Vibration Response of Ultra-Shallow Floor Beam (USFB) Composite Floors

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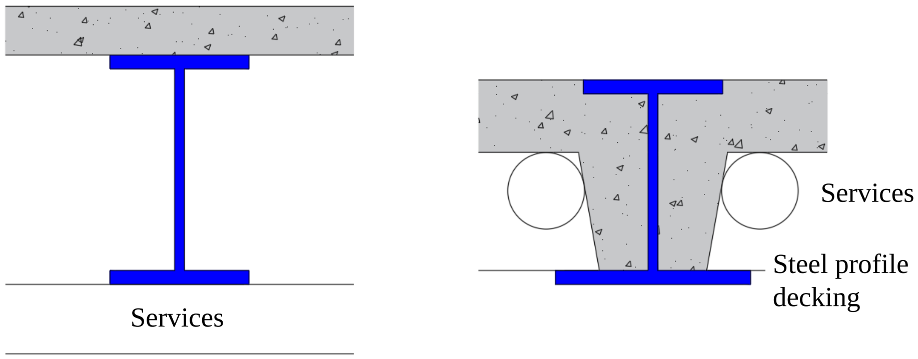
Abstract

This paper examines the vibration response of the steel-concrete composite Ultra Shallow Floor Beam (USFB®) flooring system which incorporates asymmetric steel perforated beams to accommodate the concrete floor slab within the depth of the flanges while allowing reinforcement and/or service ducts to pass through the web openings. This is a lightweight flooring system that can accommodate long spans, thus becoming susceptible to floor vibrations due to external resonant dynamic loads. To investigate the influence of slab thickness and boundary conditions on the natural frequencies of the USFB flooring system, parametric studies are conducted using a finite element model and five floor spans. The model was first validated against an experimental test conducted by the authors. Emphasis is placed on the fundamental frequency to predict the possibility of resonance of this complex flooring system with typical human-induced dynamic loads in building structures. To further facilitate the practical numerical modelling and vibration analysis of buildings with USFB floors in standard commercial structural software, an analytical method of deriving equivalent isotropic plate properties is developed and its accuracy is numerically verified vis-à-vis with detailed ABAQUS models.

Keywords: Ultra-Shallow Floor Beam; Vibration Modes; Natural Frequencies; Finite Element Methods; Composite Structures

1. Introduction

Pressing demands for environmentally and economically sustainable modern buildings call for innovating flooring solutions that minimise construction cost and weight, thus embodied carbon footprint, while allowing for optimum space utilisation within certain constraints [1–3]. However, such slender (e.g., slim or shallow) floors become particularly susceptible to resonant floor vibrations which may ultimately lead to serviceability failure [4]. This is because lightweight slender long-span floors make lightly damped and relatively flexible structural components whose lower natural frequency corresponding to the first out-of-plane mode may resonate with ordinary human-induced dynamic loads [5]. In this regard, vibration serviceability governs the design of slim flooring systems in many practical cases [6]. In this context, even though a plethora of slim steel-concrete composite (SCC) flooring systems are available to design engineers [7], the appraisal of the dynamic properties of slim floors remains an open issue as the ability of newly proposed systems for longer spans underpins the SCC competitive edge of speed of construction [8]. Note that in the traditional SCC flooring systems, the concrete slab is supported by the top flange of the downstand steel beam (**Fig. 1a**). On the antipode, in slim or shallow SCC floors, the concrete slab is located within the flanges of the steel beam (**Fig.1b**) which is enabled by the use of USFBs whose lower flange serves for supporting the concrete slab. This consideration makes it possible to reduce the structural depth which translates into cumulative savings in the floor-to-floor height leading to gaining an extra floor every 6 to 7 storeys. Reducing the floor-to-floor depths by approximately 300 mm and multiplying this by the number of building storeys can result in substantial cost savings for cladding. Constructing floors within a limited building height offers a significant economic advantage [7].



(a) (b)

Fig. 1: (a) Conventional SCC slab (b) slim SCC slab

Slim or shallow floors have become very popular in Europe and have stimulated interest of the design of such flooring systems because of the numerous economic advantages associated with it such as the reduced fire protection cost, the minimum use of shear studs, if any, and the load resistance and stiffness of the composite section with partially encases steel beams is also enhanced [9,10]. In detail, 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**) and it is also known as a 'plug' system. As the demand for lightweight structures with free-of-column floor spans increases, long-spanning SCC floors are encouraged by using perforated steel beams. A state-of-the-art methodology is that of the USFB, which also allows for possible service integration within the floor depth [11] while it utilises the rest of the steel web openings to be filled by concrete and thus create a longitudinal shear connection with or without the use of horizontal tie bars. In general, the use of perforated beams (cellular beams on this occasion) leads to a lightweight system that can span longer and does not deflect due to its weight. Further reduction is achieved by the asymmetric final beam, using a thin-walled UB section for the top tee and a thicker and wider UC section for the bottom tee, while local and global web buckling is mitigated due to the partial restrain provided by the concrete (a strut model is developed by the ‘plug’ system).

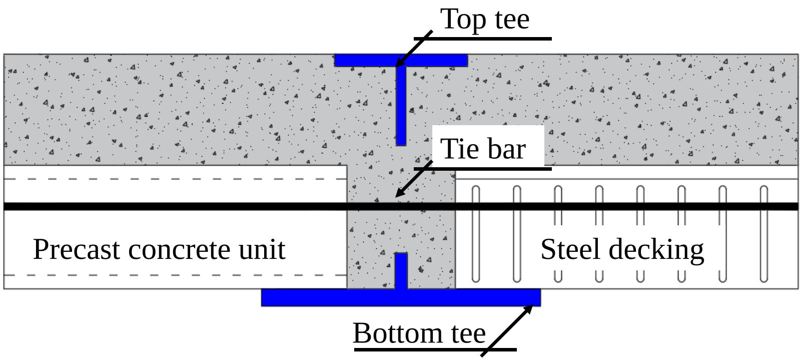


Fig. 2: Concept of composite slab with USFB

USFBs have been already used, especially in the UK, in applications such as Hospitals, University, Commercial and High-End Residential buildings. A recent example is 31-35 Craven Hill Gardens in London (**Fig. 3**). The former Hempel Hotel in Bayswater, has been developed into 18 high-end lateral apartments. The USFB in conjunction with Comflor 210 composite metal decking provided the ideal solution. Additionally, web openings within the beam have been aligned with the decking profile to permit services to also pass within the depth of the slab, creating an absolute minimum overall depth of construction. USFBs were fabricated offsite and rapidly integrated into the overall steel frame.

