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Prefabricated Composite Beams Based on Innovative Shear Connection

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ABSTRACT

Composite structures, especially steel-concrete composites have a great potential of use in the building industry. A correct combination of materials and elimination of disadvantages of used material may lead to significant savings in aspects like the amount of material used, and time needed for construction. Also cost reduction while using composite structure instead of the structure fabricated only from one material should be mentioned. The paper focuses on the design of alternative solutions for composite steel-concrete structures with encased steel beams. Simultaneously, a design model was developed using the Abaqus software environment. The exact physical properties of the individual materials were verified by experiment. Tensile strength of steel, compressive strength of concrete, bending strength of concrete in tension, and splitting tensile strength were determined along with the modulus of elasticity of concrete in compression. The correctness of the design model applied by means of the Abaqus program was experimentally verified.

1. Introduction

Deck bridges with concrete encased steel beams, where steel beams of I cross-section act as rigid tensile reinforcement, has been used in the building industry for many decades. The use of

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mentioned beams as compressed reinforcement in proven to be inefficient. Nowadays the issue of composite structures is becoming more important. Materials used for construction in building industry has many beneficial properties, but the disadvantages can’t be forgotten. To increase performance of structures and to lower disadvantageous properties of single material, two or more materials may be combined to create composite structure.

Deck bridges with concrete encased steel beams are convenient for construction of short and medium spans bridges, as they have many advantages like low construction thickness, clear static action, simple construction, short execution time, construction without supportive scaffolding, easy maintenance and many others [1]. The main disadvantage shall be inefficiency of steel I cross-section beams, used in majority of deck bridges. This brings the necessity of development of more suitable design processes and more effective arrangement of steel beams in mentioned composite structure [2]. New design methods are being published in scientific papers around the world dealing with this topic. Very often deck bridges with concrete encased steel beams are used across Europe for example in France and Germany [3,4]. There are few standards which deal with design methods of deck bridges with concrete encased steel beams. In USA bridges with concrete encased steel beams has been used for more than 90 years. Nowadays they are designed according to AASHTO LFRD Bridge Design Specifications [5]. In Czech Republic newly created “Mostový vzorový list” [6]. deals with this type of bridges. In Slovakia the situation around standards for design of the deck bridges was even more complicated as only one national standard dealing with the topic was accessible, but this document used approach of allowable stresses which does not corresponds with limit state method. Nowadays deck bridges with concrete encased steel beams are designed according to STN EN 1994-2 standard [7]. This standard describes design methods for assessment of a deck with encased beams of hollow cross-section and welded I cross-section. Bottom surface of lower flange is not covered by concrete but works as stay-in-place form. In near future new standards for design of railway bridges based on Eurocode standards should be released.

2. Concrete encased steel beams structures

Deck bridges with concrete encased steel beams consists of rolled steel section, which lays on supports of a bridge and later concrete is pour around to cover whole surface of a steel beam. Concrete interacts with those beams in compressed part of the deck, reinforcing it and perfectly prevents the beams from the loss of local and global stability (buckling). Also concrete protects beams from corrosion, therefore it is no need for anticorrosion coats and their renewal. The disadvantage is in higher use of steel and a requirement for big density of beams [8].

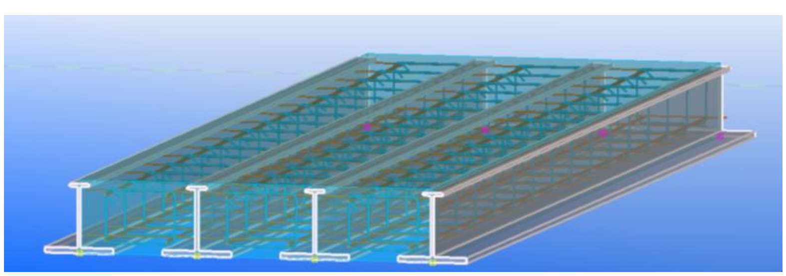

Fig. 1. Structure with concrete encased steel beams with I cross-section.

