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Experimental and Numerical Investigation of Concrete Filled Closed Section Steel Beams

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The aim of this paper is to investigate closed section steel and composite beams. Composite beams usually possess an increased stiffness compared to the regular steel profiles. As a consequence, vibrations of the composite beams are lower. What is more, composite beams have a relatively high fire resistance. In many cases, this kind of beams can be used without additional fire protection. Furthermore, when the concrete in the composite beam is compressed, it becomes confined by the steel profile. Confined concrete possesses a more favourable behaviour. It becomes more ductile and can reach a relatively high compressive strength. All those qualities make the usage of the composite constructions beneficial and effective. However, the theoretical evaluation of the composite beam resistance becomes complicated as there are many different models for the confined concrete. Another problem is contact between steel and concrete. It can be evaluated as a friction between different materials or a stiff connection between surfaces.

In this research, experimental tests are carried out. Two steel and two composite beams are tested under bending. Load-displacement curves are obtained. Mechanical properties of the concrete are investigated. Experimental results of the beam bending are compared to those obtained by the finite element analysis. Material model of the concrete confined by the steel profile is used in the analysis. The similar finite element analysis is later carried out to investigate the beams of another author. The validity of theoretical models is investigated.

Keywords: composite beam, confined concrete, buckling, finite element analysis.

Introduction

Composite steel-concrete beams are becoming more and more popular. This kind of beams combine beneficial properties. They possess a high fire resistance, stiffness and lower natural frequencies than regular steel beams. Furthermore, composite beams are not as massive as regular reinforced concrete beams and the steel profile can be used as a formwork for concrete. However, evaluation of the resistance of the composite beam is more complex.

To understand the behaviour of composite beams different authors have carried out experiments. Hassanein et. al. (2017) has done bending experiments for thin walled closed section rectangular composite beams filled with two types of concrete: regular concrete C80 and glass-fibre reinforced cementitious material FC55 and FC60. It was found that the strains in the steel profile filled with cementitious material were higher than the strains in the profile filled with regular concrete. What is more, the cracking started at the higher load. It was also found that regular concrete filled

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beams had a lower toughness and were able to absorb less energy than beams filled with cementitious material. Soundararajan and Shanmugasundaram (2008) have done a similar experimental research on closed section steel beams filled with different types of concrete: normal mix concrete (NMC), fly ash concrete (FAC), quarry waste concrete (QWC) and low strength concrete (LSC). The authors have found that filling the steel profile with NMC, FAC, QWC has increased the resistance of beam by up to 25 % and filling with LSC led to a 16 % higher strength.

Some authors have combined experimental tests and finite element analysis. Lu et. al. (2007) has done a research on non-uni-thickness welded steel beams. The beams consisted of the thicker bottom plate (t_2) and thinner top plates and webs (t_1). Authors have found that the most favourable value of ratio t_2/t_1 was 1.5-2. By using the thicknesses in this range, the resistance of the composite beam could be increased by up to 5%. The authors have also taken into account that the concrete is confined by the steel profile. Confinement model of Schneider (1998) was used in the finite element analysis of this research. This model assumes that the concrete ductility is increased, but the compressive strength remains the same as the strength of the non-confined concrete.

Zhan et. al. (2016) has carried out a research on prestressed concrete-filled steel beams. The author has found that the cracking moment was up to 4 times higher than the moment of the non-prestressed beams. Furthermore, it was noted that the prestressed strands increased the effect of confinement significantly. The authors have used the confinement model of Tomii and Sakino (1979) which is similar to the model of Schneider (1998). It was found that the experimental results fit with the results of the finite element analysis if the confined concrete model is used instead of a regular model. Considering the regular concrete model the resistance of the beam starts to decrease too early compared to the experimental results.

There are more different models to evaluate the confinement of concrete. Han (2001) created a model which is not as conservative as the model of Tomii and Sakino (1979). The author has suggested a confinement factor which depends on the steel yield strength and concrete compressive strength as well as the cross-sectional areas of those elements. This factor is used to find a compressive strength of the confined concrete. Han's model also takes into account an increased ductility of the concrete. To approve the proposed model, Han has carried out experiments on the composite beams and columns (2004).

Huang (2002) has proposed another confinement model. The compressive strength in this model is dependent only on the yield stress of steel and width to thickness ratio of the steel profile. There are also more models which describe the confinement in reinforced concrete columns.

