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MODAL ANALYSIS OF STEEL-CONCRETE COMPOSITE FLOOR IN THE RFEM 6 SOFTWARE

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Abstract

Using FEA programs, the structure's modal analysis itself is not complicated. However, in the case of a steel-concrete composite floor, a difficulty arises in the composite behaviour representation. In typical FEA programs, it is not possible to directly insert the composite structure, so the components cooperation has to be represented by substitute methods. In this case, functions such as an orthotropic material, modelling the beams as ribs interacting with the surface (concrete slab) and the use of eccentricities are useful. Besides the modelling methods in RFEM 6, a modal analysis based on the example of a floor is presented. The results are shown and the floor is assessed according to the described guidelines and classification. Based on the fundamental frequency (6.81 Hz), modal mass (58888 kg) and damping (4%), a floor acceptance class C was identified, which is suitable for the assumed office use of the area.

Keywords: steel-concrete composite floor, RFEM, natural frequency, dynamic characteristics, composite behaviour

1. INTRODUCTION

A composite behaviour is obtained by mechanically connecting two members made out of different materials so that together they behave as a single structural element without separation and longitudinal slip of the individual parts. The components work as an integral entity when the proper load-bearing capacity and stiffness of the composite are provided. Full shear connection is referred to when it is no longer possible to improve the design bending resistance by increasing the resistance of the longitudinal shear connection. Partial shear connection occurs when the design bending resistance can be increased [1–2].

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Steel-concrete composite floors are usually constructed by fixing profiled steel sheets to the steel beams with stud shear connectors and casting a layer of concrete with an anti-shrinkage reinforcement mesh. The advantage of the profiled steel sheets is their dual function, which is to provide formwork during the construction stage and the lower reinforcement of the slab during the operational stage [3].

To obtain dynamic floor characteristics, parameters such as natural frequency, modal mass and damping must be determined. The requirements for vibrations caused by standard walk in floors in general, as well as in composite floors, were specified in the *Human Induced Vibration of Steel Structures (HiVoSS)* document created by the European Commission [4–6]. Information on the analysis and design of lightweight and composite floors in relation to vibration from not only footsteps, but also from walking on stairs, machinery or synchronised group activities (for example, dancing, fitness) can be found in publication P354 from The Steel Construction Institute [7]. The vibration recommendations contained in the Eurocodes EN 1990:2002 [8], EN 1991-1-1:2002 [9], EN 1991-1-4:2005 [10], EN 1993-1-1:2005 [11] and EN 1994-1-1:2004 [2] are more general and do not provide precise guidance on how to determine dynamic characteristics for floors (Annex F of the standard [10] provides guidance only for cantilevered structures and bridges).

The dynamic floor characteristics can be examined by using computer software based on finite element method calculations [12] such as Autodesk Robot Structural Analysis Professional or RFEM software from Dlubal. More diversified possibilities in this field are offered by the Abaqus/Explicit program, as it is dedicated to dynamic issues and, besides the modelling of engineering structures, is used in the design of broadly defined machinery in many industries, e.g., shipbuilding and metallurgy [13]. Another interesting approach to studying the vibrations of structures is to use the Rigid Finite Elements Method (RFEM), as was done in the papers [14–15], where the authors created their own program in MATLAB. Publication [15] specifies a wide range of other methods used in the determination of dynamic characteristics in slab elements. Among these are the Finite Difference Method (FDM), the Finite Strip Method (FSM), and the grillage method. For simple cases of composite floors, the natural frequency and modal mass can also be determined manually using the method for orthotropic slabs, that is, with different material properties on two perpendicular directions [16].

In the context of modelling composite structures within the Abaqus/Explicit environment, it is imperative to ensure the accurate representation of the connections between components. This process necessitates a comprehensive consideration of the contact properties between the steel I-beam and the reinforced concrete floor slab, among other parameters. The reinforced concrete slab must also be accurately modelled, including the reinforcement layout and its interaction with the steel. Detailed descriptions of such models, verified experimentally, are presented in [17–18]. Furthermore, the study [19] sought to utilise numerical modelling to predict the long-term behaviour of stud connectors, incorporating the effects of time and concrete creep, which is imperative for dynamic analyses encompassing extended periods of structure operation. The authors of [20] utilised an approach underpinned by the Rigid Finite Elements Method (RFEM), employing a reinforced concrete slab model that was developed on the basis of the findings derived from experimental modal analysis. Such approaches have been demonstrated to provide significant support in the modelling of vibrations and the assessment of the dynamics of entire composite floors.

The main goal of this article was to determine the natural frequencies of a composite floor together with mode shapes and modal masses using RFEM 6 software, as well as to assess the suitability of this program for the intended purpose. The second most important task was to develop an appropriate method for modelling the composite behaviour and to represent an actual stiffness in the software.

2. GUIDELINES AND CLASSIFICATION OF FLOORS

The Eurocodes [2] and [8–11] do not provide guidance relating directly to dynamic issues in composite floors. Some of the more important general recommendations are those in Eurocode 0 [8], which recommends a dynamic analysis of the structure when the acceleration of the structure from dynamic excitation is significant. Moreover, all relevant structural elements should be included in the model along with masses, stiffnesses, damping, resistance, and also along with non-structural elements if they affect the dynamic effects. The boundary conditions must be assumed to be close to reality. Document [8] allows the application of modal analysis assuming a non-deformable geometry of the structure and a linearly performing material. The standard [8] mentions the possibility that the dynamic actions are determined as frequency or time-dependent and that the structural response is derived by appropriate methods. It is recommended to verify the serviceability limit state when the limiting frequency or amplitude of vibration specified in the serviceability requirements is exceeded. Vibration serviceability criteria are determined on the basis of the assumed use of the structure. PN-EN 1990 [8] prescribes that the serviceability of a structure and the comfort of people due to vibrations should be taken into account. It recommends that the natural frequency of an element should be greater than an appropriate value (determined according to the source of vibration and the intended use of the object and consulted with the relevant people, e.g., authorities, developer). If this condition is not fulfilled, a detailed response analysis of the structure taking damping into account must be carried out. As sources of structural vibration, the Eurocode proposes to consider machinery, steps, group activities (synchronised movements), wind actions, excitation from circular motion (from the ground), as well as other project-specific sources of vibration.

Eurocode 1 [9] contains information on resonance. If neither this effect nor significant dynamic behaviour in the object is anticipated, it is permissible to consider dynamic response effects. When there is a risk of resonance, the Standard proposes to develop a design model based on a special dynamic analysis. This risk should be considered when the object may be used, for example, by dancing, jumping or other synchronised activities of a group of people (often accompanied by music). Table 6.1 of the Standard [9] gives the recommendation that dynamic effects should be taken into account for extremely exposed categories of use such as C4 and C5. Category C4 corresponds to spaces intended for sports activities (stage, dance, gymnastics), while C5 is assigned to areas exposed to crowds (stands, stadiums, concert halls, station platforms, etc.).

PN-EN 1991-1-4 [10] takes into account the dynamic effects of wind on structures, but this does not apply to floors in a building. Annex F, on the other hand, presents a procedure for the determination of dynamic characteristics of structures (natural frequencies, logarithmic decrements of damping, equivalent masses, modes of natural vibration).

