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Behavior of Reinforced Concrete Beams Strengthened by Bottom Steel Plates with Stud Shear Connectors of Diverse Geometric and Embedding Conditions

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Abstract: The five rectangular reinforced concrete beams strengthened by bottom steel plates (SPCC beams) firmly interconnected to it by either headed-stud or ⅂-shaped shear connectors are manufactured using either high strength or normal strength concrete where trial mixer conforming to the fundamental fresh and hardened concrete constraint has been successfully produced to satisfy the standard tests of concrete in its two age stages. The variables of the tested beams where the grade of concrete, the shear connectors deformability, the spacings of shear connectors (controlling the degree of partial interaction) and shape of shear connectors. They have been loaded up to failure under the effect of a two-concentrated load system where the failure modes have been observed and the load-deflection relationships, the load-relative end slip relationships and the flexural resistance have been reported. Then, the average flexural stiffness, the degree of recovery and the average anti-slip stiffness have been evaluated from interpretations of the measured response. The experimental results show that there substantial improvements in the flexural performance and the integrity preservation have been achieved from elevating the grade of concrete embedment for the shear connectors. On the contrary, increasing the spacing of the headed-stud shear connectors twice has seriously lowered the flexural fulfillment and the integrity level. Fortunately, those serious degradations have been amended by replacing the faraway spaced headed studs by ⅂-shaped shear connectors of the same length and spacing. Hence, the degree of partial interaction has proved to own a primary effect on the SPCC beams performance. In specific, the 80% lengthening of the moderately spaced headed-stud shear connectors proves to have a significant role in elevating the flexural resistance and ductility and increasing the anti-slip stiffness. Finally, the flexural performance of the reference SPCC test beam has also been analyzed by the non-linear three dimensional finite element analysis employing Abaqus/CAE Version 6.13 program to predict its flexural performance represented by the load-deflection relationship where high levels of coincidence with the experimental evidence are achieved preserving the threshold of 90%.

Key words: Steel-plate concrete composite beams, normal strength concrete, high strength concrete, shear connectors, headed studs, flexural stiffness, relative end slip, degree of recovery, anti-slip stiffness

INTRODUCTION

This type of composite beams is called Steel Plate-Concrete Composite beams (SPCC) as shown in Fig. 1. It has many advantages in both design and construction and has been used in a diversity of applications. Their use in buildings and bridges of long spans has increased in the recent years for the benefit of increased load-carrying capacity. Hence, it is quite an appropriate selection for bridges subject to increasing vehicle loads or buildings the use of which is to change from residential to commercial. In fact, there is no concrete cover outside the steel plate, so, the weight of the structure can be reduced, especially for slabs and there is no crack exposed at the bottom of the structures.

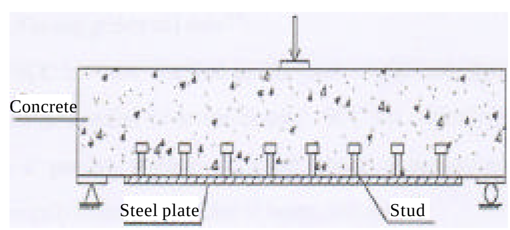

Fig. 1: Typical steel plate concrete composite SPCC beam

Furthermore, the SPCC beam is applicable to blast resistant shelters. From constructional standpoint, the steel plate can be used as a formwork during construction and can resist stresses in any direction which is more effective than reinforcing bars. Finally, the SPCC can

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also, be used in strengthening and rehabilitating existing structures (Jianguo *et al*., 2001) such as concrete bridges by strengthening the decks and girders.

