Influence of Shear Connection and End Supports onto Self-vibrations of Cold-Formed Steel Concrete Composite Floor

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Abstract. Cold-formed steel composite floors are lightweight systems whose application increased in the last few decades. According to the design guidelines, the frequency of floor systems should be more than 4 Hz while in the case of light steel floors, the natural frequency of the system should be in the high frequency range above 8 Hz. The main focus of this paper is to investigate the vibration performance of an innovative lightweight composite floor system called LWT-FLOOR. The LWT-FLOOR system is composed of spot-welded built-up cold-formed steel elements that are connected to a lightweight concrete slab. Based on laboratory tests material properties of all components of the system are obtained and the finite element model of cold-formed steel concrete composite floor is created to investigate its vibration behaviour. Numerical analyses were conducted in Abaqus/CAE, where after mesh density verification, the influence of the degree of shear connection, spot weld density, concrete type and class, steel channels cross-section thickness and the arrangement and diameter of the shear connector were analysed. The results show that the flexural rigidity of the system and vibration characteristics can be improved by changing those parameters, especially by changing steel channel cross-section characteristics and support conditions from nominally pinned to nominally rigid.

Keywords: Self-Vibrations · LWT-FLOOR Composite Beams · FE Analysis · Parametric Study

1 Introduction

According to European standards [1, 2] to achieve satisfactory vibration behaviour of buildings and their structural members under serviceability conditions aspects related to the comfort of the users and the functioning of the structure or its structural members among the aspects specified in particular National Annex should be considered. During the verification of serviceability, the structure or structural member should be kept below appropriate acceleration limits relevant to the user's comfort and functionality. For specific types of structures or structural members, the acceleration limits can be assumed to be met when the natural frequency of vibrations is kept above appropriate values. For example, the Croatian National Annex to EN 1990 [3] provides limitations of 10 Hz for

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grandstands, fitness centres, sports halls and public premises and 8 Hz for residential and office buildings. In addition to the design guidelines [4], the frequency of floor systems should be more than 4 Hz while in the case of light steel floors, the natural frequency of the system should be in the high frequency range above 8 Hz. If the natural vibration frequency of the structure or structural member is lower than the appropriate value, a more refined analysis of the dynamic response of the structure considering damping is needed.

Cold-formed steel-concrete composite systems have become more popular in the last decades and their vibration characteristics are important, especially in the case of lightweight systems. In the characterization of floor vibrations, two characteristics are important: the fundamental frequency and damping ratio. Considering that in composite steel-concrete systems, the shear connection has a great role, its influence on vibrations must be taken into consideration.

In the case where composite beams are formed using deformable connections, the dynamic solution for this kind of connection is investigated in paper [5]. The authors analysed the resulting in plane forces and deformations of the slab as well as the axial forces and deformations of the beam. The research concludes that the adopted model permits the evaluation of the time history of the in plane shear forces at the interface between the concrete slab and the beams, the knowledge of which is very important in the design of composite or prefabricated structures (with emphasis on degree and type of shear connection - shear connectors or welding). Also, great variations of the fundamental eigenfrequency with the shear connectors' stiffness are shown in the research. Furthermore, the discrepancy in the results between the proposed model and the one ignoring the in plane forces and deformations, which requires the consideration of these forces and deformations in the structural model, is more pronounced for low values of the beam height.

Another research on the influence of shear connector damage on dynamic behaviour shows that the interface slip will directly influence the integral stiffness of steel-concrete composite beam, the vertical frequencies and mode shapes [6].

Investigation in paper [7] of the influence of the shear connectors (stud bolts of 16 mm and 19 mm diameter) on the floor's natural frequencies, shows that the influence is small in the cases when the degree of shear connection goes from full shear to partial. The largest difference was up to 7%.

The investigation made by Henderson et al. [8] showed how the overall frequencies of composite specimens are higher than the non-composite section.

Furthermore, the importance and influence of shear connection to beam frequency response is also presented by Sun et al. [9]. It is concluded that stronger interfacial interaction, larger steel sub-beam and thinner concrete slab lead to higher values of the natural frequencies of a steel-concrete composite continuous beam.

A detailed description of the analytical approach to calculate vibrations of steel-concrete composite beams with partially degraded connection and applications to damage detection in structures are shown in [10]. From the research, it is concluded that the frequency variations contain information on the position of the damage.

Shen et al. [11] investigate the formulae for analysing the dynamic behaviour of composite beams with partial interaction. The research shows how to calculate the natural frequencies and the corresponding mode shapes. Also, boundary conditions can be expressed directly by proposed formulae.