Fig. 3: 31-35 Craven Hill Gardens in London (image courtesy of Westok Ltd.)

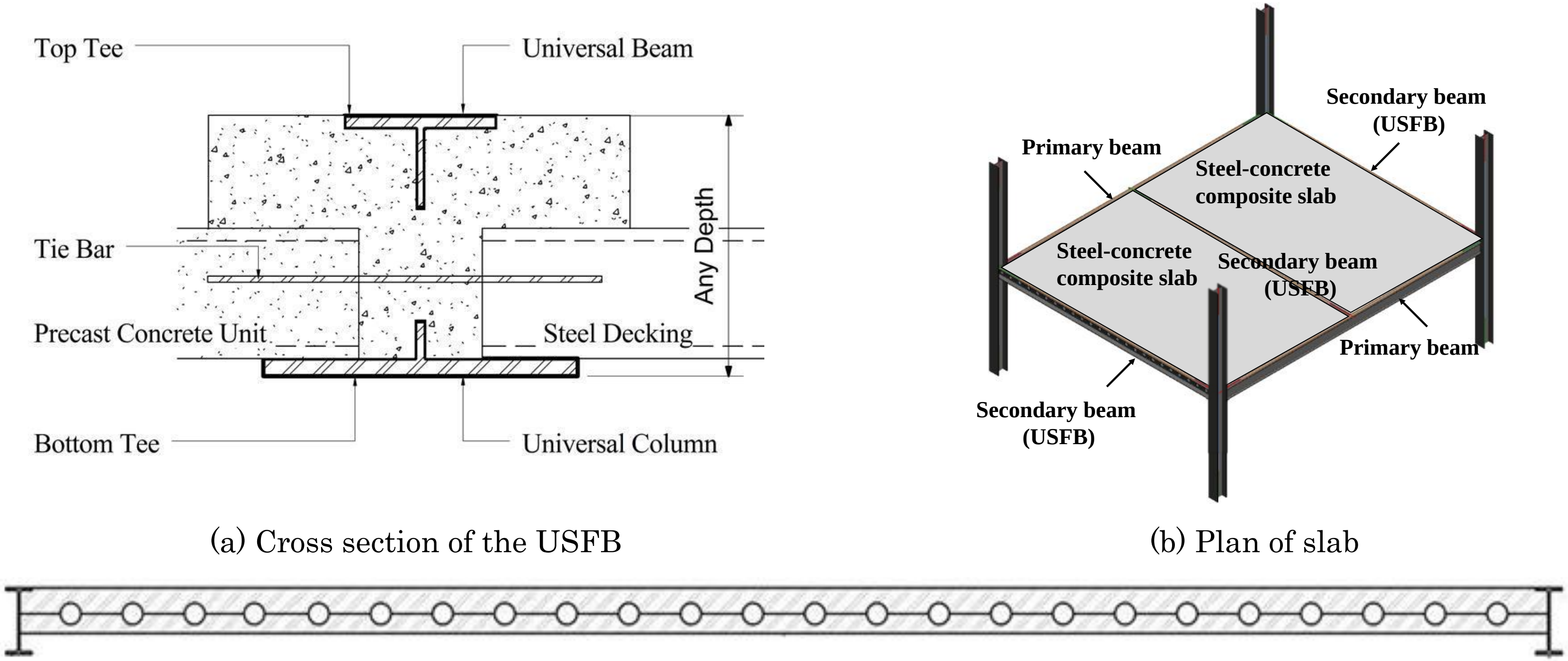
Tsavdaridis [12] and Huo [13] published the first composite USFB studies [7]. Subsequently, several studies were published. Regarding the flexural behaviour, Tsavdaridis et al. [14] carried out four-point bending tests. The authors found that the concrete encasement avoided local web buckling in the steel profile, as well as provided increased bending resistance. Huo and D'Mello [15,16] studied the shear resistance between steel and concrete. The authors showed that the shear transfer mechanisms did not influence the flexural behaviour in the elastic regime. Chen et al. [17] presented flexural tests. The results reported that failure was reached by concrete crushing. Limazie and Chen [18] formulated a design approach focusing on the plastic and yield moment resistances of composite slim floor beams. This methodology considers material nonlinearities and the composite action occurring at the steel-concrete interface. The calculation procedure demonstrated precise results when compared to experimental findings [19–22]. Limazie and Chen [23] performed a finite element parametric study to assess the influence of geometrical parameters of the USFB system. The authors verified that the resistance decreased with increasing diameter opening. Further, Limazie and Chen [24] predicted an analytical model of the shear resistance, considering the influence of both concrete in compression and tension, and the steel tie bar. John et al. [25] conducted research on a novel composite top-hat section intended for potential application in composite slim-floor construction, employing experimental testing. The newly developed top-hat sections exhibited significant resistance to both bending and buckling. This was achieved through effective stress redistributions under loading conditions corresponding to the construction stages, encompassing single-span and continuous-span scenarios. In Pereira Júnior et al. [26], the bending resistance was predicted considering USFBs with precast hollow-core slab via the finite element method. The studies presented so far investigated the flexural behaviour as well as the shear resistance of USFBs. However, lightweight flooring systems, capable of accommodating long spans are achieved through the use of the USFBs as previously discussed while the reduction in floor depth results in a flexible structure that becomes sensitive to excessive vibrations.

