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STRUCTURAL AND EXPERIMENTAL ANALYSIS OF COMPOSITE TRUSSES

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Abstract: *The composite trusses can be used for greater spans up to the 30 m, which allows better use of internal space without restricting columns. To create the interaction between steel and concrete, it is necessary to prevent the relative slip at the steel and concrete interface using the shear connectors. But the local effects of a concentrated longitudinal force and the distribution of the shear force between steel section and concrete slab, as special task, should be appropriately examined. The finite element analyses were used to investigate numerically this structural system behaviour, exploiting several computer procedures. Four steel-concrete composite truss beams were fabricated and experimentally tested to validate theoretical values. The outputs of this research are presented in the paper.*

Key words: *shear connection, numerical and experimental study.*

1. Introduction

Composite steel-concrete trusses can be considered as one of the most economical systems for building, especially for greater spans, commonly to the 20 m. The continuous structural elements of this composite type can be used for even greater spans up to the 30 m, which allows better use of internal space without restricting columns. The trusses are appropriate also to meet the requirements for building height limitation as well as the need to run complex electrical, heating, ventilating, and communication systems. Also composite steel bridges, whose carriageway deck is supported on a filigree steel truss structure and slim piers, are particularly preferable especially to ordinary concrete bridges. Thus a composite truss bridge, with its speedy assembly engineering can be a structural type which is both economically and aesthetically attractive. To create the interaction between steel parts and concrete, it is necessary to prevent the relative slip at the steel-concrete interface using the shear connectors. But the local effects of a concentrated longitudinal force and the distribution of the shear force between steel section and concrete slab, as special task, should be appropriately examined. The finite element analyses can be used to investigate numerically this structural system behaviour, exploiting several computer procedures. Nowadays, different types of shear connectors are used. In our investigation, shear connection is developed using the welded headed studs.

2. Longitudinal Shear Transfer

2.1.Truss Shear Connection Peculiarity

In actual Eurocode [1], there is no

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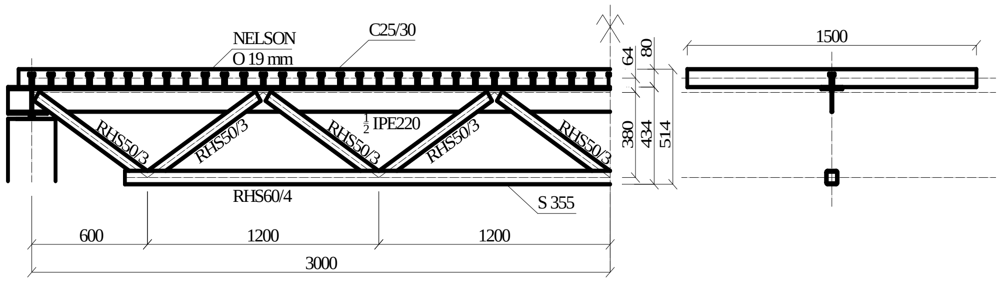


Fig. 1. *Structural geometry and acting loads*

particular recommendation for the design of composite truss. In this case, the longitudinal forces are introduced into the concrete slab locally in the nodes, where the web members are connected to the compressed chord. In this study the influence of the degree of connection, represented by the connector diameter, the impact of the top chord section and the material characteristics of steel and concrete are analysed pondering over the stiffness and the resistance of the beams and the shear forces in the connectors.

