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DYNAMIC ANALYSIS OF PROFILED STEEL SHEET DRY BOARD COMPOSITE FLOOR PANEL SUBJECTED TO HUMAN-INDUCED FORCES

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Abstract: Profiled Steel Sheet Dry Board (PSSDB) composite panel has been proven to be an effective structural system and can be exploited for a variety of structural purposes. As a flooring system, the PSSDB floor carries the out of plane bending and shear mainly in the direction of corrugation of profiled steel sheeting. For such flooring system, human induced vibrations are becoming increasingly vital serviceability and safety issues. In this paper, investigations are carried out on the vibration performances of the PSSDB floor panel. Numerical analysis using a commercially available FEA code is carried out to evaluate the performance of single span panel subjected to human induced vibration. It also establishes the Dynamic Amplification Factors (DAFs) for displacement and acceleration responses. It is observed, closer spacing of connectors in PSSDB panel and increasing the thickness of dry board significantly reduced the peak acceleration of the system. Also, vibration characteristics can be improved by increasing the amount of damping of the floor system.

1 INTRODUCTION

The Profiled Steel Sheet Dry Board (PSSDB) composite panel system consist of profiled steel sheeting connected to dry board by simple mechanical connectors has been shown to be structurally efficient under the associated bending or axially compressive loading (Wright et al., 1989; Wan Badaruzzaman and Wright HD, 1998; Wan Badaruzzaman et al., 2003; Ahmed E. and Wan Badaruzzaman, 2006; Benayoune, A.G., 1998; Ahmed E, 1999).

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.

Human-induced dynamic loads originate from various human activities on floor. Vibration caused by human activities has long been recognized as a major serviceability concern for residential floor system. Although it had not been significant problem in past for traditional reinforced concrete floors, a number of serviceability problems are needed to address for the successful exploitation of such innovative structures, which have longer spans, are lighter and have a reduced damping. To avoid vibration related problem with this PSSDB flooring system, it is desirable that a proper understanding of dynamic behavior is included in design of such floor.

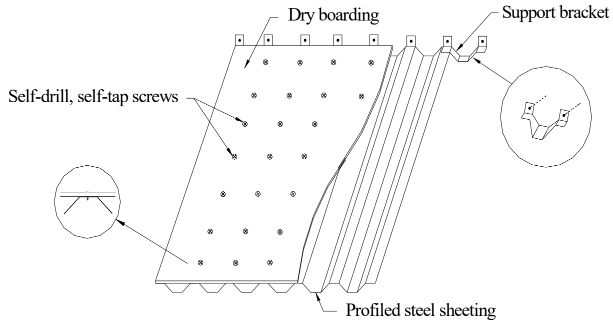

Figure 1: Profiled steel sheet dry board floor panel

In this paper, FE model of single span composite floor panel is developed for the dynamic analysis. The dynamic loads resulting from aerobics/jumping are included to investigate the performance of such panel as it is considered as giving most onerous dynamic load for the panel. These loads are applied on different activity frequencies and at different damping levels.

2 PANEL CONFIGURATION AND MATERIAL PROPERTIES

A total of eleven composite panel comprising of 1 mm thick modified bondek profiled steel sheet are attached to dry board of either 18 mm plywood, or 18 mm chipboard or cement board of various thickness (either 12, 16 and 24 mm thick) are used in this investigation. Figure 2 shows the dimension of modified Bondek II profiled steel sheeting cross section.

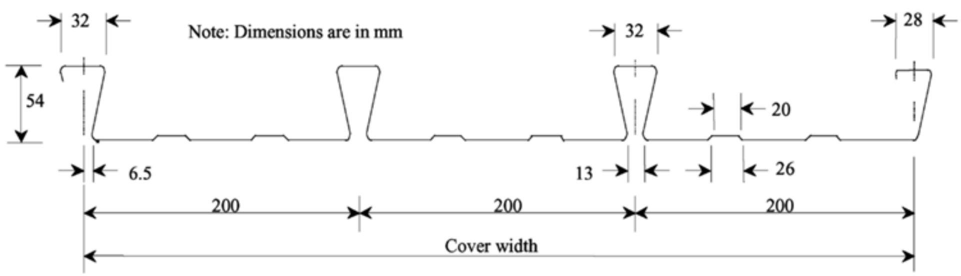

Figure 2: Modified Bondek II profiled steel sheeting.

