# PARAMETER IDENTIFICATION OF STEEL - CONCRETE COMPOSITE BEAMS BY FINITE ELEMENT METHOD

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Summary

Steel-concrete composite elements are very often used as main elements of floors or in bridge engineering as main carrying girders. This paper presents computational models and an analysis of natural vibrations conducted on steel-concrete composite beams. Simulation results were compared with experimental research results for beams in groups B1 and B2. In the group of beams B1 a connection that consisted of steel stud connectors was used whereas perforated steel slats were used in group B2. For modelling and calculations, Abaqus platform and Matlab environment were used and the finite element method (FEM) was applied. Each beam model was made in two versions that differ in the approach to modelling connection. In the first modelling approach beam elements were used whereas in the second spring elements were applied. Both models, after parameter identification, provided very good consistency with experimental research results.

Keywords: composite structures, identification, Abaqus, Matlab.

IDENTYFIKACJA PARAMETRÓW STALOWO-BETONOWYCH BELEK ZESPOLONYCH METODĄ ELEMENTÓW SKOŃCZONYCH

Streszczenie

Elementy zespolone stalowo – betonowe są najczęściej wykorzystywane jako główne elementy stropów oraz jako dźwigary nośne w mostach i wiaduktach. Niniejszy artykuł przedstawia modele obliczeniowe oraz analizę drgań swobodnych belek zespolonych stalowo – betonowych. Wyniki porównano z wynikami badań doświadczalnych belek z grupy B1 i B2. W grupie belek B1 zastosowano zespolenie w postaci stalowych sworzni zespalających, w grupie B2 zastosowano zespolenie w postaci stalowych listew perforowanych. Podczas modelowania i obliczeń użyto systemów Abaqus i Matlab, wykorzystując metodę elementów skończonych (MES). Model każdej belki wykonano dwukrotnie inaczej modelując zespolenie, raz wykorzystując w tym celu elementy belkowe, drugi raz z wykorzystaniem elementów sprężystych. Obydwa modele, po przeprowadzeniu identyfikacji ich parametrów, zapewniają wyniki o bardzo wysokiej zgodności z wynikami badań doświadczalnych.

Słowa kluczowe: konstrukcje zespolone, identyfikacja, Abaqus, Matlab.

## 1. INTRODUCTION

Steel-concrete composite beams are very often used in public space and industrial building engineering as elements of floors or in bridge engineering as main carrying girders. Special attention should be paid in each case to dynamic properties of a designed construction.

Over the past decades many studies on steel-concrete composite constructions modelled ascontinuous or discrete systems have been published [1 - 3]. The finite element method (FEM) is the most frequently used method for three-dimensional modelling [3-7]. The method's primary advantage is its validated reliability and that it can be used on a wide range of calculation platforms, including Abaqus, Nastran and Ansys. Acomprehensive review of the literature on the topic is presented elsewhere [8].

The present study presents computational models and results of natural vibration analysis for two groups of steel-concrete composite beams B1 and B2. In the group of beams B1 a connection that consisted of steel stud connectors was used whereas perforated steel slats were used in group B2. Abaqus platform was used to develop the beam models. The beams were modelled as a spatial system using both solid (reinforced concrete slab) and shell elements (steel beam). The connection between the reinforced concrete slab and the steel beam was modelled in two ways. In the first model denoted as MB, beam elements were used. In the second model denoted as MS, spring elements were applied. Both models assumed that connections can be deflected in two directions, i.e. perpendicular and parallel directions to the beam axis. Both models, after parameter identification, provided very good consistency with experimental research results.

## 2. DESCRIPTION OF BEAMS AND EXPERIMENTAL RESEARCH

The analysed beam was 3200 mm in length and consisted of a structural steel section IPE 160 and a reinforced concrete slab (600x60 mm). The structural steel section was made from S235 steel and the slab was made from C30/37 concrete. Owing to differences in type of connection, beams were divided into groups B1 and B2. The analysed beams are presented in Figure 1.

a)

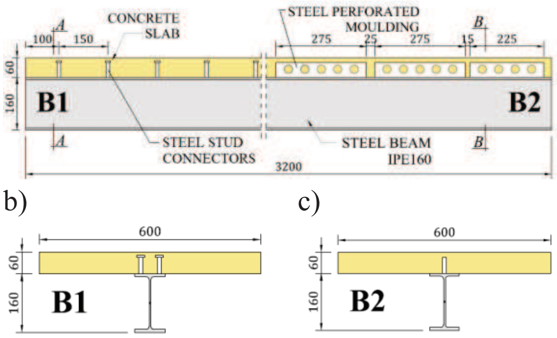


Fig. 1. Composite beams from B1 and B2 group: a) longitudinal view, b) cross-section beam B1, c) cross-section beam B2

Experimental tests were conducted on six composite beams: three from group B1 and three from group B2. Initially, the beams, were tested under static load at the level of 40% of elastic load capacity. The next stage was determination ofdynamic characteristics of the beams for a free-end beam schematic. A detailed description of the test stand and test procedure is presented in [3]. Impulse excitation was applied and acceleration in predefined measurement points was measured. A measurement grid and excitation points are presented in Figure 2.