Literature review: Reveals that a few number of studies has been performed till now on SPCC beams. The beginning was in due to Roberts and Haji-Kazemi (1989) who found significant improvement in the stiffness of the plated beams and all beams exhibited ductile failure followed by crushing of the concrete in the compression zone. Abtan (1997) conducted tests on SPCC specimens of variable steel-plate lengths, widths and thicknesses. His test results showed that external reinforcement (plates) increased flexural stiffness of the beam at all stages of loading and consequently, reduced the deflection at corresponding loads. Less deflection was obtained with increasing the length and area of plate. Al-Saraj (2000) presented a theoretical study for reinforced concrete beams strengthened mechanically by external steel plates attached to their tension side with shear connector by using finite difference method. He applied his method to previously tested where close agreement was obtained with the experimental values for different thickness and widths of the strengthening plates. Al-Hadithy and Al-Kerbooli (2008) performed laboratory tests and finite element analysis on four reinforced concrete beams cast in steel channels and other four reinforced concrete beams without bottom steel channels to examine their flexural stiffness, ductilities and ultimate bending capacities in addition to parametric effects. Few months later, Nie and Zhao (2009) carried out tests on five SPCC specimens in order to investigate their flexural behavior. From which they found that steel plate and concrete can work together very well and the SPCC beams have very good ductility. They also calculated the ultimate strength of the SPCC beams by means of the same plastic method as reinforced concrete beams. Ajeel *et al*. (2011) studied the effect of replacing internal bottom tensile steel reinforcing bars by bottom steel plates in rectangular reinforced concrete beams. They found that SPCC beams revealed composite behavior upto failure. However, they proposed a limitation to plate thickness beyond which their full flexural strength.

Al-Hadithy (2012) carried out an experimental study on the performance of reinforced concrete t-beam cast in bottom steel channels interconnected to the soffit of the reinforced concrete t-beam by headed stud shear connectors of various lengths and dimensional proportioning. He found that beams with headed studs of moderate lengths revealed substantially higher performance in the respects of flexural stiffness, ductility, ultimate resistance and relative slip constraint. Al-Hadithy and Al-Alusi (2013) published an experimental comparative research study investigating the behavior reinforced concrete t-beams strengthened by bottom steel channels interconnected by headed studs of divers distribution in the sagging-moment tension concrete media. They concluded that, the non-uniform spanwise distribution of headed studs represents an optimum selection. Two months later, Al-Hadithy *et al*. (2013) presented an experimental research study on flexural efficiency of reinforced concrete t-beams strengthened by bottom steel channels with horizontal transverse bars as shear connectors. Later, by Ali (2013) carried out experimental and numerical investigations on SPCC beams of various steel-plate thicknesses and lengths and shear-connector distributions using self-compacting concrete. He achieved substantial improvements in the flexural resistance accompanied by extremely high elevations in the flexural stiffness but significant decrease in the ductility ratio due to increasing the steel-plate thickness.

The experimental research of Al-Hadithy and Hassan (2015) on SPCC beams is directed to study the role of steel fiber, added to concrete in diverse volume fractions in enhancing the performance of those beams in which shear connectors were embedded in weak early cracked tensioned concrete media by furnishing efficient concrete embedment for the resistance of shear connectors at interfaces. Since, that disposal reduces the concrete workability and negatively affects its fresh properties especially in portions embracing steel rebars and shear connectors. They found it necessary to use self-compacting concrete to reduce such problems. Their results indicated that such steel-fiber insertion by the selected volumetric ratios led to increases in flexural stiffness and ultimate resistance and improvement of the composite beam integrity. Finally by Al-Hadithy and Hassan (2016) presented non-linear finite element modelling by ANSYS program and simplified theoretical analysis of SPCC beams using steel-fiber reinforced self-compacting concrete. They based their investigation on available experimental tests on seven SPCC beams. They attained high agreement of their ANSYS Model predictions and the experimental evidence where the maximum differences have been within the margin of 8%.