The vibration response of floors is a well-studied topic in structural dynamics particularly with regard to the characterisation of dynamic loads that cause unwanted vibrations such as human-induced walking, dancing, and jumping (human-induced). Sandun et al. [27] informed much work is yet to be done in this area for composite slabs. Indeed, Tsavdaridis and Giaralis [28] stated that detailed studies of the dynamic properties of ultra-shallow floors are lacking and for such reason, the dynamic behaviour of USFBs floors must be known. Nevertheless, the appraisal of the natural frequencies of USFB slim floors in support of vibration serviceability investigations received little attention in the open literature. As Mello et al. [29] mentioned, the issue of floor vibrations has become very prevalent and if not properly addressed, structural redesign or retrofitting becomes necessary. Ju et al. [9] stated that the performance of SCC slabs can be disputed with regard to floor vibrations, and this confirms the opinion presented by Smith et al. [30] that floor vibration is a significant serviceability issue. Zhang and Xu [31] introduced a streamlined design approach for assessing the vibration serviceability of lightweight cold-formed steel floor systems. The efficacy of the proposed design method was illustrated through the presentation of two examples. Tahmasebinia et al. [32] explored the dynamic characteristics of composite steel–concrete floor systems under free and forced vibrations, utilizing numerical and analytical methods. The research revealed that the lengths of primary and secondary beams have a substantial impact on the calculated fundamental frequencies and response factors of the simulated composite floor system. To this end, this paper investigates the dynamic characteristics of the USFB slabs through modal analyses, to determine the effect of the varying boundary conditions and concrete thicknesses on their dynamic characteristics, and to study their acceleration response.

2. Benchmark Structural Model of USFB slim floor

In this section, the benchmark structural model of USFB slim floor is described. To assess the influence on the vibration response of the USFB composite slab, the benchmark floorplate model is formed by two primary beams and three secondary USFBs, as shown in **Fig. 4**. The primary beams are connected to the columns directly while the secondary beams are connected to the primary beams via beam-to-beam connections. These beams may be assumed to be simply supported [6]. The USFBs are supporting the ‘plug’ precast unit or metal decking composite slabs, and they are controlled by the Service Limit State (SLS) criteria, such as vibrations.

Numerical and experimental studies were carried out to investigate the fundamental frequencies of flooring systems considering USFBs [28,33,34]. The results showed that the slabs with fixed supports were preferred as they yield higher natural frequencies while, as was anticipated, and with the increase of the slab span, a reduction of the natural frequencies was verified. In addition, it was verified that the variation in slab thickness (i.e., type of metal deck – shallow or deep) significantly modified the natural frequencies with a parabolic behaviour independent of the support conditions, spans, and modelling technique [28]. This type of floor beam shows an adequate vibration capacity and fire resistance however, more research is suggested in the area of fire performance of USFBs when steel and plastic fibres are employed [7].



(a) Cross section of the USFB

(b) Plan of slab

(c) Lateral view of the USFB

Fig. 4: Structural model of the composite slab

3. Finite Element Validation Study

For the purposes of this paper, the novel benchmark structure of USFB-based slim floor system in **Fig. 4** is numerically modeled in ABAQUS FE software and used for dynamic modal analyses. In this regard, it is deemed essential to appraise the potential of ABAQUS for accurate modal analyses of SCC floors and to validate salient software-specific FE modelling assumptions in support of the analysis task. To this aim, ABAQUS is used to verify the natural frequencies for a typical conventional SCC arrangement studied by Mello et al. [29] and verified by Behnia et al. [35]. Their system was composed of composite symmetrical steel girders that supported a 150mm thick concrete slab. These girders were connected to the columns which were treated as simply supported members. A plan configuration and geometric characteristics are given in **Fig. 5**.

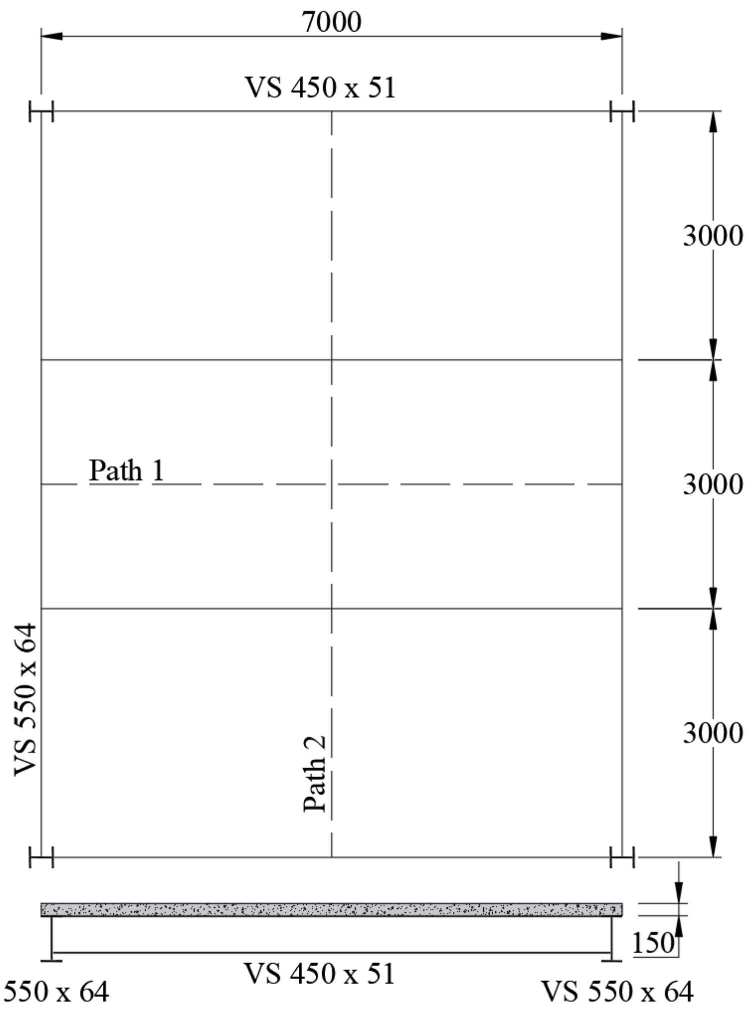


Fig. 5: Structural plan of a composite slab, adapted from [36] (in mm)

The computational model in Mello et al. [29] was developed in ANSYS using 3D elements for the girders and shell elements for the slab. In the study of Behnia et al. [35], the model was constructed in SAP2000 and considered similar modelling approaches, i.e., slab as shell elements and girders are beam elements. All steel girders and column elements were modelled with 3Dsolid elements while the concrete slab was modelled with shell elements of 5DOF. To ensure that the result of the study is within an acceptable limit, the composite slab in the mentioned baseline literature was modelled in Revit Structure 2010 and exported as an ACIS SAT file to be analysed in ABAQUS.

