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VIBRATION RESPONSE OF USFB COMPOSITE FLOORS

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Abstract: This paper is focused on the vibration response of a composite flooring system that incorporates perforated steel Ultra Shallow Floor Beams, called USFB. This is a lightweight system that can accommodate long spans; hence it is susceptible to floor vibrations excited by dynamic loads. Both experimental and computational proposed finite element (FE) studies have been conducted to investigate various geometric parameters following a comparative study on a flooring system with bare steel perforated USFBs. Emphasis was placed on the fundamental frequency to predict the possibility of resonance of this new breed of flooring systems.

1 Introduction

Nowadays, structural engineers are faced with new challenges such as innovating flooring solutions that minimise construction cost while simultaneously allow for optimum space utilisation within certain constraints. As a result, slender (e.g. slim or shallow) floors are created leading to the issue of unwanted floor vibrations, which many engineers today are not too cognisant of (Mello et al., 2008).

Despite the fact that there are many forms of flooring solutions available to the designer, within the steel-concrete composite (SCC) industry, many researchers are attempting to ascertain the dynamic properties of slim floors; not only because of its novelty to the construction sector, but also because of SCC competitive edge of speed of construction (Johnson, 1994).

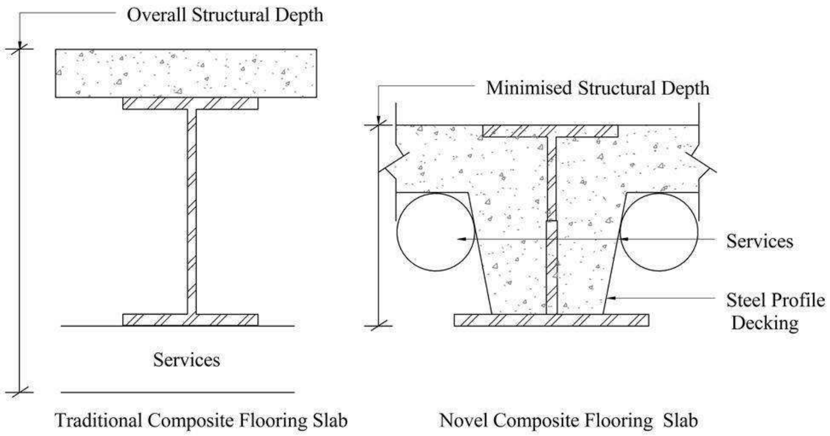


Fig. 1: Traditional SCC Slab versus Novel SCC Slab

By slim or shallow floor, it is implied that the depth of the concrete slab is located within the flanges of the steel beam as opposed to the traditional SCC flooring systems in which the slab is supported by the top flange of the steel beam (Fig. 1). In this way, it is evident that it is possible to have a reduction in the structural depth which translates into cumulative savings in the floor-to-floor height in medium to high-rise structures (Fig. 1).

According to Lawson and Leskela (1996) and Young et al. (2008), this type of floor has become very popular in Europe and has stimulated the interest of the design of such flooring systems because of the numerous economical advantages associated with it such as the reduced fire protection cost and the minimum use of shear studs, if any. It is worth mentioning that given the fact that the concrete encases the steel beam, the load resistance and stiffness of the composite section is also enhanced (Lawson and Leskela, 1996).

In order to construct these slim floors, Ultra-Shallow Floor Beams (USFBs) are made by fabricating welded or rolled steel sections to make an asymmetrical I-section that results in a wider bottom flange. This is done to provide sufficient bearing distances for the steel decking or the precast concrete units (Fig. 2).

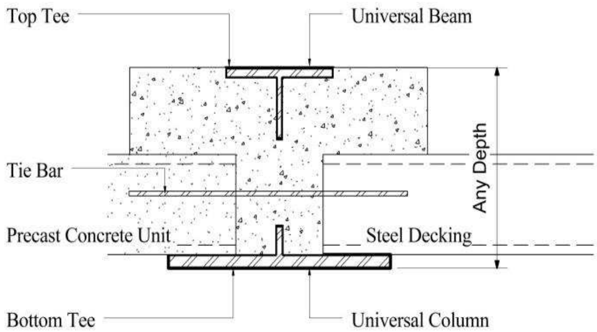


Fig. 2: Concept of Novel Composite Slab with USFB

As the demand for lightweight structures with clear floor spans increases, long spanning SCC floors are encouraged through the use of perforated steel beams (e.g. USFB), which also allow for possible service integration within the floor depth (Tsavdaridis et al., 2013).