Research significance and scope: This study comprises a laboratory experimental study (supplemented with finite-element modelling) to investigate the behavior of SPCC beams. Four principal parametric studies have been carried out to investigate the performance of the monotonously loaded SPCC beams. Those parameters include strength of concrete whether normal or high, degree of flexibility in the post-yielding stage, by varying the shanks lengths of the stud shear connectors, shape of the shear connector whether the traditional headed stud or the ˥-shaped shear connector and degree of partial interaction, depending on variation of spanwise spacing. Those four parameters have direct effects on the ultimate load capacity, average flexural stiffness, degree of recovery and average anti-slip stiffness. Finally, a verification study including the construction of a non-linear finite element model by Abaqus for the standard tested SPCC beam has been implemented.

MATERIALS AND METHODS

Experimental program

Variety of the test spcc beams: The experimental program consisted of a total of five SPCC beams with different parameters. They were statistically tested to determine the mean value of the ultimate static load Pu and mid-span deflection and relative end slip for the beam specimens. For studying the effects of the test parameters, they were designated as M.N., M.H., M.L., M.S. and M.A. The tested SPCC beams were simply supported ones of 1900 mm span, cross section (125×200) mm cross-section and 2-Ø8 mm longitudinal steel reinforcing bars at top and bottom. Uniformly spaced stirrups for shear resistance were formed from 4 mm diameter steel reinforcing bars spaced at 100 mm. The headed stud shear connectors were 8 mm in diameter for all tested beams but they varied in their lengths where four test beams have been provided by 50 mm length headed studs and other beam has been provided by 90 mm length headed stud. Anyway, the shear connectors were placed at uniform spacings along the centerlines of the steel plates. The full details of the test beams and the parameters are presented in Table 1, Fig. 2 and 3.

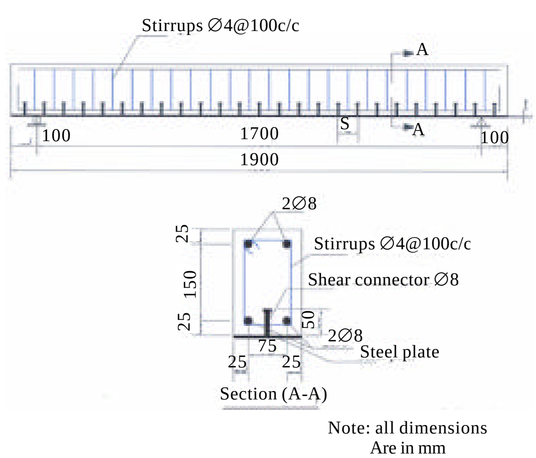

Fig. 2: Typical simply supported SPCC beam layout

Test setup and procedure: The five tests SPCC beams were subjected to loading in a 1000-kN- capacity universal loading machinery and frame system shown in Fig. 4. Test setup deals with the two main components named the supports and loading systems. The tested beams were simply supported at ends over a span of 1700 mm center to center of supports. A steel beam (I-section) was placed over the beam centerline with a total length of 1000 mm in order to transfer the applied point load into two point loads on the beam. Figure 5 provides the description of the test set up and instrumentation. The testing process for the five SPCC beams passed through several stages as described below.

Installation of the SPCC beam: Where each test beam was placed on the rigid support in the loading frame and the system work was checked by applying initial displacement to take the zero displacement level of the beam and then it was released soon afterwords.

Loading process: The test was controlled by the LVDT. Load-deflection was conducted at a displacement rate of 0.01 mm/sec and recorded.

Data recording: Instantaneous recording of the loads and displacements started, since, the instant at which of the hydraulic jack came into contact with the specimen where the first data record was equal to zero.