3.1. Material Properties

To retrieve the dynamic response of the flooring system from ABAQUS, it was necessary to assign material properties such as its density, Young's Modulus, and Poisson's ratios. However, to represent realistic material properties, the yield stresses of the materials were assigned. The mechanical properties created for the model are given in **Table 1**.

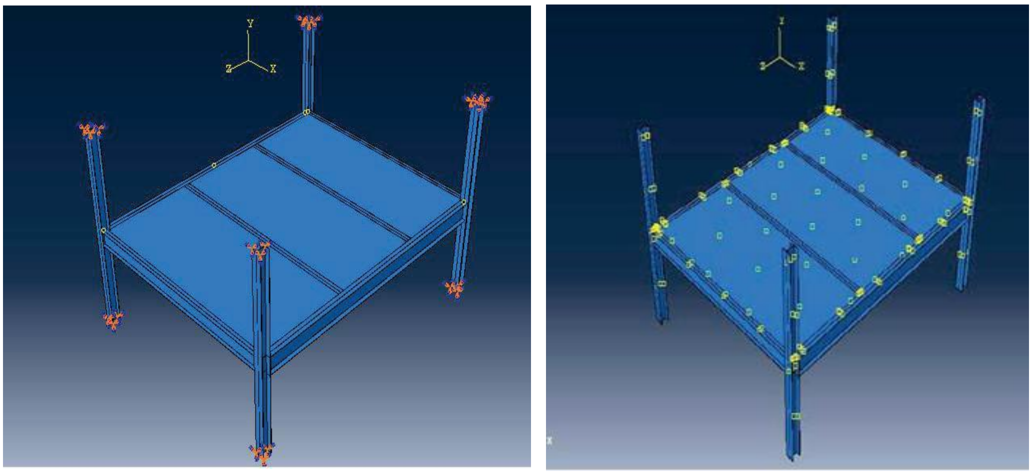
Table 1: Material properties

Material	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio	Yield stress (MPa)
Steel	7800	200	0.3	300
Concrete	2350	24	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 with AIT [37] and Rabbat and Russel [38].

3.2. Boundary Conditions

Following the modelling assumptions of Mello et al. [36] and Behnia et al. [35], both the top and bottom column end boundary conditions are treated as simply supported, i.e., Ux, Uy, and Uz = 0 (**Fig. 6a**). No boundary conditions were applied at beam-column regions as interaction in these areas were catered for by contact elements (**Fig. 6b**). As previously mentioned, the slab was secured to the steel girders using contact elements.

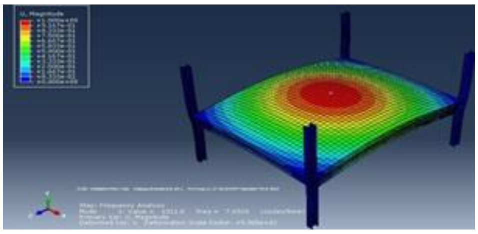


(a) Boundary conditions (b) Contact regions

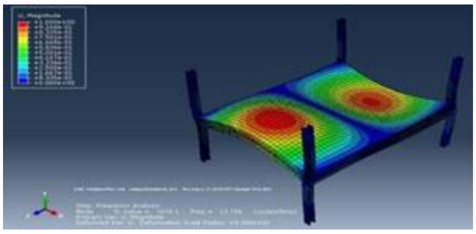
Fig. 6: Boundary conditions and contact

3.3. Validation Results

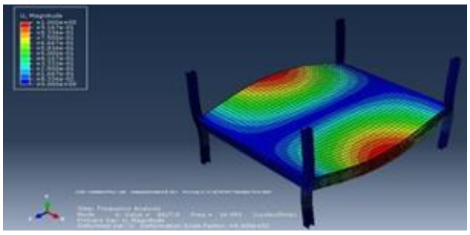
In gathering the results of the validated composite slab, the natural frequencies and mode shapes for the structure were extracted and compared with those obtained from the benchmark research of Mello et al. [29] and Behnia et al. [35]. The satisfactory correlation of the results can be seen hereafter in **Fig. 7** and **Table 2**. Even though the mentioned results are satisfactory, a further investigation has probed into the influence of using the dynamic modulus of elasticity for concrete as proposed by Smith et al. [30] in the SCI P354. This value for Young's Modulus of concrete was taken as 38 GPa. In adopting the modified Young's Modulus for concrete in the FE model, better results were obtained, hence a stronger correlation. Therefore, it is deduced that the finite element modelling approaches and techniques used in creating the flooring system studied by Mello et al. [29] are appropriate and can be employed to build the computational model of this current study which seeks to derive the dynamic properties of another composite flooring system, the USFB, incorporating asymmetric steel perforated ultra-shallow floor beams.



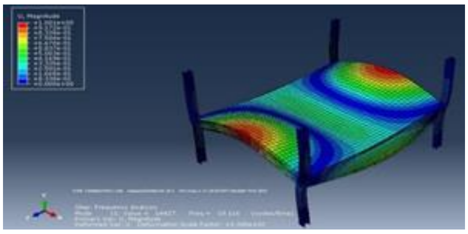
(a) 1st natural frequency, f_{01}=7.65 Hz



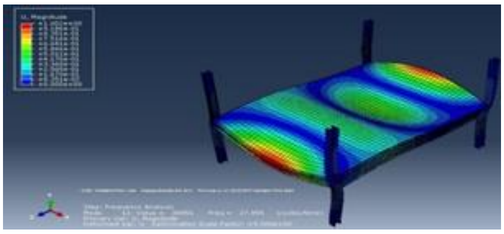
(b) 2nd natural frequency, f_{02}=13.76 Hz



