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Numerical analysis for the beam with composite dowels connector

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ABSTRACT:
The focus of the study was on the numerical analysis of the model of the beam integrated with the innovative shape of connector in the form of the cut-out web. The model can be used as an integrated binding joist or bridge girder. This type of connector was a specifically shaped part of the web of the steel section. The first part of the study was focused on the analytical design of the integrated beam. A hot-rolled cross-section was chosen from the half of the hot-rolled HEB section. The second part of the study was modelling of the inte-grated beam. Beam geometry, load and boundary conditions were used as in the first part of the study. ADINA software, based on the finite elements method, was used for numerical analysis. The HEB steel section and the reinforced concrete slab were modelled by means of 3D Solid elements, whereas the reinforcement bars were modelled using truss type ele-ments. The stresses and strain in the steel and concrete elements, distribution of forces in reinforcement bars and concrete cracking were evaluated.

KEYWORDS:
integrated structures; steel-concrete integrated beam; connector for integration; FEM

1. Introduction

Steel and concrete integrated floor structures have been already popular in the industrial construction sector. Steel-concrete composite structures are result of well connection between steel construction elements and reinforced concrete or compressed, eventually with others construction elements made of concrete. The composite behaviour is a combination of two parts of construction element in such a way that during calculation they could be treated as a one single system. Steel-concrete composite structures arised from improvement of monolithic reinforced concrete construction with self-supporting reinforcement. Mechanical connectors are required to connect a steel beam with a reinforced concrete slab. Below introduced shear transfer scheme by the popular headed stud shear connectors. Shear force F passed to the connector through the flange of steel beam is balanced by the resultant of compressive stresses in the concrete. In the case of the standard load to the industrial floors and warehouse floors, the typical solutions of integrated concrete slabs with steel beams have been widely known. Large load of around 20÷25 kN/m^2 leads to the problems with the height of the steel section, which increases

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the height of industrial objects, with particular focus on warehouse areas [1, 2], as well as the defined problems can be supported by the professional experience of a building constructor of author. One of the especially interesting solutions is the system of connectors made of the specially formed web of the steel beam. Despite the atypical cutout of the web, this does not represent a technical problem. Nowadays, each important factory which manufactures steel structures is equipped in machinery for precise sheet metal cutting. The solution of the integrated floor made of reinforced concrete slab connected with the I-beam with the web cut out in a specific way has been used in bridge structures. Therefore, it can be also used for the heavily loaded industrial and warehouse floors.

2. Structure of the integrated beam

The first attempts to use perfobond strip integration were made in the eighties of the 20th century [3]. This was flat steel section with holes, welded to the top flange of the steel beam and embedded in concrete (Fig. 1). Integrated beams with the connector in the form of the cut-out web called concrete dowels were used to the end of the 20th century, when the steel and concrete integrated bridge was designed for the first time using the VFT methodology (Verbund-Fertigteil-Träger – prefabricated composite beam) [4].

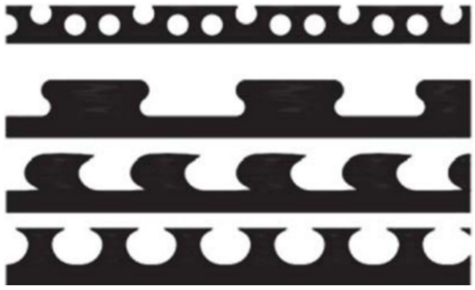

Fig. 1. The *perfobond* strip and various shapes of *composite dowels* [4]

Integrated structures using connectors in the form of shaped section web started to be developed in the eighties of the 20th century. Development of this type of structures in the following years resulted in preparation of the Guidelines for design of prefabricated enduring beams based on innovative shear transmission [5]. The overview of historical and modern solutions for integration were presented in the study [6] (Fig. 2).

In the design practice, there are cases of the load to warehouse floors reaching 20÷25 kN/m^2. The solutions presented in the studies [3] can be adjusted, on smaller scale and with some modifications, to industrial warehouse floors. This study analysed the integrated beam (Fig. 3) in the form of the hot-rolled HEB 600 section (1) cut in half with adequate shaping of the web (2) in order to ensure integration. The support was provided by a flat steel section welded to the web of the steel beam (3). The flat section can represent the support for the trapezoidal sheet metal, which will perform the function of the permanent formwork. The reinforced concrete part is represented by the concrete slab with 130 mm thickness (4). The reinforcement bars (5) were located in the symmetry axis of the integrating cutout.