All the composite panels are having the dimension of 620 mm by 2400 mm. The two components, i.e. the board and steel sheet are connected by using self-tapping screws at various selected spacing from 50 to 200 mm in each rib. The following table shows the specimens detail:

Table 1: Specimens detail

Panel no.	Span (mm)	Thickness and Sheet type	Thickness and Board type	Connector spacing in each rib
1,2 and 3	2200	1mm thick, modified Bondek II sheeting	18 mm, Plywood	50,100 and 200 mm respectively
4, 5 and 6			18 mm, chipboard	
7,8 and 9			16mm, cement board	
10 and 11			24 and12 mm respectively, cement board	Connectors at 200 mm centers in each rib

Laboratory tests are conducted to evaluate the individual component material properties of PSSDB panel. Table 2 and Table 3 provide the necessary physical and material properties of various components needed for the analysis of the composite panel.

Table 2: Properties of modified Bondek II profiled steel sheeting

Nominal thickness (mm)	Depth of profile (mm)	Weight (Kg/m^3)	Height to neutral axis (mm)	Area of steel (mm^2/m)	Moment of inertia (cm^4/m)	Moment capacity (kNm/m)
1.0	54	8000	14.43	1633.5	63.68	8.2

Table 3: Properties of dry boards

Type of board	Density of board (Kg/m3)	Young's modulus (MPa)		Bending strength (MPa)	
		parallel to grain	Perpendicular to grain	Parallel to grain	Perpendicular to grain
18 mm 5-ply plywood	700	5300	9775	40.4	66.5
18 mm chipboard	650	1950	1950	11.4	11.4
16 mm cement board	1250	4500	4500	8.4	8.4

The capacity of screw connection is 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 (Ahmed E., 1999) are shown in Table 4.

Table 4: Connector stiffness and capacity for different types of board

Board type	Connectors' stiffness (N/mm)	Connectors' capacity (kN)
18 mm plywood	730	3.1
16 mm cement board	625	3.0
18 mm chipboard	470	2.8

3 FINITE ELEMENT MODELING

The profiled steel sheet dry board composite panel consisted of three main structural components, namely, the dry board, profiled steel sheeting and connectors (refer to Figure 1). In analyzing the response of such structure, it is essential that each of the constituent parts be properly modeled. In the modeling, the profiled steel sheet is taken as an assembly of isotropic thin shell elements. The dry board is modelled as either isotropic or orthotropic thin shell elements depending on the board type. The shell elements having finite thickness are assumed to lie on the centroid plane of the original plate and are connected to adjacent plates at their extremities (see Figure 3).