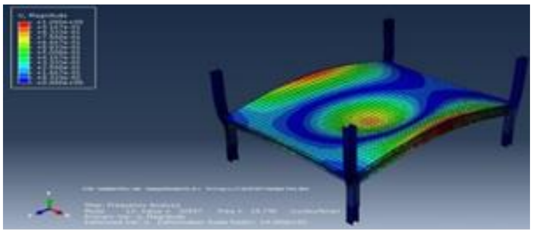
(c) 3rd natural frequency, f_{03}=14.95 Hz



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



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



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

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

Table 2: Validations Results

Mode	Natural frequencies (Hz)			Average relative error (%)
	Present study	Mello et al. [29]	Behnia et al. [35]	
1	7.65	7.42	7.44	2.90
2	13.76	14.70	13.69	3.65
3	14.95	15.23	15.6	3.06
4	19.12	20.32	19.2	3.30
5	27.96	30.82	29.6	8.00
6	28.74	31.86	31	9.30

4. Parametric Study

The length of the USFB model remained constant at 7.4m while the slab span varied between 2.5m and 4.5m (**Fig. 4b**); more specifically: 7.4m x 5m, 7.4m x 6m, 7.4m x 7m, 7.4m x 8m and 7.4m x 9m. Modelling of the USFB system was done by using the commercial software ABAQUS CAE. V6.10. As shown in **Fig. 4b**, the two-bay floor arrangement consisted of secondary beams 210x127/254x55 ACB and supported by 305x127x42UB primary beams. To practically represent construction procedures, structural coping (notching) of 62.2mm was applied to the secondary USFBs (**Fig. 4c**). The structural properties of the perforated USFB were developed by combining two sections; namely the UB 305x127x37 and UC 254x254x73, considering the upper and lower tee, respectively. The primary beams were the UB 305x127x42. The structural concrete depth varied throughout the analyses and 1.2mm thickness was adopted for the decking, assuming the properties of a 210ComFlor steel decking.

Modal analysis was carried out to extract the natural frequencies and to assess how this dynamic response changes with concrete depth and boundary conditions. The vibration mode shapes were examined as well. This investigation was performed on five-floor spans (7.4m x 5m, 7.4m x 6m, 7.4m x 7m, 7.4m x 8m, 7.4m x 9m) to develop rational limits for such floors with USFBs. For each floor, the concrete thickness was varied to 75mm, 100mm, 125mm, 152.4mm, 175mm, and 200mm. Also, the influence of the boundary conditions was assessed, considering fully fixed and pinned. In the second stage, a linear perturbation steady state modal dynamic analysis was conducted to assess the acceleration performance of the USFB flooring system under a human-induced load model suggested by Murray et al. [39] and Mello et al. [29]. Throughout this study, a notional damping of 3% was utilised by Bachmann, et al. [40].

A total of 60 finite element models are defined parametrically aiming to quantify the influence of the concrete thickness and boundary on the vibration response of the USFB composite flooring system for the five investigated floor spans. The following section discusses the results as a function of the parameters investigated in the present study.

5. Results and Discussion

5.1. Influence of Concrete Thickness

To investigate the influence of concrete slab thickness on the vibration response, six different values of thickness in the range of 75mm-200mm are examined. For the four lowest natural frequencies, nonlinear and non-monotonic trends of natural frequency versus concrete slab thickness are observed. Specifically, natural frequency lowers as slab thickness increases up to the value of 152.4mm above which natural frequency increases. These trends hold in slabs with fixed as well as pinned supports (**Fig. 8**).

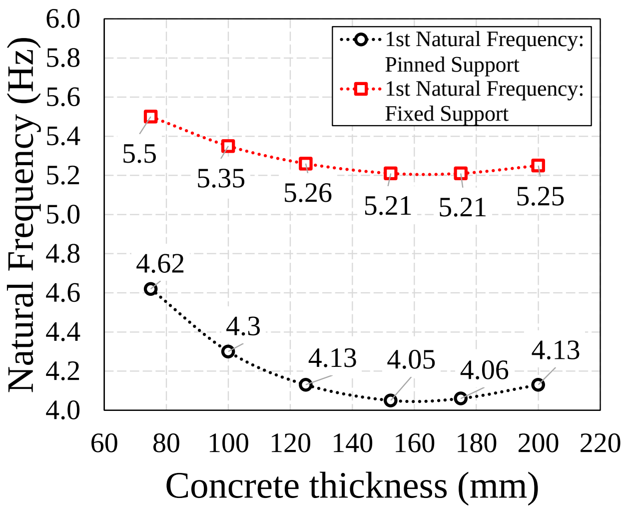


Fig. 8: Influence of concrete thickness on boundary conditions

Notably, this non-monotonic relationship of natural frequency with slab thickness may first appear as being counter-intuitive as the increase of slab thickness results in increased floor mass with consequent lowering of natural frequency. However, as the concrete slab thickness increases above the mid-height of the USFB, concrete material fills significantly the web openings as well as interacts more with the top web of the USFB, thus creating a larger effective steel-concrete composite action. Consequently, this leads to higher flexural stiffness of the composite floor at an increasing rate with concrete slab thickness which apparently exceeds the overall increase of floor mass, resulting in higher natural frequency values with slab thickness. Still, for higher modes, an almost monotonically increasing trend of natural frequencies with depth is observed (**Fig. 9**).