The National Annex to PN-EN 1993-1-1 [11] for a steel-structured floor in a public building gives a condition where the natural frequency of the floor (for spans above 12 m) is to be a minimum of 5 Hz. Verification of this requirement may be omitted for a deflection of no more than 10 mm for a quasi-permanent combination.

The Standard for the design of steel-concrete composite structures, PN-EN 1994-1-1 [2], sets a condition that allows the use of a composite slab under dynamic actions only if the composite behaviour does not lose its properties during service. In the case of a composite slab under seismic loading, it will be necessary to use an appropriate design method.

The requirements for vibrations induced by normal user walk in floors in general, as well as in composite floors, were determined on the basis of the *Human Induced Vibration of Steel Structures (HiVoSS)* guidelines developed by the European Commission [4–6]. The definition of the dynamic floor characteristics consists of the determination of natural frequencies, modal masses and damping. The first two parameters can be calculated using finite element analysis (FEA) based software [12]. For each mode of natural vibration, the structure has a different frequency and modal mass (the excited part of the total element mass). The basic formula describing the natural frequency (2.1) for determining the dynamic characteristics of the floor is shown below [6].

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \tag{2.1}$$

where:
f – natural frequency [Hz];
K – stiffness [N/m];
M – mass [kg].
The damping can be obtained from the values in [6] by summing up the damping from furniture, construction materials and room finish. Table 1 contains the data from the aforementioned document.

Table 1. Damping determination – table based on *HiVoSS* document [6]

Type	**Damping (% of critical damping)**
Structural damping D_1	
Wood	6%
Concrete	2%
Steel	1%
Steel-concrete	1%
Damping due to furniture D_2	
Traditional office for 1 to 3 persons with separation walls	2%
Paperless office	0%
Open plan office	1%
Library	1%
Houses	1%
Schools	0%
Gymnastic	0%
Damping due to finishes D_3	
Ceiling under the floor	1%
Free floating floor	0%
Swimming screed	1%
Total Damping $D = D_1 + D_2 + D_3$	

The way a user perceives vibrations and how much they make the user uncomfortable depends on individual conditions and factors such as age, health, the activity being performed (e.g. in a surgeon's job, vibrations are required to be less perceptible than on a production hall), position (the person may be lying, standing or sitting) and the direction of the vibrations. Due to the wide variety of variables, it is assumed that the vibration of the structure will meet the expectations of the majority, but not all users. Adopting an OS-RMS value allows a universal determination of human-induced vibration. OS-RMS is the value of the acceleration that is the response of the floor to one human step, where OS stands for one step and RMS stands for root mean square. The dynamic response of the structure depends, among other things, on the user's speed, weight, type of footwear, but also on the type of floor finish layers. The value to be applied to the floor assessment is the 90 percentile of the total set of OS-RMS values determined for different combinations of human speed and weight. This magnitude is denoted OS-RMS90 and, based on the specified dynamic properties of the floor (natural frequency, modal mass, damping), can be read from the graphs provided in the *HiVoSS* document [6].

The diagrams also help to assign the floor to one of six acceptance classes. Class A identifies the floor with the lowest OS-RMS90 values and Class F with the highest. The *HiVoSS* guidelines [6] suggest what the intended use of a floor might be based on its class (Table 2).

Table 2. Floor classes and recommended use – table based on *HiVoSS* document [6]

Class	OS-RMS$_{90}$		Function of Floor										
	Lower limit	Upper limit	Critical workspace	Health	Education	Residential	Office	Meeting	Retail	Hotel	Prison	Industrial	Sport
A	0.0	0.1	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended
B	0.1	0.2	Critical	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended
C	0.2	0.8	Not recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended
D	0.8	3.2	Not recommended	Critical	Critical	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended
E	3.2	12.8	Not recommended	Not recommended	Not recommended	Critical	Critical	Critical	Critical	Critical	Critical	Recommended	Recommended
F	12.8	51.2	Not recommended	Not recommended	Not recommended	Not recommended	Not recommended	Not recommended	Not recommended	Not recommended	Not recommended	Critical	Critical

Legend

- Recommended
- Critical
- Not recommended

Publication P354 [7] identifies ranges of frequencies generated by a vibration source based on measurements. It has been estimated that the pace frequency (f_p) of human steps can occur in the range of 1.5 Hz to 2.5 Hz, but the more likely values of 1.8 Hz to 2.2 Hz are proposed to be used for calculations. When it is not possible for the user to develop speed due to short distances in a space or the specific purpose of the area, it is recommended to assume the frequency value as 1.8 Hz. Such locations may include, for example, flats and operating theatres. Flat floor surfaces differ from stairs in terms of the force size from steps and their frequency. For the rapid stepping down, the value ranges from 3 Hz to 4 Hz or even 4.5 Hz. The floor can be affected by a synchronised group of people or a crowd. This can be the case with rhythmic activities such as aerobics, dancing, fitness classes, etc. Repetitive movements to music from one person also produce effects different from those for walking. The frequency for group activities can be taken from 1.5 Hz to 2.8 Hz, and for individual movement from 1.5 Hz to 3.5 Hz. It is worth taking into account that the density of people for ballroom dancing will be 2 persons/m^2 and for aerobics, gymnastics etc. 0.25 persons/m^2.

In composite floors, the beams behave as if they are continuous, even though they may have been designed as simply supported in the static model. This is due to the low level of allowable stresses and deflections during dynamic analysis of the structure. As a result of the continuity of the floor, when the floor is expected to be used during rhythmic activities, it should be taken into account that the dynamic response of the structure may also be transmitted to surrounding areas. It is not recommended to situate office, public or residential spaces in the vicinity of such areas. Dynamic activities (e.g. dancing) also contribute to additional deflection and acceleration of the floor through induced vibration. This effect should be accounted for in the space above and below such a floor. The best location for floors designed for rhythmic activities is on the lower levels of the building, as the effect of dynamic influences is smallest for the rest of the building.

The outputs from the finite element analysis are modal masses, modal frequencies and vibration mode shapes. The shape of the vibration mode can appear as either a normalised unity or a normalised mass. For a mode shape with a normalised mass, the displacements are derived so that the modal mass is 1 kg. For a mode shape with normalised unity, on the other hand, the maximum displacement for each mode is assumed to be dimensionless 1. In this case, it is necessary to determine the maximum kinetic energy for each form, e.g., using FEA software. It should be noted that some calculation programs do not provide the modal mass directly as output, but the effective mass or mass contribution.

When analysing the response of a structure, the aim is to find the peak value (maximum response). The analysis should be carried out for a spectrum of floor frequencies based on the frequency range of human steps. Although the path of the footsteps only momentarily passes through the most responsive point of the floor, it is assumed that the force causing the response is located at this sensitive point. Based on the value of the fundamental frequency, we can divide floors into low-frequency and high-frequency floors. Based on the data presented in [7], the limits between low-frequency and high-frequency floors are included in Table 3, depending on the purpose of the floor.