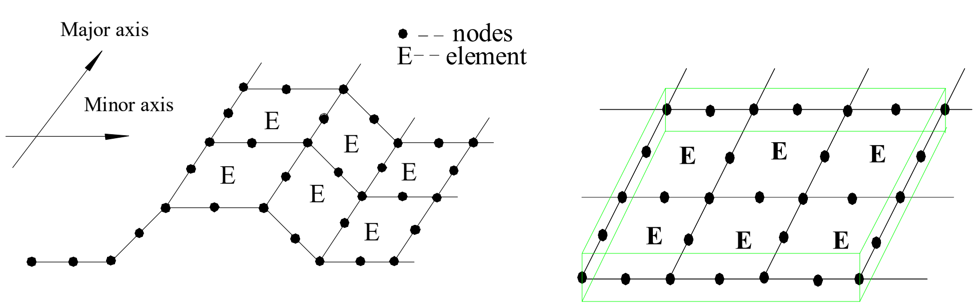

Figure 3: Typical idealization of Steel sheet and Dry Board

The screw connections between the dry board and steel sheeting act as a shear connector. It is necessary to model the connections that will allow partial interaction behavior. In the modeling, the screw connectors are replaced by a uniform thickness thin shell element. It is necessary that the shear deformability of such an element should represent the flexibility of the connectors and spacing. It is assumed that the shear connectors are attached to the nodes on the middle plane of the dry board and to the middle plane to the upper flanges of the steel sheeting. The concept of dummy plate (Kristek and Studnica,1982) is applied assuming that the shear force on the connector is the main cause of connection failure. The Young's modulus of the shear connector which is the input parameter in FE analysis is given by (Wan Badaruzzaman, 1994):

[1] $$E = \frac{2k_s h(1+\nu)}{ts}$$

Where,
k_s = connector modulus or stiffness in N/mm (refer to Table 4)
s = spacing of the connector in mm
h = height of the dummy plate, i.e, distance between the centroid of the two plates in mm
t = thickness of the dummy plate and
ν= Poisson's ratio of the dummy plate

The finite element method enables various support conditions to be considered at the ends of the plate structures by specifying appropriate displacement components at the nodal points situated at the end sections. For the present situations, the end supports are simulated as simply supported one.

3.1 Determination of Natural Frequency

The natural frequency analysis of the FE models mentioned earlier has been carried out. Table 5 is showing the first and second natural frequencies (f_{01} and f_{02}) of the panel considered in the paper. It was observed from the analysis that the associated mode shape for the first natural frequency was the simple bending mode whereas for the second natural frequency the associated mode was the twisting mode. The first natural frequency is important for such panel as these panels were excited in its fundamental mode. The second natural frequency of panels have been tabulated as it will be used in calculating the damping coefficient of panels.

Table 5: Natural Frequency of Panels

Panel no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
f_{01} (Hz)	27.11	25.55	24.39	25.55	24.67	23.98	23.44	22.26	21.38	22.86	19.29
f_{02} (Hz)	29.90	28.01	26.71	27.26	25.97	25.09	25.85	24.26	23.16	24.11	23.03

3.2 Verification 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 (1989), Williams et al. (1994), Bachmann and Pretlove (1995), Brand and Murray (1999) yielded various method to estimate natural frequencies of floors. In this paper, fundamental natural frequency of the floor panels obtained from numerical analyses are compared for verification with the generally used analytical solution in Design Guide on Vibration of Floors (Wyatt 1989). This analytical solution for fundamental natural frequency is given as:

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

Where ‘m’ is the mass per unit length (unit in tons/m if EI is expressed in kNm^2, or kg/m if EI 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 Eq. 2, it is necessary to calculate the actual value of EI of the composite panel. In this paper, the EI values of the various panels are determined from the full scale experimentation in the laboratory. The test procedure followed was that of conventional bending test and essentially, similar to that of DIN 18807 Part 2 (DIN 18807 Part 2, 1987). The panels were tested on simple span of 2.2 m using a uniform line load at the mid span location. The deflection values were measured at middle and quarter span locations along the mid-width line using displacement transducers.

From the results obtained experimentally, it is observed that all tests conducted are exhibiting similar load-deflection characteristic. Typical load-deflection curves (refer to Figure 4) taken from Tests 2, 5 and 8 (see Table 1) show 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 load and the corresponding mid-width/mid-span deflection measurements taken from the tests are then used to obtain the EI values of the composite panels. After getting the EI values of the composite panel from the experiment, the corresponding values of natural frequencies are evaluated from Eq. 2.