3. Proposed solution for deck bridges

A pursuit of reaching maximum possible effectiveness of a cross-section brought us to hypothesis to design steel profile which will mostly act in the tensile area of future composite bridge. Various types of steel cross-section were considered. Our aim is to design and experimentally verify deck bridges with modified steel profiles to achieve higher efficiency, mainly by reducing the amount of steel needed.

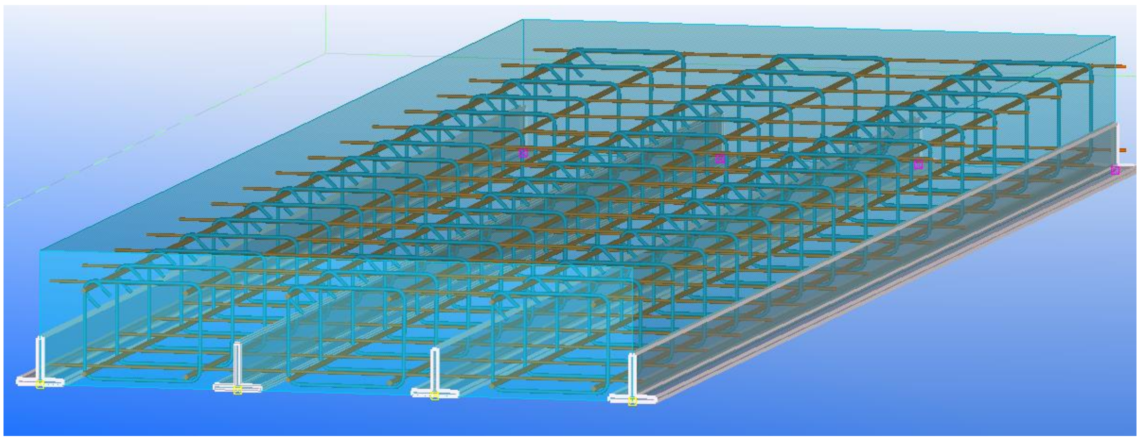

Fig. 2. Modified steel beams in steel-concrete composite structure.

In the laboratory a set of specimens of modified shapes of steel cross-sections was designed and tested. The agenda of experimental research includes tests of five types of specimens in real size with concrete encased steel strips with different modifications to secure interaction between steel and concrete. Length of all specimens was 6000 mm and width was 900 mm. Thickness was 270 mm, which was derived from ground plan dimensions of the specimens in order to assume layout of steel reinforcement as in a real structure. There are two steel beams in each specimen. Those beams were supported in longitudinal direction by additional bar reinforcement of the diameter of 12 mm in the border area of the specimens to provide stability of the beams and interaction with lateral reinforcement. The aim of this scientific analysis is to propose and experimentally verify deck bridges with concrete encased modified steel beams in order to reach material savings in the way leading to higher efficiency of a design. Based on the experimental results two types composite structure were chosen, which were later modified. Bottom face of the tested structure was lightened by arch form between the rigid steel reinforcement.