HSQ (Hedlunds Svetsade Q-balk) beams are usually used to build a slim floor structure (Pajari 2010 and Bzdawka 2012). This is enabled by the usage of the bottom flange of the beam as a support for the deck slab. However, HSQ beams are usually used as a simple steel construction. In order to increase the stiffness and the fire resistance of the HSQ beam, it was decided to fill it with concrete. There are several papers that investigate the closed section rectangular composite beams (Han 2004, Lu et. al. 2007 and Hassanein et. al. 2017) or steel HSQ beams (Pajari 2010 and Bzdawka 2012), but in the scope of reviewed papers, there was no information about HSQ beams filled with concrete. As a consequence, the research needs to be carried out to evaluate the effect of the infill concrete for the load-deflection behaviour of the HSQ beams.

Four specimens of 1.5 m length beams have been tested under bending during the course of the experimental programme. Two beams (N1-S and N2-S) of different cross-sections consisted of welded steel plates. Two other beams were identical welded steel profiles as those mentioned before, but were later filled with concrete. The latter specimens N1-C and N2-C are considered composite. Cross-sections of specimens are presented in Table 1. All the dimensions were approximately two times smaller than the beams usually used for the construction of the buildings.

It was decided to vary only the height and thickness of the web to obtain the beams having different bending resistances while also avoiding an increased consumption of the materials.

Table 1

Marking and cross section of beam specimens

Specimen	N1-S	N2-S	N1-C	N2-C
Cross-section				

Fig. 1

Steel (left) and composite (right) beam specimen



Steel HSQ beams were placed vertically and were gradually filled with concrete. The concrete was poured by 3-4 steps and compacted manually by using the steel bar. Beam specimens are presented in Fig. 1. The concrete specimens were casted

at the same time. All the specimens were covered and left to cure under the laboratory conditions for 28 days.

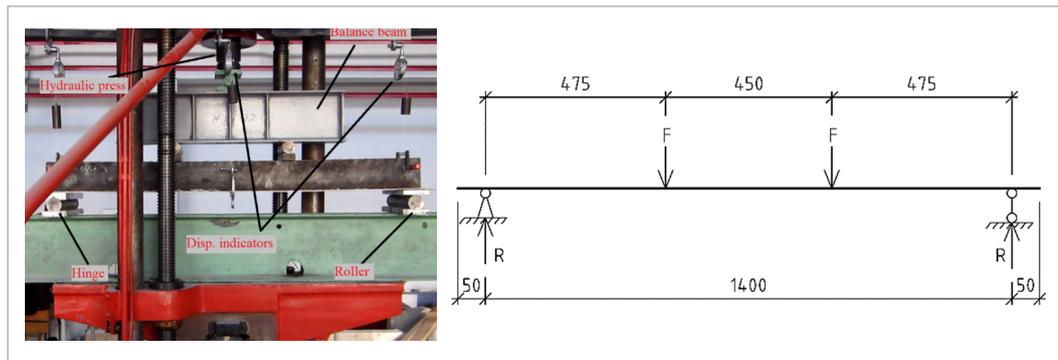
Nine cubic 100x100x100 specimens were tested under compression to find the compressive strength of the concrete which was used to fill the composite beams. Six specimens (100x100x400) were tested under bending using one concentrated force applied at the centre. The bending resistance was later used to calculate the tensile strength of the concrete. Four 100x100x300 specimens were also tested to find the elastic modulus of the concrete. Toni Technik 2020 press was used to test the concrete specimens.

The arrangement of the beam bending experiment is presented in Fig. 2 (left). The beam was placed on two supports: one hinge and one roller. The load was applied to the balance beam by the hydraulic press. The balance beam distributed the load on two cylinders with the base plates of 50 mm width. Positions of supports and loads are presented in Fig. 2 (right).

The 50 tons capacity hydraulic press GRM-1 was used to test the beams. The load was applied to the beam by stages. Preliminary analytical calculations were made before the start of the experiments to obtain the position of neutral axis and plastic bending resistance of each beam. At each

Fig. 2

Experimental test setup (left) and load scheme (right)



stage the load was increased by approximately 10% of the calculated ultimate load during the period of 60-90 seconds. The displacements were measured by three deflection indicators (located at the supports and the middle of the beam) at each stage. Finally, the deflection was calculated by eliminating the deformation of the supports.

