffness of composite panel

To determine the experimental bending stiffness of the composite PSSDB panel system, a full-scale flexural test is carried out in the laboratory. Figure 4 shows the 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 [2]. The panel was tested over a simple span of 1400 mm 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. Figure 5 shows the load-deflection behavior of the panel at mid-width, mid-span location. It is observed from the graph that the initial load-deflection response is linear and elastic and this elastic response continued until just before failure. The final failure occurred when the upper flanges of the steel sheeting buckled. The differences between load values and deflection values within the elastic range are the input into the simple beam theory as shown in Eq. (1) to obtain the EI value of the composite panel.

$$\Delta = \frac{PL^3}{48EI} \qquad \text{Eq. (1)}$$

Where, *EI* is the bending stiffness of the composite section, *L* is span between centers of support (mm), *P* is increment in Load (kN) on the straight line portion of the load-deflection curve and Δ is the increment in deflection *(mm)* corresponding to the increment in load.

Figure 4: Test arrangement and instrumentation detail

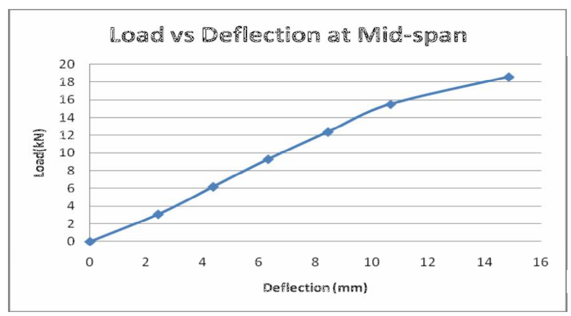

Figure 5: Typical load-deflection behavior of test panel

(b) Determination of Natural frequency using Impact Heel test

To investigate the natural frequency of the PSSDB panel due to vibration, standard impact heel test is carried out in the laboratory. Pulse vibration analyzer available in the Mechanical Engineering laboratory of UNIMAS is used to conduct this test. In this test, a heel drop excitation is exerted on the floor panel. An average person sit-up at the mid span on the test floor, raise his heel to about 50 mm and produce a sudden impact on the floor. The resulting acceleration time history is measured by the accelerometer placed near the feet of the test person. The result can be interpreted using acceleration vs. time graph. Figure 6 shows the typical heel impact acceleration response at the mid location of the panel. To get reliable result, four heel impact tests are carried out on the selected floor panel. To determine the fundamental frequency of PSSDB system, the acceleration verses time response is converted to frequency verses magnitude values using Fourier analysis. Figure 7 shows the Fourier amplitude spectrum analysis of the test panel. The first successive well-defined peak of frequency will indicate the natural frequency of the panel system.

From the time-acceleration plots in Figure 6, the damping coefficients are also calculated from Eq. (2) as presented by Ellis in 2000 [3]:

$$\xi = \frac{1}{2n\pi} \log_e \frac{A_o}{A_n} \qquad \text{Eq. (2)}$$

In the above equation, A_o and A_n are the amplitudes of '*n*" successive peaks of the acceleration–time response plot. Damping obtained from the equation mentioned above is "Log decrement damping'. Murray [4] 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.