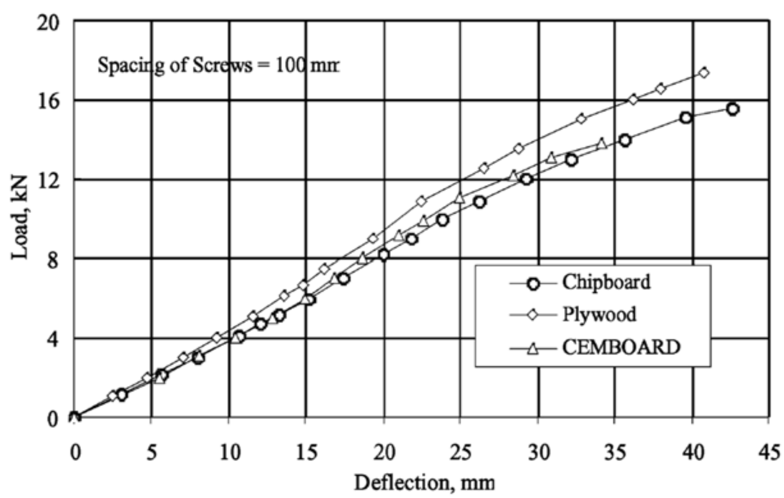

Figure 4: Typical load-deflection behavior of PSSDB panels (Connector spacing=100 mm)

3.2.1 Observation and discussions

The fundamental natural frequency of the specimens’ are calculated from the static test result of the specimens. The experimental stiffness that derived from the load–deflection behavior of the composite panels are used to evaluate the fundamental natural frequencies of the panels. Column 3 of Table 6 shows the fundamental natural frequency of the tested eleven specimens, which have the same length-width ratio but different structural mode. Column 4 of Table 6 is giving the corresponding finite element analysis results for fundamental natural frequency.

Table 6: Comparison of results for the specimens

1	2	3	4	5
Specimen no.	Experimental stiffness(kNm^2/m)	Fundamental frequency (Hz)	FEM frequency(Hz)	comment
1	209	29.3	27.11	18mm Plywood, spacing 50, 100, & 200 mm
2	168	26.3	25.55	
3	141	24.0	24.39	
4	180	27.6	25.55	18mm Chipboard, spacing 50,100 &200mm
5	150	25.2	24.67	
6	138	24.2	23.98	
7	215	26.2	23.44	16mm Cement board, spacing 50,100, &200mm
8	166	22.9	22.26	
9	142	21.3	21.38	
10	157	22.7	22.86	24mm Cement board, spacing 200
11	138	19.6	19.29	12mm Cement board, spacing 200

For all the panels, the finite element analysis results agree very closely to the results obtained from the expression mentioned in Eq. 2. However, slight variations between the results are observed for the test 1, 2, 4 and 7. This slight variation is mainly attributed to the inaccuracy in getting the experimental EI values of the composite panels.

It is observed from the Table 6 that the spacing of connectors along the rib affects the natural frequency of the composite panel. The closer the spacing the higher was the stiffness and hence, the higher was the fundamental frequency. Fundamental frequency becomes smaller with the increased spacing of connectors. The variation of the type of boards has also affected the vibration characteristic of the panel. For the panels that using Plywood are giving higher first natural frequency values as compared to other two types of boarding.

3.3 DAF limits of displacement

The Dynamic Amplification Factors (DAF) limits for the floor panels considered in this paper were determined from the static analysis of the panels. Un-factored loads are applied on the entire floor panel and the corresponding deflections at mid span location are noted. A live-load of 0.4 kPa was used as the static load posed by the occupants considering the average weight of a person is 70 kg in 1.75m^2 floor-space. The static deflection values for the panels are calculated from the experimental stiffness values given in Table 6 (Δ_{static}). The serviceability deflection limit (Δ_{allow}) for static design can be taken as span/250 or 20 mm for the composite floor design (BS 5954: Part 4 1994). The DAF limit for displacement are obtained by dividing Δ_{allow} by Δ_{static} and the values are 9.25,7.44 and 6.24 for panel using plywood; 7.97, 6.64, 6.11 for panel using chipboard; 9.52,7.35,6.29 for the panel using cement board having 50 mm,100 mm and 200 m spacing of connectors. For panel 10 and 11 where 24mm and 12mm thick board were used and connector spacing was 200 mm, the DAF's limit for displacement are 6.95 and 6.11 respectively.