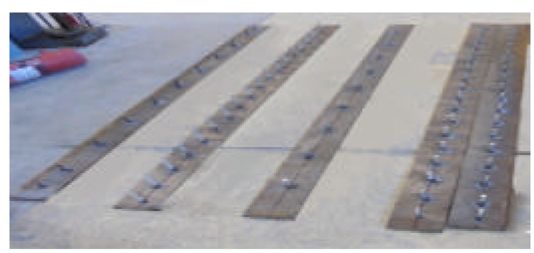

Fig. 3: Shear connectors attached to the steel plates by collar welding

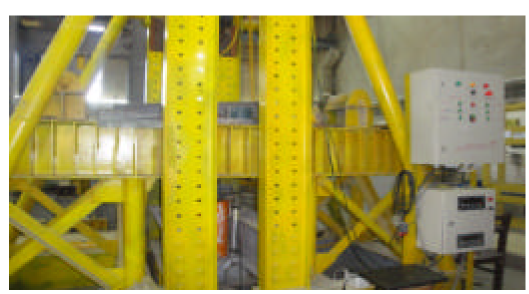

Fig. 4: Front view of the 1000 kN capacity testing apparatus in the Civil Engineering Laboratory at Al-Nahrain University

Table 1: The diversity of the manufactured test composite beams

Beam mark	Length of shear connectors (mm)	Spacing between shear connectors (mm)	Shape of shear connectors	Grade of concrete
MN	50	100	Headed stud	Normal strength
MH	50	100	Headed stud	High strength
ML	90	100	Headed stud	Normal strength
MS	50	200	Headed stud	Normal strength
MA	50	200	⅂-shaped	Normal strength

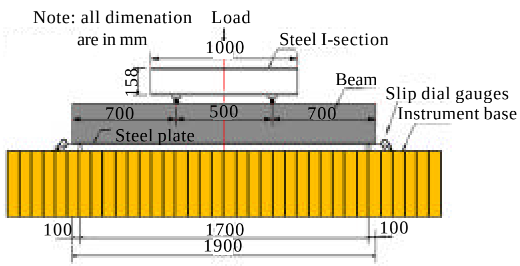

Fig. 5: Schematic diagram of the test arrangement

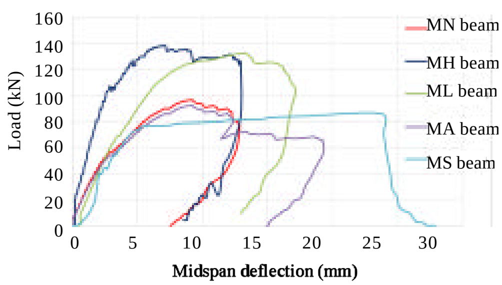

Fig. 6: Load versus mid-span deflection relations for the five SPCC test beams

RESULTS AND DISCUSSION

The SPCC beams MN, MH, ML, MS and MA were subjected to a vertical monotonic load until they exhibited severe damage, the test results of each of those prototypes represent an independent parameter in the present comparative study.

The ultimate vertical loads with the corresponding deflection values under the load, relative end slips and the failure modes for the five test SPCC beams are given in Table 2 while their relations of load versus deflection beneath the load are shown in Fig. 6 and their load versus relative end slip relations are given in Fig. 7.

Four principal parametric studies were carried out to investigate the performance of the monotonously loaded prototypes, the parameters include variation of spacing of headed stud shear connectors. Ductile deformability level in the post-yielding stage by varying the headed stud length. Grade of concrete, whether normal concrete strength or high concrete strength and shape of the shear connector whether the traditional headed stud or the ⅂-shaped shear connector. Those four parameters

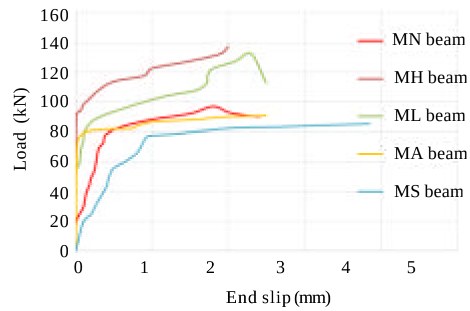

Fig. 7: Relationships of load versus relative horizontal end slip relationships for the five SPCC test beams