Even though a lightweight flooring solution that is capable of accommodating long spans is achieved through the use of the USFB, the reduction in floor depth results in a flexible structure that becomes sensitive to excessive vibrations. As Mello et al. (2008) mentioned, the issue of floor vibrations has become very prevalent and if not properly addressed, structural redesign or retrofitting becomes necessary. Young et al. (2008) states that the performance of SCC slabs can be disputed with regards to floor vibrations and this is in line with the opinion presented by Smith et al. (2009) that floor vibration is a significant serviceability issue. Therefore, the design of ultra-shallow floors should be primarily for serviceability conditions (i.e. vibrations).

As the vibration response of floors is a well studied topic in structural dynamics particularly with regards to the characterisation of dynamic loads that cause unwanted vibrations such as walking, dancing and jumping, Sandun et al. (2009) revealed that much work is yet to be done. In addition, Tsavdaridis and Giaralis (2011) stated that detailed studies on the dynamic properties of ultra-shallow floors are lacking and for such reason, the dynamic behaviour of USFBs floors must be known.

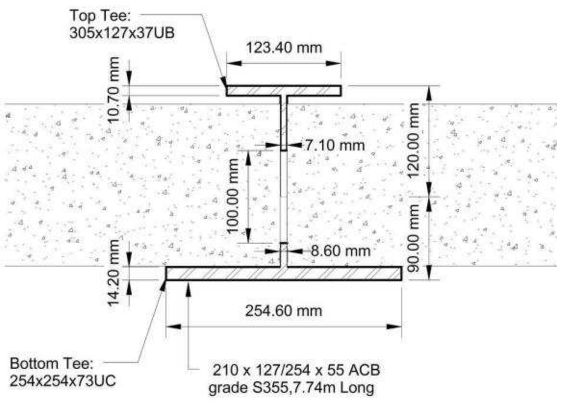
2 Objectives

The objectives of the study are:

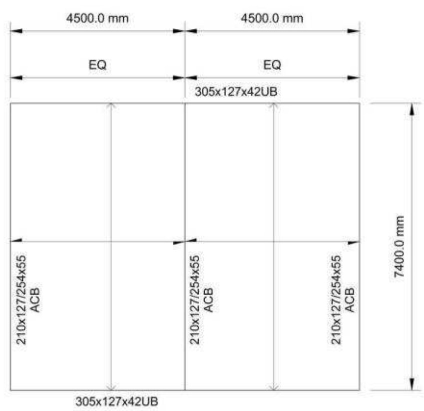
a) To generate the dynamic characteristics of the novel composite slabs through modal analyses.
b) To determine the effect of the varying concrete thicknesses and boundary conditions on their dynamic characteristics.
c) To investigate the acceleration response of the worst case floor span.

3 The Structural Model

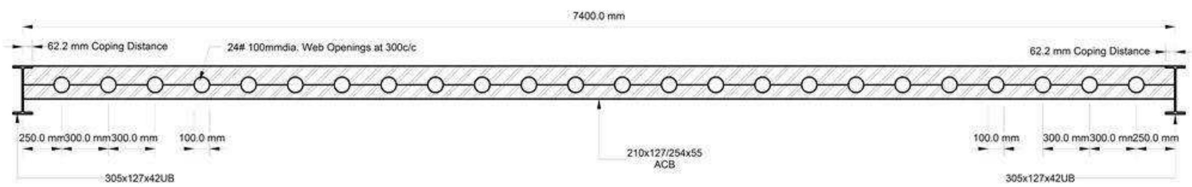
The SCC flooring system investigated comprised of a perforated steel USFB which was treated with both pinned and fixed supports for the ease of comparison. In addition, the concrete depth varied in order to draw their influence on the vibration response of the novel composite slab. The length of the USFB model remained constant at 7.4m while the slab span also varied between 2.5m and 4.5m (Fig. 3b); more specifically: 7.4mx5m, 7.4mx6m, 7.4mx7m, 7.4mx8m and 7.4mx9m.



a) Cross-Section of the USFB



b) Structural Plan of Slab



c) Longitudinal Section of the USFB

Fig. 3: Structural Model of the Composite Slab

The structural properties of the perforated USFB were developed by combining two sections; namely the 305x127x37UB and 254x254x73UC. Primary beams were the 305x127x42UB. Geometric properties of these sections are summarised in Table 1. The structural concrete depth varied throughout the analyses, and 1.2mm thickness was adopted for the decking, assuming a 210ComFlor steel decking properties. Material properties are synopsised in Table 2.