Cubic concrete specimens were tested under compression. The results are presented in the Table 2. Specimens 1.1C-1.5C are made of the concrete which was used for the composite beam N1-C. The standard deviation and coefficient of variation of the results of this series is 2.43 MPa and 0.0503 respectively. Other specimens 2.1C-2.4C are made of the concrete which was used to fill the beam N2-C. The standard deviation and coefficient of variation of the results of this series is 3.4 MPa and 0.0671 respectively. Prism specimens were tested to find the modulus of elasticity of the concrete. The results are presented in the Table 3. Specimens 1.1E and 1.2E were made of the concrete which was used to fill the composite beam N1-C. The other two specimens were made of the concrete used for the beam N2-C.

Only two specimens were casted for each of the series. For the statistical analysis the possible scatter of the results could be evaluated by using the coefficient of variation of similar specimens tested in the research carried out by Kelpša (2017). Coefficient of variation of the results of the modulus of elasticity was 0.0229 in the research of Kelpša (2017). As a consequence, the standard deviation for the specimens 1.1E and 1.2E is 713.7 MPa and 716.3 MPa for the specimens 2.1E and 2.2E. According to those values, it can be stated that the results are reasonable. When the reliability is 0.95, the maximum standard deviation is 887.3 MPa for the specimens 1.1E and 1.2E and 890.5 MPa for the specimens 2.1E and 2.2E which is only 2.85 % of the maximum error.

Prism specimens were tested to find the bending resistance of the concrete. Obtained results were used to calculate the tensile strength of concrete. The results are presented in Table 4.

Specimen mark	<i>b</i> , mm	<i>h</i> , mm	<i>F</i> , kN	f_{cub} , MPa	$f_{avg,cub}$, MPa	f_{cm} , MPa
1.1C	101.5	98.7	510.8	50.988	48.238	40.104
1.2C	100.6	99.5	498.6	49.812		
1.3C	98.2	99.8	433.5	44.233		
1.4C	98.6	101.2	466.9	46.791		
1.5C	96.7	100.8	481.2	49.367		
2.1C	100.5	100.5	525	51.979	50.643	41.638
2.2C	101.4	101.9	470.1	45.497		
2.3C	100.9	100.7	500	49.210		
2.4C	101.1	100.3	566.7	55.886		

Specimen mark	<i>b</i> , mm	<i>h</i> , mm	<i>E</i> , GPa	E_{avg} , GPa
1.1E	100.6	99.3	31.216	31.167
1.2E	101.5	100.4	31.117	
2.1E	102.1	100.6	31.246	31.281
2.2E	101.7	99.5	31.315	

Specimen mark	<i>b</i> , mm	<i>h</i> , mm	<i>F</i> , kN	$f_{ctm,Fl}$, MPa	f_{ct} , MPa	f_{ctm} , MPa
1.1T	99.1	99.5	10.85	5.640	3.759	3.767
1.2T	98.6	101.9	11.35	5.654	3.774	
1.3T	100.7	100.1	11.18	5.651	3.767	
2.1T	99.8	102.2	12.51	6.121	4.086	3.853
2.2T	99.2	100.8	11.15	5.642	3.763	
2.3T	98.8	101.1	11.01	5.560	3.710	

Material properties

Table 2

Dimensions and compressive strength of concrete cubes

Table 3

Dimensions and modulus of elasticity of concrete prisms

Table 4

Dimensions, bending resistance and tensile strength of concrete prisms

Experimental results

Three specimens were casted for each of the two series. The reliability of the results of the tensile strength was evaluated in the same way as the results of the modulus of elasticity. The coefficient of variation of the results of the tensile strength was 0.099 in the research of Kelpša (2017). In this case, the maximum error is 17 % which is reasonable for the results of the tensile strength.