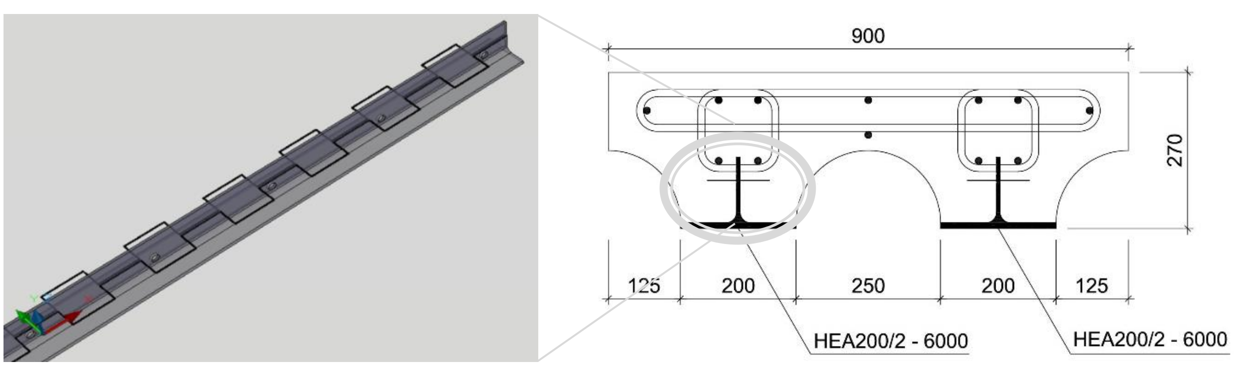

Fig. 3. Cross-section of beam NV2 with composite action using reinforcement loops.

4. Experimental loading test

Short term tests of the beams tested in described experimental analysis were provided in the laboratory of Faculty of Civil Engineering in Košice. After putting the specimen in loading frame they were automatically loaded by dead load of self-weight, as tested beams were fabricated (casting of concrete and hardening) on the pad. Maximum bending moment recorded from self-weight was M_g = 27,33 kNm. The specimens were tested in four point bending test. Two forces were applied on the surface of the specimen 2000 mm from the edge of the beam. Axial distance between those forces was set to 1800 mm and free edge was extended 100 mm behind the support (Fig. 4). Specimens were loaded by one hydraulic press and forces were divided in two by walking beam. The beam was supported by pin support on one side and by roller support on the other.

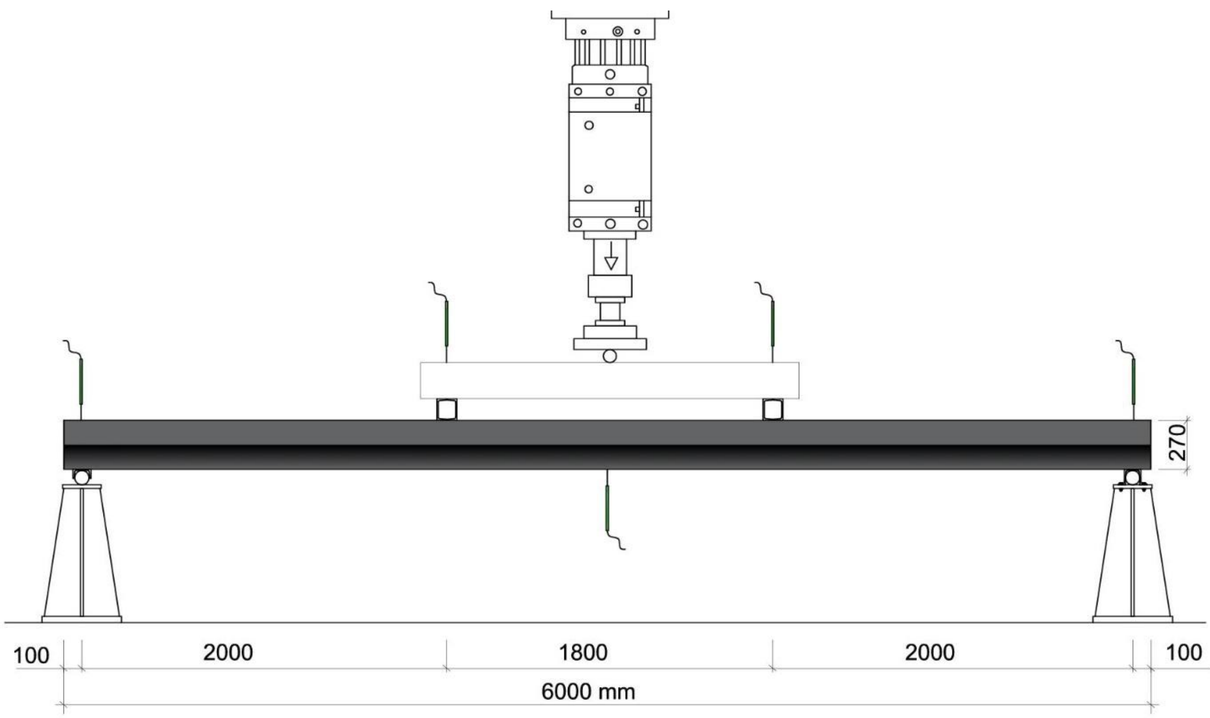

Fig. 4. Static scheme of composite beam and layout of sensors.