The aim of the work was to analyse an innovative type of connector. The detail of the cut-out of the web of the steel beam is presented in Figure 4. The cutout with the width of 100 mm and height of 60 mm was shaped so that after cutting the steel section, the halves represent two identical elements.

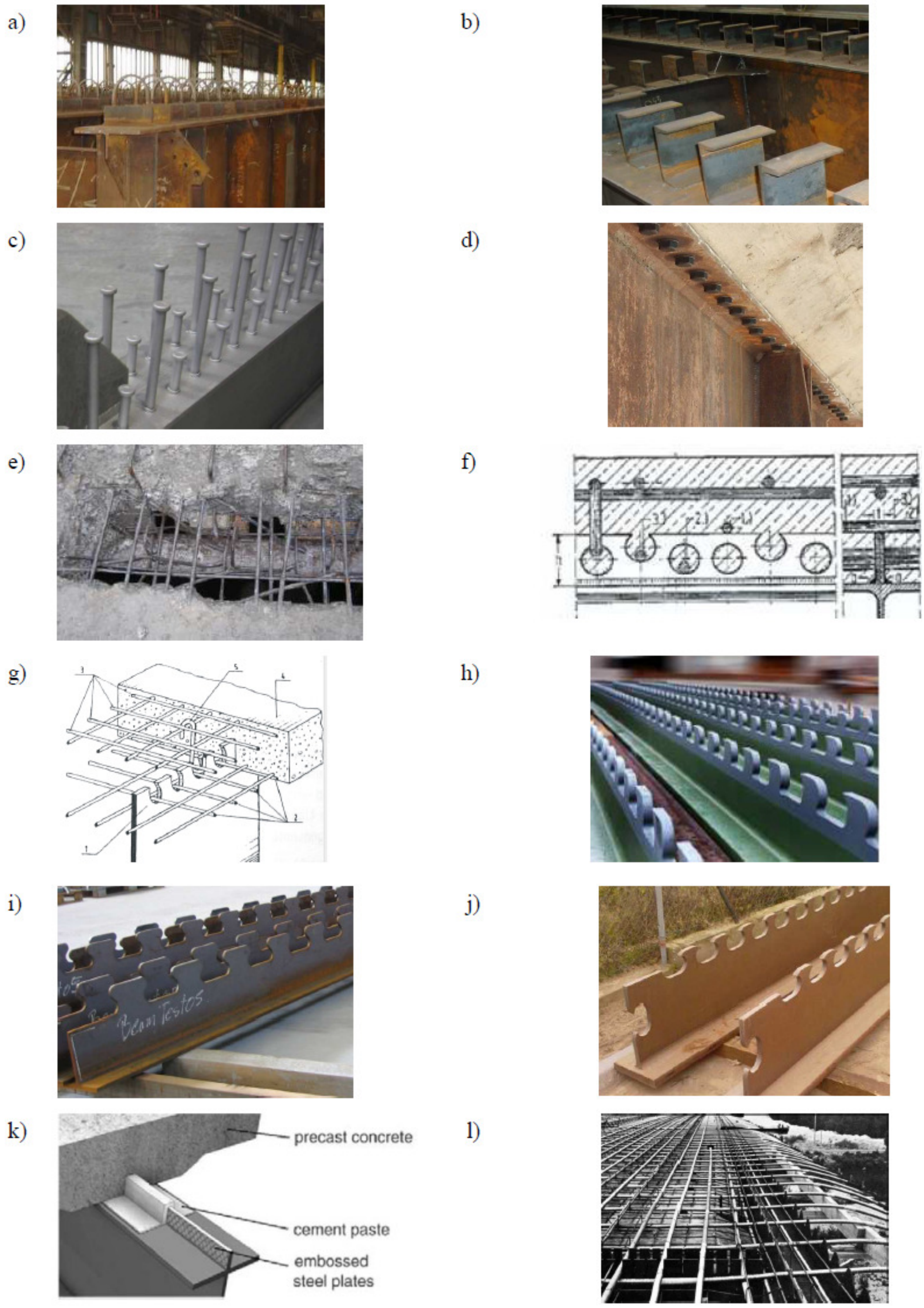

Fig. 2. Different types of shear connectors: a,b) block connectors, c) welded studs, d) screws, e) welded bars, f) perfobond strip (concrete dowels), g) kombi (concrete dowels), h) shark fin shape (composite dowels), i) puzzle shape (composite dowels), j) final CL shape (composite dowels), k) shear connection based on friction, l) shear connection based on friction by prestressed cables [6-11]

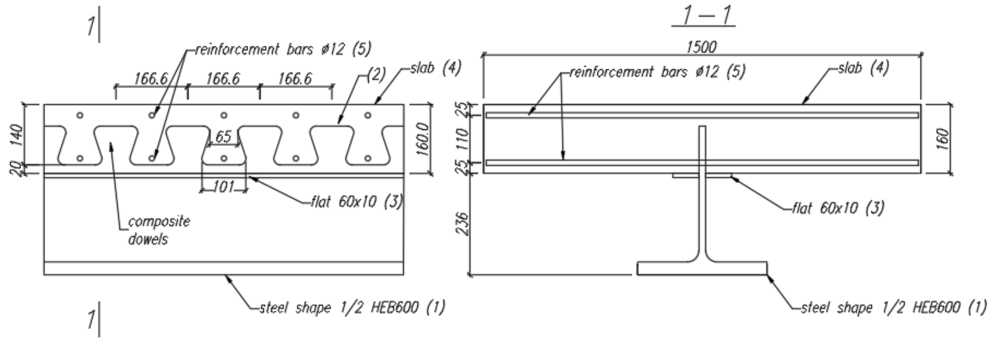

Fig. 3. The designed integrated beam: 1 – steel beam of ½ HEB600, 2 – connector in the form of a cutout, 3 – flat steel sections 60x10 mm, 4 – reinforced concrete slab, thickness: 130 mm, 5 – bar reinforcement ø12 mm

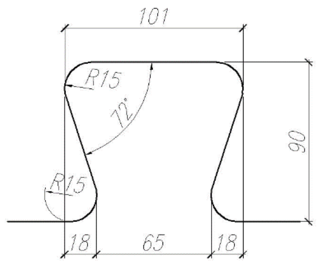