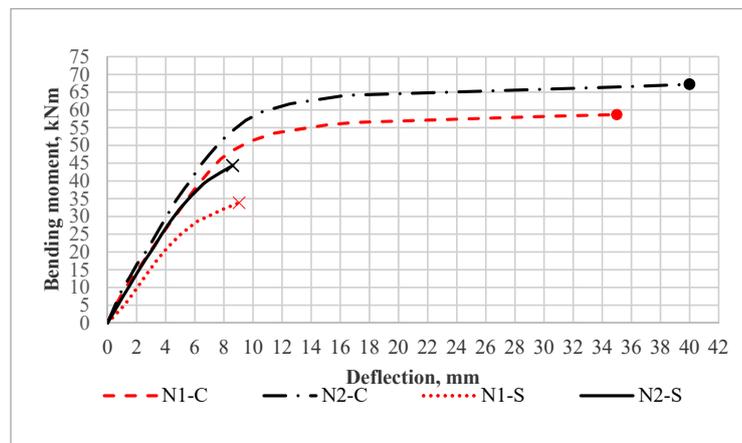
Steel had a grade of S355J2+N, but it was not tested during the experimental programme. The assumed stress-strain curve is presented in Fig. 5.

Load-displacement curves of the beams are presented in Fig. 3. The loading of the steel beams (N1-S and N2-S) was stopped soon after the first plastic deformations occurred. It was due to the fact that the webs of the steel beams started to buckle locally in the places where the load was applied. When the buckling occurred, the resistance of the beams started to decrease. The deflection at the moment when the experiment was stopped was 8-9 mm. The early local buckling occurred partly due to discontinuous welding between webs and flanges of the beam which caused stress concentrations.

The composite beams (N1-C and N2-C) reached plastic bending resistance and their load-displacement curves were almost horizontal when the experiment was stopped (Fig. 3). There was

no sudden collapse and no local buckling was observed in this case. The bending of the composite beams was stopped when the displacement was increasing without increasing the load.

It was noticed that the composite beams possessed a 52-74 % higher bending resistance than the steel beams. Furthermore, the first plastic



deformations in the composite beams occurred when the 35-50 % higher load was applied. Beams filled with concrete also had an increased resistance to local buckling. As a consequence, it can be stated that filling the HSQ beam with concrete had a positive effect on the flexural behaviour. Although more materials were used, the concrete is relatively cheap compared to steel. Furthermore, filling the beam with concrete should also increase the fire resistance of the construction. However, to prove and evaluate this increase of fire resistance, further research is required.

Finite element modelling of experimental beams

Finite element analysis (FEA) software ABAQUS was used during this research. Four numerical finite element models (FEM) were created to analyse the load-deflection behaviour of the experimental beams.

Material properties and constitutive models

Non-linear stress-strain material model of confined concrete suggested by Han (2001) was used in this research. The model assumes that the concrete confined by the steel profile reaches a higher compressive strength than f_{cm} . It also suggests that after reaching the compressive strength the concrete becomes more plastic and its resistance decreases slower than the resistance of the regular concrete. The main parameter in this model is confinement factor ζ which depends on the cross-sectional area of concrete and steel, yield strength of steel and compressive strength of concrete:

$$\alpha = \frac{A_s \cdot f_{sy}}{A_c \cdot f_{ck}} \quad (1)$$

where: – cross-sectional area of steel profile; – cross-sectional area of concrete; – yield strength of steel; – compressive strength of concrete which is calculated as 67% of the compressive strength of cubic blocks.

The behaviour of concrete was described by the stress and non-linear strain dependence in the “concrete damaged plasticity model” in ABAQUS. This model is a continuum, plasticity-based, damage model for concrete. It assumes that the main two failure mechanisms are tensile cracking and compressive crushing of the concrete material. It was assumed that the concrete has a Poisson’s ratio of 0.2. The stress-strain dependence of the tested concrete is presented in Fig. 4.

Elastic modulus of the steel was assumed to be 210.6 GPa and Poisson’s ratio – 0.3. Plastic properties were described as the true stress-plastic strain dependence. The model of steel proposed by Han (2001) was used in this research.

The steel grade was known to be S355, but the exact yield and ultimate strength was not tested during this research. However, different authors have found that the yield strength of steel (grade S355) is usually higher than 400 MPa. Outinen, J. and Mäkeläinen, P. (1995) have reported that their tested S355 class steel had a yield strength of 406.1 MPa, ultimate stress of 526.9 MPa and elasticity modulus of 210.6 GPa. The same values have also been used in the finite element analysis of this research. It was chosen to use those values in order to fit the experimental and FEA results better. The stress-strain dependence used for the analysis of the beams in ABAQUS is presented in Fig. 5.