Table 3. Cut-off values between low-frequency and high-frequency floors – table based on document [7]

Floor type	**Low to high frequency cut-off**
Open plan offices, general floors etc.	10 Hz
Enclosed spaces, e.g., residential, operating theatre	8 Hz
Staircases	12 Hz
Floors subject to rhythmic activities	24 Hz

Both types of floors must be analysed for transient response. However, low-frequency floors must additionally be examined for steady-state response. For low-frequency floors, steady-state response is important when one of the natural frequencies is similar to the harmonic component of human walking. All modes with natural frequencies less than the cut-off values (Table 3) increased by 2 Hz should be considered at steady state. The transient response mainly comes from the impulse group (steps). In this situation, those modes with natural frequencies up to twice the fundamental frequency (first vibration mode) should be considered.

In a typical situation, the excitation point coincides with the response point and should be located so that the resulting response of the structure is as large as possible. When investigating the floor response of a room, which originates from steps in a corridor, the excitation and response points should be selected so that the maximum amplitude of displacement is obtained at the appropriate locations of each mode. The next step is to sum the obtained steady-state acceleration values, which have been determined separately for all vibration modes as a response to each harmonic component.

Document [7] also presents a simplified analysis for steel floors, which can also be applied to composite floors. When the analysed floor is a typical composite floor, where the slabs are supported on a series of secondary beams and these on rigid primary beams, it is necessary to consider the secondary beam mode and the primary beam mode. The former mode is characterised by a fixed boundary condition (the slab is continuous) and the assumption of a non-deformable primary beam on which the simply supported secondary beams vibrate. The second mode represents the situation where the primary beams are considered as freely supported elements vibrating around the columns, and the slab and secondary beams as restrained at the ends. For both variants, it is necessary to determine the natural frequency, of which the smaller value is called the fundamental frequency.

It is required that the entire floor as well as its separate components have a natural frequency of 3 Hz and higher. Otherwise, human footsteps can cause effects similar to resonance or resonance itself.

A floor that is affected by vibration sources other than normal footsteps has different requirements. A floor structure operated during rhythmic activity must have a fundamental frequency of at least 8.4 Hz in the vertical direction and 4 Hz in the horizontal direction, or carry a dynamic load included as a separate imposed load case. If the limit value in the vertical direction is not reached, the dynamic load must be determined and checked to ensure that the floor is able to carry it. When the horizontal direction condition is not satisfied, a calculation program can be used, with the understanding that the horizontal frequency is dependent on the bracing system. Furthermore, the natural frequency must be computed for an empty object and for the proper form of vibration. It is necessary to determine the response of the floor and check whether the frequency exceeds 24 Hz. If it is higher, the floor is classified as non-responsive at the serviceability limit state.

Another special example concerns floors in hospitals. Especially because of the demanding requirements for vibration levels in operating theatres, the use of hot-rolled steel profiles (e.g. Slimdek®) is recommended. In hospitals, apart from vibrations caused by steps in the corridor, consideration is given to vibrations in the operating theatres (with a frequency of 1.8 Hz) and from walking in the vicinity of patients (with a frequency of 1.5 Hz to 1.8 Hz). In the medical industry, machines can be found that are extremely sensitive to vibration and need to be additionally secured against the negative effects of vibration. When designing, it is important to be aware that some machines cause vibrations themselves and it may be necessary to contact the manufacturer.

Furthermore, car parks do not have to satisfy overly rigorous vibration requirements because of the user being mainly in the vehicle or only temporarily walking. In both positions, the user's perception of dynamic effects is reduced and, consequently, vibrations do not affect personal comfort exceedingly [7].

3. MODELLING OF COMPOSITE FLOOR IN THE RFEM 6 SOFTWARE

Modelling in RFEM 6 should preferably start with the setting of all input fields available in the ‘Base Data’ dialog box according to the considered floor. It contains tabs for the selection of standards, type of model (1D, 2D, 3D), add-ons and other settings. To obtain the dynamic characteristics of the structure being modelled in RFEM, the add-on ‘Modal Analysis’ has to be activated.

The floor should be considered as a single degree of freedom system. When creating the model in the software, it is important to be aware that it may deviate from the design model for the ultimate limit state, including the boundary conditions (the pinned connection in ULS may be a fixed one in the floor vibration analysis). It is also necessary to use the dynamic elastic modulus of concrete ($E_{c,dyn}$), which is 110% of the Young's modulus (E_{cm}) [4-7].

During the modelling stage of the composite floor, it is essential to ensure that the steel and concrete components cooperate with each other. In actual construction, stud shear connectors are responsible for this, but performing a modal analysis in a numerical model requires providing composite behaviour differently. Commonly used FEA programs for structures are dedicated separately to, e.g., reinforced concrete, steel or timber, but there are no modules directly targeted at composite elements. Substitute methods can be used to model a composite floor, for which the suggestions in both Dlubal's online article [21] and Builder magazine [22] can be helpful. Although the latter is addressed to users of

Autodesk Robot Structural Analysis, some of the recommendations may be applicable for designing in RFEM.

The first approach to represent the composite behaviour in [21] involves dividing the steel beam and concrete slab at the locations of the stud shear connectors and placing all components as beam-type member elements along a common axis. To ensure that the bottom of the concrete element was in contact with the top of the steel beam, all elements were assigned a relevant eccentricity. The ‘Allow Double Member’ option was activated, obtaining a series of common nodes for the concrete and steel components at the points of actual connections.

The second presented modelling possibility differs from the previous one by positioning the components on two independent lines, which means that in the vertical direction they were offset manually instead of using an eccentricity. Then, the cooperation between them was provided by rigid members inserted where stud shear connectors would be located.

The last suggested option is to insert the concrete part as a surface with an associated cooperating member type ‘rib’, which corresponds to a steel beam. In this case, the composite element is not divided into smaller parts, but rigid members are also used at its ends. The correct positioning of the sections relative to each other was set by the rib eccentricity.

In the Builder article [22], the first modelling proposal is to use the ‘offset’ option between the concrete section inserted as a panel and the steel beam inserted as a member.

Another suggested approach is to manually displace the components (panel and member) and connect them with dense rigid members.

Moreover, paper [22] mentions the possibility of modelling in other ways, e.g., increasing the degree of simplification by replacing the concrete panel with a member (with manual offset), or in the opposite way – detailing the model using panels for the concrete slab and the web of the steel beam, with members for the flanges of the steel beam. However, such accuracy is not needed when the model is created for dynamic analysis only, and it is important that references [21–22] focus mainly on the determination of internal forces.

Regarding the modelling of component connections, a guideline can be taken from publication P354 [7], more specifically the chapter on modelling in FEA programs, where it was recommended to enter all connections as rigid for the purposes of dynamic analysis. It is also suggested that the support conditions of the beam elements along the perimeter of the floor in clad buildings ensure that there is no displacement for the three directions, but allow freedom of rotation. To fulfil this condition, a pinned member support in RFEM 6 distributed in the axes of the perimeter beams can be used. A further guideline for composite floors on profiled sheets is to model the slab as an orthotropic shell element with a constant thickness equal to the height of the topping concrete and a realistic eccentricity relative to the steel beam. In the direction transverse to the spanning direction of the profiled sheet, the material properties of the concrete are normal, unmodified, and in the longitudinal direction of the profiled sheet, the stiffness of the profiled concrete ribs must be included in the dynamic modulus of the topping concrete layer. Their weight should also be inserted into the model, e.g., by including them in the density of the concrete slab. When the eccentricity cannot be entered, it is possible to determine the stiffness of the composite element and then calculate the beam stiffness as the difference between the stiffness of the composite element and the stiffness of the concrete. Although this is less accurate than the model with eccentricity option, it allows consideration of the offset within the stiffness. Additionally, the plate can be considered as continuous. If core walls pass through the considered floor, it can be modelled as rigid at the joint [7].