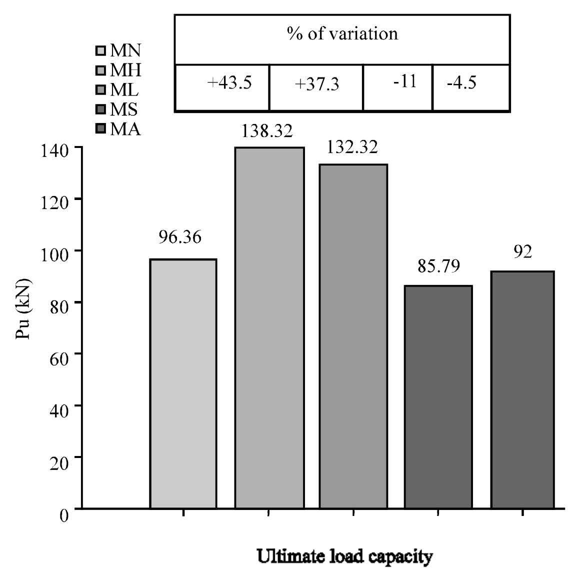

Fig. 8: Effects of the experimentally investigated parameters on the ultimate load capacity for the tested SPCC beams

practised direct effects on the ultimate load capacity, average flexural stiffness, degree of recovery and average anti-slip stiffness as given in Table 3.

Discussion of the experimental outcome

Ultimate load capacity: Figure 8 shows that, the highest value of the ultimate load carrying capacity can be achieved either by increasing compressive strength of concrete from 41.8 MPa (in beam MN) to 82.4 MPa (in beam MH) or and by increasing the studs length from 50

Table 2: Values of the ulitmate vertical load and the corresponding deflection beneath the load and relative end slip with the failure modes for the five tested SPCC beams

Beam mark	Ultimate load (KN)	Deflection beneathb the load (mm)	Relative end slip (mm)	Failure mode
MN	96.36	9.11	2.40	Flexural-shear failure
MH	138.20	6.99	2.00	Flexural-shear failure
ML	132.32	13.31	2.50	Flexural-shear failure
MS	85.79	23.75	3.85	Flexural-shear failure
MA	92.00	9.22	3.00	Flexural-shear failure

Table 3: Comprehensive interpretation of the drawn experimental result for five test SPCC beams monotonously loaded up to failure

	Flexural behavior						Integrity level	
Beam mark (1)	$P_u^{(2)}$ (kN)	$\Delta P_u^{(2)}$ (mm)	ASF(3) (kN/mm)	$\Delta_{max}^{(4)}$ (mm)	$\Delta_{final}^{(5)}$ (mm)	DR(6) (ratio)	$\delta_u^{(7)}$ (mm)	AASS(8)
MN	96.360	9.110	10.5774	12.88	7.520	41.6149	2.40	40.1500
MH	138.32	6.990	19.7883	12.99	8.530	34.3341	2.00	69.1600
ML	132.32	13.31	9.94140	17.10	12.97	24.1520	2.50	52.9280
MS	85.790	23.75	3.61220	25.31	25.31	0.00000	3.85	22.2831
MA	92.000	9.220	9.97830	19.27	14.27	22.5739	3.00	30.6667

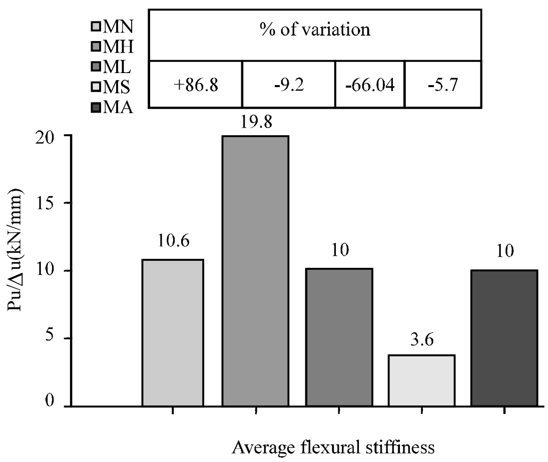

Fig. 9: Effects of the experimentally investigated parameters on the average flexural stiffness for the tested SPCC beams

