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The natural frequencies of composite Profiled Steel Sheet Dry Board with Concrete infill (PSSDBC) system

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Abstract

This paper aims to measure natural frequencies of Profiled Steel Sheet Dry Board (PSSDB) with Concrete infill (PSSDBC) system. For this purpose, experimental tests by estimation of Frequency Response Function (FRF) and a numerical method by development of Finite Element Model (FEM) are used. The connection stiffness between Peva45 as Profiled Steel Sheet (PSS) and different concrete grades of 25 (C25), 30 (C30), and 35 (C35) are measured by push-out tests to be used in the FEM. The effect of presence of concrete in the PSSDB system on the natural frequencies such as Fundamental Natural Frequency (FNF) of the system is investigated. The variability in the FNF of the studied system under different parameters such as concrete grades, thicknesses of PSS and Dry Board (DB), and boundary conditions is determined. In a wide numerical study, the FNF of the PSSDBC system with practical dimensions is revealed for different lengths, widths, and boundary conditions. The results help designer predict serviceability and design criteria of the studied panels.

Keywords

natural frequency, profiled steel sheet dry board, frequency response function, modal analysis, push-out test, low and high frequency floors, human comfort.

1 INTRODUCTION

According to Wright and Evans [51], using profiled steel sheeting in composite slabs dominated floor constructions during the eighties. They performed some tests on several types of sheeting and carried out researches on the behavior of the sheeting under the wet concrete loading during the construction phase and the slab performance under service loading after hardening of the concrete. The results showed the possibility of using sheeting alone as a flooring system. The wearing surface was provided by attachment of boarding to the sheeting which increased the strength and stiffness of the system [51]. Then, a new composite component was presented which is known as PSSDB system [52] with many advantages [48]. The PSSDB system is a composite structural system which consists of the PSS and DB as its main elements. These elements are attached together by self-drilling and self-tapping screws as is illustrated in Fig. 1.

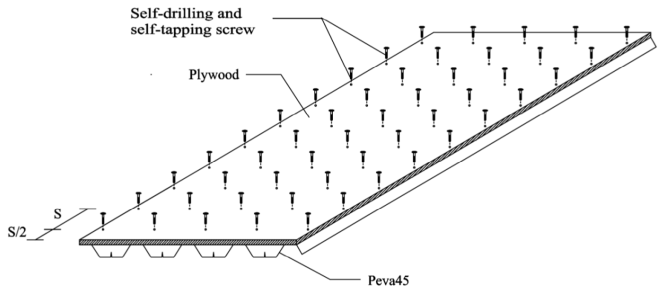


Figure 1 Profiled steel sheet dry board system.

Studies on different subjects of various applications of the PSSDB system such as; floor, roof, and wall have been performed since 1994. Also, study on using infill in the PSSDB system was started by the experimental use of Rockwool and sand [42] and the theoretical use of concrete [44] to increase the fire resistance performance of the PSSDB system. Research on enhancing the stiffness of the PSSDB system by presence of concrete as an infill has been also performed by: introducing concrete as an infill in trough of the PSS and topping of the DB [46], theoretical and experimental evaluation [45], and introducing two innovative sections of the PSSDBC flooring system [43, 47].

Soedel [38] declared that knowing about natural frequency of a structure is crucial for two reasons; firstly, from a design viewpoint, for example prediction about the occurrence of resonance conditions on the structure, and secondly, to obtain forced response of the structure.

Many reports and studies are available to show that the FNF of a floor system is the most important value to reveal its serviceability under human activities. In this case, Wiss and Parmelee [49] presented a response rating formula, Murray [33] proposed a formula for the critical damping ratio, Ellingwood and Talin predicted the maximum acceleration of a floor mid-span [18], Ebrahimpour and Sack presented a literature on the critical FNF for wood and lightweight construction [16], and Murray et al. proposed a design criteria graph with respect to the peak acceleration and FNF of a floor system [32].

Studies on dynamic characteristics of the structural system with focusing on their natural frequencies have been performed from last decades [3, 4, 13, 14, 41]. Hurst and Lezotte conducted an analytical and experimental study on the natural frequency of the plywood-joist system considering the effect of joist size on the results. Plywood was nailed to joists in their study [27]. In the same study, Filiatrault et al. revealed natural frequency and mode shapes of a plywood-joist system for different boundary conditions by finite strip method and compared with experimental test results which showed to have a very good agreement. They also discussed on the effects of different parameters on the natural frequency of the system [20]. Fukuwa et al. evaluated dynamic properties of a prefabricated steel building by obtaining the natural frequency and damping ratio of the system for various construction stages. Effects of non-structural members on the results were investigated in their study [21]. El-Dardiry et al. determined the natural frequency of a long-span flat concrete floor by using a suitable FEM and an experimental heel-drop test. They considered several FEMs and refined them by comparing their results with experimental test results, and then the most suitable FEM was presented [17]. Ferreira and Fasshauer performed a free vibration study on a composite plate by an innovative numerical method. Results of different thickness-to-length ratios were determined and discussed in their study [19]. Xing and Liu derived successfully the natural modes of a rectangular orthotropic plate by exact solution of mathematical statements for three different boundary conditions [53]. Ju et al. developed a new composite floor system and measured the natural frequencies and damping ratios of the system by experimental tests for three different construction steps; steel erection stage, concrete casting stage, and finishing stage. They compared the results with international codes to evaluate the serviceability of the proposed floor system and obtained good vibration characteristics [28].

Study on the natural frequency of the PSSDB system is limited to an experimental study done by Wright et al. [52] to identify the FNF of the system with considering PMF100 as the PSS and chipboard as the DB. It was reported that since the PSSDB system is slender and flexible in nature, the natural frequency of the system may be low and is perceivable by users. In the case of serviceability of floor, it has been also stated that floor with the FNF lower than approximately 7 Hz is considered to be uncomfortable to users [52]. Moreover, Gandomkar et al. studied experimentally and numerically the natural frequencies of the PSSDB system considering the effect of different parameters on the FNF of the studied system [23].