4 FE Model of the USFB System

Modelling of this new composite floor type was done by using popular commercial software ABAQUS CAE V.6.10. As it is shown in Fig. 3b, the two-bay floor arrangement consisted of secondary beams 210x127/254x55 ACB and supported by 305x127x42UB primary beams. In order to practically represent construction procedures, structural coping (notching) of 62.2mm was applied to the secondary USFBs (Fig. 3c).

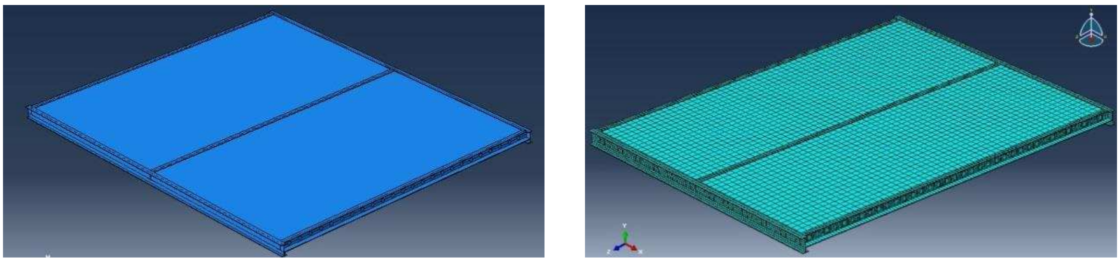
Table 1: Geometric Properties of Steel Sections

	Mass Kg/m	Depth mm (h)	Width mm (b)	Web Thickness t_w (mm)	Flange Thick-ness t_f (mm)
Top Tee: 305x127x37UB	37	304.4	123.4	7.1	10.7
Bottom Tee: 254x254x73UC	73.1	254.1	254.6	8.6	14.2
Primary Beam: 305x127x42UB	41.9	307.2	124.3	8.0	12.1

Table 2: Material Properties of Structural Model

Material	Density ρ (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio (ν)	Yield Stress (MPa)
Steel	7800	200	0.3	355
Concrete	2350	38	0.2	25

The beams were modelled with 3D solid elements while the steel decking was modelled by linear 3D plane shell elements (S4R). The concrete slab was modelled by 3D linear solid elements (C3D8R). The interface model was created with contact elements between the materials of steel and concrete. This was done by applying coefficients of friction between the steel-to-steel and steel-to-concrete of 0.42 and 0.57 respectively, in accordance to AIT (2014) and Rabbat and Russel, (1985). The final solid and meshed models are shown in Fig. 4.



a) FE model of two-bay Slab b) Final meshed model of Slab

Fig 1: Finite Element Model of Composite Slab with USFB

5 FE Model Verification

As Cunha and Caetano (2006) as well as Wei-Xin, et al. (2004) mentioned, in order to ensure that the results of finite element models are accurate and reliable, good correlation procedures between the FE model and a physical model are required. Based on this, verification was done on the FE models used in this study.

5.1 Validation of the Bare Steel USFB Model

Prior to conducting the parametric study on the examined composite flooring system, an experimental study was completed on a 7.74m bare steel perforated USFB in the George Earl laboratory at the University of Leeds (Fig. 5). An impact hammer (model 5803A by Dytran Instruments) equipped with an embed force sensor is used to excite the transverse flexural modes of vibration of the beam specimen by hitting it downwards along the gravitational axis.