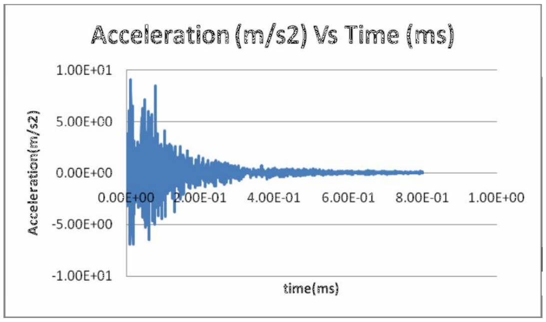

Figure 6: Typical acceleration responses at mid-span

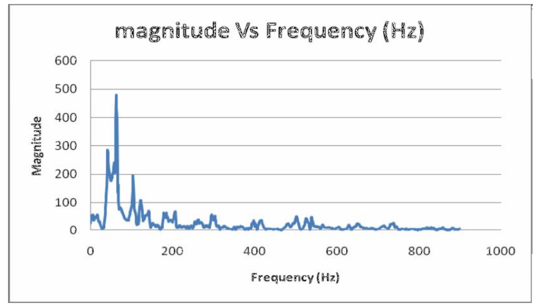

Figure 7: Fourier amplitude spectrum analysis of the test panel

IV. THEORETICAL STUDY

(a) Determination of composite stiffness using analytical study

To determine the theoretical composite stiffness of the PSSDB system, elastic full interaction analysis is used. This analysis implies that there is negligible slip at the steel section and board interface. Figure 8 shows the cross section and strain distribution for the repeating section of the panel. The theory of transformed section is used in this analysis by assuming both board and steel as linearly elastic material. This enables the composite section to be replaced by an equivalent all steel cross section. Finally, the moment of inertia for the composite section can be determined using Eq. (3), when the elastic neutral axis *'y'* of the composite PSSDB cross-section lies within the steel section.

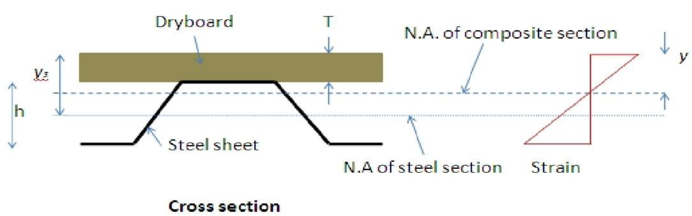

Figure 8: Strain distribution diagram for the repeating section of panel

$$I = I_x + A_s(y_s - y)^2 + \frac{bT^2}{12m} + \frac{bT}{m}(y - \frac{T}{2})^2 \qquad \text{Eq. (3)}$$

where, I_x and A_s are the second moment of inertia and area of steel section about its neutral axis, y_s is the depth of neutral axis of steel section alone, m is the modular ratio and is given by $m = E_s/E_b$

Composite stiffness of PSSDB system is obtained from multiplication of second moment of inertia of composite section (I_c) to the modulus elasticity of steel sheet (E_s). Value for modulus elasticity of steel sheet is obtained from the manufacture manual of SDP-51 profiled steel sheet. Table 4 shows the analytical result of composite stiffness for test panel consisting of 12mm plywood and 1mm thick SDP-51profiled steel sheet.

Table 4: Analytical result of composite PSSDB test panel

Panel description	Neutral axis depth, y (mm)	Modulus of elasticity, E_s (kN/mm^2)	I_c (mm^4/m)	E_sI_c (kN-m^2/m)
1mm thick SDP-51 with 12 mm Plywood board	31.08	210	873621.18	183

(b) 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 [5], Williams et al. [6], Bachmann and Pretlove [7] and Brand and Murray [8] yielded various method to estimate natural frequencies of floors. In this paper, fundamental natural frequency of the test floor panel is obtained from the generally used analytical solution given in Design Guide on Vibration of Floors [5]. This analytical solution for fundamental natural frequency is given as:

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

Where 'm' is the mass per unit length (unit in tons/m if EI is expresses in kNm^2, or kg/m if EI expressed in Nm^2), L is the span in meters, E is the modulus of elasticity, I is the second moment of area 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 supported, 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* value of the test panel was determined from the full scale experimentation in the laboratory as mentioned in the experimental study section.

V. RESULTS & DISCUSSIONS

(a) Discussion of Results for Flexural Test

The *EI* value of the test panel as calculated from the slope of the load-deflection diagram was $83kN\text{-}m^2/m$. This value is much lesser than the fully composite stiffness of the test panel as calculated from the expression given in Eq. (3). 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, always partial interaction 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 one. The actual stiffness of the panels depends on the connector modulus and its spacing. It also depends to a certain extent on the types of board and steel sheet thickness. 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 one. Considering the above, the experimental *EI* value of the panel will be used in the subsequent calculation of the paper.