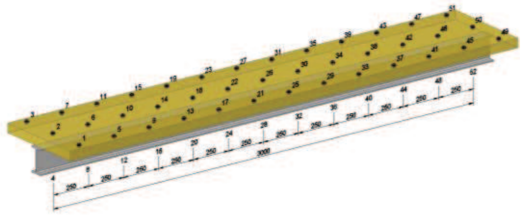

Fig. 2. Grid of measurement points

## 3. FEM BEAM MODEL

While defining the computational model, it was assumed that the beam has a static schematic with free ends and that its cross-section is constant at all its length. The model was defined on Abaqus platform as a spatial system with independently modelled reinforced concrete slab, steel beam and connection. At this point of the research study it was decided that an expanded version of the model consisting of shell and solid elements be used. Shell elements (S8R) were used to define a structural steel section IPE 160. A finite element mesh was generated that consisted of 4 elements at the web ofthe beam, 4 elements along the width of a flange which were spaced every 50 mm along the length ofthe beam. The reinforced concrete slab was modelled with solid elements of the first order (C3D81). A finite element mesh was generated that consisted of 2 elements along the height of the slab and of 14 elements along the width of the beam (with a thickening in the central area where the slab was connected to the structural steel section) which were spaced every 50 mm along the length of thebeam. This division of the beam into finite elements is presented in Figure 3.

a) b)

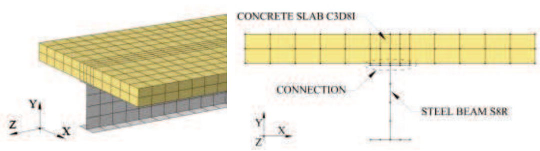


Fig. 3. FEM model of the analysed composite beam: a) view of the beam, b) cross-section

The connection is modelled (Figure 4) between shell element nodes and solid element nodes which are evenly spaced along the length and width ofthetop flange of the steel section.

a) b)

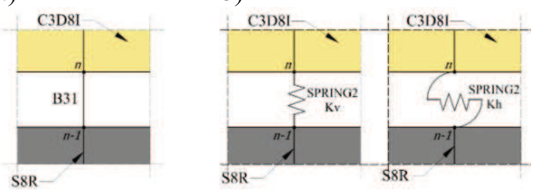


Fig. 4. FEM model of connection for composite beam: a) connection in MB model, b) connection in MS model

B31 beam elements were used in the first model (MB model). SPRING2 elements were used in thesecond model (MS model). Stiffness of theconnection in two directions was assumed. Thestiffness along the horizontal direction (the axis z) was denoted as Kh and that in the vertical direction (the axis y) was denoted as Kv. In MB model, the stiffness of connection was changed bychanging parameters that defined B31 beam elements, i.e. a change of the cross-sectional area Areflected a change in stiffness Kv whereas achange of the moment of inertia J reflected achange in stiffness Kh. In MS model two independent groups of spring elements SPRING2 were used. The first group was responsible for stiffness Kh (along the axis z) while the second group was responsible for the interaction between steel and concrete along the vertical direction (the axis y) - stiffness Kv. The stiffness ofconnection in the axis x (horizontal, perpendicular to the beam axis) was neglected owing to the scope of analysed modes of the beam vibrations.

## 4. DYNAMIC EQUATION OF MOTION

The dynamic equation of motion can be written as

$$\mathrm{M}\ddot{\mathrm{q}} + \mathrm{C}\dot{\mathrm{q}} + \mathrm{K}\mathrm{q} = \mathrm{P} \qquad 4.1$$

where M is inertia matrix, C is damping matrix, K is the matrix of system stiffness, P is the vector of outside forces acting on the system, and q is the vector of generalised coordinates. For free vibration Equation 4.1 takes the following form

$$\mathrm{M}\ddot{\mathrm{q}} + \mathrm{K}\mathrm{q} = 0 \qquad 4.2$$

The frequency and the mode vector of natural vibration for the modelled composite beam can be found using Equations:

$$\det(\mathrm{K} - \omega^2\mathrm{M}) = 0 \qquad 4.3$$

$$(\mathrm{K} - \omega^2\mathrm{M})\Phi = 0 \qquad 4.4$$

where ω is the frequency of natural vibration.