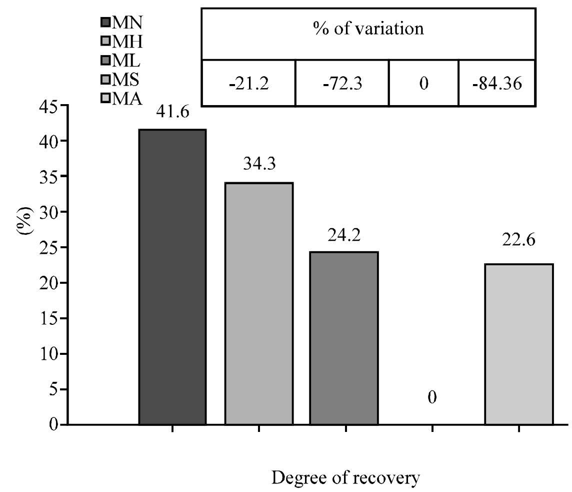

Fig. 10: Effects of the experimentally investigated parameters on the degree of recovery DR for the tested SPCC beams

mm (in beam MN) to 90 mm (in beam ML). The increases in the ultimate load capacity were 43.5 and 37.3%, respectively. However, the figure indicates that the ultimate load capacity of the MS beam have decreased by 11% with lessening the number of shear studs to the half.

Average flexural stiffness: Figure 9 shows that, the average flexural stiffness of MS beam decreased by 66.04% with reducing number of the headed stud shear connectors from 18-9. Meanwhile, it can be noticed that the average flexural stiffness of the high strength concrete beam MH increased by 86.8%. The figure indicates the effect of the ⅂-shaped shear connector in beam MA on flexural stiffness increase by 5.7% when compared with beam MS (of headed stud type of shear connectors and same spacing).

Degree of recovery: Inspection of Fig. 10 demonstrates that the degree of recovery DR endured a dramatic decrease attaining 84.36% in the case of MS beam having ⅂-shaped shear connectors of double spacing. Meanwhile, it decreased by about 72.3% when increasing the overall lengths of headed stud shear connectors from 50-90 mm.

Average anti-slip stiffness: From Fig. 11, it is observed that, the average anti-slip stiffness AASS of MH and ML beams increased by 72.1 and 31.6%, respectively. However, 44.5 and 23.6% decreases in the value of that property were achieved in MS and MA beams, respectively, owing to the degree of partial interaction effect.

Abaqus Model and verification

Definition: A finite element model has been constructed, by using Abaqus package for the standard SPCC beam MN, its accuracy should be verified on the bases of comparison with the experimental results.

Table 4: Numerical and experimental results of SPCC beam MN

	Ultimate load P_u(kN)			Mid span deflection Δ_u(mm)		
Modeled beam	Experimental	Abaqus	Diff. (%)	Experimental	Abaqus	Diff. (%)
MN	96.36	98.01	1.71	9.11	9.43	3.51

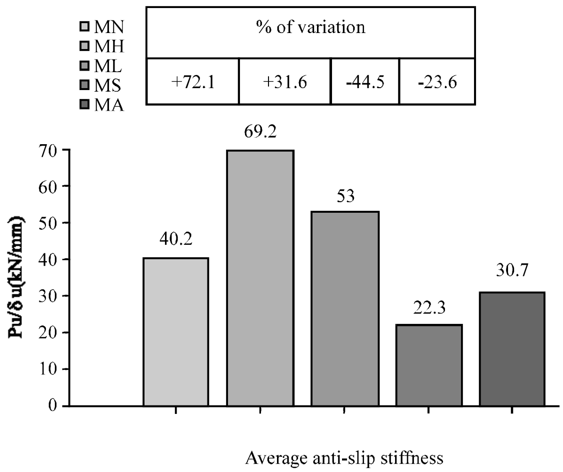

Fig. 11: Effects of the experimentally investigated parameters on the average anti-slip stiffness AASS for the tested SPCC beams