The load was gradually increased by 20 kN by hydraulic press. The beam was unloaded twice during the test. First time it was unloaded at load of 210 kN to load of 50 kN. Second time at the value of the load of 350 kN to 150 kN. The force was recorded in hydraulic press and distribution of forces in walking beam was assumed to be equal. After consolidation of deflections at each loading step, deflections by inductive sensors and strains by strain gauges were recorded. Strain gauges were placed on the spots on steel beams which were predicted to be the most affected by bending forces. Inductive sensors recorded deflection in the middle of span and in close proximity of supports.

Fig. 5. Loading test being performed on the specimen.

After exceeding tensile strength of concrete, micro cracks appeared in the part of concrete in tension. Those cracks were expanding in proportions as the load was increasing up to reaching the plastic neutral axis. The tests were stopped if it wasn't able to rise load applied on the beam. There was significant increase in deflection without any increment in loading force. During the tests the strains in steel beams were measured and recorded by strain gauges. Inductive sensors noted deflection in the middle of span of the beam and around supports. Relationships between the load and the deflection at mid-span is shown in the figure 6.

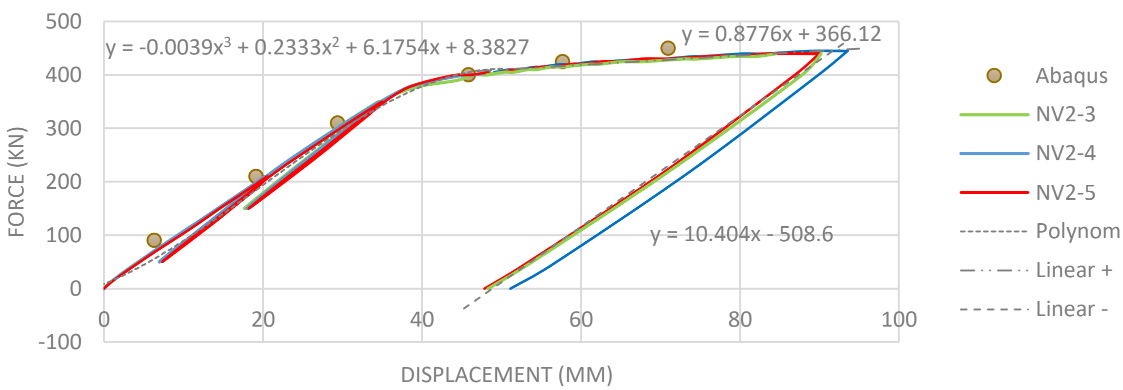

Fig. 6. Load-deflection relationship diagram.

5. Numerical analysis in Abaqus

Numerical model is based on experimental analysis of tested specimens in laboratory. 3D model of composite beam is shown in figure 4. Numerical analysis of the beam was performed in Abaqus software. The symmetry of the beam and load was used in model, so only half of the beam was modelled. The load was introduced through cylinders of 70 mm in diameter, which were mounted on the rigid 40 mm thick bar. The beam was support by linear supports at both ends. Supports and action of forces correspond with the procedure during experimental analysis.

The elements of concrete, steel beams and steel reinforcement bars consist of 3D finite elements. Plastic deformations of concrete and steel elements were taken into consideration.