4.0 Dynamic Analysis

Linear transient dynamic analysis is carried out on all single panel FE models to evaluate the DAFs for displacement and acceleration responses. The load model representing aerobic activities presented by other researchers is incorporated in the analysis. The aerobic/jumping event was particularly chosen as it is considered giving higher loads in exciting the single span floor panel. The mathematical model (Ginty, Derwent et al. 2001, Bachmann and Ammann 1987, Smith 2002) used in the paper for loading is:

[3] $$F(t) = G\left[1 + \sum r_i \sin(2\pi f_p t)\right]$$

Where $F(t)$ is the force, G is the static weight of the occupant, r_i is the fourier coefficients and f_p is the pacing frequency and t is the time. The fourier coefficients used in this paper corresponds to the human action of aerobic/jumping and the value used for r_1 is 1.5, for r_2 0.6 and for r_3 0.1 (Ginty, Derwent et al. 2001, Bachmann and Ammmann 1987). The pacing frequency in Eq. 3 is also depends on human action and based on literature; the pacing frequency ranges from 2.2 Hz to 2.8 Hz in a step of 0.2 is considered in this work. The load-time functions can be incorporated in the FE code using loading curve problem in transient analysis. Four separate damping level starting from low damping ratio 1.6 to high damping 12 are considered in the paper. The input parameter in mass proportional damping and stiffness proportional damping can be evaluated from the following equation (Clough and Penzien 1993):

[4] $$\begin{bmatrix} a \\ b \end{bmatrix} = \frac{2\xi}{f_m + f_n} \begin{bmatrix} f_m f_n \\ 1 \end{bmatrix}$$

4.1 Responses of FE model

The responses for displacements and accelerations on single span panels are evaluated from the linear transient analysis. The activity has simulated for 5 second with a time step of 0.005 second. This simulation time has given sufficient time to reach steady state condition.

4.1.1 DAF for displacement for Human induced load

The DAFs for displacement are calculated by dividing the dynamic deflection by the corresponding static deflection. The dynamic deflection is obtained from the dynamic analysis using displacement time history graph. Figure 5 shows a typical displacement-time history response of single panel (for test Panel 7) subjected to human induced load.

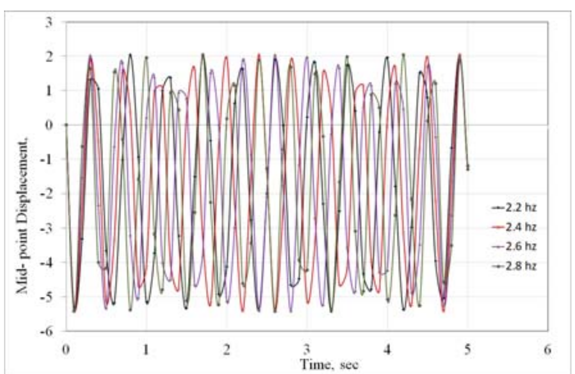

Figure 5 Typical displacement time history under jumping loading

Using these displacement time histories, DAFs for panels are calculated. Figure 6 below shows the DAF for displacement for two different typical damping levels of 1.6%, and 12%.