Figure 1 shows a typical portion of a reference composite sample, consisting of a concrete deck 1500.80 mm and a steel truss beam, whose the top chord was designed as ½ IPE 220, the bottom chord a rectangular hollow section 60x60x4 and the web members were from RHS 50x50x3. During the analytical phase of this composite truss, the finite-element-based software Castem [2] was used to evaluate the structural integrity of the system. Serious considerations had to be given to proper representation of the geometric characteristics. To ensure a full composite action, shear headed studs connectors 19 mm in diameter were welded at the interface between the concrete slab and the truss top chord to resist interface shear. Therefore, it was important during the initial modelling stages to take into account the node positions as key locations of interest. Thus the model with a higher degree of refinement could be assembled such that important results could be obtained at these zones. Proper type and shape of the elements had also to be considered since different mesh size could sometimes cause significant variations in results. The resulting computer model was used to evaluate the structure system for actions, represented by a series of load cases applied to the structural model. An example of application of the loads is presented also in Fig.1. The analysis was performed with the characteristic values of material properties and obvious assumptions on elastic-plastic stress-strain diagrams of steel S355 and concrete class C25/30, commonly used in practice. The non-linear behaviour of the shear connection was modelled using beam elements uniformly distributed with a regular spacing equal to 100 mm along the span and located between the neutral axis of the top chord and the concrete slab.

2.2. Shear Connection Properties

First of all the influence of the connectors size considering numerous theoretical values of shank diameter varying from 0.1 to 100 mm on truss beam stiffness was analysed. These values represent the progression of the degree of shear stud connection in the truss from no connection to full interaction. It was recognized that the usual diameter of 19 mm is quite sufficient to obtain a full

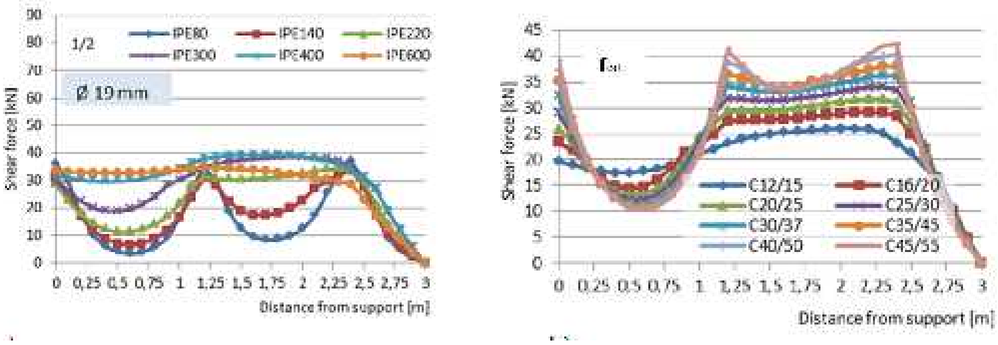


Fig. 2. *Influence of chord sections and concrete strength on shear force distributions*

connection. Moreover, the composite effect obtained by the shear connector diameter variation can increase even twice the stiffness of the truss with no connection in comparison to the composite truss beam with full connection.

The results of the next investigation focused on the effect of the top chord section on distribution of the shear forces in the frequently used 19 mm diameter connectors along the beams are shown in Fig. 2a for different top chord sections. This phenomenon is influenced by the ratio of geometry and resistance between the connector and the top chord section. Thus, it is necessary to optimize this ratio. Otherwise, the connectors in the panel area would transfer the predominant portion of shear forces in comparison to the obvious zones on the chord between the nodes.

The influence of the material characteristics of concrete and structural steel on the distribution of shear forces in the connectors was analysed in the additional parametrical study. The concrete strength is an input value used to calculate the shear resistance of headed studs. Therefore, the greater value of concrete strength can provide a better shear force transfer in the connection. However the concrete strength does not affect significantly the shape of stress distribution by connectors as shown in Fig. 2b. Impact of steel strength of truss material on the shear force distribution in the connectors is small and can be neglected.