In accordance with Middleton and Brownjohn [31], there is little energy in the higher harmonics after four harmonics of a walking force (approximately 10 Hz). A floor is High Frequency Floor (HFF), if it has a FNF above 10 Hz. But, it is known as a Low Frequency Floor (LFF) if it is dominated by resonance from the first four harmonics of a walking force. Ljunggren et al. [29] stated that some researchers (Ohlsson, Wyatt & Dier, and Talja et al.) suggested two different design criteria for floor; deflection criteria for HFF and an acceleration limit for LFF. However, Murray et al. [32] recommended acceleration limit for LFF and HFF and a minimum static stiffness of 1 kN/mm under concentrated load as an additional check for HFF. Therefore, knowing about the FNF of a floor system can uncover: i) approach of floor design and occurrence of resonance under human walking load by revealing the category of the floor as LFF or HFF and ii) comfort level of a floor system.

Using non-structural systems such as partitions on a finished floor system and permanent drywall partitions has an effect on the damping value of the floor system in comparison with a bare floor [15]. Therefore, knowing about damping ratio of a bare floor system can help designers select almost real damping ratio in the dynamic analysis of the system.

This paper by consideration of four goals attempts to present an investigation on the natural frequencies of the PSSSBC system under different conditions. The first one is to identify the natural frequencies and damping ratios of the PSSDBC system by experimental study; the results will be also used to verify FEM. Secondly, is to develop FEM in order to obtain the natural frequencies of the PSSDBC system. Thirdly, is to experimentally identify connection stiffness between Peva45 and different grades of concrete (25, 30, and 35) to show the effect of concrete grade on the FNF of the PSSDBC system. Fourthly, is to determine the effect of various selected parameters on the FNF through verified FEMs. The FNFs of panels with practical dimensions are investigated for different boundary conditions through development of fifteen FEMs. These developed panels when applied as a flooring system are also categorized as LFF or HFF to reveal the occurrence of resonance under human walking load and design criteria, and also whether they are comfortable or not for human occupant.

2 EXPERIMENTAL DETAILS

As stated, one of the objectives of this paper is to experimentally identify the natural frequencies and damping ratios of the PSSDBC system. For this purpose, three specimens were prepared as illustrated in Fig. 2. As mentioned before, Gandomkar et al. [23] studied the natural frequencies of the PSSDB system without concrete infill selecting 0.8 mm Peva45 thick as the PSS, 18 mm plywood thick as the DB, and DS-FH 432 self-drilling and self-tapping screws with 200 mm screw spacing. In this study, the PSSDBC sample was also prepared with similar materials as the PSSDB sample in Ref. [23] adding grade 30 concrete as an infill material in trough of Peva45. The tests on the specimens were carried out 28 days after their preparation in the laboratory. The length and width of all specimens have been considered as 2400 mm and 795 mm, respectively.

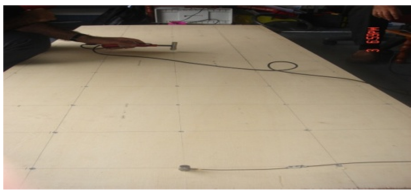


Figure 2 The PSSDBC system during the test.

Natural frequencies of the samples were measured by estimation of their FRFs. Excitation and response signals of the studied systems were recorded and measured in order to obtain this purpose. Bruel & Kjaer portable and multi-channel PULSE analyzer type 3560D, ENDEVCO accelerometer type 751-100, and impact hammer type 2302-10 were used as the measuring devices and also Bruel & Kjaer Pulse LabShop was the measurement software. Damping ratios of the systems were also outcomes of the tests.

3 STRUCTURAL MODEL

The structural model of the sample is shown in Fig. 3. The characteristics of the studied system are presented in the following sections.

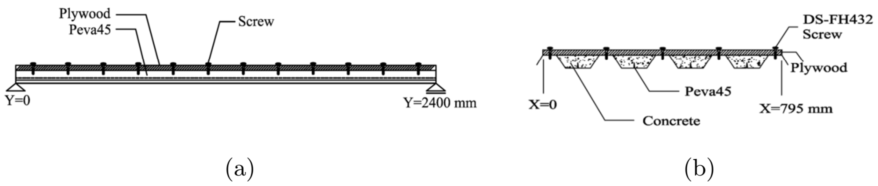


Figure 3 Structural model of the PSSDBC system (a) Longitudinal section (b) Transverse section.

3.1 Properties of materials

In this study, dynamic Young's modulus of materials was used as an input of FEMs. According to Murray et al. [32], the dynamic Young's modulus for steel can be chosen similar to its static value [7], i.e. 2.10×10^5 MPa. However, for plywood, based on the study carried out by Narayanamurti et al. in Hu [26], Matsumoto and Tsutsumi [30], and also Bos and Casagrande [5], the dynamic Young's modulus was found to be higher than its static value. The property of the plywood is mostly isotropic because of its manufacturing process [39]. Ahmed [1] stated that although dry boards may be found as isotropic or orthotropic in nature, they can be modeled as isotropic plates without any difficulties. In this study, the plywood has been considered to have the isotropic property and the static Young's modulus of plywood which is available in the local market has been adopted as 7164 MPa [54], while the dynamic value was chosen 10% greater than its static value according to Bos and Casagrande [5].

In accordance with BS 8110 [6], the static Young's modulus of concrete was determined as 24597 MPa for grade 30 concrete. Pavic et al. reported that according to some researchers, the dynamic modulus of elasticity of concrete is recommended as the static modulus with increasing by 10%-25% [35]. On the other hand, da Silva et al. discussed that according to Murray et al. [32] in situations where the composite slab is subjected to dynamic excitations concrete becomes stiffer than the case when it is subjected to pure static loads. This issue suggests a 35% increase in the Young's modulus of the conventional concrete [12]. Therefore, a 33206 MPa dynamic modulus of elasticity was adopted for grade 30 concrete in this study.

The Poisson's ratios were adopted as 0.3 for Peva45 and 0.2 for plywood and concrete. Also, the density of Peva45 and plywood were chosen 7850 kg/m^3 and 600 kg/m^3, respectively. Furthermore, the density of concrete was determined as 2273 kg/m^3 in the laboratory.

3.2 Connection stiffness

The stiffness of screws which are connections between Peva45 and plywood and also between Peva45 and concrete in the PSSDB and PSSDBC system was obtained by push-out tests [2, 25, 34]. The push-out tests were carried out to determine the stiffness of shear connectors which is needed in the finite element analysis. Nordin et al. [34] performed a study to identify stiffness of screws between Peva45-Cemboard, Cemboard-Timber, and Peva45-Plywood by push-out tests. It was found that the shear connection stiffness between Peva45 and plywood was 610 N/mm [34].