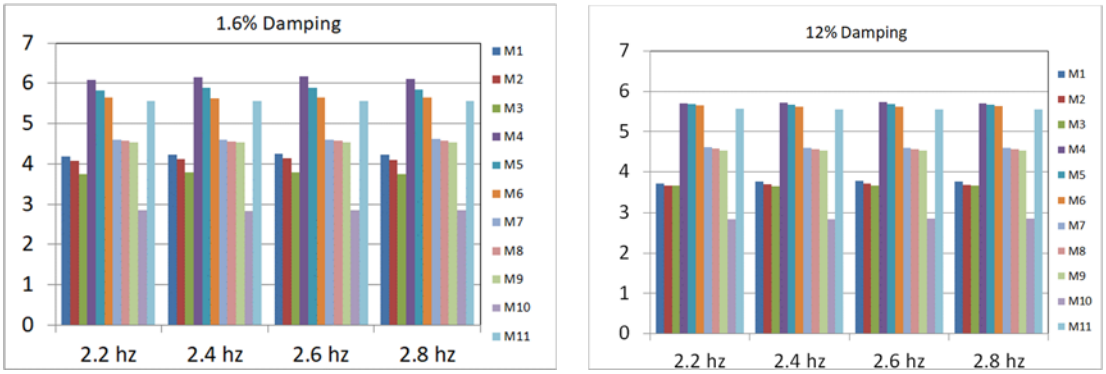

Figure 6: DAF for displacement at two different damping levels of 1.6%, and 12%

It is observed that DAFs have not yielded beyond the DAF limits mentioned earlier in Section 3.3. The DAF's for displacement were given maximum at lower damping level while higher damping level provided the lowest DAF for displacement. The variation of DAF for displacement were wide from 2.839 to 6.167 under aerobics/jumping loads.

To determine a possible relationship for dynamic amplification under aerobic /jumping loading, the averaged DAF (of each panel) at each frequency ratio was used in obtaining the variation of DAF with respect to frequency ratio and is presented in Figure 7 below:

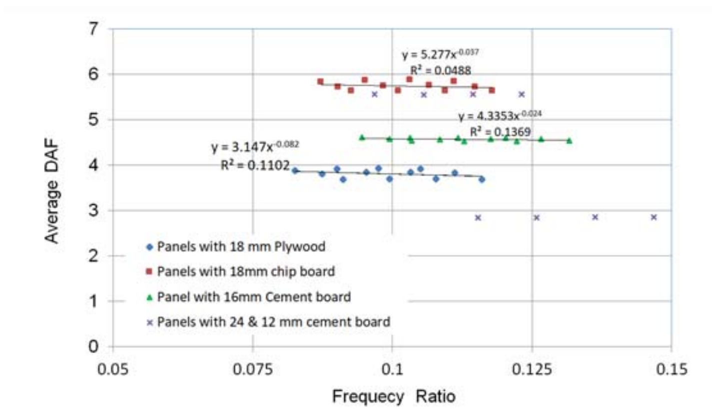

Figure 7: Variation of DAF with frequency ratio

4.1.2 Acceleration responses for human induced load

Acceleration response for aerobic loads on the single panel were also noted. Figure 8 shows the typical acceleration response of the panel obtained from the analysis. The acceleration responses are giving similar trends as that of DAF for displacement. In human perceptibility prospective, the acceleration responses were beyond the AISC Design Guide 11 of 0.05g revealed that the single models have caused vibration problems to the occupants of residential and office building.

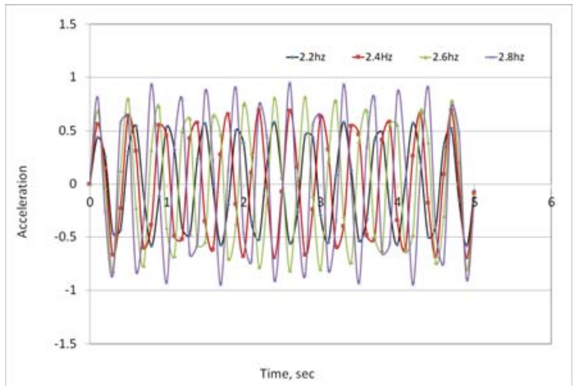

Figure 8: Acceleration Response at Various frequencies of Typical Panel 7

5 CONCLUSION

In this paper, the fundamental natural frequency of PSSDB floor panels are evaluated from the experimental stiffness value and then compared with the numerical result. The factors affecting the natural frequency are also considered in this paper. The finite element models are subjected to human induced loads to establish DAF for displacement and acceleration responses. The acceleration responses due to this aerobic/jumping loading were beyond the recommended peak acceleration for human comfort for vibrations due to human activities in residence and offices. Closer spacing of connectors in PSSDB panel and increasing the thickness of dry board significantly reduced the peak acceleration of the system. Also, vibration characteristics can be improved by increasing the amount of damping of the floor system.

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