3. Push-out Testing

The shear capacity and the load-slip relation are the most important characteristics for the design of the composite structure. The standard push-out tests may be obviously used for finding approximately this relation. To investigate behaviour of connection with different configuration and spacing of the headed stud connectors, five sets labelled as SP1, SP2, SP3, SP4 and SP5, each comprising tree push-out specimens, shown in Fig. 3, were prepared. Thus fifteen standard tests have been carried out. They consisted of a steel beam HEB 260, two concrete slabs attached to the flanges of the steel beam and stud connectors of steel S235J2 with a shank diameter of 10 mm and 50 mm in height. Slabs of concrete class C25/30 were 620 mm long, 600 mm wide. Only in the case of the first specimen SP1, the slab thickness was 150 mm. The other specimens had slabs just 100 mm thick. In the specimens SP1 and SP2, the steel and concrete elements were attached by four stud connectors at each flange using automatic welding procedure. Six studs were welded at each flange of steel members SP3, SP4 and SP5. The longitudinal distances between the connectors differed, too. In SP1 and SP2, these spacing parallel to the loading direction was 250 mm, only 60 mm in SP3 and SP4, then 40 mm in SP5. Transversal spacing was160 mm, with exception of SP5 reduced at 32 mm.

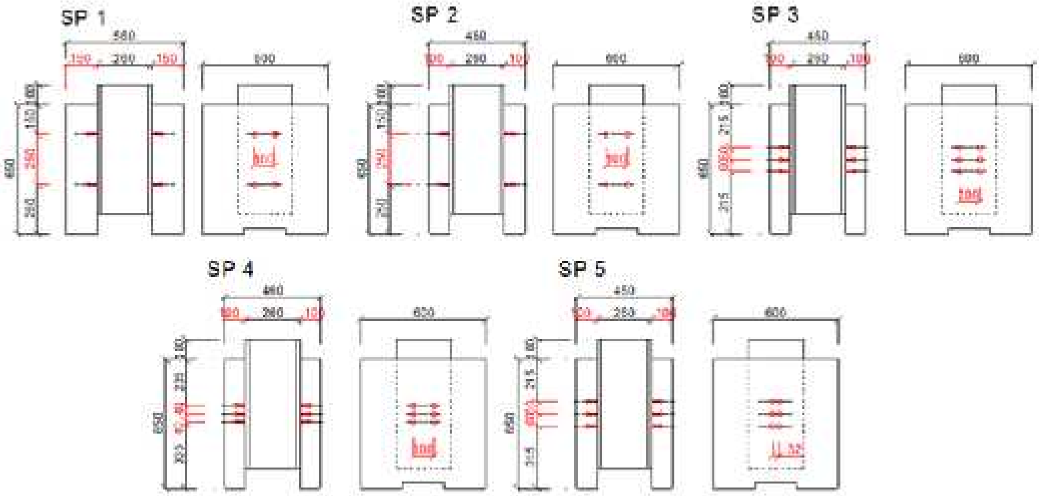


Fig. 3. *Details of push-out test specimens*

According to standard procedure of EC 4 [1], the load was applied in increments of 20 kN from 0 to 100 kN (40% of the expected failure load), then returned to 12 kN (5% of the expected failure load). Later loading was repeated 25 times between 12 kN and 200 kN. At each load increment, readings of the slip between the steel beam and the concrete were recorded. During this cycling loading the specimens remained in good condition, the slabs and the steel beam worked well together, the cracks had not yet been developed at that time. At the end of the 25th cycle, loading was changed from load control to slip control. The slip controlled load continued up to the failure at the speed of 1mm/2 min. At the load of 300 kN, the interface between steel and concrete was delaminated and the slip of 1 mm was achieved. Beyond the load of 300 kN, the cracks began to appear in the slabs. The test ended with the shear of the connectors at the load of 300 kN. The failure of the specimens occurred by shear of the connectors at the loads per one stud given in Table 1. Value $P_{u,min}$ means minimum ultimate load carried by one connector and $P_{Rk,exp} = 0.9P_{u,min}$ equivalent experimental design value. Corresponding slip amounts are also listed in Table 1.

For finite element modelling, nonlinear analysis software ATENA [3] was selected. It is capable to simulate a real behaviour of concrete structures including concrete cracking, crushing and reinforcement yielding.