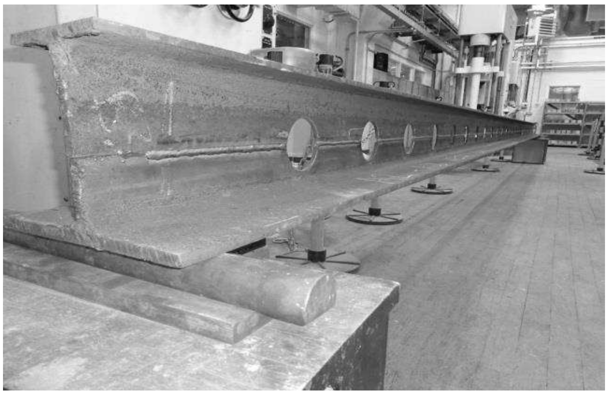


Fig 5: Experimental USFB

The section properties of this USFB is similar to that described in Table 1 and seen in Fig. 5. In order to extract the fundmental frequencies, an experimental modal analysis (EMA) was peformed on the test specimen and the data acquired post-processed in MATLAB. Subsequently, a simply supported FE model was generated in ABAQUS CAE v.6.10 to validate the FE procedures. The results shown in Table 3 compared well based on the acceptable percentage error of 15% supported by (Shah, 2002).

Table 3: Comparison of Experimental and FE Results on Bare Steel USFB

In –plane Natural Frequencies (Hz)				Percentage of Error (%)		
Current Experimental Study (MATLAB)			FEM			
Configuration 1	Configuration 2	Configuration 3	ABAQUS	C1	C2	C3
11.77	11.76	11.72	10.68	10.2	10.11	9.74
41.16	42.01	42.07	41.30	0.34	1.72	1.86
80.74	81.48	81.64	88.19	9.2	8.23	8.02
170.29	162.86	163.39	160.73	5.94	1.33	1.65
231.30	237.14	236.60	214.66	7.75	10.47	10.22
294.44	298.68	296.03	282.47	4.23	5.74	4.80

5.2 Validation the FE SCC Slab Model

Moreover, validation of a FE slab model was deemed necessary and conducted by deriving the natural frequencies for the flooring arragement studied by Mello et al. (2008) and later on verified by Behnia et al. (2013). This was also also achieved using ABAQUS CAE v.6.10.

In the FE model, the 9mx7m slab arrangement (Fig. 6) used by Mello et al. (2008) was considered with the properties shown in Table 4 and Fig. 6. Though column heights were unknown, for the research validation 6m height columns were adopted to model a typical floor-floor height of 3m. All steel girders and column elements were modelled with 3Dsolid elements while the concrete slab was modelled with shell elements of 5DOF. The material properties were compliant to those indicated in Table 2. Good correlation results were achieved as it can be seen in Fig. 7 and Table 5.

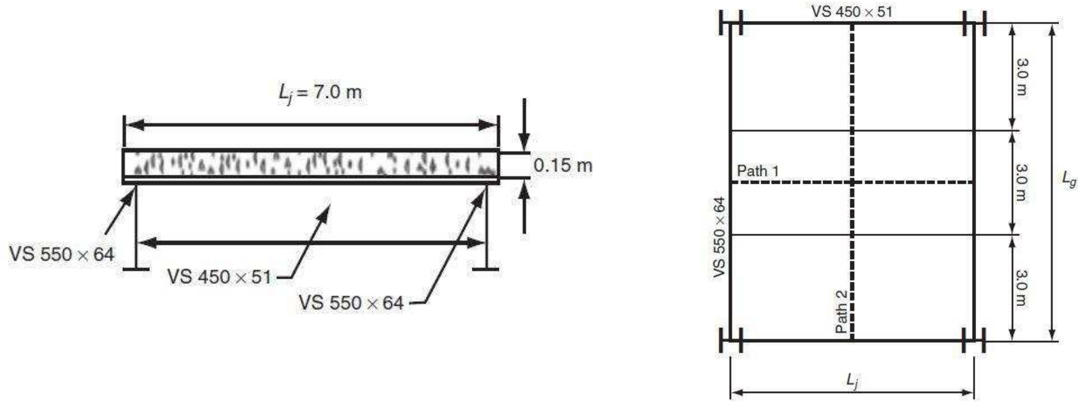
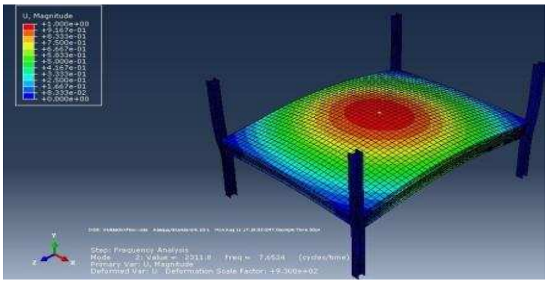