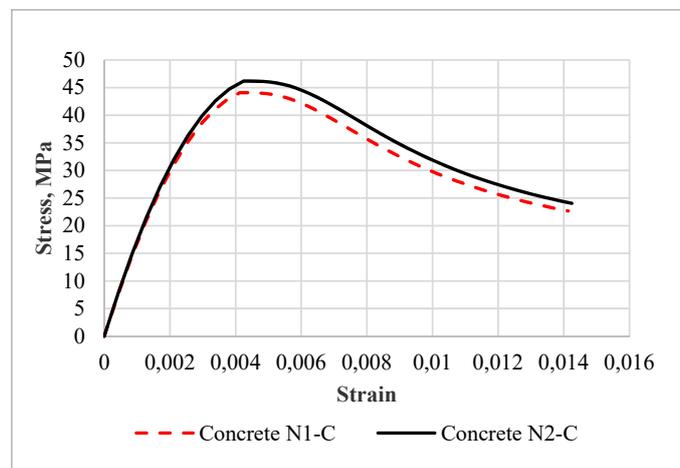


Fig. 4

Stress-strain dependence of confined concrete

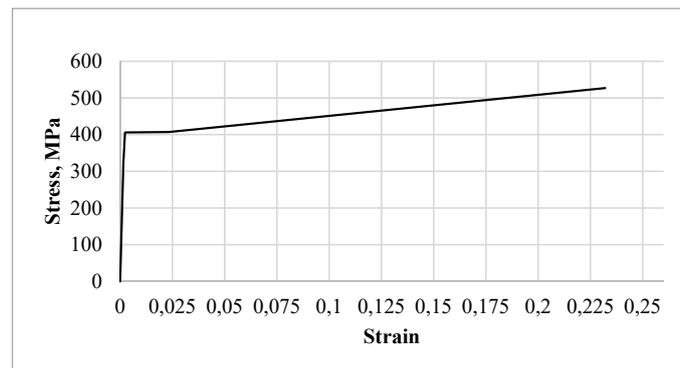


Fig. 5

Stress-strain dependence of steel

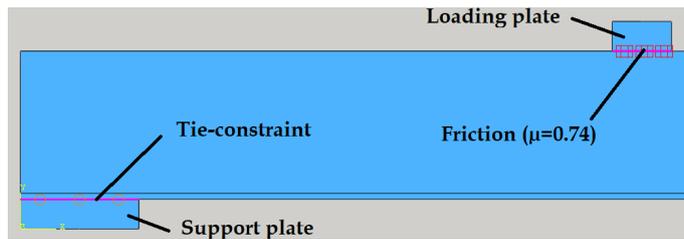
Elements, mesh, contact and boundary conditions

C3DR 8-node linear bricks with reduced integration have been used as the elements for steel and concrete. The finite element problem includes local buckling and it was found that the results depend on the size of mesh. By trying different mesh size, it was found that the FEM results were closest to experimental when 12 mm elements were used. The bigger size of mesh led to a stiffer load-deflection behaviour and the smaller size of mesh made the beam more susceptible to local buckling. Composite and steel beam models consisted of approximately 5000-6000 and 8000-9000 elements respectively. Composite beams had less elements because only the quarter of each composite beam was modelled to minimize the time needed for the FEM calculation.

The steel beams have been connected to the bottom plates using “tie-constraint” command. Bot-

Fig. 6

Positions of plates and contact properties



tom plates have been supported using one hinged and one roller support. Contact between the steel profile and loading plates was described as a frictional behaviour with the coefficient of 0.74 as stated by Grigoriev, I. et al. (1997).

A quarter of the model was created for both of the composite beams. Constraints in the directions of two axes were added to simulate the symmetry planes. Contact between the steel profile and concrete was described as a frictional behaviour with the coefficient of 0.65 as stated by Rabbat, B. G. and Russell, H. G. (1985). Positions of plates and their contact properties are presented in Fig. 6. The principal scheme was presented in Fig. 2. In ABAQUS, the line supports were added to the bottom surfaces of the support plates. Left and right support plate was supported with a hinged and roller support respectively.

Line load was applied to the loading plates on top of the beams. It was described as a gradually increasing load until the midpoint of the beam reached a prescribed deflection.