## 5. PARAMETER IDENTIFICATION

The first identified element of the model was substitute Young's modulus of the reinforced concrete slab Ec which accounted for the influence of the slab's longitudinal reinforcement. The second and the third identified elements were the stiffness of connection $K_h$ and $K_v$. In MB model the stiffness of connection was indirectly identified bydetermination of cross-sectional area A and moment of inertia J for B31 elements.

The best fit of computational and experimental free vibration frequency values was assumed to be consistency criterion. Consequently, the minimised index S can be given by:

$$S = \sum_{i=1}^{5}\left(\frac{f_{i\_flex}^{exp} - f_{i\_flex}^{com}}{f_{i\_flex}^{exp}}\right)^2 + \left(\frac{f_{1\_long}^{exp} - f_{1\_long}^{com}}{f_{1\_long}^{exp}}\right)^2 \qquad 4.5$$

where S is the sum of squares of relative deviations of computational and experimental frequencies. The first five modes of flexural vibrations were represented by $\mathrm{f_{i_flex}}$and the frequency of fundamental mode of axial vibrations by $\mathrm{f_{1\_long}}$.

To optimise the identification process of the three above described parameters, the calculation programs were connected to create a calculation loop. The identification process was controlled inMatlab environment. Using a script developed inPython language, Matlab generated aparameterised model which was then sent over to be analysed in Abaqus. Analysis results were sent back to Matlab where optimisation procedures were used to decide what possible changes were to be introduced to the identified parameters. The procedure was repeated until the minimum of index S was reached. The process was fully automated.

Tables 1 and 2 present a comparison of experimental and computational results of free vibration frequencies determined for five modes of flexural vibrations and one mode of axial vibrations.

Table 1. Beam B1. Identification results – frequencies, relative errors, identified parameters

| | | MODEL MB | | MODEL MS | |
|---|---|---|---|---|---|
| Mode of vibration | $f_{i,exp,}$ [Hz] | $f_{i,com,}$ [Hz] | Relative errors | $f_{i,com,}$ [Hz] | Relative errors |
| $1_f$ | 74,9 | 75,4 | 0,7 | 74,8 | 0,1 |
| $2_f$ | 173,5 | 172,1 | -0,8 | 173,4 | 0 |
| $3_f$ | 274,8 | 275,1 | 0,1 | 276,7 | -0,7 |
| $4_f$ | 375,4 | 375,5 | 0 | 374,6 | 0,2 |
| $5_f$ | 474,9 | 475,9 | 0,2 | 471,1 | 0,8 |
| $1_a$ | 593,9 | 594,5 | 0,1 | 593,9 | 0 |
| RESULTS | S | 1,19E-04 | RESULTS | S | 1,19E-04 |
| | $E_c$[N/m$^2$] | 2,94E+10 | | $E_c$[N/m$^2$] | 2,94E+10 |
| | $A_{zesp}$ [m$^2$] | 1,26E-06 | | $K_v$ [N/m] | 3,83E+07 |
| | $J_{y,zesp}$ [m$^4$] | 1,01E-10 | | $K_h$ [N/m] | 4,64E+07 |

Table 2. Beam B2. Identification results – frequencies, relative errors, identified parameters

| | | MODEL MB | | MODEL MS | |
|---|---|---|---|---|---|
| Mode of vibration | $f_{i,exp,}$ [Hz] | $f_{i,com,}$ [Hz] | Relative errors | $f_{i,com,}$ [Hz] | Relative errors |
| $1_f$ | 74,9 | 76,1 | 0,02 | 75,3 | 0,6 |
| $2_f$ | 173,5 | 178,4 | 0,03 | 179,4 | 0,4 |
| $3_f$ | 274,8 | 287,8 | 0,05 | 290,4 | -0,1 |
| $4_f$ | 375,4 | 392,9 | 0,04 | 394,5 | -0,3 |
| $5_f$ | 474,9 | 496,3 | 0,04 | 494,4 | 0,2 |
| $1_a$ | 593,9 | 593,4 | 0,00 | 586,1 | 0,5 |
| RESULTS | S | 7,50E-03 | RESULTS | S | 8,61E-05 |
| | $E_c$[N/m$^2$] | 2,94E+10 | | $E_c$[N/m$^2$] | 2,94E+10 |
| | $A_{zesp}$ [m$^2$] | 5,63E-06 | | $K_v$ [N/m] | 1,39E+08 |
| | $J_{y,zesp}$ [m$^4$] | 1,25E-10 | | $K_h$ [N/m] | 3,40E+08 |

The next step was an analysis of the modes of free vibrations. The points in the computational model, for which modal vector components were determined, were assumed so that they overlapped with the measurement grid used in the experimental research - see Figure 5. Vector components in the vertical direction (the axis y) were analysed.