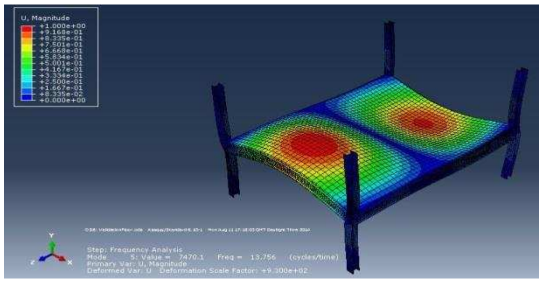
Fig 6: Cross-Section and Plan of Slab Arrangement in Mello et al. (2008)

Table 4: Geometric Properties of Structural Elements in Mello et al. (2008)

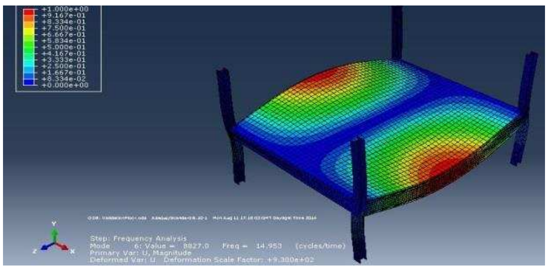
	Height (mm)	**Flange Width (mm)**	**Top Flange Thickness (mm)**	**Bottom Flange Thickness (mm)**	**Web Thickness (mm)**
VS I 550x64	500	250	9.5	9.5	6.3
VS I 450x51	450	200	9.5	9.5	6.3
CS I 300x62	300	300	9.5	9.5	8



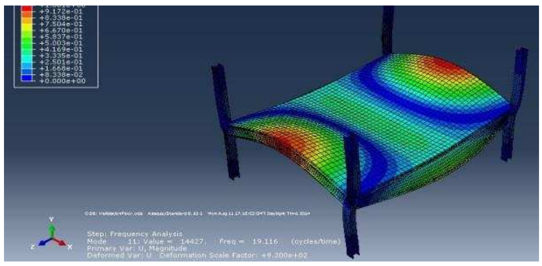
1st natural frequency, f_{01}=7.65 Hz



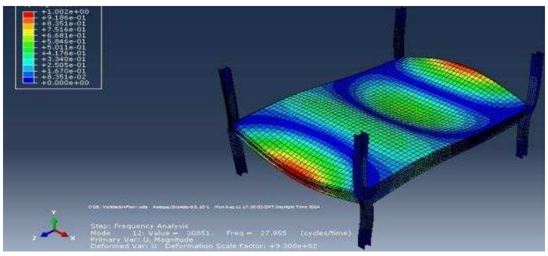
2nd natural frequency, f_{02}=13.76 Hz



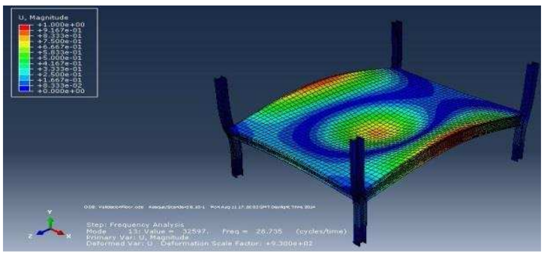
3rd natural frequency, f_{03}=14.95 Hz



4th natural frequency, f_{04}=19.12 Hz



5th natural frequency, f_{05}=27.96 Hz



6th natural frequency, f_{06}=28.74 Hz

Fig. 7: The mode shapes and natural frequencies for validation study

Table 5: Validated Results of Composite Slab

Mode	Natural Frequencies (Hz)			Average Percentage Error (%)
	Current Study	Mello et al., 2008	Behnia et al., 2013	
1	7.65	7.42	7.44	2.90
2	13.76	14.70	13.69	3.65
3	14.95	15.23	15.60	3.06
4	19.12	20.32	19.20	3.30
5	27.96	30.82	29.60	8.00
6	28.74	31.86	31.00	9.30

6 Parametric Study

Modal analysis was carried out to primarily extract the natural frequencies and to assess how this dynamic response changes with concrete depth and boundary conditions alterations. The vibration mode shapes were also examined. This investigation was performed on five different floor spans (7.4mx5m, 7.4mx6m, 7.4mx7m, 7.4mx8m, 7.4mx9m) so as to develop the rational limits about the vertical plane for such USFB floors. In the second stage, a linear perturbation steady state modal dynamic analysis was conducted to assess the acceleration performance of this novel composite floor under a human induced load model suggested by Murray et al. (2003) and Mello et al. (2008). Throughout this study, a notional damping of 3% was utilised in accordance with Bachmann et al., 1995.