The connection between Peva45 and concrete as an infill in trough of Peva45 is also a partial interaction problem. Harsoyo found the connection stiffness between Peva45 and C30 by push-out tests where Cemboard and wood were selected as covering [25].

This paper has focused on finding the connection stiffness between Peva45 and concrete with different grades of C25, C30, and C35 by push-out tests where covering has been chosen as plywood. Nine specimens were prepared for three different grades of concrete, each three samples. Fig. 4 shows detailed arrangements of the test.

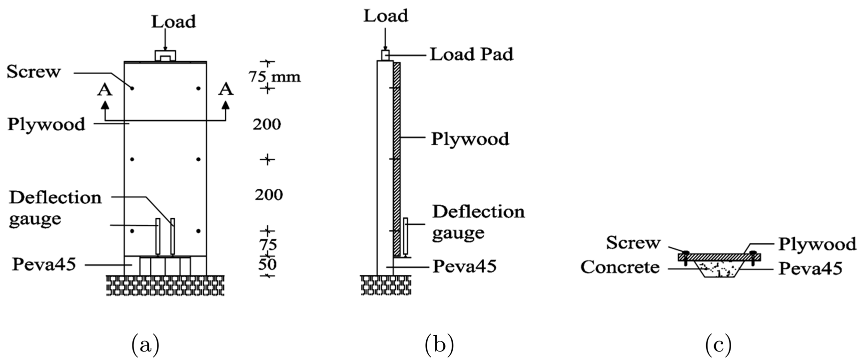


Figure 4 Detailed arrangements of the push-out test: (a) Front view (b) Side view (c) Section A-A.

Load-Slip curves obtained from results of the push-out tests to determine the connection stiffness between Peva45 and concrete grades of 25, 30, and 35 have been shown in Fig. 5.

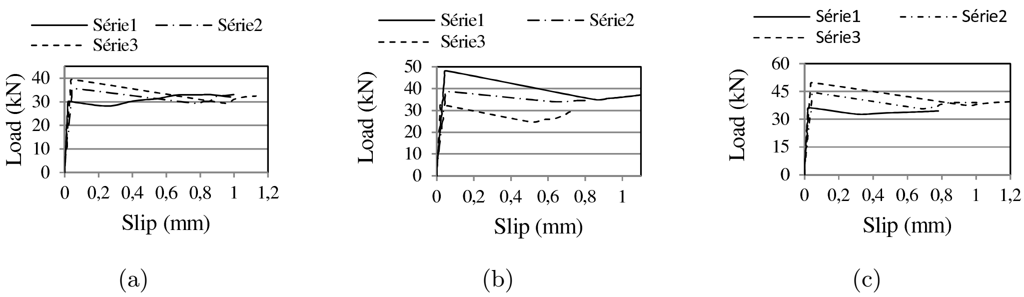


Figure 5 Load-Slip curves between Peva45 and (a) C25 (b) C30 (c) C35.

The results demonstrated that concrete grades were effective on the shear connection stiffness. The shear connection between Peva45 and concrete has been replaced by springs and modeled by the element of COMBIN14 in FEMs. This connection stiffness has been determined 350 kN/mm, 386 kN/mm and 417.60 kN/mm respectively for C25, C30, and C35 where spacing between the springs was considered 200 mm. The results showed that by the use of C30 instead of C25 and C35 instead of C30 the connection stiffness increased about 10.3% and 8.2%, respectively.

4 COMPUTATIONAL MODEL

In this study, the natural frequencies of the PSSDBC system were also determined through development of a finite element model to meet the second goal by implementation of the ANSYS program [40]. The developed finite element model was analyzed by "Modal analysis". Two methods were selected to evaluate natural frequencies of the system. The first method was eigenvalue solver of "Block Lanczos" to obtain undamped natural frequencies of the studied system which is available for eigenvalue problems in large symmetric models [40]. Shifted Block Lanczos algorithm is the theoretical base of this eigensolver whilst more information about this algorithm can be found in Ref. [24]. A variation of the classical Lanczos algorithm is the Block Lanczos algorithm where the Lanczos recursion is conducted with a block of vectors. Further theoretical points on the classical Lanczos algorithm are existed in Ref. [11] and in the study performed by Rajakumar and Rogers (1991) [40]. By the use of a check method, this procedure is applicable to find eigenfrequencies of a system without missing any modes. This solver carries out rightly when the model consists of shell elements or a combination of shell and solid elements. The second one was "QR damped" [40] method to evaluate damped natural frequencies (eigenvalues) and corresponding mode shapes (eigenvectors) of the studied system. This procedure utilizes QR algorithm to compute the eigenvalues of the system whilst further information about the algorithm can be also found in Ref. [37]. Moreover, according to ANSYS [40], the eigenvectors are extracted by using the inverse iteration method presented by Wilkinson and Reinsch (1971). The "QR damped" method presents good results for structural systems with light damping. Any types of damping such as; proportional or non-proportional symmetric damping or non-symmetrical gyroscopic damping matrix (see manual of Ref. [40] for more information) can be used in this method. The "QR damped" eigensolver performs best in larger models. If there is nonsymmetrical stiffness in the model, this approach can also support it.

In the PSSDBC computational model, the PSS and DB were made of SHELL281 element as a suitable element for analyzing thin to moderately-thick shell structures [40]. In addition, the self-drilling and self-tapping screws were represented by COMBIN14 element as connection between Peva45 and plywood and also concrete and Peva45. In this study, structural method of connection between concrete and Peva45 was used as a method which presented in Ref. [25]. Moreover, SOLID65 element was assumed for modeling the concrete in the computational model.

Fig. 6 illustrates the procedure of modeling Peva45, concrete, and plywood in the simulation for one bay of the studied system. The connection between elements of Peva45 and concrete [25], plywood and concrete, and also Peva45 and plywood in the simulation is performed by using spring element (COMBIN14) in three directions (X, Y, and Z).