Regarding floor loads in the dynamic parameters determination, the realistic fraction of imposed load needs to be included in the floor mass, which, for example for office and residential buildings, is between 10% and 20% of the imposed load. What is important the additional mass results in vibration damping. In case of very light floors, a representative mass of one person is additionally considered, which is assumed to be min. 30 kg. The unfactored self-weight, together with loads from finishes, installations, etc., should be included as a uniformly distributed surface load [4–6]. To determine the dynamic characteristics in RFEM 6, a new load case with the analysis type 'modal analysis' has to be created. The above-mentioned loads can be entered as static analysis cases to create one characteristic combination in the serviceability limit state. Even when the statics in a particular model will not be elaborated, in the 'modal analysis' load case the mentioned combination can easily be selected from the list under the field named 'import masses only from load case/load combination'. Then, the program will automatically convert the previously entered loads into masses for modal analysis.

4. EXAMPLE

4.1. Description of the floor structure

The natural frequency determination in RFEM 6 together with the evaluation of the acceptance class will be presented on the example of a steel-concrete composite floor on a profiled sheet with office use (category of use B). It is assumed that the facades of the building in which the floor is located are provided with a continuous cladding.

The structure consists of HEB 700 primary beams on which HEA 220 secondary beams were supported. These elements were assigned S275 steel. Headed stud shear connectors (SD (KB) PN-EN ISO 13918 [23]) with a diameter of 22 mm and a height of 100 mm, welded to the steel beams, were assumed. On the primary beam, there is one row of connectors, but they are spaced alternately so as not to interfere with the convex stiffening of the profiled sheet. On the secondary beam, there are two rows of studs with 132 mm spacing. Cofraplus 60 trapezoidal shape sheets with a length of 8.4 m were provided, with drilled holes for the studs. Concrete of class C30/37, cast *in situ*, was selected. The total thickness of the slab was taken as 130 mm. An anti-shrinkage Q131 reinforcement mesh was used in the topping concrete layer (the 72 mm layer above the 58 mm thick profiled sheet).

Fig. 1 includes a scheme of the axial spacing of the primary beams (shown in red) and secondary beams (shown in blue). A cross-section through the floor (in the direction transverse to the decking) is shown in Fig. 2, where half of the symmetrical secondary beam can be seen along with the other floor elements. The spacing of the stud connectors on the beam is also described. The stud distances on half of the primary beam are shown in Fig. 3.

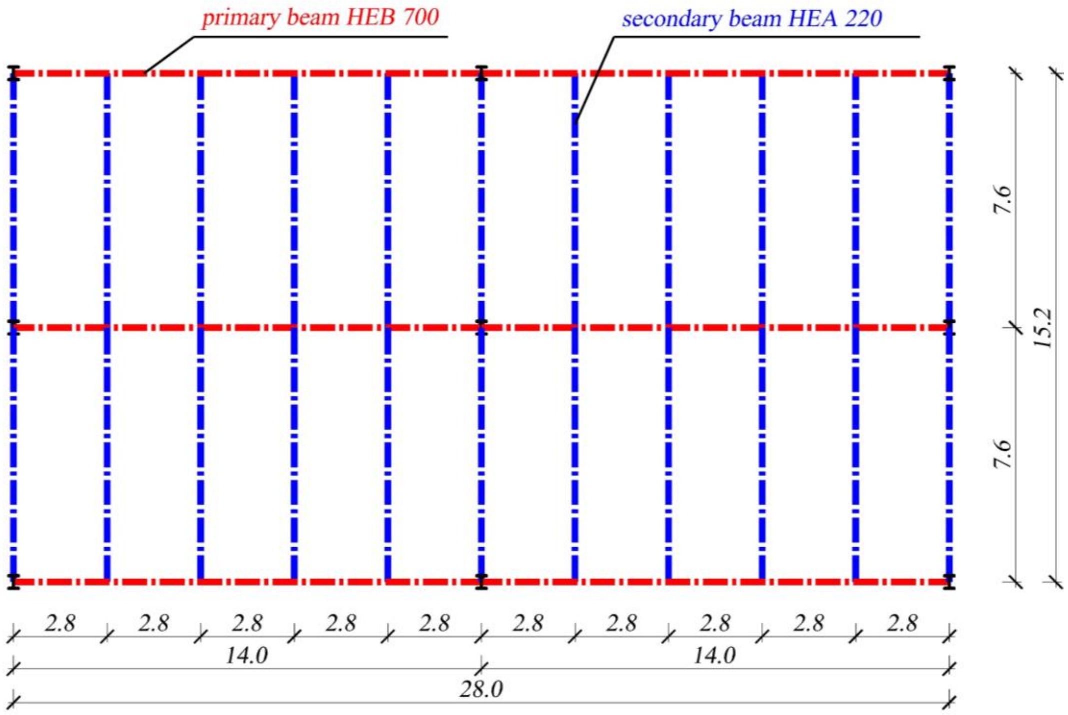

Fig. 1. Scheme of axial beam spacing (dimensions in metres)

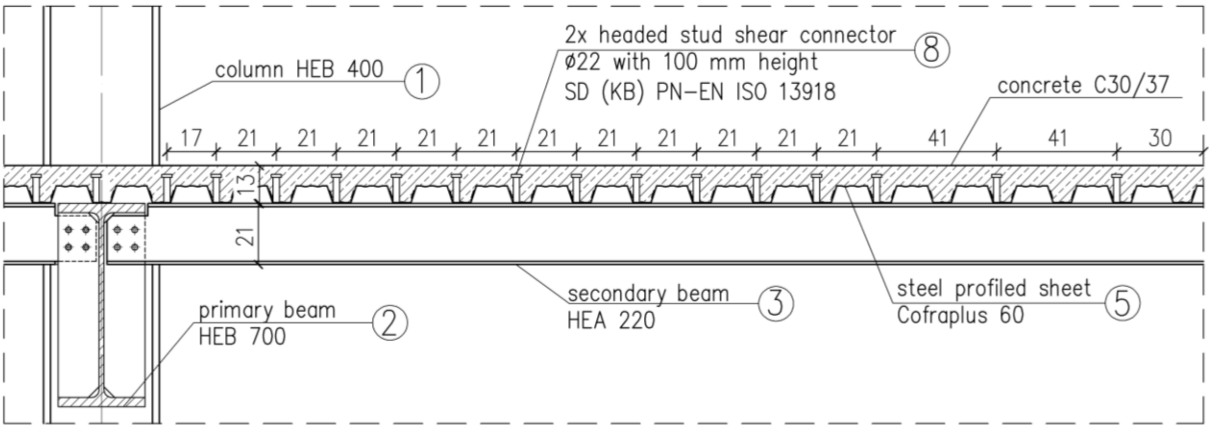

Fig. 2. Floor cross-section – half view of secondary beam (dimensions in centimetres)