Fig. 4. Details of cutout. The designed integrated beam's span is 6 m. The distance between the beams is 3 m

3. Analytical calculation

The analysis concerned the integrated beam as presented below (Fig. 5). The calculated effective width of the beam Leff is 150 cm. In order to simplify the analytical model of the integrated beam, the shape of the trapezoidal sheet metal which can be used as formwork for the concrete slab was neglected. Integration is obtained by means of the formed connectors cut out in the web of the beam as illustrated in Figure 4. Analytical calculations were performed for the concrete slab made of C30/37 concrete with the characteristic compression strength of 30 MPa and Young's modulus for the concrete of E_{cm} 33 GPa. The steel beam was made of S235JR steel with the yield point of 235 MPa and Young's modulus of 210 GPa.

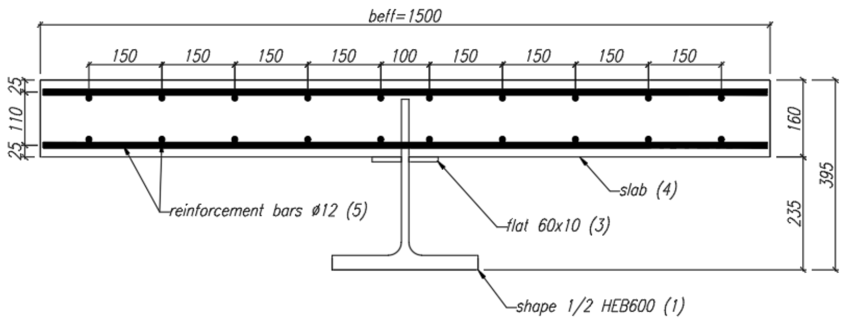

Fig. 5. The cross-section of the analysed integrated beam with distribution of the main reinforcement in the slab

Calculations were performed for the useful load to the floor of 25 kN/m^2.