(b) Discussion of Result for Impact Heel Test

There are 4 sets of tests had been conducted in order to get an accurate average natural frequency for the PSSDB test-panel. The test results are analyzed and expressed in Table 5. The average natural frequency for the test panel was 59.25.

Table 5: Natural frequency for each tests

Experiment	Natural frequency (Hz)
Test 1	63
Test 2	58
Test 3	56
Test 4	60
average	59.25

Table 6 shows the comparison of fundamental natural frequency obtained from impact heel test and theoretical natural frequency using experimental EI value. A very close agreement between these two results indicates the validity of the expression mentioned in Eq. (4) in getting the natural frequency of such composite panel. Also, it validates the accuracy of the *EI* values obtained from the flexural test.

Table 6: Comparison of natural frequency for test panel

Natural frequency, f_n	
Experimental (obtained from Impact heel test)	Analytical (Using Eq. 4 with EI value obtained from flexural test)
59.25 Hz	53.03 Hz

The heel impact test result shows that the natural frequency varies between 56 Hz to 63 Hz for the test panel considered in this paper. For this shorter span panel, the natural frequency was well above the limiting value of 8 Hz. It should be noted that lower natural frequency below 8 Hz can cause uneasy feeling to the occupants [9]. Beside the natural frequency, the heel impact test result was used to estimate the damping coefficient of the test panel and it is on average 3.2% (log decrement damping) for the test panel.

(c) Effect of Span Length

In building industries, the span length of composite PSSDB panel will be between 2-3m for normal office and residential houses. To investigate the effect of span length of PSSDB panel, Eq. (4) can be used to predict the theoretical natural frequency for different span length of the panel. Table 7 shows the natural frequency for PSSDB system comprising of 1mm thick SDP-51 sheet with 12mm thick, 5-ply plywood board composite panels for different span length.

Table 7: Natural frequency of PSSDB panel for different span length

Span length (m)	SDP51-1mm with 12mm,5 ply board
	Natural frequency (Hz)
1.4	53.0 Hz
2.2	21.5 Hz
2.5	16.6Hz
3.0	11.5 Hz
3.5	8.5 Hz

Based on the result shown in Table 7, it is shown that the change in span length results a significant change in its natural frequency. Smaller spans will produce larger frequency, where longer spans will produce smaller frequency. For panel with 2.2 m span, it shows a natural frequency of around 21.5 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 3.5m span, natural frequency obtained is 8.5 Hz which is nearly to the limiting value of 8 Hz. Thus, from this study, it can be concluded that PSSDB panel comprising of 1mm thick SDP-51 with 12mm thick plywood will give satisfactory performance up to 3.5 m length of span and beyond this span length it will cause discomfort to the occupants of the building.

(d) Effect of panel stiffness on Natural Frequency

The spacing of connectors along the rib affects the natural frequency of the composite panel. The closer the spacing, the higher will be the stiffness and hence, the higher will be the fundamental frequency. Fundamental frequency becomes smaller with the increased spacing of connectors. It was observed using Eq. (3) that the use of thicker board in general increases the stiffness *(EI)* values of the panel and gives relatively higher value for the natural frequency. It was concluded that besides the span length; the factors influencing bending stiffness such as board thickness, connector spacing, sheet thickness can influence the natural frequency of the PSSDB floor system. The higher natural frequency will produces less vibration and thus acceptable for human comfort.

VI. CONCLUSION

Both theoretical and experimental investigations have been carried out to evaluate the bending and flexural 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 (refer to 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.

- Material properties such as dry board and steel sheeting thicknesses, spacing and rigidity of connectors contribute significantly 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 will generate more vibration due to decreased natural frequency. In this paper, it was shown that the effective and practical span length for PSSDB panel would be between 2-3 m.

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