Kansinally and Tsavdaridis [12] investigated vibration response of a composite floor system composed of ultra shallow floor beams. The influence of fixed and pinned boundary conditions is analysed. The research concludes that in the case of fixed boundary conditions and concrete slab thickness of 100 mm, high natural frequencies for all mode shapes are observed. In the case of pinned supports, natural frequencies for the first three mode shapes are analysed. It is concluded that natural frequencies are increased by 16–24% for pinned boundary conditions compared to fixed boundary conditions. Parabolic behaviour of natural frequencies is observed in the case of the first four modes where the slab thickness is decreased. More research on the topic of boundary conditions is shown in [13, 14].

In addition to the aforementioned, the influence of the thickness of the slab and concrete grade on composite floor vibration behaviour is investigated in paper [15]. The parametric study with different concrete grades showed negligible influence on dynamic behaviour for all analysed cases (C16/20, C25/30, C35/45, C45/55). On the other side, a great influence can be observed for slabs having small aspect ratios (1:1, 1:1.5, 1:2) by increasing the thickness of the slab.

Another investigation on the thickness of concrete slab is conducted in order to determine the minimum slab thickness of a reinforced concrete building to prevent undesirable vibration [16]. It is concluded that the floor frequency decreases with increasing floor panel aspect ratio. Furthermore, by increasing slab thickness, the floor frequency increases and by increasing span length, the floor frequency is reduced.

Considering the different parameters that can affect the natural frequencies of the system, different standards analyse the same issue in order to prevent negative consequences [17, 18]. For example, US codes and standards, which are investigated in paper [19], say that vibration serviceability criteria for floor structures are human-induced dynamic loads, human perception of structural vibrations and structural vibration control and should be checked. Thus human-induced dynamic loads are important generators of vibrations. If compared to European standards [1], it is only mentioned that the verification of serviceability limit states should consider vibrations that cause discomfort to people or that limit the functional effectiveness of the structure. Detailed analyses of the spectral modelling approach for crowd-rhythmic activities performed on steel-concrete composite floors is shown in [20] where the influence of jumping and skipping and design-oriented method is presented for a simplified evaluation of floor response for analysed rhythmic activities.

This paper investigates vibration performance on the LWT-FLOOR composite system which is described in paper [21]. The influence of the degree of shear connection, spot weld density, concrete class and type, steel cross-section thickness, the diameter of the shear connector and boundary conditions on the vibrations are analysed.

2 Numerical and Parametric Analyses

Numerical analysis is performed in Abaqus Standard software [22] using Frequency analysis. Models are formed of built-up cold-formed steel beam and concrete slab which is laid on metal sheet. The overall height of a composite steel-concrete beam is 520 mm, where the height of built-up steel beam is 400 mm. Beam length is 6 m and the concrete slab effective width is 1500 mm, as shown in Fig. 1. The model is formed of four channel height of 120 mm, while the thickness is changed (0.8 mm, 1.0 mm, 2.5 mm and 3.0 mm), four shear plates height of 400 mm and thickness of 1.0 mm and corrugated web with rib height of 60 mm, thickness of 1.0 mm and height of 400 mm. Additional boundary conditions simulating symmetry along the beam are applied along the longer edges of the concrete slab. This means that the complete model consists of two steel beams and a 3 m wide concrete slab.

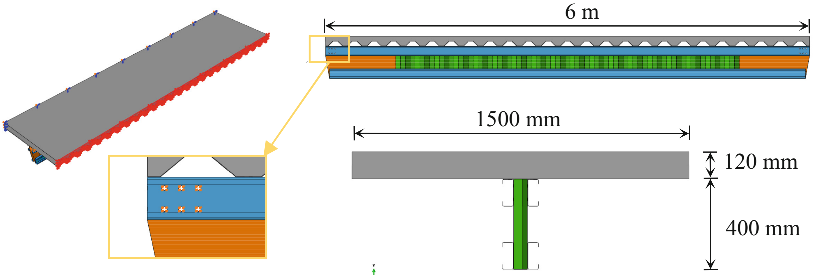


Fig. 1. Geometry and boundary conditions of LWT-FLOOR composite beam.

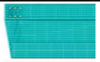
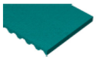
Imperfections are not included in the analysis so the first step before parametric frequency analysis is related to mesh density verification. The initial model based on research provided in [23] consists of finite elements and mesh densities described in the following text. Elements of steel beams are defined as S4R elements, while for concrete slabs and bolts, C3D8R elements are used. Chosen mesh size for steel elements is 15 mm, for a concrete slab is 30 mm, and for bolts is 5 mm.