Fig. 4 shows a comparison between the load-slip curves obtained experimentally and numerically using the finite element method. The load per stud was recorded from fifteen specimen tests, starting SP1 to SP5, illustrated by corresponding group of lines I-1 to V-3, respectively. Theoretical results from numerical analyses of the specimen set SP1 are characterised by line FEM. Minimal values indicated in the picture are also in Table 1. Theoretical and experimental values of forces as well as slip confirm a good agreement between the test and the theory in the range of practically applied loading.

The supplementary comparison of results can be judged also as rather good, if the extremely complex of material grouping and welding procedure are considered. The current move towards generating design data by using numerical models in place of experiments calls for careful attention to random variables. By considering experiments, random variables are usually represented implicitly, leading to a scatter in the results.

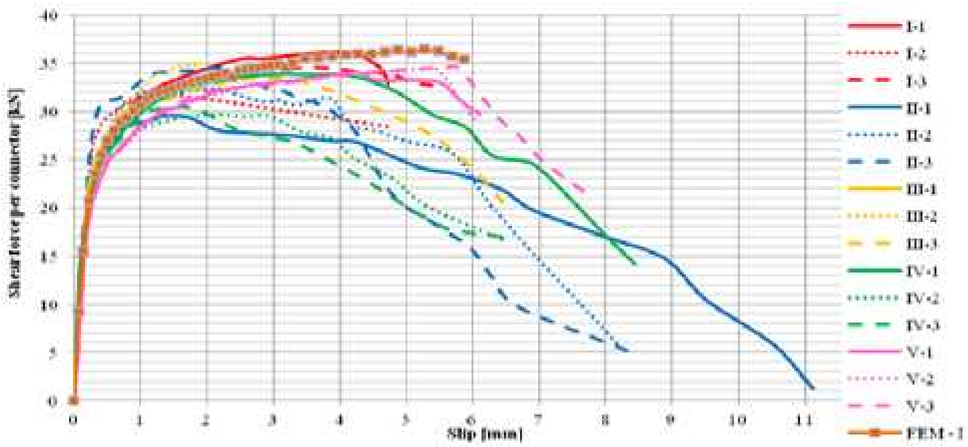


Fig. 4. *Comparison of test and numerical results*

Therefore, there is a need to further review the use of numerical model for producing reliable design data. Since local connection in truss beams is sensitive to choice of the stud location and properties as well as geometric characteristics in these composite structural elements, it would be particularly important to ensure that the variation of input parameters is accounted for.

Carrying capacity of single stud [kN] and slip value [mm] Table 1

specimen	$P_{u,min}$	$P_{Rk,exp}$	s_{uk}
SP1	31,91	28,71	4,5
SP2	29,48	26,53	4,4
SP3	33,29	29,96	4,7
SP4	29,64	26,67	4,1
SP5	34,09	30,68	5,9

4. Composite Truss Beam Tests

4.1. Load Bending Testing

To analyse the real behaviour of steel-concrete composite trusses, experimental investigation has been executed. Four same steel-concrete composite truss beams of span 3.75 m were prepared (Fig.5). Shear connection was provided by headed stud of diameter 10 mm and height 50 mm located above the nodes. For this configuration, the hypothesis, that the longitudinal forces are introduced into the concrete slab only locally in the nodes, was followed. Steel truss components were made from the steel S235. Upper chord of the beam was made from ½ IPE 160, bottom chord from two welded UPE 120 in box component, outside web members from square hollow section SHS 70x70x6.3 and the inner diagonals from the square hollow SHS 40x40x3. Concrete slab of size 800x100 mm was made with demand on concrete grade

C25/30. Transversal and longitudinal reinforcement was formed from the bars ϕR10. Loading was applied in the thirds of span above internal nodes as shown in Fig. 5. The experimental measurement is illustrated on the first truss specimen (Fig.6).

Strains were recorded in both chords and web members of the girders as well as concrete slab by system of sixteen strain gauges. The details of observed locations in cross sections are designated as T1 to T16.