In this case and according to Fig. 6, the nodes D2 and D10 were respectively connected to the nodes P2 and P10 in which stiffness of springs were adopted as 610 N/mm [34] in X and Y direction (see section 3.2) and as 10^5 N/mm in Z (vertical) direction (see Fig. 6). The nodes CT3, CB4, CB5, CB7, CB8, CT9, and D6 were respectively connected to the nodes P3, P4, P5, P7, P8, P9, and CT6, in the same way as mentioned above, with 1 N/mm [25] stiffness of

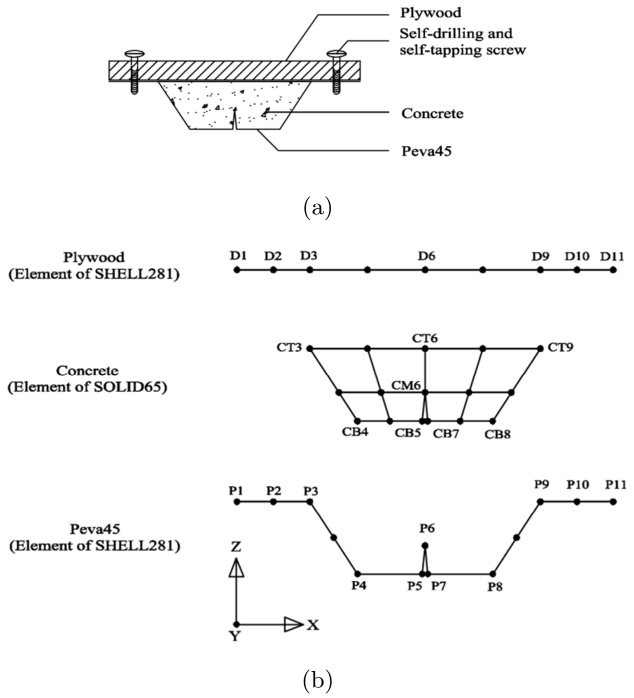


Figure 6 (a) One bay PSSDBC structural system (b) Situation of nodes in elements of one bay PSSDBC system.

springs for all directions (X, Y, and Z). When C30 was used as concrete infill, the node CM6 was connected to the node P6 with 386000 N/mm stiffness of springs in X and Y direction (see section 3.2) and 10^6 N/mm stiffness of springs in Z direction.

5 OBSERVATION OF RESULTS AND COMPARISON

Results of this section are presented in two parts; experimental tests and finite element simulations. Then, the experimental and finite element results are compared to show the accuracy of the FEM of the PSSDBC system.

This section has also concentrated on revealing the effect of concrete on the natural frequencies of the PSSDB system by comparing the experimental results of the current study with results of Ref. [23].

5.1 Experimental results

The FRF of the studied system is shown in Fig. 7. The first six natural frequencies of the system and damping ratios corresponding to the natural frequencies are summarized in Tab. 1. Also, the natural frequencies and their corresponding damping ratios of the PSSDB system are presented in Tab. 1 [23].

All six natural frequencies of the PSSDBC system were measured less than the PSSDB

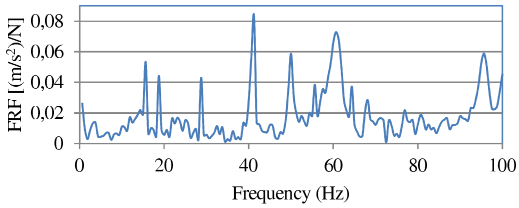


Figure 7 Experimental estimation of FRF between excitation at point A and response at point B *(Note: The points A and B were selected in y=1200 and y=2200 mm (figure 3.a) respectively, along the length and middle point of width for PSSDBC panel).*

Table 1 First six natural frequencies and corresponding damping ratios of the PSSDB [23] and PSSDBC systems.

Mode No.	PSSDB		PSSDBC	
	NF (Hz)	DR (%)	NF (Hz)$^{(a)}$	DR (%)
1	17.50	1.400	15.0	2.900
2	21.3	1.890	18.8	1.520
3	46.3	0.840	28.8	0.831
4	55.6	0.994	41.3	2.540
5	Missing	–	Missing	–
6	67.5	0.884	50.0	1.03

Note: NF = Natural Frequency & DR= Damping Ratio. Also for further discussion, the label of (a) has been considered as T1Ca in the following.

system as the FNF of the PSSDBC system was uncovered to be lower than that of the PSSDB system by 14.29%. This issue might be occurred because of introducing concrete as an infill in the PSSDB system which increased both stiffness [43, 45–47] and mass of the system, therefore, prediction of the increase or decrease of the FNF of the PSSDBC system in comparison with the PSSDB system is a complicated item that can only be revealed by experimental or numerical methods. The FNF of the PSSDBC system was determined well above 10 Hz, therefore, the panel was in HFF category [31] and also comfortable for users [52].

The status of two natural frequencies in Tab. 1 was (missing) for the natural frequency of the mode number 5 for the both systems while the natural frequencies of this mode were available in their FEMs (Tab. 2). The reason of this absence has been revealed by evaluation of their mode shapes. These modes were in the transverse direction of accelerations that they were measured. Therefore, the modes did not appear in the experiments.

The damping ratios corresponding to the FNF of the PSSDB and PSSDBC systems were measured by 1.40% [23], and 2.90%, respectively. This issue reveals the performance of using concrete in the PSSDB system to confront with dynamic loads as Gandomkar and Wan Badaruzzaman [22] uncovered this point experimentally.

5.2 Finite element results

The experimentally observed FRF of the PSSDBC system presented its damped natural frequencies. Therefore, in the simulation, damped natural frequencies of the system were determined by QR damped method through the ANSYS finite element package. In QR damped method, damping of the system is introduced by Rayleigh damping approach. According to Chowhury and Dasgupta, only the first few modes of a structure are contributed in the dynamic response of a structure with large degrees of freedom (around 3 at minimum and about 25 at maximum) [9]. In this study, the first six (6) modes were considered to be significant on the dynamic behavior of the system. Then, Rayleigh damping coefficients were determined [10] and used in the simulation. The first six undamped and damped natural frequencies of the studied system are summarized in Tab. 2.

Table 2 First six undamped and damped natural frequencies of the PSSDBC system.

Mode No.		1	2	3	4	5	6
Natural	Undamped	14.404	17.172	28.763	44.757	47.300	48.276
frequency (Hz)	Damped$^{(b)}$	14.398	17.166	28.754	44.741	47.281	48.256

Note: For further discussion, the label of (b) has been considered as T2Rb in the following.