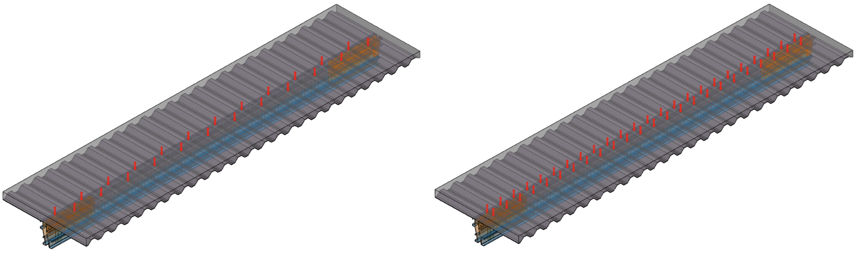
After several mesh refinement trials, the mesh size for steel elements of 10 mm, concrete slab of 15 mm and bolts of 5 mm resulted in satisfactory convergency in obtained self-vibration frequencies. The results of the mesh density study are presented in Table 1.

The steel elements are made of steel grade S350 GD whose material properties are determined by laboratory tests [24]. The concrete material properties (LC 12/13, LC 16/18, LC 20/28; NC 20/25, NC 25/30, NC 30/37) are calculated according to EN 1992-1-1 [25] and [26]. The thickness of the corrugated web and shear plates is 1.0 mm while the analysed thicknesses of the channel are 0.8 mm, 1.0 mm, 2.5 mm and 3.0 mm.

Different degrees of shear connection (SC) are analysed. The full degree of SC is achieved when a tie constraint is used between the upper flange of the C profile and metal sheet, and between metal sheet and concrete slab. On the other hand, different degrees of SC are established by the physical modelling of shear connectors. Bolts M12 (diameter of 12 mm) and M16 (diameter of 16 mm) are used as shear connectors in staggered arrangement (Fig. 2a) or arrangement in pairs (Fig. 2b).

Table 1. Mesh density study – natural frequencies [Hz].

	CONCRETE SLAB				STEEL ELEMENTS				
MODE MESH	1	2	3			1	2	3	
30	21.73	64.24	68.69		15	21.81	64.58	73.17	
15	21.81	64.58	73.17		10	21.60	63.70	72.45	
10	21.82	64.67	74.27		7	21.60	63.81	72.37	
7	21.82	64.70	75.0		5	21.51	63.42	71.96	
					2	21.51	63.38	71.98	



a. staggered

b. in pairs

Fig. 2. Shear connectors arrangements.

Connection between steel elements (CbSE) is ensured by tie constraint which ties two surfaces together so that there is no relative motion between them, and by spot welds (two or three along profile height). Spot welds are defined as point-based fasteners as described in paper [27].

Table 2 shows the differences in numerical models analysed in this research. Taking into account the influence of the degree of SC, spot weld density, concrete type (CT), channel thickness (T), boundary conditions (BC) and the arrangement and diameter of the shear connectors, 26 numerical models were formed. In further text, the nomenclature “Model X-LC” is used for models with lightweight concrete (LC) and “Model X-NC” for models with normal concrete (NC) models.

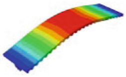
Table 2. Numerical models.

NAME		CT	T [mm]	SC	CbSE	BC
Model 1	LC	LC 16/18	2.5	tie	tie	simple
	NC	NC 25/30				
Model 2	LC	LC 16/18	2.5	in pairs – M12	tie	simple
	NC	NC 25/30				
Model 3	LC	LC 16/18	2.5	staggered – M12	tie	simple
	NC	NC 25/30				
Model 4	LC	LC 16/18	2.5	in pairs – M16	tie	simple
	NC	NC 25/30				
Model 5	LC	LC 16/18	2.5	staggered – M16	tie	simple
	NC	NC 25/30				
Model 6	LC	LC 16/18	2.5	tie	2	simple
	NC	NC 25/30				
Model 7	LC	LC 16/18	2.5	tie	3	simple
	NC	NC 25/30				
Model 8	LC	LC 12/13	2.5	tie	tie	simple
	NC	NC 20/25				
Model 9	LC	LC 20/28	2.5	tie	tie	simple
	NC	NC 30/37				
Model 10	LC	LC 16/18	3.0	tie	tie	simple
	NC	NC 25/30				
Model 11	LC	LC 16/18	1.0	tie	tie	simple
	NC	NC 25/30				
Model 12	LC	LC 16/18	0.8	tie	tie	simple
	NC	NC 25/30				
Model 13	LC	LC 16/18	2.5	tie	tie	rigid
	NC	NC 25/30				

3 Results and Discussion

Considering different influences on the natural frequencies of the LWT-FLOOR composite system, Table 3 and Table 4 show the values of natural frequencies [in Hz] for the first three modes of each model. The values of natural frequencies for the first three modes for Model 6 and Model 7 are shown separately in Table 4 because of the different mode shapes from Models presented in Table 3. Those different mode shapes are related to spot-weld connections between steel elements.