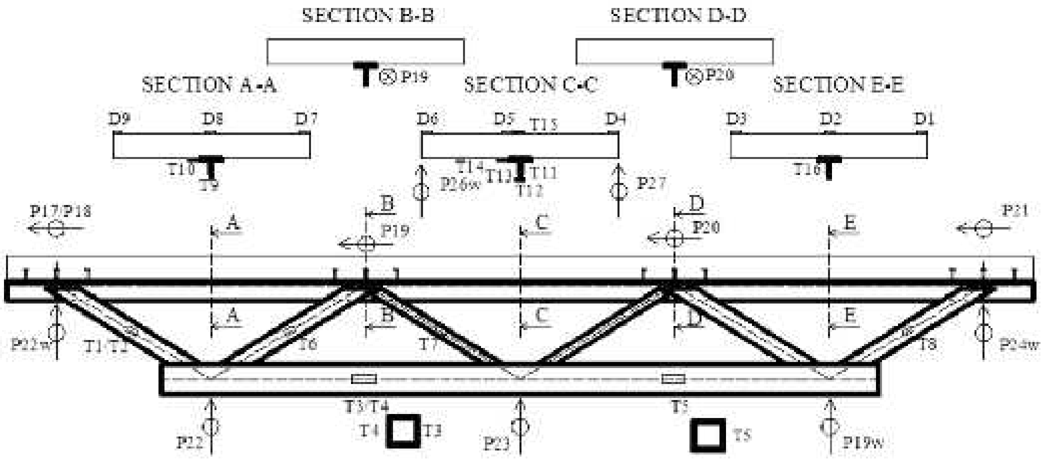


Fig. 5. Components of composite truss specimen.

During the testing the end slips of concrete slab have been measured using displacement sensors. The deflection transducers P22 and P24 were placed on the girders ends, in the middle P23 and near the quarter part of a simple span.

Fig. 6. *Loading and measurement system*

Data received from the strain gauge package are digitized and sent to the notebook. This computer was used to communicate with the measurement system for commands regarding data acquisition, calibration, initialization, downloading and display. The experimental deflections initially were increasing proportionally to the loading level of 325 kN. This value of an elastic limit load carrying capacity was in correlation with the result of the analyses according to EC4 [1]. The overall truss deflections under supplementary loading were growing slightly nonlinearly and develop an ultimate permanent downwards deflection 33 mm at the end of test.

Under small load, the stress distribution in strut sections was rather uniform and progress proportionally. However, with increasing load, the diagram presented new faster stress development. Especially the upper chord has yielded rapidly in the mid-span sections, where it was subjected to bending and compression, because of the beam deflections. Finally the chord failed by local instability. The comparison of stresses must be judged also as good if the extremely complex character of composite truss is considered. The experimental load - carrying capacity of the specimen was 530 kN. Comparison between the numerical and experimental values shows a good agreement.

The slips in shear connection were small in the beginning along the composite beam span. From a symmetrical distribution of slips between the two beams ends observed at the beginning of test; the slip diagram finally became more unsymmetrical in irreversible portion. The extreme final slip at the truss end was 8,1 mm and at the others edge only 5,9 mm. The limit state can be defined by the load under which the connectors in the support zone failed by shearing [4]. Thus the bending failure of connectors in span does not need to be taken in consideration, due to favourable load transmission.

4.2. Vibration Analysis of Specimens

Possible non-destructive technique for identification of structural component behaviour can be based on dynamic properties modification. Successive investigation in several stages may permit to recognize advanced propagation of damages in structural elements as a function of rising loading. Figure 7 represents increasing and dropping loading steps. They started from the theoretically initial untouched first state without loading and going to the final stage of beam resistance exhausting.