6.1 Results

The results presented reveal the influence of concrete thickness and boundary on the vibration response of the novel composite flooring system for the five investigated floor spans. The details of the parameters studied were:

- Concrete thicknesses: 75mm,100mm,125mm,150mm,175mm and 200mm.
- Boundary Conditions: fully fixed and pinned.

6.1.1 Influence of Concrete Thickness

To investigate the influence of slab thickness (h_c) on the vibration response, six thicknesses in the range of 75mm-200mm were examined. It was observed that there was a parabolic behaviour of the natural frequencies with the first four modes with decreasing slab thicknesses. However, when slabs with higher than 150mm thickness were examined, the natural frequencies increased. This behaviour was evident in both slabs with fixed as well as pinned supports (Fig. 8).

6.1.2 Influence of Boundary Conditions

Considering fixed boundary conditions, it was assumed that the expected interaction between the primary supporting beam (305x127x42UB) and the structural columns would be fully fixed; meaning all translational and rotational degrees of freedom were zero. On the other hand, the pinned connections restrict only the in-plane translations and rotations about in the vertical plane.

In case of fixed supports and 100mm concrete thickness, high natural frequencies for all the vibration modes were observed (Fig. 10). Comparing to the model with pinned supports, there was an increased percentage of 24.4%, 39.8% and 16.8% for the natural frequencies of the first, second and third vibration modes, respectively. When higher vibration modes considered, the percentage of increase was reduced to 4.1%, 8.5%, 2.2%, 2.9% and 8.4% for the remaining analysed modes. This trend was also confirmed for the results with the model using concrete thickness of 200mm. These indicate that the reduction percentage values for the 4th, 5th, 6th, 7th and 8th mode were 10.5%, 2.1%, 5.3% and 0.1%, respectively.

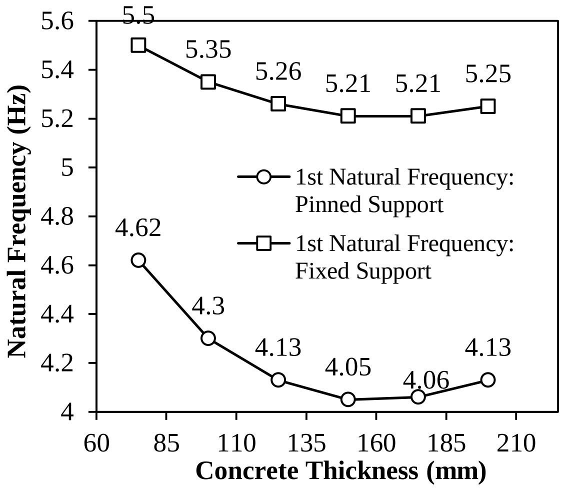


Fig. 8: Influence of Concrete Depth with Fixed and Pinned Supports

The increase in natural frequencies in earlier modes is linked to the inherent characteristic of a fixed support to stiffen the structure by dissuading rotations and translations. On the other hand, it is surmised that in higher modes of vibration, the fixed-end supports tend to mislay their full strength and stiffness, thereby beginning to experience some degree of rotations which resulting in a reduction in the percentage increase of natural frequencies.

6.1.3 Acceleration Responses

A floor which is well above the minimum natural frequency limit can perform poorly whilst one with a lower natural frequency can perform exceptionally well in terms of the acceleration response (MacSteel, 2003). In the current analysis, only the slab arrangement with the lowest natural frequency was examined. This was the 7.4mx9m with 150mm concrete thicnkess, pinned supports and 1st natural frequency of 3.02Hz. The concentrated forced with a sinusoidal response was applied for 0.33s (1/f) at the middle of the slab and centre of the USFB beam. The maximum recorded acceleration for the load at the centre of the USFB beam was 87.92mm/s^2 while at the middle of the slab was 73.98mm/s^2; both occuring at frequencies of 3.01Hz (Fig. 11).