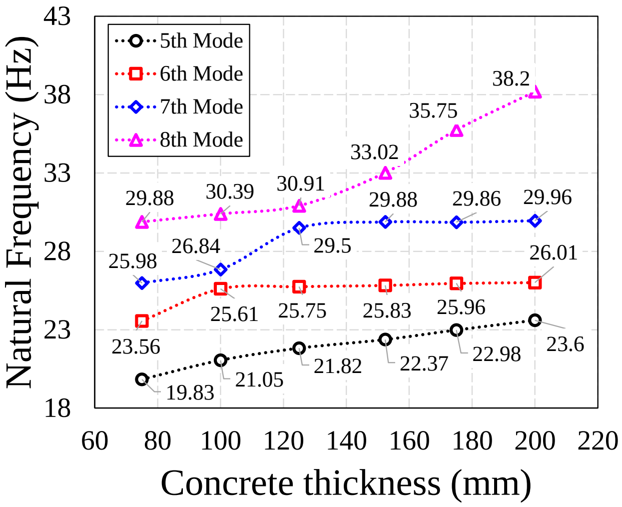


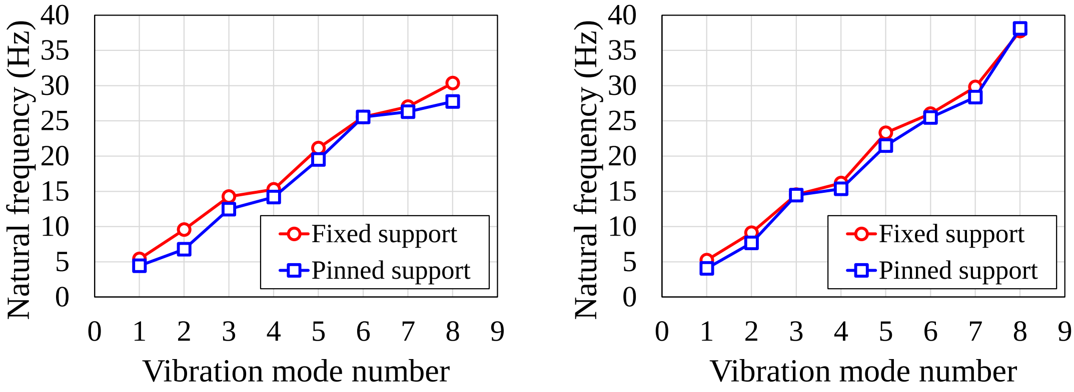
Fig. 9: Influence of concrete thickness on higher modes

5.2. Influence of Boundary Conditions

Considering fixed boundary conditions, it was assumed that the expected connection between the primary supporting beam (UB 305x127x42) and the structural columns would be fully fixed; meaning all translational and rotational degrees of freedom were set to zero. On the other hand, the pinned connection restricts only the in-plane translations and rotations about the vertical plane.

In the case of fixed supports and 100mm concrete thickness, high natural frequencies for all the vibration modes were observed (**Fig. 10a**). 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 were 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 (**Fig. 10b**). These indicate that the reduction percentage values for the 4th, 5th, 6th, 7th, and 8th modes were 10.5%, 2.1%, 5.3%, and 0.1%, respectively.

The increase in natural frequencies in lower modes is linked to the inherent characteristic of 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 and resulting in a reduction in the percentage increase of natural frequencies.

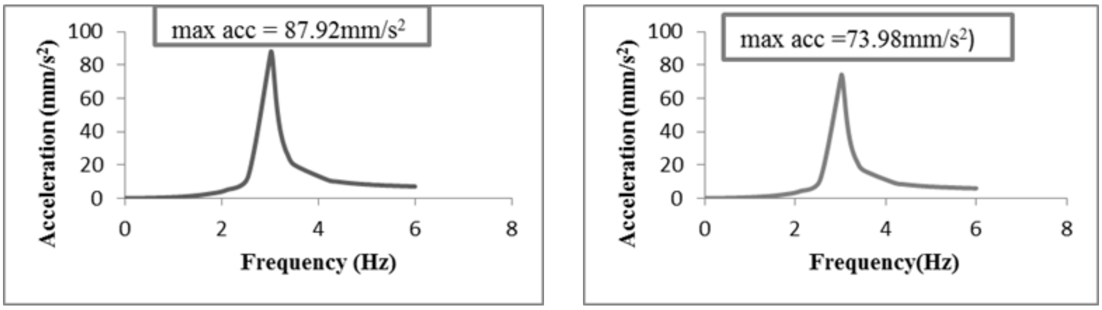


(a) (b)

Fig. 10: Influence of boundary condition on vibration response of USFB composite slab: (a) $h_c = 100$mm and (b) $h_c = 200$mm

5.3. Acceleration Response

A floor that 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 [41]. In this analysis, only the slab arrangement with the lowest natural frequency was examined. This was the 7.4m x 9m with 150mm concrete thickness, pinned supports, and 1st natural frequency of 3.02Hz. The concentrated force 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 occurring at frequencies of 3.01Hz (**Fig. 11**). The accelerations recorded are satisfactory based on the criteria presented in Murray et al. [39] and Bachmann et al. [40]. Plotting the frequency of 3.01Hz with 87.92mm/s^2 (0.8g) against the guidance published by Murray et al. [39], it demonstrates that the floor's acceleration response is slightly under the threshold considered for residential and office buildings. According to Bachmann et al. [40], the floor is well below the acceptable limit of 100mm/s². Therefore, though the fundamental frequency of 3.02Hz may indicate possible resonance, the acceleration performance is deemed acceptable according to existing literature.



(a) Load at centre of USFB (b) Load at middle of slab

Fig. 11: Acceleration responses

6. Simplified Isotropic Equivalent Flat Plate Model

In this section, a simplified modelling approach for the USFB composite slab of **Fig. 4** is proposed, aiming to expedite preliminary vibration serviceability assessment in buildings. The approach uses an isotropic flat plate model as a proxy of USFB composite slabs without accounting for the primary beams and columns as graphically demonstrated in **Fig. 12**. In this setting, the same flat plate model may be coupled with different primary beams and columns to estimate the first transverse natural frequency of the composite floor, which is most critical for serviceability verification, without the need for detailed modelling of the USFB slab. Importantly, the flat plate proxy may be readily implemented in standard FE software used for the design of buildings as the need for detailed representation of the perforated (secondary) beams is circumvented. The presentation begins with the methodology and criteria adopted for deriving equivalent properties of the flat plate model and proceeds with furnishing pertinent numerical data for assessing its accuracy by comparing the first transverse natural frequency of the complete models with detailed USFB slab vis-à-vis the equivalent flat slab (**Fig. 12**).