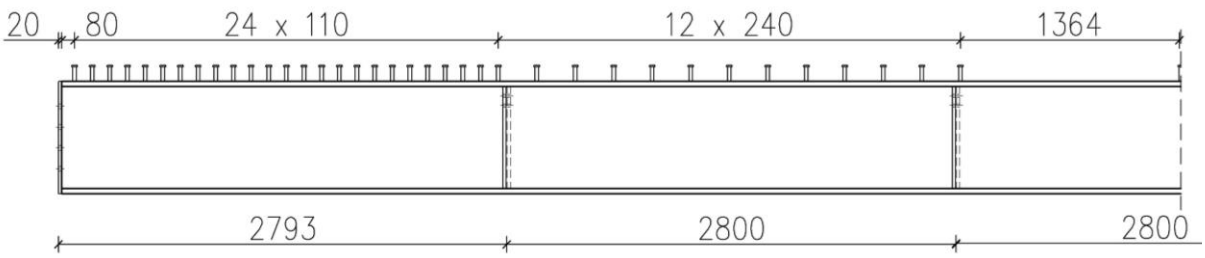

Fig. 3. Stud shear connectors spacing on half of the primary beam (dimensions in millimetres)

4.2. Description of the floor modelling

The modelling in RFEM 6 started with the basic settings, such as the selection of the 3D model type (with activation of member elements and surfaces), the activation of the additional add-on for the dynamic analysis ‘modal analysis’, the selection of country-specific standards (in this case for Poland), as well as the assumption of the gravitational acceleration as 9.81 m/s^2.

During the composite behaviour modelling, recommendations from previously described articles [21–22] were followed. Whilst both considered a single steel-concrete composite beam, it was decided to attempt implementing suggested modelling principles to the entire floor. As the articles [21–22] do not discuss dynamic aspects, modelling approaches that are sufficient to provide composite behaviour and correct support conditions were chosen. The focus was not on the determination of bending moments, shear forces or other internal forces. Of several approaches to modelling the composite behaviour in the numerical model, option No. 3 described in [21] was chosen, which involves the input of a concrete slab using the ‘surface’ option and the application of a member type ‘rib’ that is assigned to and interacts with mentioned ‘surface’. An additional connection at the points, where primary beams join with secondary ones along the edges of the floor, are vertical rigid-type members. Moreover, to ensure that the stiffness of the structure is realistic, the eccentricity described in the following paragraphs was applied.

The material of the secondary and primary beams, which is isotropic S275 steel, was selected directly from a software database. Regarding the concrete slab, the topping concrete in the numerical model has a thickness of 72 mm in the ZX plane, while in the ZY plane there are additionally concrete ribs that form the infill of the profiled steel sheets. To enable the modelling of a slab with constant thickness and varying properties on orthogonal directions, an user-defined material with orthotropic material model option was applied. The orthotropic material model allows a different surface stiffness to be implemented in two perpendicular directions, which is used, for example, in modelling the properties of ribbed slabs, glass fibre reinforced plastics, or reinforcement directions of slabs [2423]. The specified material parameters are described below. In addition to the calculated values, a coefficient of thermal expansion of 0.000010 1/°C, a shear modulus of 13750 N/mm2 in all directions, and a Poisson's ratio of 0.2 in the XY direction and 0.059 in the YX direction were used.

The static elastic modulus of concrete was converted to dynamic elastic modulus (4.1) based on the *HiVoSS* document [6]. The value of the dynamic modulus of elasticity of concrete for the direction perpendicular to the secondary beams (in the ZY plane, along the X axis) can be determined using formula (4.2) from a publication from the Steel Construction Institute [7].

$$E_{c,dyn} = 1.1 \cdot E_{cm} \tag{4.1}$$

$$E_{cx,dyn} = \frac{12 \cdot E_{c,dyn} \cdot I_{c,x}}{b \cdot {h_c}^3} \tag{4.2}$$

where:
b – is the width of the considered slab section [mm];
E_{cm} – is the secant elastic modulus of concrete [N/mm^2];
$E_{c,dyn}$ – is the dynamic elastic modulus of concrete along the Y axis [N/mm^2];
$E_{cx,dyn}$ – is the dynamic elastic modulus of concrete along the X axis [N/mm^2];
h_c – is the thickness of the topping concrete (above the profile) [mm];
$I_{c,x}$ – is the moment of inertia of the profiled concrete slab section (along X direction) [mm^4].

In addition, in order to make the results more realistic, it was decided to include the stiffness of the steel profiled plate in the calculations besides the stiffness of the concrete layer of the slab.

A necessary step was to bring the cross-section into homogeneity of the material in both directions by means of the coefficient denoted by equation (4.3).

$$n = \frac{E_S}{E_{c,dyn}} \tag{4.3}$$

This step made it possible to determine the moments of inertia of the equivalent section, uniform in material in the X and Y directions (I_X, I_Y), and therefore also the equivalent dynamic elastic modules in the X and Y directions (E_X, E_Y). The data and final results are presented in Table 4.

Table 4. Determination of equivalent dynamic elastic modulus – data and results

Symbol	Parameter explanation	Value
	Data	
E_{cm}	secant elastic modulus of concrete	$32000 \frac{N}{mm^2}$
E_S	Young's modulus of the profiled steel sheet	$210000 \frac{N}{mm^2}$
b	the width of the considered slab fragment	$1000\ mm$
b_0	width of rib at mid-height	$81.5\ mm$
b_s	distance between profiled sheet ribs	$207\ mm$
h	overall height of the concrete section	$130\ mm$
h_p	rib height	$58\ mm$
h_c	height of topping concrete	$72\ mm$
d_p	distance from upper surface of concrete to centre of gravity of profiled sheeting	$96.7\ mm$
t_s	thickness of profiled steel sheet	$0.75\ mm$
A_{pe}	cross-sectional area of the profiled sheet per 1 m width of the sheet	$1029 \frac{mm^2}{m}$
I_{eff}	moment of inertia of the profiled sheet per 1 m of sheeting width	$426000 \frac{mm^4}{m}$
	Results	
$E_{c,dyn}$	dynamic elastic modulus of concrete	$35200 \frac{N}{mm^2}$
n	ratio of Young's modulus of steel to dynamic Young's modulus of concrete	5.97
I_X	moment of inertia in the X direction (for equivalent cross-section, uniform in material)	$20951864\ mm^4$
$\boldsymbol{E_X}$	equivalent dynamic elastic modulus in the X direction (assigned to a slab of constant thickness, taking into account orthotropic properties and profiled sheeting)	$\mathbf{141457.42} \boldsymbol{\frac{N}{mm^2}}$
I_Y	moment of inertia in the Y direction (for equivalent cross-section, uniform in material)	$6147952\ mm^4$
$\boldsymbol{E_Y}$	equivalent dynamic elastic modulus in the Y direction (assigned to a slab of constant thickness, taking into account orthotropic properties and profiled sheeting)	$\mathbf{41508.16} \boldsymbol{\frac{N}{mm^2}}$

A surface with a 72 mm uniform thickness was modelled in the program without the ribs filling the profiled sheeting, hence a new (substitute) concrete density was specified in which the ribs were included. The values of typical density of concrete (ρ) and equivalent density of the concrete ribbed slab (ρ^*), as well as the equivalent self-weight (γ^*), are shown below.

$$\rho = 2500\ \frac{kg}{m^3}$$

$$\rho^* = 3265.44\ \frac{kg}{m^3}$$

$$\gamma^* = 32.03\ \frac{kN}{m^3}$$

Next, the modelling of the structural elements was carried out, which started with the introduction of lines in the XY plane according to the scheme shown in Fig. 1.