Comparison of FEM and experimental results

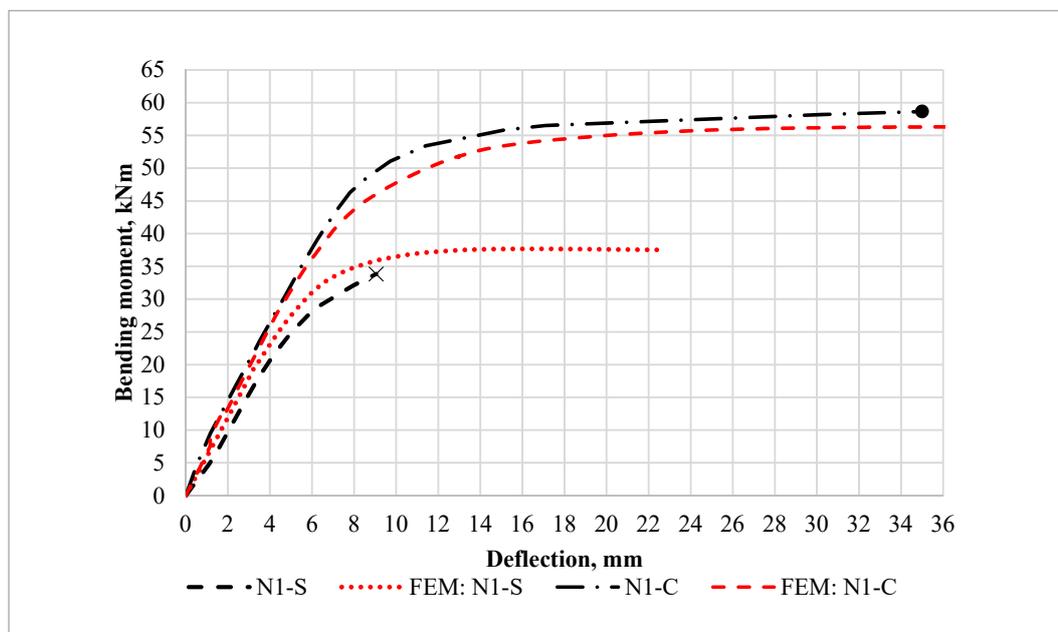
The FEA has been carried out. Load-deflection curves were obtained. The comparison between the experimental and FEA results of the beams N1-S and N1-C is presented in Fig. 7. It is noticeable that the FEM models managed to capture the load-deflection behaviour accurately. The bending moment of the beam N1-S in FEM analysis was found to be higher by 5.5 % than the experimental moment at the maximum experimental deflection (9 mm).

However, experimental beam N1-C exhibited a stiffer load-deflection behaviour than the FEM model shows. The experimental bending moment was higher by 4 % than the FEM bending moment when the plastic bending resistance was reached (horizontal part of the curves N1-C and FEM: N1-C).

The comparison between the experimental and FEA results of the beams N2-S and N2-C is presented in Fig. 8. The load-deflection behaviour exhibits similar tendencies as the beams discussed

Fig. 7

Comparison of experimental and FEA load-deflection behaviour of beams N1-S and N1-C