Tab. 2 reveals that the difference between the undamped and damped natural frequencies of the studied system is very small. Also, the results show that the undamped natural frequencies of the system in all of the first six modes are greater than their corresponding damped natural frequencies. Caughey and O'Kelly stated that in a system with classical normal modes, the damped natural frequencies are always less than or equal to their corresponding undamped natural frequencies [8]. Piersol et al. [36] declared that generally classical normal modes exist in a structure without damping or with particular types of damping. Therefore, according to the results of this study, measured damping of the studied system can be considered as a particular damping for the system which can be used in the dynamic analysis of the bare PSSDBC system.

5.3 Comparison of experimental and finite element results

As stated, the FRF of the system presents its damped natural frequencies. However, undamped and damped natural frequencies of the studied system were measured very close to each other by the numerical method. Nevertheless, damped natural frequencies of the system which measured by FEM are compared with its damped natural frequencies that have been evaluated by the test in order to reveal more accurate errors. The error of the numerical results is calculated by Eq. (1) and presented in Tab. 3.

$$Error\ \ (\%) = \frac{|tests\ value\ - finite\ element\ value|}{test\ value} = \frac{|T1Ca\ \ - -T2Rb|}{T1Ca} \tag{1}$$

The mentioned errors in Tab. 3 show a reasonable accuracy of the FEMs. It approved that the performed convergence study on the FEMs which was a combination of the SHELL281,

Table 3 Error of FEM of the studied system.

Mode No.	1	2	3	4	5	6
Error (%)	4.01	8.69	0.16	8.33	-	3.49

SOLID65, and COMBIN14 elements was suitable to predict the natural frequencies of the studied system. The difference between the results of the experiment and FEMs may be due to the following reasons:

1. Finite element method is a numerical approximate method.
2. Imperfection of the PSS, DB, and self-drilling and self-tapping screw in the test specimens was not implemented in FEMs.
3. The height of the PSS was only 45 mm, therefore, hand compactor was used to compact concrete in trough of the PSS. The compaction of concrete might not be suitable which caused much microscopic separation between the embossment of Peva45 and concrete.
4. The surface of the PSS might not be clean, i.e. oily, therefore, the connection between concrete and the PSS was not complete.
5. The shrinkage happens in concrete after concrete hardening; therefore, the actual elevation of concrete in the PSSDBC in the test might not be similar to the considered elevation of concrete in the FEMs.

6 EFFECT OF CONCRETE GRADE ON THE FNF OF THE STUDIED SYSTEM

To evaluate the effect of concrete grade on the FNF of the PSSDBC system, three different concrete grades of C25, C30, and C35 have been chosen. According to BS 8110 [6] and da Silva et al. [12], the static and dynamic Young' modulus were respectively adopted as 22454 MPa & 30312 MPa for C25 and as 26567 MPa & 35866 MPa for C35.The connection stiffness between different grades of concrete and Peva45 was also measured in the earlier section. By the use of these values, the FNFs of the PSSDBC system with C25 and C35 were evaluated 14.041 Hz and 14.730 Hz, respectively. These results showed that the FNF of the system enhanced 2.52% by using C30 instead of C25, and 2.26% by the use of C35 instead of C30. Therefore, the grade of concrete does not have significant effect on the FNF of the PSSDBC system.

7 PARAMETRIC STUDY

A series of parametric studies based on the FEMs of the PSSDBC system were performed to identify the FNF of the system in different conditions. The PSSDBC system consisted of, as the control sample, 0.8 mm thick Peva45 and 18 mm thick plywood which were connected to each other by DS-FH 432 self-drilling and self-tapping screws with 200 mm screw spacing.

Also, concrete grade of C30 was selected as an infill material in trough of Peva45. The supports of the samples have been chosen as pin supports at Y=0 and roller at Y=2400 mm (Fig. 3.a), both in the bottom flange of the PSS. Dimensions of the studied panel were selected 2400 mm as the length and 795 mm as the width. A series of studies were performed to uncover the FNF of the PSSDBC panels with practical dimensions. Their categorization and comfortableness were also revealed.

7.1 Effect of thickness of Peva45 and Plywood

The thickness of Peva45 was considered 0.8 mm and 1.0 mm and also the thickness of plywood was adopted 9.252 mm, 12.7 mm, 18 mm, 23 mm, and 25 mm which are available in the local market.

Effects of thickness of Peva45 and plywood on the FNF of the PSSDBC system are presented in Tab. 4. The results showed that increasing the thickness of Peva45 and plywood respectively enhanced and decreased the FNF of the system. Therefore, this point revealed that the effectiveness of the plywood mass is higher than its stiffness on the FNF of the system. Also, the effectiveness of the Peva45 stiffness was shown to be higher than its mass. By changing thickness of Peva45 from 0.8 mm to 1.0 mm and thickness of plywood from 9.252 mm to 25 mm it has been shown that the FNF of the system increased and decreased by an average value of 3.11% and 3.94%, respectively. The maximum and minimum values of the FNF of the PSSDBC system were identified as 15.199 Hz (for maximum thickness of Peva45 and minimum thickness of plywood) and 14.146 Hz (for maximum thickness of plywood and minimum thickness of Peva45), respectively. Therefore, by changing the thickness of the main elements, the FNF of the system increased only a maximum of 7.44%. The minimum value of the FNF of the PSSDBC shows well above 10 Hz, therefore, the studied system was in the category of HFF [31] and comfortable for occupants [52].

Table 4 Effect of thickness of Peva45 and plywood on the FNF of the system.

	Peva45	Plywood				
		t=9.252 mm	t=12.7 mm	t=18 mm	t=23 mm	t=25 mm
FNF (Hz)	t=0.8 mm	14.727	14.549	14.404	14.182	14.146
	t=1.0 mm	15.199	15.019	14.790	14.641	14.601

7.2 Effect of boundary conditions

Effect of different boundary conditions on the FNF of the PSSDBC system with changing support conditions has been considered as three situations such as; effect of sliding and rotation at the end supports perpendicular to the strong direction of the PSS (sliding parallel with Y direction of the plan, Figure 8), effect of locating support under the top flange and web of the PSS at two ends of the length, and effect of adding support parallel with the strong direction of the PSS (parallel with Y direction of the plan, Figure 10).