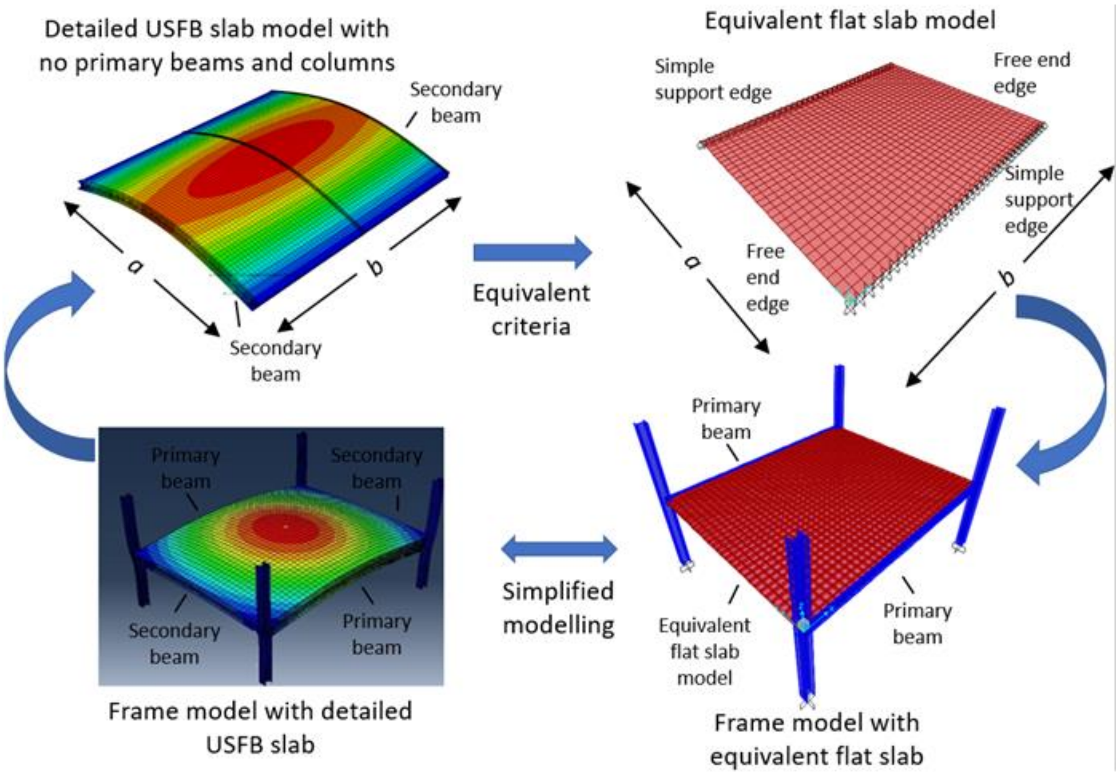


Fig. 12: Graphical visualisation of equivalent flat plate modelling and utilisation

6.1. Derivation of Equivalent Flat Plate Model Properties

The proposed isotropic flat plate model proxy has the same plan-view dimensions, *a* and *b*, as the USFB composite slab (**Fig. 12**). It is further assumed that the flat plate model has the Poisson ratio (v), and modulus of elasticity (E) of the concrete of the USFB slab. This assumption relies on taking that the most representative material in a USFB slab, from a global phenomenological perspective, is the concrete which is a common assumption in composite slabs (e.g., El-Dardiry and Ji [42]). The two remaining properties in defining the flat plate model, namely the equivalent mass density (ρ_{eq}) and the equivalent thickness (h_{eq}) are determined by enforcing the following two criteria:

i. The flat plate model has the same total mass as the USFB slab (m_{USFB});
ii. The flat plate model has the same first transverse natural frequency as the USFB slab (f_{USFB}) assuming simple support conditions along the

primary beam edges and free end conditions along the secondary beam edges.

Notably, criterion (i) ensures that the flat plate model contributes the same gravitational loading and seismic mass as the USFB slab in the FE modelling of a building. This consideration facilitates the practicality of the herein proposed equivalent slab modelling. Moreover, criterion (ii) safeguards that the flat plate model is most relevant for vibration serviceability assessments in buildings with USFB slabs. With regards to the assumed supporting conditions in criterion (ii), it is worth noting that several different supports have been examined and it was found that the assumption of mixed supports for the flat plate model (i.e., free ends along the two edges parallel to the perforated/secondary beams and simple supports along the primary beam edges) strike the best balance between accuracy and model complexity.

Criterion (i) is readily enforced by satisfying the following equality:

$$\rho_{eq} h_{eq} = \frac{m_{USFB}}{ab}. \tag{1}$$

Further, criterion (ii) yields

$$h_{eq} = \left[\frac{48\pi^2 a^3 (1-v^2) m_{USFB} f_{USFB}^2}{9.87^2 E b}\right]^{1/3}. \tag{2}$$

The latter equation is derived by using the closed-form expression for the first natural frequency of an isotropic rectangular thin plate with thickness h, planar dimensions a and b, mass density ρ, modulus of elasticity E, and Poisson ratio v for mixed free end and simple supports, as shown in **Fig. 12,** given as [43]

$$f_1 = \frac{9.87}{2\pi a^2} \sqrt{\frac{E h^2}{12\rho(1-v^2)}}. \tag{03}$$

To this end, **Eqs. (1) and (2)** can be used straightforwardly to compute the equivalent flat plate model properties h_{eq} and ρ_{eq} given the mass and the first natural frequency of the USFB plate, m_{USFB} and f_{USFB}, respectively.

6.2. Numerical Verification of the Flat Plate Model

The usefulness and accuracy of the proposed flat plate proxy model is herein exemplified by considering the same set of USFB slabs presented in section 2 (**Fig. 4**). The set includes 5 different USFB slab dimensions with fixed primary beam length b=7.4m and varying secondary beam length a. For each dimension, 5 different concrete slab thicknesses are studied: three shallow slab cases (concrete thickness of 75mm, 100mm, and 125mm) and the two limiting cases with concrete slab filling completely the web openings of the secondary perforated beams (concrete thickness of 154.2mm) and with concrete slab fully encasing the perforated beams (concrete thickness of 200mm). The geometrical properties of the slabs are provided in **Fig. 12**. Both options are typical construction methods used for USFB flooring systems.