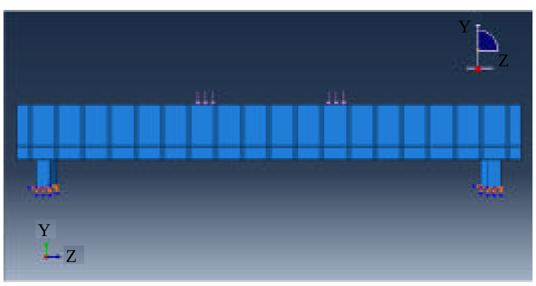

Fig. 12: Modeling and meshing of the concrete media, boundary conditions for simple end supports for the SPCC beam MN

Concrete damage plasticity model has been used to describe the behavior of SPCC beam. Moreover, an 8-node linear brick element designated (C3D8R) has been used for modeling shear connectors, steel plate and concrete. Figure 12 shows the modeled standard SPCC beam.

Correlation between finite-element prediction and experimental evidence: The load versus slip relationship obtained from the present numerical model by Abaqus and its corresponding one extracted from the experimental investigation for the reference beam MN are presented in Fig. 13. It illustrates the close behavior of the numerical model relevant to the experimentally tested SPCC beam at the ultimate load stage. Table 4 shows the ultimate and

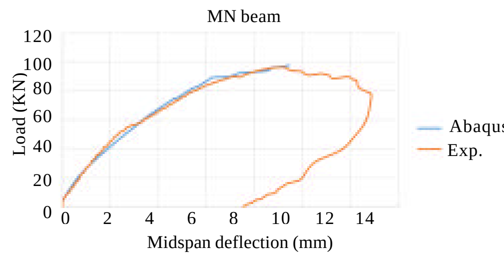

Fig. 13: Load versus mid-span deflection relationships till failure obtained from the present Abaqus Model and from experimental evidence for the reference SPCC beam

failure loads and their corresponding mid-span deflection results for both the experimental beam and the finite element model and percentages of variation between them.

CONCLUSION

The following conclusions have been drawn, so far:

Ultimate load capacity: The individual impacts of the high strength concrete and the increase of the headed studs length cause substantial increases in the ultimate load capacity by 43.5 and 37.3%, respectively. Meanwhile, decreasing number of the uniformly distributed headed stud shear connectors to the half and using ⅂-shaped of shear connectors (with a double spacing) causes reduction in the ultimate load capacity attaining 11 and 4.5%, respectively.

Average flexural stiffness: Doubling the 41 MPa concrete compressive strength causes large raising in the average flexural stiffness up to 86.8%. However, a sharp drop amounting to 66.04% in the average flexural stiffness value takes place with reducing the number of the uniformly distributed headed stud shear connectors to the half or shortening shear studs length to the half. However, the (80%) lengthening of the normal length headed studs and the use of ⅂-shaped shear connectors (with double spacing) causes 10% lowering in the average flexural stiffness.

Degree of recovery: The specified decrease of the shear connectors spacing, lengthening the headed stud shear connectors and elevating the grade of concrete cause considerable decrements in the degree of recovery by 84.36, 72.3 and 21.2%, respectively.

Average anti-slip stiffness: Tremendous successive increases of this parameter attaining 72.1 and 31.6%, respectively, take place with replacing NSC of grade 41 by HSC of grade 82 and with increasing lengths of the headed studs from 50- 90 mm. Meanwhile, lowering of the degree of partial interaction (by reducing the number of headed stud shear connectors to the half) and its combination with using ⅂-shaped of shear connector instead of headed stud ones cause decreases in the value of the average anti-slip stiffness by 44.5 and 23.6%, respectively.

Validity of the presented finite element model: The percentages of difference between the response of the physical SPCC beam and its corresponding numerical model are as low as 1.71 and 3.51% for ultimate load capacity and mid-span deflection, respectively.

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