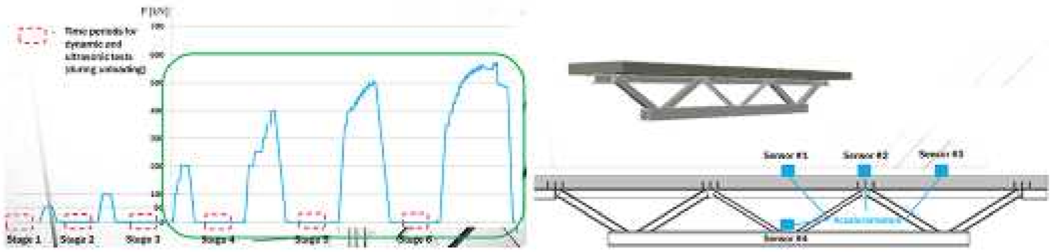


Fig. 7. *Subsequent stages of measurements, acceleration sensor locations*

In every unloaded stage, the truss free vibrations have been excited using a steel hammer two kilograms weight. Generated vertical accelerations have been recorded by four sensors, situated according Fig. 7. Knock was applied at the upper concrete deck side and in the vicinity of accelerometers. Each of measurements was reiterated three times. Accelerograms processing by Fourier´s transformation can provide proper frequencies of free vibrations and eliminate extreme amplitudes of waves from recorded signals, supposing that low damping of trusses can influence only marginally frequencies of ideal free vibrations.

Forms of natural vibration and corresponding frequency values were determined. The dynamic analysis was executed using Autodesk numerical model.

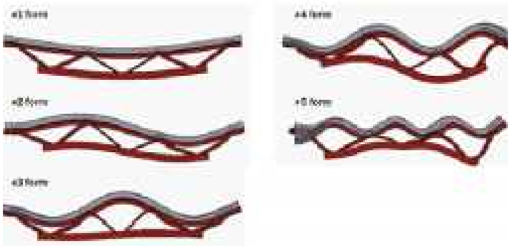


Fig. 8. *Forms of free flexural vibrations*

As example, the first five bending shapes of the structure are shown in Fig. 8.

The corresponding numerical values are listed in Tab. 2. Primarily theoretical frequencies in this table correspond to the infinitely stiff connection at the steel concrete interface. Then, the more realistic values relate to the experimentally determined actual rigidity, specified by a factor k = 54 MN/m are given in the second column. Also, it can be concluded that frequencies are decreasing progressively due to gradual damage propagation in the truss concrete deck. At the end of loading, this frequency depletion varies from 8 to 20 %. Evidentially, the decrease ratio to the initial values for higher free vibrations is greater, probably due to damping and boundary effects.

Free vibration frequencies from finite numerical model and test Table 2

	FEM		Experiment					
			Load capacity utilization [P_{MAX}]					
Form	Virgin state		Virgin state	10% [55kN]	20% [100kN]	40% [200kN]	60% [400kN]	80% [500kN]
	$k_v \to \infty$	k_v=54MN/m						
1	53,4	39,31	39	37,56	37,56	36,12	36,12	36,12
2	79,4	71,02	72	66,45	65	62,12	62,12	62
3	108,2	114,77	111,2	108,4	107	102,6	102,6	101,1
4	148,2	152,05	158,9	153,1	144,5	143	141,6	132
5	180,7	182,13	195	193,6	193,6	189,3	186,4	177,7
6	223,3	225,47	216,7	216,7	216,7	212,4	206,6	204
7	336,8	346,44	302	300,5	300	294,7	283,2	273
8	429,3	406,13	388	387,2	385,7	375,6	355,4	335,2
9	518,6	537,4	502,7	501,3	501,3	494,1	485,4	466,6
10	630,2	653	585	573,5	573,5	567,8	524,4	505

4.3. Deck Ultrasonic Investigation

Propagation time and velocity of waves are reliable parameters in ultrasonic diagnostic of structural materials, especially by means of longitudinal type of waves with highest transmission velocity. An average value of velocity can be obtained by measuring wave time propagation between sending and receiving points. Usually sender and receiver are located perpendicularly at opposite side of a tested specimen providing a shortest and quickest running route.