The boundary lines forming the perimeter of the floor were assigned surface No. 1. A fixed thickness d equal to 72 mm and the user-created material described above were assigned to the surface. The remaining lines in the XY plane are integrated into surface No. 1. Following the guidelines of document SCI P354 [7], the eccentricity option was used so that the slab is at the actual distance from the beams, as shown by variant (a) in Fig. 4. The offset between the slab bottom (surface thickness) and the zero XY plane was set as 58 mm, which is the height of the profiled ribs.

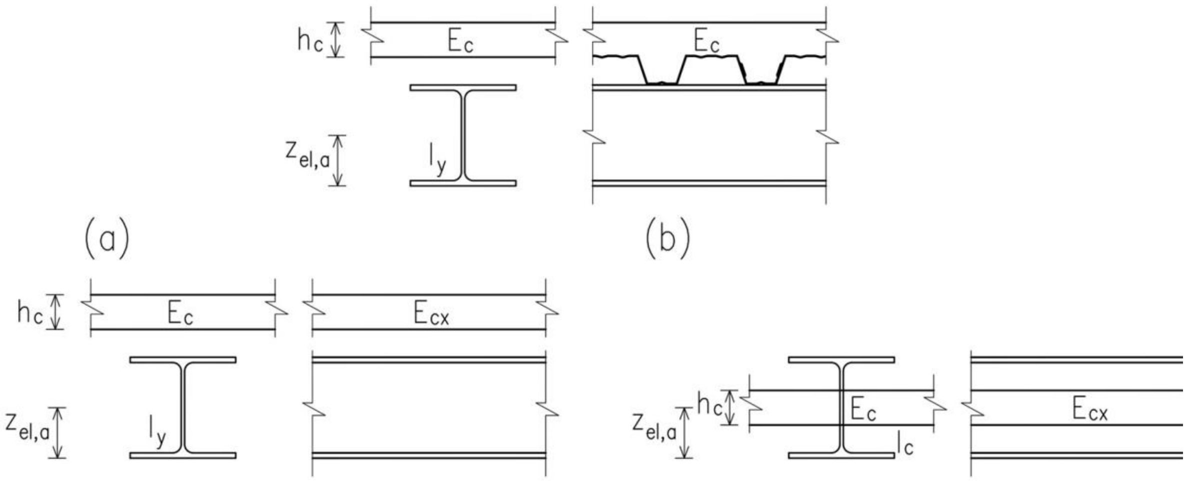

Fig. 4. Modelling variants of a profiled concrete slab – drawing based on document [7]

All primary and secondary beams were created with rib-type members and assigned to surface No. 1. For all primary and secondary beams, the eccentricity option was activated so that their top fibres were located in the XY plane of the model. This was implemented by offsetting the upper beam flanges from the middle of the slab thickness by 94 mm.

Rigid-type members were formed by modelling vertical lines at nodes around the perimeter of the structure, which were led from the axis of the primary beams to the centre of the concrete surface thickness, giving a length of 0.444 m.

Figures 5–7 contain views of the structure in RFEM 6.

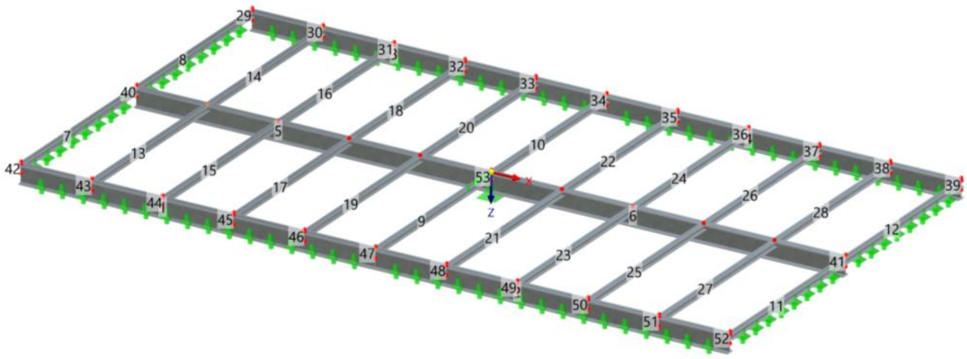

Fig. 5. Axonometric view of beam system – view from RFEM 6

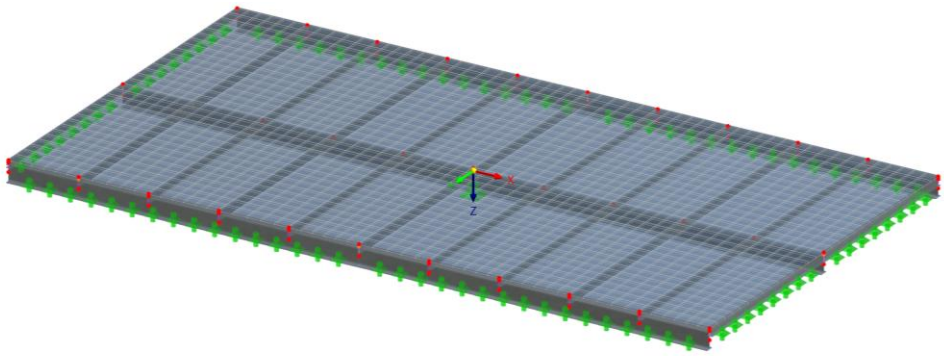

Fig. 6. Axonometric view of beams and slab including mesh – view from RFEM 6

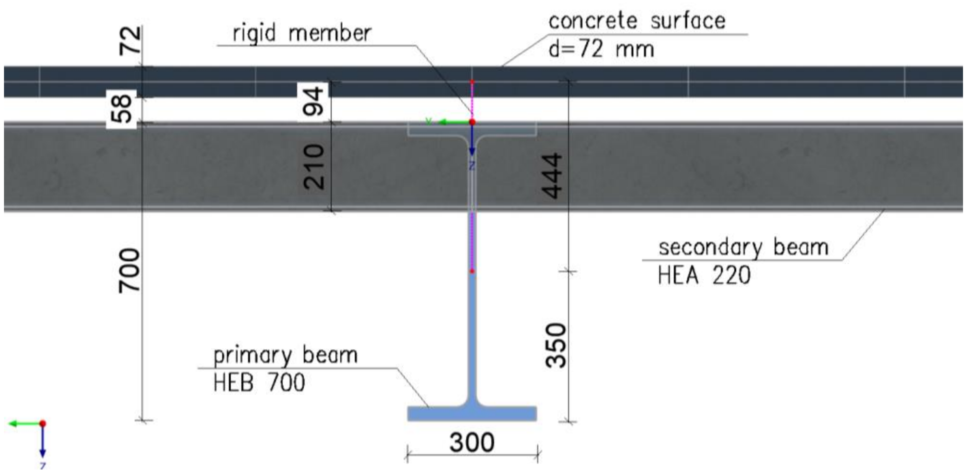

Fig. 7. Side view of floor system – view from RFEM 6

Following the solution suggested in document [7], all joints were considered as rigid, and all the perimeter beams were supported in axes by pinned member supports. Furthermore, at the centre of the floor a pinned nodal support (instead of a column) was used, which is entered at the height of the main beams' axis.