7.2.1 Effect of sliding and rotation of supports

Effect of sliding and rotation of the bottom PSS flanges at the end supports along the X direction on changing the FNF of the PSSDBC system is studied for different support conditions as shown in Fig. 8. These involve i) pin (P) and roller (R) (control sample), ii) P-P, iii) P-F (fixed), iv) R-F, and v) F-F end supports perpendicular to the strong direction of the PSS. Tab. 5 shows the FNF of the studied system under different end support conditions.

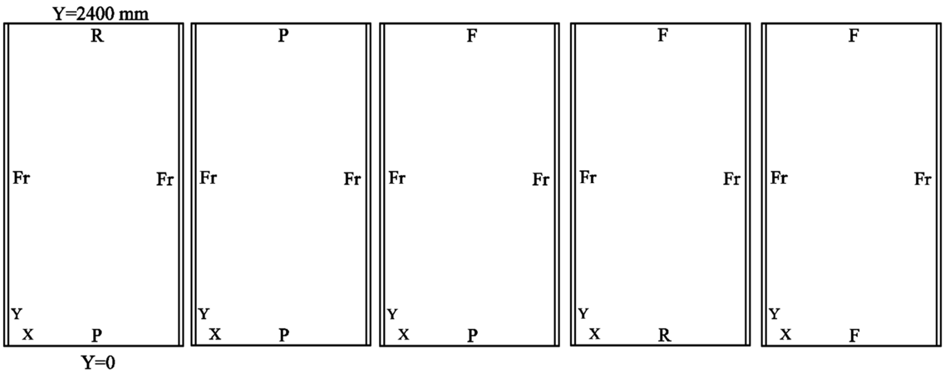


Figure 8 Various end support conditions perpendicular to the strong direction of the PSS (*Fr* = *Free*).

Table 5 The FNF of the PSSDBC system under different types of end supports perpendicular to the strong direction of the PSS.

Type of Support	P-R	P-P	P-F	R-F	F-F
FNF (Hz)	14.404	19.502	19.531	14.428	19.561

As it is shown in Tab. 5, if roller support is converted into pin support, in other words, if support does not have sliding in Y direction of the plan, the FNF of the PSSDBC system will be increased by 35.39%. On the other hand, using fix support instead of pin support (P-F instead of P-P) does not have a considerable effect on the FNF of the system. This conversion increased the FNF of the studied system by only 0.15%. Therefore, it revealed that control of rotation does not have a significant effect on the FNF of the system.

7.2.2 Effect of adding supports under the top flange and web of the PSS

The supports in the experimental tests and FEM were considered under the bottom flange of the PSS (Figure 9). Tab. 6 shows the FNF of the PSSDBC system under some other boundary conditions.

By adding supports under the top and bottom flanges of the PSS (M.II, Fig. 9), the FNF of the PSSDBC system in comparison with M.I was increased by 34.38%. If supports are located under the top & bottom flanges and web of the PSS (M.III, Fig. 9), the FNF of the PSSDBC system comparing with M.I is enhanced by 39.86%. These results demonstrated that adding

Table 6 Effect of adding supports under the top flange and web of the PSS on the FNF.

Model of support	P-R support in bottom flange (M.I)	P-R support under bottom and top flanges (M.II)	P-R support under bottom and top flanges and web of PSS (M.III)
FNF (Hz)	14.404	19.356	20.145

supports under the top flange of the PSS (M.II) had an apparent effect on the increase of the FNF of the studied system. However, considering support under the web of the PSS (M.III) in comparison with M.II improves the FNF of the PSSDBC system by only 5.48%. These results help designers select shapes of supports under Peva45 to have greater values of FNF.

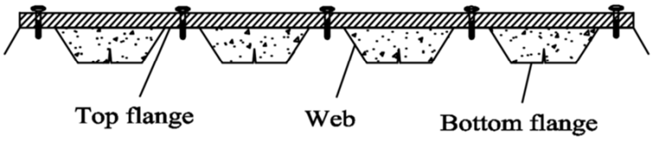


Figure 9 Illustration of supports under top & bottom flanges and web of the PSS.

7.2.3 Effect of adding support parallel to longitudinal side edges

The supports of the longitudinal side edges (support in X=0 and 795 mm, Fig. 3.b) for the control sample were considered free (unconstrained). Different additional support conditions which were investigated at the longitudinal side edges are illustrated in Fig. 10.

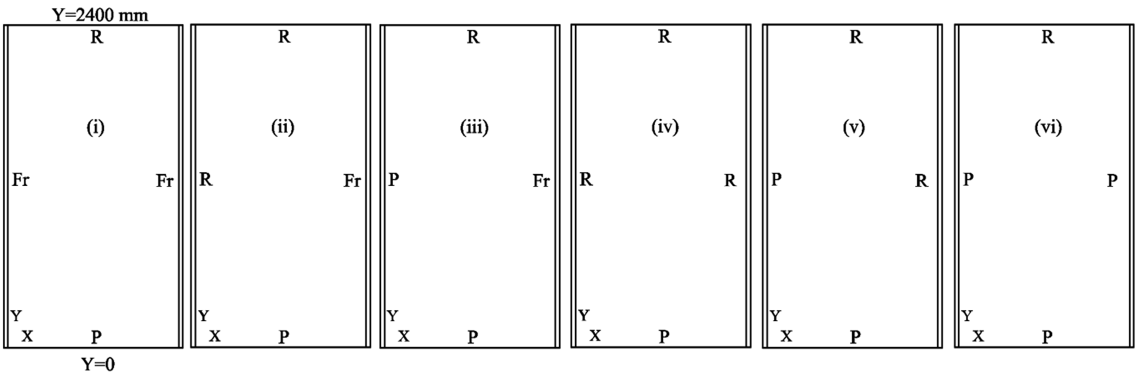


Figure 10 Different support conditions parallel to the strong direction of the PSS.

Tab. 7 summarizes the FNF of the PSSDBC system under various support conditions which illustrated in Fig. 10.

Table 7 Effect of adding supports parallel to the strong direction of the PSS on the FNF.

Model of support	(i)	(ii)	(iii)	(iv)	(v)	(vi)
FNF (Hz)	14.404	15.441	16.269	20.575	22.104	23.696

Tab. 7 reveals that considering roller and pin supports in Y direction in only one edge of the panel increased the FNF of the system by 7.20% and 12.95%. It uncovered that if the support is converted from roller into pin, in other words, if sliding of the support is controlled in the wide side of the panel, the FNF of the system will be increased by 5.75% (12.95%-7.2%). However, by restraining both longitudinal side edges as supports models of (iv), (v), and (vi), the increase of FNF is much more pronounced, i.e. an increase of 42.84%, 53.46%, and 64.51%, respectively. It is obvious from the above that if only three sides of the PSSDBC panel were supported; restraining the sliding in the X direction at the longitudinal side edges would not change much the FNF. When all four sides of the panels were supported instead of only three it became much more significant.