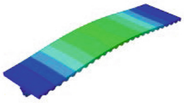
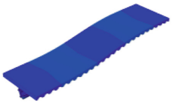
Table 3. Natural frequencies for models with tied steel elements [Hz].

MODES MODELS		MODE 1	MODE 2	MODE 3
				
1	LC	21.60	63.70	72.45
	NC	19.00	57.06	80.89
2	LC	21.52	63.17	71.77
	NC	18.93	56.57	80.09
3	LC	21.20	60.39	67.55
	NC	18.61	53.78	72.92
4	LC	21.37	62.92	71.93
	NC	18.80	56.30	80.21
5	LC	21.51	63.11	71.72
	NC	18.93	56.49	80.00
8	LC	21.22	62.26	67.51
	NC	18.94	56.81	79.30
9	LC	21.63	63.81	72.86
	NC	19.06	57.28	82.28
10	LC	23.36	67.56	72.24
	NC	20.77	61.06	80.77
11	LC	15.92	49.01	73.06
	NC	13.68	42.91	75.56
12	LC	12.60	38.74	69.79
	NC	10.83	33.96	63.06
13	LC	31.50	68.60	73.81
	NC	28.60	60.97	82.35

The influence of the degree of shear connection can be observed by comparing the results of Models 1, 2 and 3. It is shown how the value of natural frequency decreases by decreasing the degree of shear connection. Furthermore, observing the results of models with the same arrangement of shear connectors and different diameters (Model 2-Model 4; Model 3-Model 5), it is concluded that, models with shear connector diameter of 12 mm achieve higher frequency for modes 1 and 2. However, for mode 3, models with a shear connector diameter of 16 mm achieve higher frequency than models with a shear connector diameter of 12 mm. Analysis of models with different concrete classes (Model 1, Model 8, Model 9) shows that by increasing concrete class, the value of natural frequency increases as well. Furthermore, comparing the results of models marked by LC and NC of the same model number, it is concluded that models formed of NC have lower frequency levels of modes 1 and 2 than those formed from LC, while for mode 3 the opposite occurs. Furthermore, by analysing the influence of the different thicknesses of the channel steel section, it is concluded that the level of frequency increases in the first two modes when increasing the thickness of the channel section. Also, comparing results for Models 1 and 13 where different boundary conditions are defined, it is concluded that by changing boundary conditions from nominally simple to nominally pinned, the natural frequency is increased.

In Table 4, modes and values of natural frequencies are shown for models where steel parts are connected using two (Model 6) and three (Model 7) spot welds. These models do not have the same behaviour for the first three modes as models in Table 3 because of the local mode shapes of the steel girder. Neglecting local mode shapes Table 4 shows global modes, i.e. modes 1, 4 and 7.

Table 4. Natural frequencies of Models 6 and 7 with spot welded steel elements [Hz].

MODES MODELS		MODE 1 	MODE 4 	MODE 7 
6	LC	17.66	43.32	64.017
	NC	15.64	38.96	65.57
7	LC	17.69	43.38	64.73
	NC	15.67	39.00	66.38

From the results presented in Table 4, it is concluded that a larger number of spot welds cause a higher natural frequency of the system. This is expected due to the increased stiffness of the system.

4 Conclusions

In this study, the influence of several parameters on natural frequencies of cold-formed steel–concrete composite floor system LWT-FLOOR level is investigated. Varying parameters are the degree of shear connection, shear connector diameter, spot weld density, concrete type, steel cross-section thickness, and boundary conditions.

From all presented results, it can be concluded that by increasing all analysed parameters (the degree of shear connection, shear connector diameter, spot weld density, steel cross-section thickness) and by choosing the greater class of concrete and changing boundary conditions from nominally simple to nominally pinned, the level of natural frequency is increased.

Analysing the degree of shear connection in vibration behaviour, it is shown that the value of natural frequency decreases by decreasing the degree of shear connection. Furthermore, by increasing the diameter of the shear connector, the natural frequencies decrease for the first two modes, but in the third mode, the frequency for models with larger shear connector diameters achieves a higher value.

Changing concrete classes shows that by increasing concrete class, the value of natural frequency increases as well. Furthermore, comparing models with lightweight concrete and normal concrete, it is shown that models with normal concrete have lower frequency levels than those with lightweight concrete (for modes 1 and 2). Furthermore, authors concluded that the level of frequency increases in the first two modes when increasing the thickness of the channel section. Also, by changing boundary conditions from nominally pinned to nominally rigid, the natural frequency is increased.

Furthermore, it is shown that the LWT-FLOOR composite floor system for all analysed cases has a frequency in the range from 15 Hz to 31 Hz which is higher than the 4 Hz required by literature and classifies the analysed system in the category of applicable floor structures according to the level of vibrations.

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