The next step was to enter the loads into the program. The self-weight of the secondary beams, primary beams and concrete slab were calculated automatically in RFEM 6. However, other structural components such as profiled sheets, anti-shrinkage reinforcement mesh and studs required manual input of load cases. The loads of the installations, the layers of the floor finishes (a swimming screed was assumed) and the realistic fraction of imposed load were also input separately [4–6]. The latter load was taken as 15%, which is within the range between 10% and 20% mentioned in publication [6]. According to [9], for category of use B, which corresponds to office space, the value of the characteristic imposed load was taken as 3.00 kN/m^2 in order to calculate the real part from this value. Table 5 summarises the load values entered in RFEM 6, together with a description of how the load is applied.

Table 5. Load values inserted in RFEM 6

Load Case	Description	Load value	Load application
PO1	self-weight of elements modelled in the program	-	automatically generated by the software
PO2	self-weight of other structural components (profiled sheet and reinforcement)	0.104 kN/m^2	surface load
PO3	self-weight of other structural components (stud shear connectors)	0.028 kN/m	member load on secondary beam
		0.019 kN/m	member load on primary beam
PO4	installations	0.300 kN/m^2	surface load
PO5	floor finishing layers	1.800 kN/m^2	surface load
PO6	realistic fraction of the imposed load	0.450 kN/m^2	surface load

A modal analysis load case was entered in which the mass was imported from a single characteristic combination with all six permanent load cases assigned (from Table 5).

4.3. Results and evaluation of the floor

The final stage of modelling is to run the calculations, read the results and assess the floor.

The following figures (Figures 8–17) illustrate the first ten mode shapes. Table 6 contains the results of the natural frequencies and modal masses assigned to each of the vibration modes.

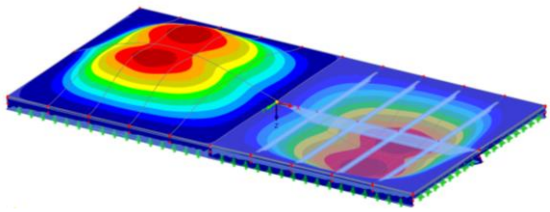

Fig. 8. Mode shape No. 1

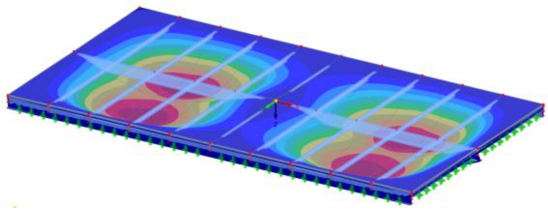

Fig. 9. Mode shape No. 2

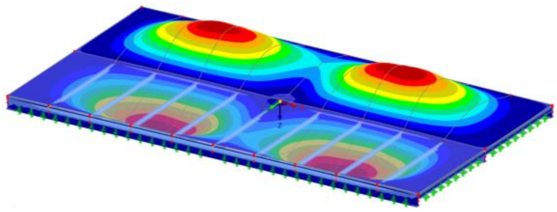

Fig. 10. Mode shape No. 3

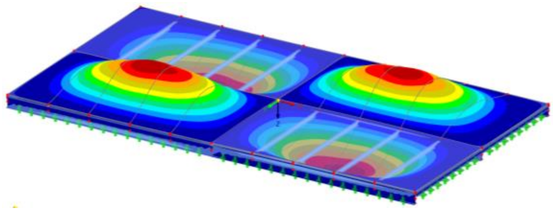

Fig. 11. Mode shape No. 4

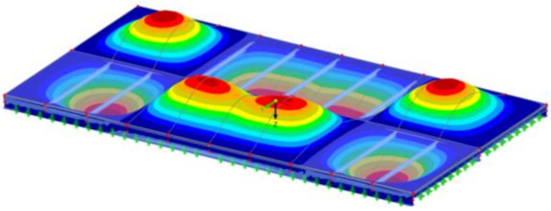

Fig. 12. Mode shape No. 5

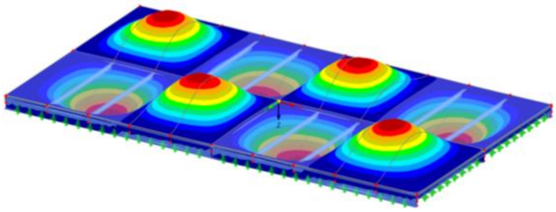

Fig. 13. Mode shape No. 6

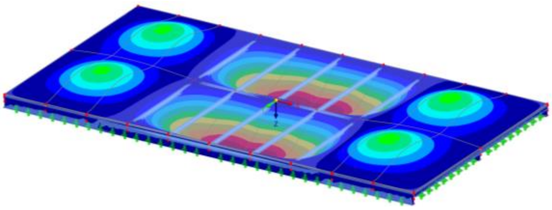

Fig. 14. Mode shape No. 7

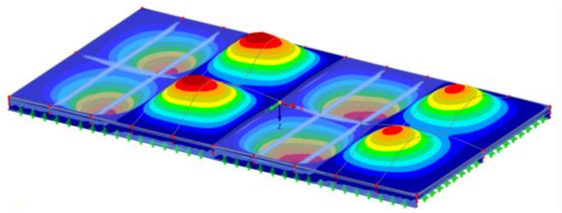

Fig. 15. Mode shape No. 8

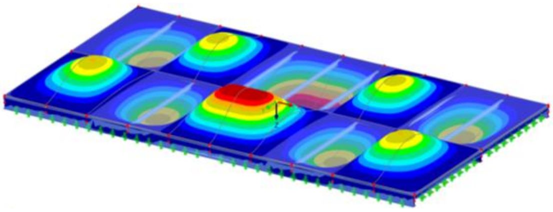

Fig. 16. Mode shape No. 9

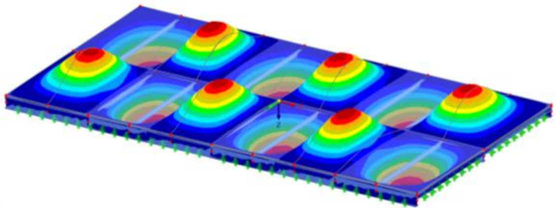

Fig. 17. Mode shape No. 10

Table 6. Results of natural frequencies and modal masses

Mode No.	1	2	3	4	5	6	7	8	9	10
***f* [Hz]**	6.81	7.41	7.45	7.72	9.10	9.21	10.58	10.85	11.02	11.99
***M* [kg]**	58888	55501	46143	45054	51798	45216	28910	39915	31142	46044

The evaluation of the composite floor was based on the fundamental frequency, as follows:

$$f_1 = 6.81\ Hz$$

The damping value was assumed based on Table 1. For a floor with a composite structure, furniture typical for an open-plan office, a swimming screed finishing and with a ceiling under the floor, the following total damping value was obtained:

$$D = 4\%$$

For the above damping, a suitable diagram was selected from document [16] to extract the OS- RMS_{90} value (Fig. 18).