7.3 The FNF of panels with practical dimensions

Peva45 is available in the local market by the width of 795 mm and maximum length of 15 m. Also, maximum length and width of plywood are 2400 mm and 1200 mm, respectively. Therefore, to prepare panels with practical dimensions with sizes greater than the size of Peva45 or plywood, some pieces of Peva45 and plywood should be used together. Fifteen models in four different lengths, i.e. 1200 mm, 2400 mm, 3600 mm and 4800 mm involving one, two, three, and four repeating sections of the system were developed which were combinations of elements the same as the control sample, verified by experiments, as shown in Fig. 3.b and Figs. 11-13. In all fifteen models, the length and width of all pieces of the plywood have been chosen as 2400 mm and 795 mm, respectively. Also, the length of Peva45 has been chosen as the length of the panels for all models. In addition, grade 30 concrete was considered as an infill in trough of Peva45.

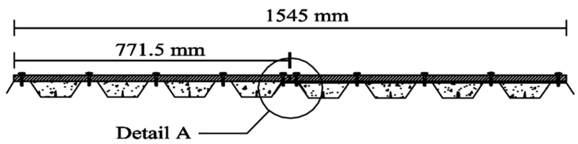


Figure 11 The PSSDBC panel with two repeating sections.

The connection between two adjacent side by side panels (detail A) was considered as a typical lap joint idea as presented in Fig. 14. Wright and Evans [50] reported the connectivity characteristics of such joint. As can be seen in Fig. 14, the nodes i(2) and j(2) are respectively connected to the nodes i(3) and j(3) which have complete freedom in the longitudinal and rotational directions while assumed to have complete connection in the vertical and lateral

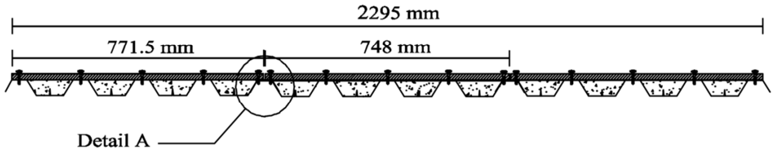


Figure 12 The PSSDBC panel with three repeating sections.

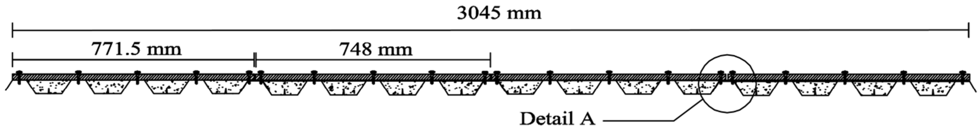
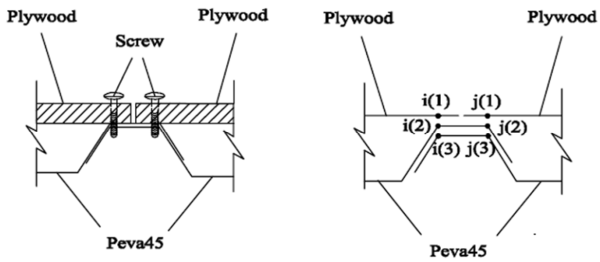


Figure 13 The PSSDBC panel with four repeating sections.

directions [50]. As stated, the connections of the nodes i(1) and j(1) respectively to the nodes i(2) and j(2) (Peva45 to plywood) are represented by results of the study done by Nordin et al. [34].



(a) (b)

Figure 14 Detail A: (a) Constructional model (b) Analytical model.

Tab. 8 presents the characteristics and the FNF of the panels with practical dimensions. The categorization of the panels as to whether they are LFF or HFF is carried out. The comfortableness of the panels based on Ref. [52] is also investigated. All panels had pin-roller support in X direction (Fig. 3) and free-free support in Y direction (Model 0).

The width of the panels with only end supports perpendicular to the strong direction of the PSS did not significantly affect the FNF of the system, as the panels with the same length and widths of 795 mm, 1545 mm, 2295 mm, and 3045 mm had close values to each other in terms of the FNF. The reason was about the similar enhancement of the stiffness and mass by the increase of the width. However, the FNF of the panel with the width of 3045 mm was a bit greater than the FRF of the panel with the width of 2295 mm and the latter was greater than 1545 mm. It may be due to the increase of the stiffness of the panels by using lap joints in the panels with two pieces of Peva45 (one lap joint), three pieces of Peva45 (two lap joints), and four pieces of Peva45 (three lap joints). Because the thickness of Peva45 is double in the

Table 8 Characteristics, FNF, and evaluation of the developed PSSDBC models (Model 0).

Name of panel	Length (mm)	Width (mm)	FNF (Hz)	Status of the studied system (b)	(c)
1PP1LL	1200	795	47.672	HFF	Ok
1PP2LL$^{(a)}$	2400	795	14.404	HFF	Ok
1PP3LL	3600	795	6.5513	LFF	Failed
1PP4LL	4800	795	3.7009	LFF	Failed
2PP1LL	1200	1545	50.995	HFF	Ok
2PP2LL	2400	1545	14.359	HFF	Ok
2PP3LL	3600	1545	6.4161	LFF	Failed
2PP4LL	4800	1545	3.6072	LFF	Failed
3PP1LL	1200	2295	52.202	HFF	Ok
3PP2LL	2400	2295	14.373	HFF	Ok
3PP3LL	3600	2295	6.4196	LFF	Failed
3PP4LL	4800	2295	3.6466	LFF	Failed
4PP1LL	1200	3045	52.520	HFF	Ok
4PP2LL	2400	3045	14.462	HFF	Ok
4PP3LL	3600	3045	6.4564	LFF	Failed
4PP4LL	4800	3045	3.6478	LFF	Failed

(a) Control sample
(b) Categorization of system as LFF or HFF [31]
(c) Comfortableness of panels for occupants [52]

location of the lap joint, while, according to the lap joint idea the connection between two pieces of Peva45 is not complete.