The computational bending load capacity of the integrated beam was 953.3 kNm. The main stresses from the characteristic load in the steel beam were 110.7 MPa, whereas stresses in the concrete slab were 10.5 MPa. The calculated deflections were 7.3 mm, with the permissible deflection adopted for the secondary beam L/250 of 24 mm.

4. FEM based numerical analysis

4.1. Assuptions for the numerical model

The model of geometry and FEM computations for the analysed beam were prepared using Adina 9.2 software. For the material of the steel section, the elastic model of structural steel S235 was adopted, with the following parameters:
- density ρ = 7850 kg/m^3
- Poisson's ratio ν = 0.3
- Young's modulus E_a = 210 GPa
- yield point f_y = 235 MPa

For the material of the reinforcement bars, the elastic model of steel A-IIIN RB500W was adopted, with the following parameters:
- density ρ = 7850 kg/m^3
- Poisson's ratio ν = 0.3
- Young's modulus E_s = 205 GPa
- yield point f_{sk} = 500 MPa

For the concrete C30/37, the model with the following parameters was adopted:
- density ρ = 2500 kg/m^3
- secant modulus of elasticity E_{cm} = 32 GPa
- mean concrete axial tensile strength f_{ctm} = 2.9 MPa
- characteristics compressive cylinder strength of concrete at 28 days f_{cm} = 38 MPa
- the lowest strain at which compressive strength of concrete is ε_{c1} = 2.2‰
- final compressive strength of concrete f_{ck} = 30 MPa
- strain limit ε_{cu2} = 3.5‰.

The load applied to the model was 25 kPa (Fig. 6). Two types of support were added to the model: pinned non-sliding support (D) and sliding support, with possibility of moving in X axis (C). Furthermore, on lateral surfaces of the slab, the boundary conditions were added (B) that permitted movements in Z and X axis. The span of the slab in the FEM model was assumed as consistent with the actual state i.e. 3.0 m.

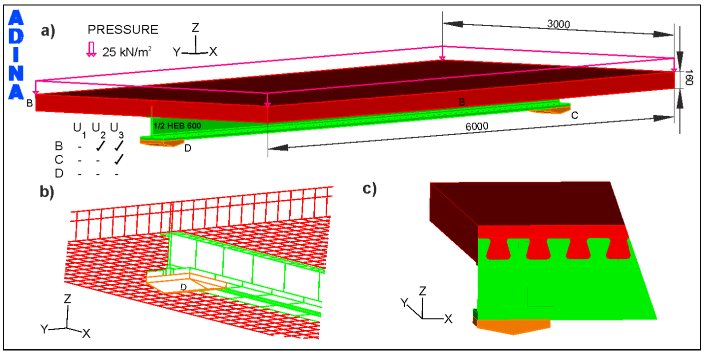

Fig. 6. Method to load the integrated beam and boundary conditions of the support

The geometrical model is composed of the 3D solid elements (27-node elements) for the steel section and concrete. Furthermore, the reinforcement bars and stirrups were modelled as one-dimensional 3-node bar elements of truss type. Trass elements carry axial load, i.e. tensile or compressive load. The modelling of reinforcing bars as truss elements made it easier to build a geometry, as well as shortened the calculation time in relation to the full model with 3D elements. The rebar elements were the interaction between the reinforcing bars and concrete slab.

4.2. Results of the numerical analysis

Verification of the numerical analysis was based on the comparison of the results obtained in Adina software with analytical calculations. Comparison concerned the main stresses in concrete and steel sections and displacements of the integrated beam in the centre of the span. Figure 7 presents the maximal deflection of the integrated beam for the load with its own weight, half of the useful load and maximal useful load of 25 kN/m^2 adopted for the analysed beam. Maximal displacement of the integrated beam calculated using the method of equivalent cross-section is 7.30 mm, whereas maximal model deflection determined in the numerical model is 6.79 mm.