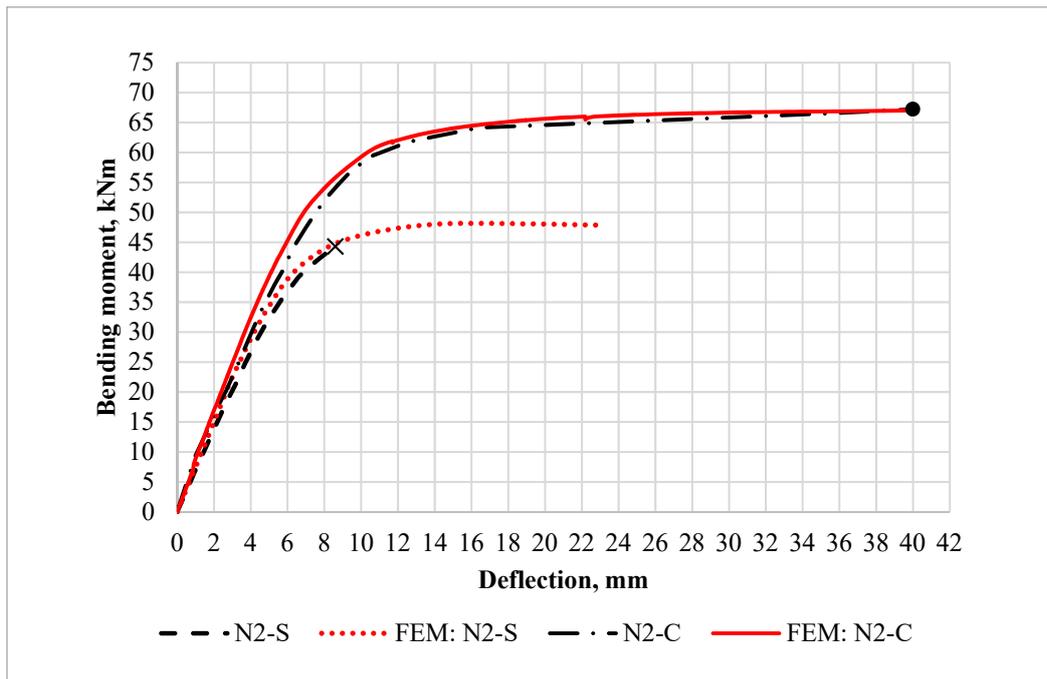


Fig. 8

Comparison of experimental and FEA load-deflection behaviour of beams N2-S and N2-C

before. The bending moment of the beam N2-S in FEM model was found to be higher by 1 % than experimental moment at the maximum experimental deflection (8.6 mm). Beam N2-C analysed by FEM has reached the same deflection when the bending moment was higher by up to 1.5 % in the plastic region of the load-deflection curve.

The difference of the bending moments at the same deflection was up to 5.5 % considering all of the beams. This leads to the conclusion that the material models were chosen appropriately. The most likely source of inaccuracy is the fact that the steel tension tests have not been carried out. The yield strength of the steel was assumed to be 406.1 MPa and ultimate stress – 526.9 MPa. It could have been marginally different for individual beams and for elements having a different thickness. Furthermore, the welds between plate elements of beams were discontinuous. This led to the decreased bending capacity of the beams.

Verification of the finite element model

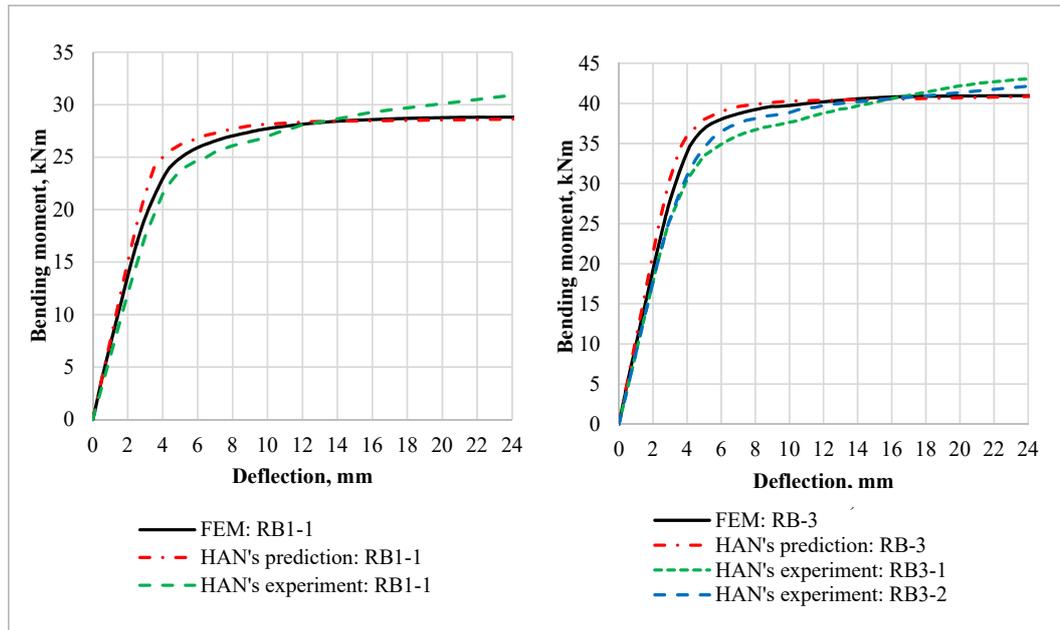
In order to evaluate the validity of the chosen finite element modelling techniques in this paper three more beams have been analysed by FEM. The experimental tests for those beams have been carried out by Han (2004). The yield strength of the steel was tested by the author. Han (2004) has found that the steel of the beams RB1-1, RB3-1 and RB3-2 had a yield strength of 330.1 MPa, 321.1 and 321.1 MPa respectively. The author has also made a prediction of the load-deflection behaviour using a theoretical method.