In every unloaded stage, similarly as during dynamic testing, velocity propagation of ultrasonic waves with frequency of 54 kHz among selected concrete deck points was recorded (Fig. 9). This measurement was repeated three times. Beside two points at the opposite deck surfaces, the adjacent points and in addition also two postponed points were taken into consideration. The average velocity determined from registered times are listed in the table at the Fig. 10. The results indicate the velocity decrease about 30% especially for skew wave movement. For the shortest transversal wave paths between points on opposite sides, the average velocity variations were less significant. The main reason is that cracks started developing and then rising in the crosswise direction of the truss, so matching the wave paths (Fig. 9).

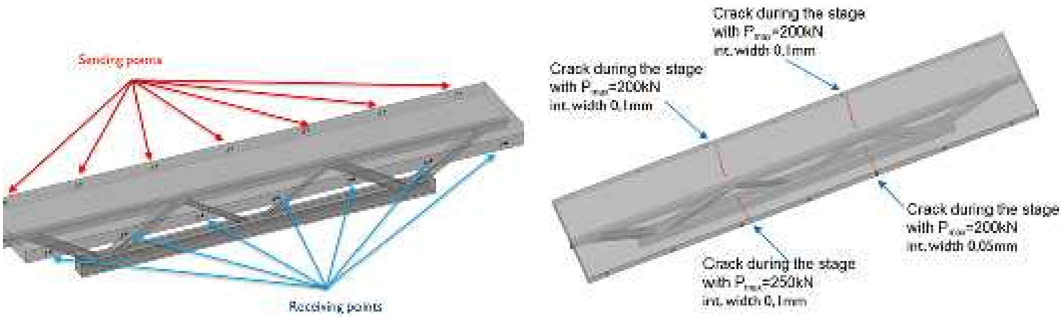
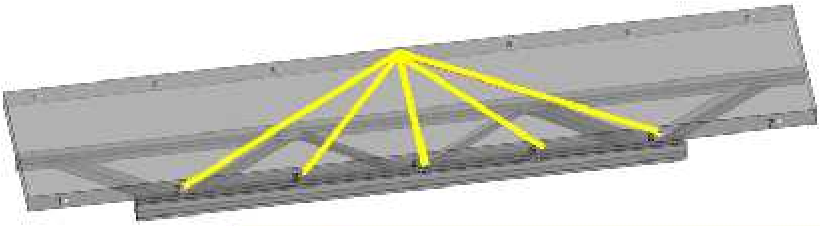


Fig. 9. *Localization of measuring points and visible cracks during testing*

The presented procedure may identify damaged concrete zones due to stress actions. Moreover, the obtained results allow predicting degree and cracking location in the truss deck before appearing at its surface. In the case of tested truss, the cracks became observable only after the third loading stage (Fig. 10).



		The average speed of the propagation of ultrasound waves in various stages [m/s]					
		I stage	II stage	III stage	IV stage	V stage	VI stage
from point „i"	to p. „i"	4208,3	4181,9	4168,8	4160,2	4155,8	4054,7
	to p. „i-1" and „i+1"	4044,6	4003,1	3979,6	3957,9	3820,8	3594,9
	to p. „i-2" and „i+2"	4581,9	4531,5	4298,0	4124,7	3670,7	3425,1

Fig. 10: *Average wave velocity among selected points*

5. Concluding Remarks

The experimental program of push-out and bending test of composite truss beam provided useful test results. The promising finite element models are in progress using solid elements and local damage evolution of concrete. The aim is to investigate the local phenomena between the connectors and the top chord on all the length including the panel points.

Dynamic and ultrasonic non-destructive investigation methods represent effective tools for identification of inner non-evident imperfection also in the case of composite trusses. Deck cracking could be predicted in selected concrete part from beginning of truss loading.

Acknowledgement

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