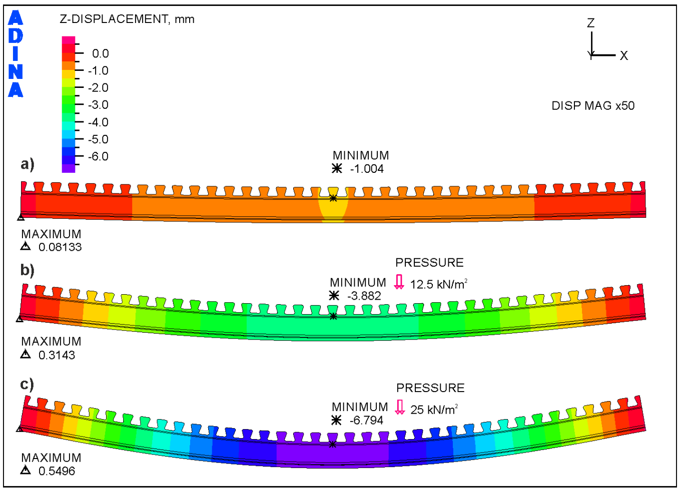

Fig. 7. Maximal beam deflection in the centre of the span at the load with its own weight, half of the useful load and maximal useful load of 25 kN/m^2

Figure 8 illustrates the main stresses and directional XX stresses in the steel beam at maximal adopted useful load to the slab. Maximal tensile stresses of 100.4 MPa are observed in the centre of the span.

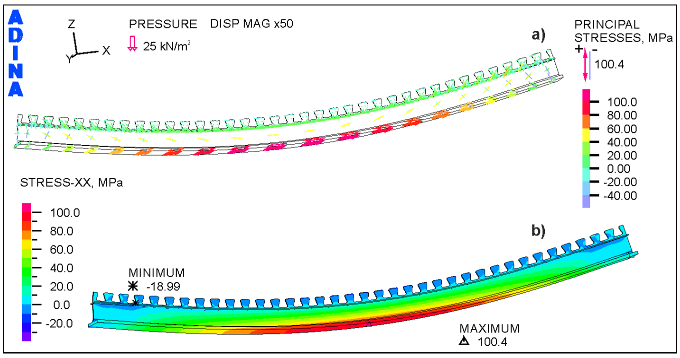

Fig. 8. Maximal stresses in the steel beam under the assumed useful load of 25 kN/m^2:
a) main stresses in the beam, b) directional XX stresses

Figure 9 shows the main stresses and directional XX stresses in the concrete slab. Figure 9a presents maximal stresses in the concrete slab cross-section in the centre of the span of 7.47 MPa (compressive stresses), whereas Figure 9b illustrates the distribution of directional XX stresses with indicated local concentration of stresses at the cutout over the support (14.16 MPa).

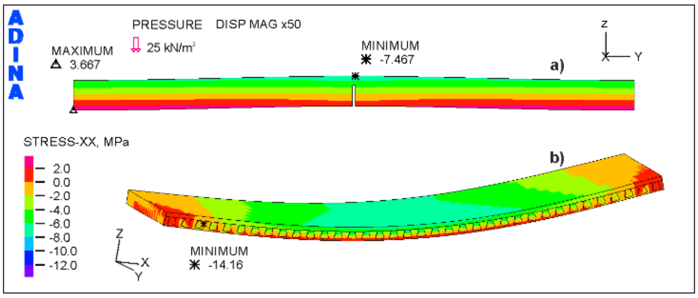

Fig. 9. Maximal stresses in the concrete slab at the assumed useful load of 25 kN/m^2: a) stresses in the centre of the span, b) directional XX stresses

Figure 10 presents the detail of stresses in the connector and 60x10 flat steel section in the most stressed beam cutout. Maximal stresses occur as consistent with the distribution of the transverse force in the near-support zone (support D), reaching the value of 10.98 MPa for compressive stresses and 13.03 MPa for tensile stresses. Concentration of stresses of 59.41 MPa was observed at the flat steel section.