The experimental and theoretical load-deflection curves of the beams RB1-1, RB3-1 and RB3-2 are presented in Fig. 9. The load-deflection curves obtained during this research using FEM are presented in the same charts.

It is noticeable that Han's (2004) theoretical predictions were close to his experimental results. All of the beams have shown a similar trend. First plastic deformations during Han's (2004) experiments occurred earlier than those in the theoretical Han's (2004) predictions. Furthermore, it can be seen that when considerable plastic deformations occur and the deflection is more than 16 mm a higher load is needed to reach the same deflection in the experimental situation. The experimental load is higher by up to 8 % than Han's theoretical prediction when the deflection is 24 mm.

Fig. 9

Han's (2004) experimental, Han's (2004) theoretical and FEM load-deflection curves of beam RB1-1 (left) and beams RB3-1, RB3-2 (right)



The difference is smaller when the deflection is lower. However, it shows a trend of an increasing difference when the deflection is increasing.

Han's (2004) theoretical prediction has shown very similar results to the FEA prediction made during this research. It was noticed that the FEA prediction is more accurate in the load-deflection curve region where the first plastic deformations occur. For example, when the deflection is equal to 4 mm, Han's (2004) theoretical load prediction is up to 16 % higher than the load during the experiment. Load obtained by FEM during this research is up to 9 % higher than Han's (2004) experimental load, when the deflection is 4 mm.

Conclusions

1 Experimental tests have shown that the composite beams possessed a 52-74 % higher bending resistance than the steel beams. The first plastic deformations in the composite beams occurred when the 35-50 % higher load was applied.

2 During the finite element analysis of the tested HSQ beams it has been found that the FEM load at the same deflection for the steel beams was up to 5.5 % higher than the experimental load. The difference of the load for the composite beams was up to 4 %. As expected, the experimental beams have exhibited a softer load-deflection behaviour than the FEM models, because the experimental beams consisted of separate steel plates welded with discontinuous welds which caused local stress concentrations while FEM beams were modelled as a single profile without welds.

3 FEA carried out in this research has shown similar but more exact results than Han's theoretical prediction compared to Han's experimental load-deflection curves of the composite beams. Han's theoretically predicted load was up to 16 % higher than the experimental load when the first plastic deformations occurred and the deflection was 4 mm. The difference between FEM load and experimental load was only 9 %. When the deflection was 24 mm, experimental load was up to 8 % higher than both Han's theoretically predicted load and FEM predicted load in this research. Although Han's theoretical beam calculation method is easier to use than FEM, the usage of it is restricted to rectangular composite profiles only, while FEM is a universal method which also yields more exact results.

- 4 Han's stress-strain models of steel and confined concrete proved to be suitable to obtain the relatively accurate FEM prediction of the load-deflection behaviour of steel and composite beams. To increase the precision of FEM results further, it is suggested to evaluate the initial geometrical imperfections and residual stresses of welded steel plates.
- 5 It is necessary to carry out a mesh sensitivity analysis when analysing steel and composite beams using FEM. It was noticed that the most accurate results for most of the models were obtained when using 12 mm mesh size. Increasing the mesh size of the composite beam to 15 mm led to a stiffer load-deflection behaviour and up to 4 % higher plastic bending resistance while beams with a mesh size of 10 mm had a 3 % lower plastic bending resistance. The mesh size of the steel beam had a higher impact on the results. Up to 6 % higher and up to 5% lower plastic bending resistances were observed when using 15 mm and 10 mm mesh respectively compared to the results obtained when using 12 mm mesh size. Decreasing the mesh size further, in most cases has shown an increased tendency to the local buckling of the steel profile at the load application and support zones.
- 6 Filling the steel HSQ beam with concrete increased the stiffness and bending resistance of it significantly. In order to develop the concept of a composite HSQ beam, it is suggested to carry out a further research on the steel bar reinforced composite HSQ beams and evaluate the fire resistance of it.

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