As it is obvious, the length of the system has a direct effect on its FNF. The results on the studied panels showed that the FNF of the system with the length of greater than 3600 mm was uncomfortable [52]; therefore, they will be in the category of LFF.

Comparing results of Ref. [23] and the current study, it was revealed that the presence of concrete did not have a considerable effect on the decrease of the FNF of the PSSDB system with the length of 1200 mm. However, this presence significantly affected the reduction of the FNF of the PSSDB system with the lengths of 2400 mm, 3600 mm, and 4800mm, as in practical panels i.e. 3PP3LL, 3PP4LL, 4PP3LL, and 4PP4LL the maximum decrease in the FNF of the panels was 14.69%. However, this value was identified for grade 30 concrete and it can be reduced a little by higher concrete grades.

Increase in the FNF of a floor system is required since the floor is needed to be away from resonance under human walking load and to become comfortable for users. If panels are supported at all sides, the FNF of the system will be increased. Depending on the control of sliding in supports, roller or pin supports can be used in all sides. For this case, all panels with the lengths of 3600 mm and 4800 mm were selected in order to increase their FNFs through three boundary conditions as shown in Fig. 15. Tab. 9 summarizes the increased FNFs of the panels corresponding to these boundary conditions. It also illustrates comfortableness of the studied panels.

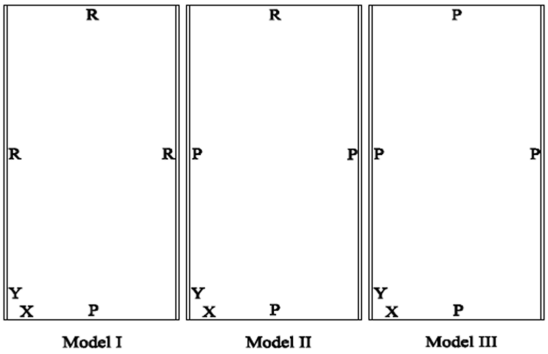


Figure 15 Model of boundary conditions for increasing the FNF of LFF panels.

Table 9 The FNF and status of the LFF panels under different models of boundary conditions.

Name of panel	Model I			Model II			Model III		
	FNF(Hz)	Status		FNF(Hz)	Status		FNF(Hz)	Status	
		(a)	(b)		(a)	(b)		(a)	(b)
1PP3LL	10.553	HFF	Ok	11.995	HFF	Ok	13.849	HFF	Ok
1PP4LL	8.4804	LFF	Ok	9.3032	LFF	Ok	10.538	HFF	Ok
2PP3LL	8.6752	LFF	Ok	9.2672	LFF	Ok	11.094	HFF	Ok
2PP4LL	6.1109	LFF	Failed	6.4991	LFF	Failed	7.5774	LFF	Ok
3PP3LL	7.4285	LFF	Failed	7.6840	LFF	Failed	9.9078	LFF	Ok
3PP4LL	4.9487	LFF	Failed	5.1470	LFF	Failed	6.3689	LFF	Failed
4PP3LL	6.9895	LFF	Failed	7.1232	LFF	Failed	9.5346	LFF	Ok
4PP4LL	4.4343	LFF	Failed	4.5477	LFF	Failed	5.8844	LFF	Failed

(a) Categorization of system as LFF or HFF [31]
(b) Comfortableness of panels for occupants [52]

The FNFs of panels with supports models I, II, and III are compared with model 0. The percentages of the increase in the FNFs of the systems are presented in Tab. 10.

These results showed that control of sliding in the supports in X side of the plan for the systems with the width greater than 795 mm does not considerably affect the FNF of the system. However, effect of control of sliding in Y direction showed a significant effect in all studied models. Effectiveness of using supports in all sides of the panels reduced by increasing width of the panels. By using supports even in model III, the panels with the length of 4800 mm and widths of 2295 mm and 3045 mm were still uncomfortable for users, therefore, were as LFF. In addition, the panels with the length of 4800 mm and width of 1545 mm and also

Table 10 Percentages of the increase in the FNF of the LFF panels by comparison of model 0 with models I, II, and III.

Name of panel	Model of support condition parallel with Y direction			Percentage of increase in the FNF by control of sliding in supports	
				Comparison of Model II with Model I	Comparison of Model III with Model II
	Model I	Model II	Model III	X direction	Y direction
1PP3LL	61.08 (%)	83.09	111.39	22.01 (%)	28.3
1PP4LL	129.14	151.38	184.74	22.24	33.36
2PP3LL	35.21	44.44	72.91	9.23	28.47
2PP4LL	69.41	80.17	110.06	10.76	29.89
3PP3LL	15.72	19.70	54.34	3.98	34.64
3PP4LL	35.71	41.15	74.65	5.44	33.5
4PP3LL	8.26	10.33	47.68	2.07	37.35
4PP4LL	21.56	24.67	61.31	3.11	36.64

length of 3600 mm and widths of 2295 mm and 3045 mm were showed to be in the category of LFF but they were comfortable.

8 CONCLUSIONS

As a conclusion, this paper reveals experimentally and numerically the natural frequency of the PSSDBC system to find the effects of different parameters on the FNF of the system. Comparing the experimental results of the earlier and current studies demonstrated that the natural frequencies of the PSSDBC system were less than the PSSDB system. The effect of concrete on reducing the FNF of the panels was more significant in panels with 795 mm width than the panels with the width of greater than 795 mm (for the practical panels). Damping ratio corresponding to the FNF of the PSSDBC system was observed to be more than the PSSDB system which shows the performance of the presence of concrete in the PSSDB system to confront with dynamic loads. The results discovered that changing thickness of the PSS and DB, using supports under both the top and bottom flanges of the PSS, control of sliding along the strong direction of the PSS at the end supports, and number of side edges being supported, all considerably affected the increase of the FNF of the system. However, control of sliding along the weak direction of the PSS at the side edge supports, grade of concrete, rotations at all ends and side edge supports, support conditions under the web of the PSS, all do not have apparent effects on changing the FNF of the studied panels. Identification of the FNF of the panels with practical dimensions with end supports only shows that the FNF of the panels with the same length and different widths are very close to each other. However, a small difference between the FNFs of the panels with lap joint may be occurred by increasing the thickness of Peva45 in the location of the lap joint. It was revealed that the significant increase in the FNF of the PSSDBC floor system with practical dimensions is possible via boundary conditions.

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