Table 3 reports the mass, m_{USFB}, and first natural frequency f_{USFB} of all 25 slabs derived from standard modal analysis applied to detailed models developed in ABAQUS. Following the approach detailed in the previous section, the models do not include primary beams. Instead, simple support conditions are assumed along the primary beam edges. This data is used to determine equivalent flat slab properties, h_{eq} and ρ_{eq}, for all 25 USFB slabs from **Eqs. (1) and (2)**, also presented in **Table 3**. It is seen that the equivalent thickness increases with increasing concrete thickness, but this is not necessarily true for the equivalent mass density which attains a lower value for USFBs with fully encased perforated beams in concrete (concrete thickness 200mm) compared to shallower concrete slab thickness of 125mm. Moreover, equivalent thickness reduces while equivalent mass density increases as the USFB slab dimensions increase for the same concrete thickness. Overall, the trends and data of equivalent slab properties in Table 1 are indicative and applicable for a wide range of practical USFB slab applications, and thus may be safely used, possibly through interpolation, by practising engineers.

Table 3: Equivalent flat slab properties

Dimensions (m x m)	Concrete thickness (mm)	m_{USFB} (kg)	f_{USFB} (Hz)	ρ_{eq} (kg/m³)	h_{eq} (mm)
7.4 x 5.0	75	8324	4.50	1894	118.8
	100	10498	4.18	2320	122.3
	125	12672	4.02	2701	126.8
	152.4	15054	3.97	3055	133.2

	200	19193	6.81	2506	207.0
7.4 x 6.0	75	9745	4.10	1980	110.9
	100	12353	3.87	2412	115.3
	125	14962	3.76	2795	120.6
	152.4	17821	3.74	3148	127.5
	200	22787	6.70	2515	204.1
7.4 x 7.0	75	11165	3.78	2067	104.3
	100	14208	3.61	2504	109.5
	125	17252	3.54	2886	115.4
	152.4	20587	3.56	3235	122.8
	200	26381	6.60	2528	201.5
7.4 x 8.0	75	12586	3.50	2155	98.6
	100	16064	3.38	2596	104.5
	125	19542	3.35	2976	110.9
	152.4	23353	3.39	3322	118.7
	200	29976	6.49	2547	198.8
7.4 x 9.0	75	14006	3.25	2250	93.5
	100	17919	3.17	2692	99.9
	125	21831	3.17	3071	106.8
	152.4	26120	3.24	3414	114.9
	200	33570	6.36	2574	195.8

The accuracy of the equivalent slab model for preliminary floor serviceability verifications is gauged by considering two different sets of 25 FE frame models each, which include primary beams and columns. The first set of frame models is developed in ABAQUS and embeds detailed modelling of the USFB slab as discussed in section 2. The second set of frame models is developed in SAP2000 software, taken as a paradigm of commercial FE software used by practitioners for the design of buildings. It uses the equivalent flat slab modelled by standard shell elements with h_{eq} and ρ_{eq} properties, as described in section 2. Modal analysis is applied to all models and the fundamental transverse natural frequencies are reported in **Table 4** together with the percentage of error between the two. It is found that the simplified frame model with the equivalent flat slab is always stiffer (i.e., higher natural frequency) than the detailed ABAQUS frame model. With a few exceptions - notably the fully encased in concrete perforated beams, the error is well below 10% which is regarded as acceptable given the significant simplification in the FE modelling and analysis achieved by the flat slab model approach. These results highlight the practical usefulness and appropriateness of the proposed simplified modelling approach.

Table 4: Accuracy verification of the equivalent slab model

Dimensions (m x m)	**Concrete thickness (mm)**	**1st natural frequency of frame model with flat slab proxy [Hz]**	f_{USFB} **[Hz]**	**Error (%)**
	75	75	5.52	5.04
	100	100	5.10	4.90
7.4 x 5.0	125	125	4.91	4.83
	152.4	152.4	4.82	4.84
	200	200	7.83	7.25
	75	75	4.84	4.36
	100	100	4.52	4.27
7.4 x 6.0	125	125	4.40	4.26
	152.4	152.4	4.36	4.30
	200	200	7.23	6.54
	75	75	4.28	3.91
	100	100	4.06	3.85
7.4 x 7.0	125	125	3.95	3.84
	152.4	152.4	3.94	3.89
	200	200	6.59	5.80
	75	75	3.82	3.49
	100	100	3.65	3.44
7.4 x 8.0	125	125	3.57	3.44
	152.4	152.4	3.57	3.48
	200	200	5.88	5.06
	75	75	3.38	3.14
	100	100	3.26	3.09
7.4 x 9.0	125	125	3.21	3.08
	152.4	152.4	3.20	3.11
	200	200	5.15	4.39

7. Concluding Remarks

The presented study developed a finite element model, which was based on Mello et al. [29] and Behnia et al. [35] results, to predict the vibration response of composite Ultra Shallow Floor Beam (USFB) flooring system. A parametric study was conducted, and the influence of the floor size, concrete thickness, and boundary conditions was assessed. The main conclusions of the research were:

i. Less participation of increased mass in earlier vibration modes. A parabolic behaviour was verified with the variation of concrete thickness, considering the first natural frequency. The maximum and minimum values of natural frequency were verified for thicknesses of 75mm and 150mm, respectively. These were associated with two possibilities. The first referred to the reduction of mass, thus increasing the frequency of vibration. The second, for thicknesses greater than 150mm, it was the result of the interaction between stiffness and mass, showing that the greater the thickness, the greater the contact surface with the USFB.

ii. Eight vibration modes were analysed. It was found that fixed supports had higher values of natural frequencies compared to pinned supports. The percentage difference can reach 40% considering the first three modes. Concerning the others vibration modes, the percentage difference had a maximum value of 8.4% for the eighth mode. Thus, slabs with fixed supports yield higher natural frequencies and are preferable.

iii. There is potential for the use of composite slabs with USFBs as frequencies were higher than minimum floor frequency of 3Hz. It is proposed as an ideal solution for very thin slabs that behave optimally due to stiffness and boundary conditions.

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