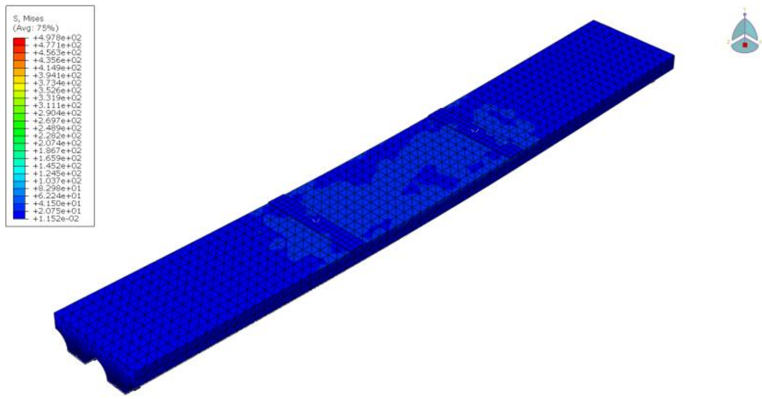

Fig. 7. Model of the specimen created in Abaqus software.

For modelling concrete part of the beam “Concrete Damaged Plasticity“ modelling material was chosen. As solver “Explicit dynamics” was picked, where the acting time of force was set to 0,1 s. Contact between the support and the beam was considered as general “Explicit Contact”. Contacts between concrete and steel was modelled as rigid joints [9]. Results of numerical analysis were compared to experimental analysis results. Software Abaqus simulates crack formation using plastic model of concrete. In reality there is no material in a crack. Mentioned software uses a model where it puts Elastic-Perfectly Plastic material in the crack. In the modelled beam the crack appears in concrete as plastic deformations. At the point of crack initiation towards the centre of the beam, where the stress is the greatest, plastic behaviour of the steel occurs. The stresses decrease towards the supports (Fig. 8).

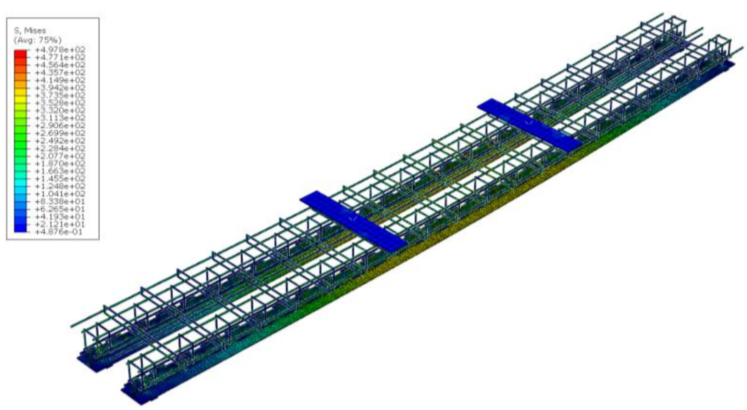

Fig. 8. Relative plastic behaviour of rigid steel reinforcement.

In addition to the relative deformations and stresses, the deflection is a significant indicator of the structural behaviour. The deflection depends on the stiffness of the element. The deflection is the highest in mid-span, but its magnitude depends on the stiffness of the whole element. The stiffness of concrete encased steel beams varies along the length. In the parts of the beam where tensile stresses do not exceed tensile strength of concrete, a bending stiffness is E1. This stiffness is estimated taking into account whole concrete area of the cross-section. The stiffness of cross-sections where cracks are fully developed EI1 is calculated excluding the concrete in tension. In the parts of beam between those two mentioned areas the stiffness changes gradually. In experimental analysis the deflections was recorded at several points. The following diagram compares the measured deflections in the centre of the span in experiments with the results obtained from the numerical model (Fig. 6).

6. Conclusion

Experimental analysis has shown that the resistance of lightweighted concrete beams with inverted T-shaped steel beams with secured continuous coupling is comparable to concrete beams with I cross-sections steel beams.

The values obtained from experiments were compared with results from numerical model created in the ABAQUS program, which provides the possibility of modelling concrete with the possibility of simulating plastic deformation. Such a model is necessary to describe the behaviour of a real structure in which concrete also acts in the tension. Comparison of experimental test results and numerical models shows good agreement. For further investigation and processing of the parametric study it will be possible to use existing model from Abaqus software.

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