A comparison of corresponding experimental and computational modal vectors for the first four modes of flexural vibrations was conducted using MAC (Modal Assurance Criterion).

$$MAC = \frac{(\boldsymbol{\psi}_{exp}{}^{H}\boldsymbol{\psi}_{com})(\boldsymbol{\psi}_{com}{}^{H}\boldsymbol{\psi}_{exp})}{\boldsymbol{\psi}_{exp}{}^{H}\boldsymbol{\psi}_{exp}\boldsymbol{\psi}_{com}{}^{H}\boldsymbol{\psi}_{com}} \qquad 4.6$$

where $\boldsymbol{\psi}_{exp}$ is the modal vector of the modes of vibration obtained in the experimental research and $\boldsymbol{\psi}_{num}$ is the modal vector determined with the computational model.

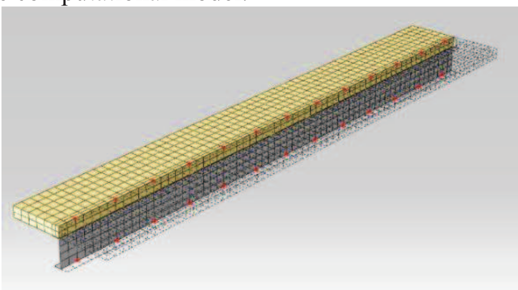

Fig. 5. The measurement grid used in the experimental research

A comparison of experimental and computational (MB model) modal vectors corresponding to the second flexural mode of vibrations is presented in Figure 6.

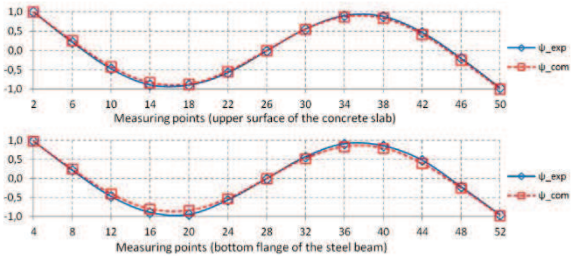


Fig. 6. Comparison of normalized modal vectors, second mode of flexural vibrations, MB model, vertical direction - axis *y*

MAC values for five flexural mode of vibrations for MB and MS models are presented in Table 3.

Table 3. MAC values for MB and MS models

| BEAM | B1 | | B2 | |
|---|---|---|---|---|
| MODEL | MB | MS | MB | MS |
| $1_f$ | 1,00 | 1,00 | 1,00 | 1,00 |
| $2_f$ | 1,00 | 1,00 | 1,00 | 1,00 |
| $3_f$ | 0,99 | 0,98 | 0,98 | 0,98 |
| $4_f$ | 0,99 | 0,93 | 0,98 | 0,98 |
| $5_f$ | 0,95 | 0,81 | 0,67 | 0,57 |

## 6. CONCLUSIONS

The developed FEM models of steel-concrete composite beams B1 and B2 are highly consistent with real beams. The identification of selected parameters provided a very good fit of free vibration frequencies (a precision of ~1%). A further analysis of modal vectors confirmed their high consistency (MAC ~1.0). Combining computation programs into an automated computation loop optimised and accelerated the process of parameter identification. Acomparison of two connection modelling techniques - MS and Mb models - revealed that MS better reflects the behaviour of a real structure. Using MS model it is also possible to directly define connection stiffness whereas in MB model it is possible only through indirect modifications of the values of cross-sectional area A and moment of inertia J for B31 elements.

The time required for solving an individual task was much shorter for MS model which is important bearing in mind that during identification process every model is repeatedly recalculated.

The identified models were used to analyse beams with locally damaged connection. Simulation results are being analysed.

The future plans include a development of simplified FEM models of composite beams using shell elements for modelling the concrete part and beam elements for modelling the steel part.

## 7. ACKNOWLEDGMENTS

This research was carried out with the financial support of the Ministry of Science and Higher Education in Poland in the years 2010–2012.

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