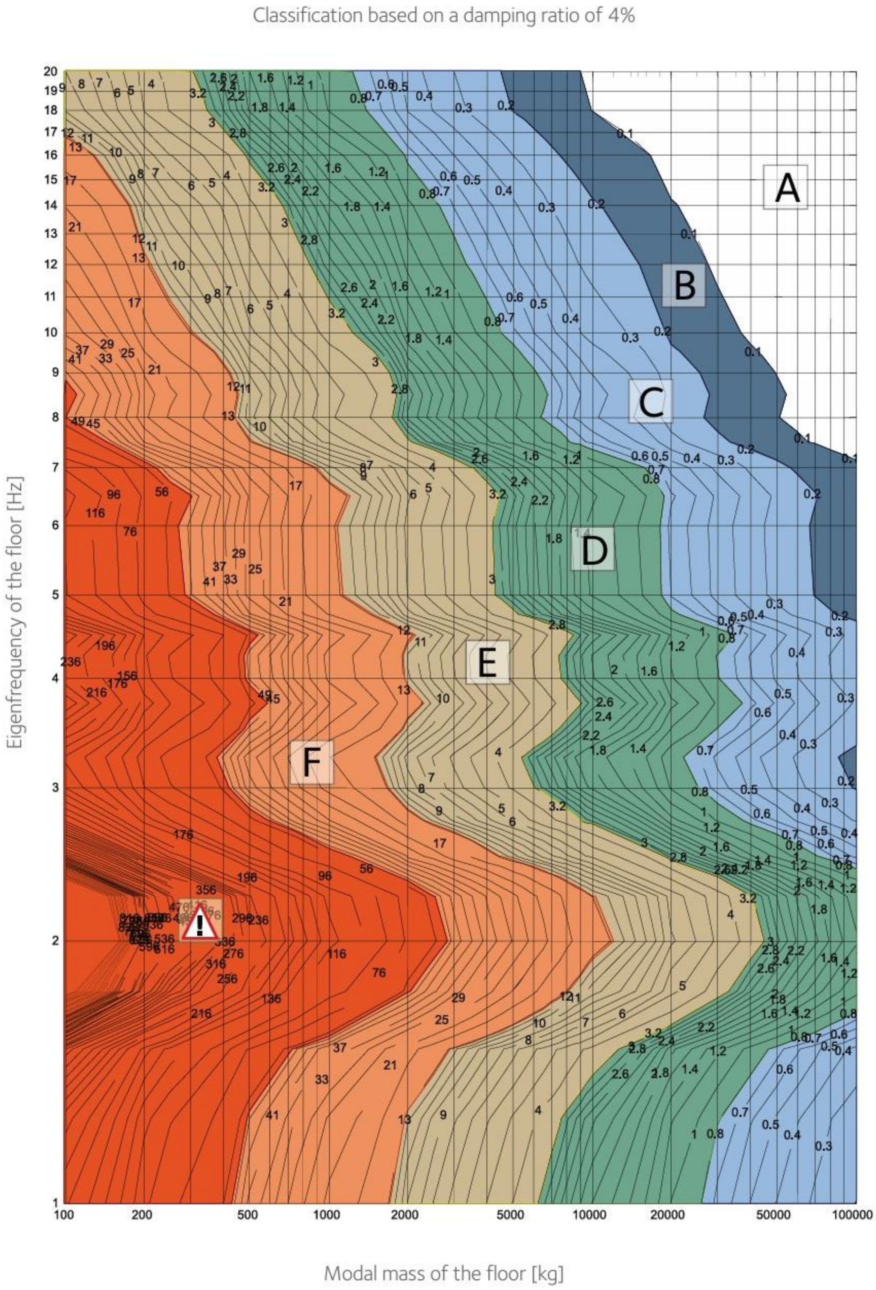

Fig. 18. Plot of OS-RMS$_{90}$ values at 4% damping – picture from document [16]

The noted value of OS-RMS$_{90}$ is equal to:

$$OS - RMS_{90} = 0.21$$

This corresponds to acceptance class C, which is one of the recommended classes for office use floors, as noted in Table 2.

According to Table 3, the limiting value between low-frequency and high-frequency office floors is 10 Hz.

$$6.81\ Hz < 10\ Hz$$

The fundamental frequency is below the cut-off value, so it is a low-frequency floor.

Based on the guidelines described in the previous chapters, the following criteria for assessing the risk of resonance with human steps can be adopted:

- If the fundamental frequency is less than 3 Hz, there is a high risk of the structure resonating with human steps, so the condition is not fulfilled and the floor should be redesigned;
- If the fundamental frequency is between 3 Hz and 12 Hz, the actual design should consider transient and steady-state response analysis. The 12 Hz value originates from the office floor limit of 10 Hz (Table 3), increased by 2 Hz according to [7];
- When the fundamental frequency is greater than 12 Hz, it is sufficient to include only a transient response analysis in the actual design. In this situation, the risk of resonance between the floor structure and people's steps is negligible.

Based on this, an assessment was carried out:

$$3\ Hz < 6.81\ Hz < 12\ Hz$$

In reality, the steady-state and transient floor response needs to be analysed to exclude the risk of resonance with the steps.

5. CONCLUSIONS

Numerous possibilities and methods are available for the determination of dynamic floor characteristics. Whilst for composite floors the representation of composite behaviour in FEA software can be an additional difficulty, guidance from [21–22] can be applied. When a simple modal analysis needs to be performed, resulting in basic parameters (mode shapes, natural frequencies, modal masses etc.), FEA programs such as Autodesk Robot Structural Analysis Professional or Dlubal's RFEM may be sufficient. When the considered problem requires a detailed dynamic analysis, it is worth using Abaqus/Explicit program, which is specifically designed for dynamic issues. For most floors, the main and crucial source of vibration is human walking. Numerous requirements and guidance on this subject for composite floors are given in the *HiVoSS* documents [4–6] and in a publication from the Steel Construction Institute [7].

The main results obtained from the floor analysis are a fundamental frequency of 6.81 Hz with a modal mass equal to 58888 kg. For the assumed damping of 4%, the OS-RMS_{90} value was found to be 0.21. The floor qualifies for acceptance class C, which is one of the recommended classes for office floors. In actual design the floor presented in the example should be checked for the steady-state and transient response to avoid the risk of resonance with human footsteps.

The main conclusions are summarised below:

- It is possible to use FEA software to model a composite floor,
- These programs can be applied to determine the dynamic characteristics of structures,
- Depending on the selected software and used methods, slightly different results can be obtained,
- It is necessary to use substitute methods to model the composite behaviour since there is no program option for direct modelling of composite structures,
- It may occur that the entered support conditions do not perfectly represent the actual ones,

- The 'surface' option with interacting 'ribs' available in RFEM 6 appeared to be the most convenient to use.

An additional note is that the example floor discussed in the paper was originally created for a parametric analysis to examine how modifications would affect natural frequencies of the structure. Numerous parameters were edited, such as material class, steel profiles, topping concrete thickness, member spacing, member lengths and loads.

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