The accelerations recorded are considered to be satisfactory based on the criteria presented in Murray et al. (2003) and Bachmann et al. (1995). Plotting the frequency of 3.01Hz with 87.92mm/s^2 (0.8g) against the guidance published by Murray et al. (2003), demonstrates that the floor's acceleration response is slightly under the threshold considered for residential and office buildings. According to Bachmann et al. (1995), the floor is well below the acceptable limit of 100mm/s^2. Therefore, though the fundamental frequency of 3.02Hz may indicate possible resonance, the acceleration performance is deemed acceptable according to existing literature stated.

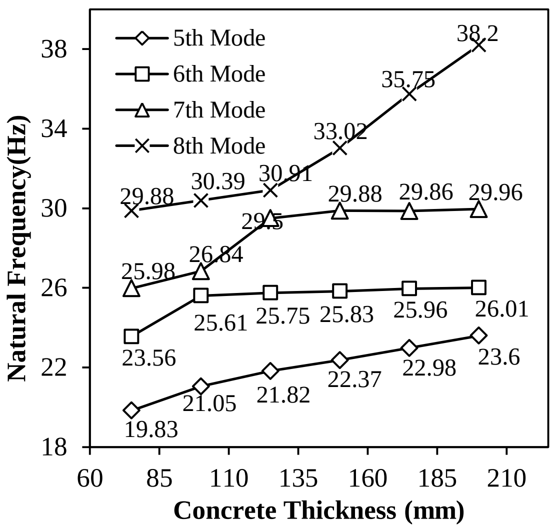


Fig. 9: Concrete Influence on Higher Modes

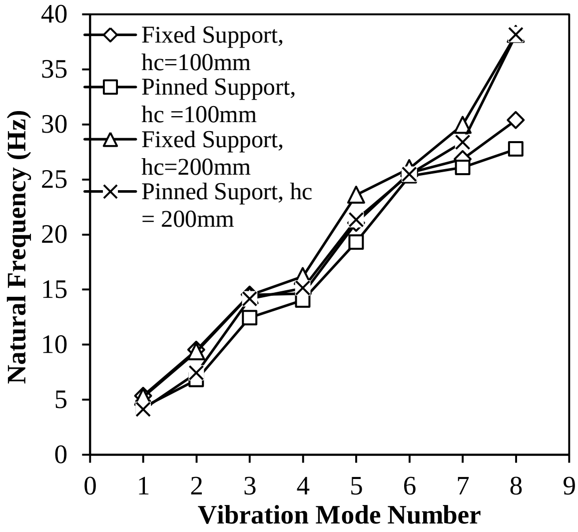
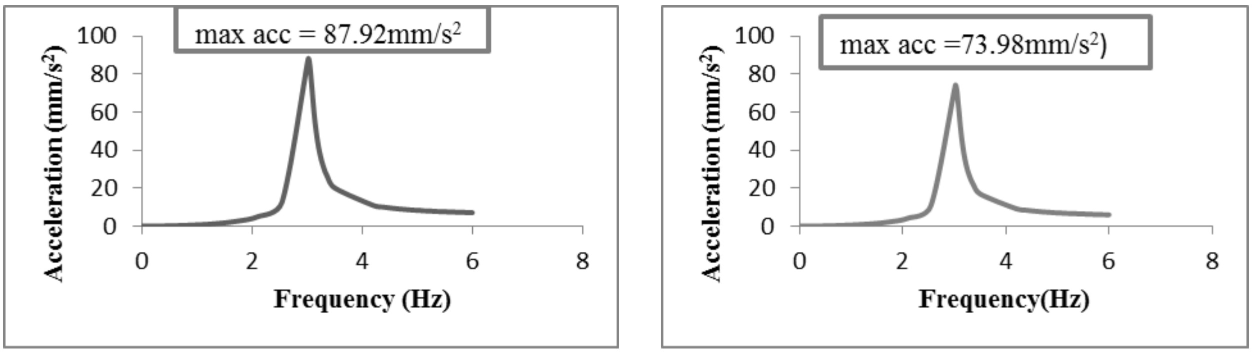


Fig. 10: Influence of Boundary Condition on Vibration Response of Novel Composite Slab



a) Load at centre of USFB

b) Load at Middle of Slab

Fig. 11: Acceleration Responses

7 Conclusions

The main conclusions of the research were:

- Less participation of increased mass in earlier vibration modes.
- Slabs with fixed supports yield higher natural frequencies and are preferable.
- Increasing slab spans reduced the natural frequencies.
- Potential for the use of composite slabs with USFBs as frequencies were higher than minimum floor frequency of 3Hz.

Acknowledgments

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