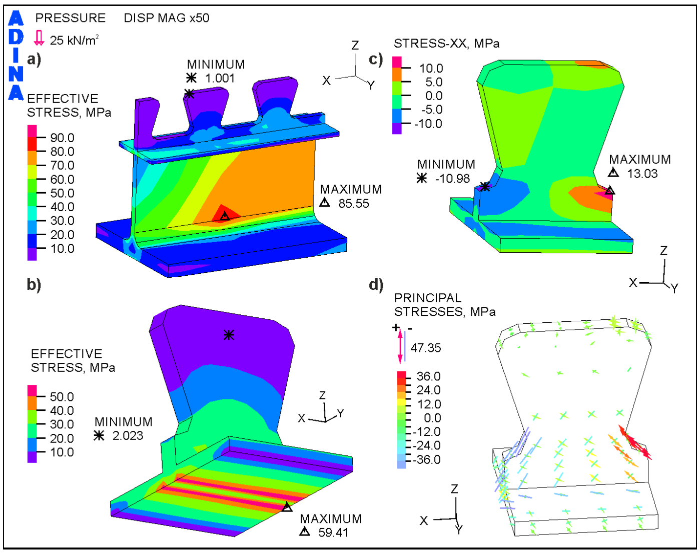

Fig. 10. Stresses in the connector and 60x10 flat steel section over the support D: a) general view, b) concentration of stresses at the flat section, c) directional stresses X-X, d) main stresses

5. Conclusions

The goal of the authors was to create the numerical model of the integrated steel and concrete beam in the Adina software. The paper represents the effect of preliminary studies performed by authors on the model of the floor beam used in warehouses with high useful load. The necessity to reduce the height of the designed floors forces designers to search for new methods to use modern construction technologies. The analysis presented in the study leads to the following conclusions:

– Steel sections with puzzle-shaped cutouts represent a good proposal for the steel-concrete integrated beams used for warehouse floors.
– Beam load capacity is 953.3 kNm and, with useful load of 25 kN/m^2, the cross-section is used at the level of 61%.
– Ratio of maximal displacement determined using the finite element method to the analytical method is 0.95 (maximal displacement of the integrated beam calculated using the method of equivalent cross-section is 7.30 mm, maximal model deflection determined in the numerical model is 6.79 mm).
– Ratio of maximal stresses in steel, this value is 0.91 (maximal main stresses from the characteristic load in the steel beam were 110.7 MPa, maximal model stresses in steel determined in the numerical model is 100,4 MPa).
– Ratio of stresses in the case of the concrete slab was 0.71 (maximal main stresses in the concrete slab were 10.5 MPa, maximal stresses in the concrete slab cross-section in the numerical model is 7.47 MPa).
– The greater difference between determination of stresses in the numerical model and analytical determination is likely to have been caused by model cracking. This may be due to the width of the concrete slab.
– The numerical model adopted in the Adina software precisely reflects the level of stresses and strain. Therefore, in further work, a parametric analysis of steel-concrete composite beams with composite dowels is planned.

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Analiza numeryczna belki z łącznikami „composite dowels"

STRESZCZENIE:
Celem pracy była analiza numeryczna modelu belki zespolonej z nowatorskim kształtem łącznikiem w postaci wyciętego środnika. Rozpatrywany model może mieć zastosowanie jako zespolony podciąg stropowy lub dźwigar mostowy. Badany rodzaj łącznika był odpowiednio wyprofilowaną częścią środnika

kształtownika stalowego. Pierwsza część pracy polegała na analitycznym zaprojektowaniu belki zespolonej. Dobrano przekrój gorącowalcowany z połowy kształtownika gorącowalcowanego HEB. Druga część pracy polegała na zamodelowaniu belki zespolonej. Geometrię belki, obciążenie oraz warunki brzegowe zastosowano takie, jak w części pierwszej pracy. Analizę numeryczną przeprowadzono za pomocą programu ADINA System opartego na metodzie elementów skończonych. Profil stalowy HEB i płytę żelbetową zamodelowano za pomocą elementów typu 3D Solid, natomiast pręty zbrojeniowe zamodelowano za pomocą elementów typu truss. Dokonano oceny naprężeń i odkształceń w elemencie stalowym i betonowym, rozkładu sił w prętach zbrojenia oraz zarysowania betonu.

SŁOWA KLUCZOWE:
konstrukcje zespole; belka zespolona stalowo-betonowa; łącznik do zespoleń; MES