Experimental and analytical study of the steel-concrete-steel beam under flexural behavior

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ABSTRACT

Steel-Concrete-Steel beam or as known in other engineering phrases (Sandwich Beam) is part of the modern structural frames which assist the interactions between concrete and steel, knowing that this parts of structure looks similar to the sandwich slab.

However these structural parts are new in use and differ from the standard reinforced concrete beam where as in these newly used techniques there are many benefits such as: the interactions between sandwich beam parts is more powerful and has a better exterior look.

The sandwich beam can be created by replacing the main longitudinal Steel bars for the tension and compression with an equivalent one of steel plates and binding both the top and bottom plates using stud connectors that replace strips on the standard reinforced concrete beam and filling all the spaces between the two plates with concrete.

In this research study the three cases of the sandwich beams with the following dimensions: (150 mm width*250 mm height*1300 mm length) and comparing the results with a control concrete beam of the following dimensions: (150 mm width*300 mm height*1300 mm length).

All of the cases were tested under the effect of two point load with a space of one third from each side of the beams end from of the net length to observe the flexural loads.

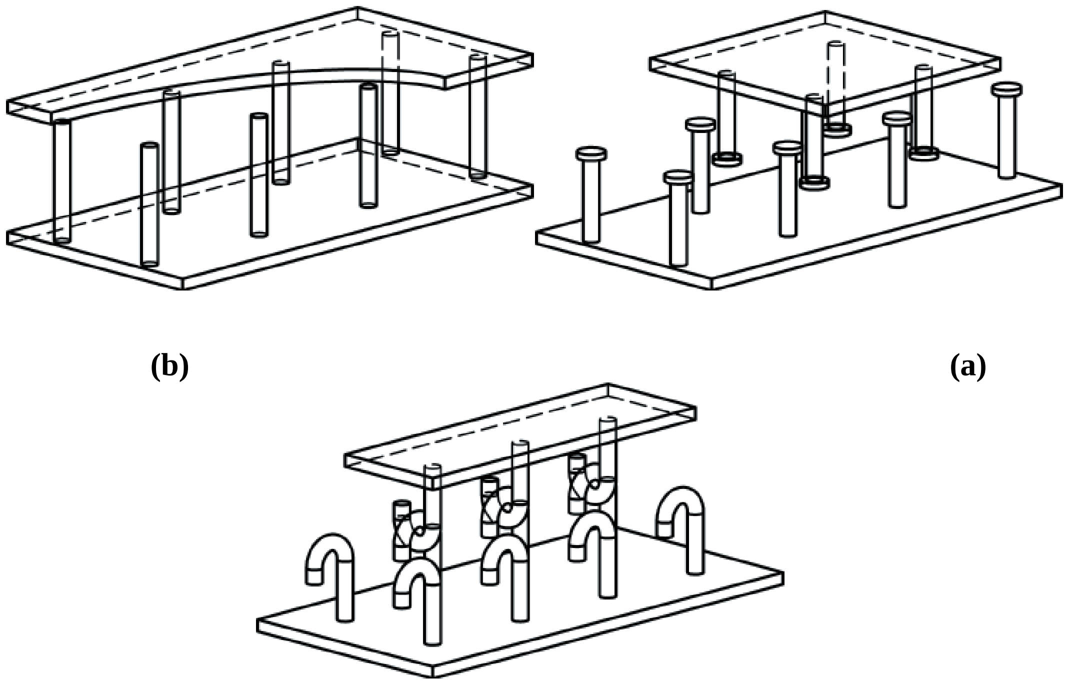
Also all of the practical results were compared to the theoretical results using Finite Element Methods Techniques which is included in a well- known computer program that is ANSYS (version 11) and it has been noticed that all of the practical results are close together with the analytical ones.

Keywords: steel; flexural behavior, stud connectors, sandwich beam, composite.

1. INTRODUCTION

The need for large structures with higher specific strength and stiffness is increasing. This is especially true of recent engineering structures where there is an interest in increasing payload to structure weight ratios. To deliver such structures, engineers can either find a new structural material or produce a new structural topology. The former method is however quite difficult to complete because qualification of new materials is expensive and time consuming. The latter method is more realistically possible because engineers can select any combination of existing materials and arrange them into a desired structural topology such as a sandwich structure.

A steel-concrete-steel (SCS) sandwich beam represents a special form of sandwich structure .It consists of steel face plates and concrete core which are connected together by mean of a series of shear connectors. The state-of-the-art construction forms of SCS sandwich structures are (a) double-skin sandwich construction (DSC), (b) Bi-Steel sandwich construction (Bi-Steel), and (c) alternative SCS sandwich construction. They are different only due to the pattern of their shear connectors, as shown in Figure (1) follow.



(b) **(a)**

(c)

Figure 1. Sketch of (a) double-skin, (b) Bi-Steel, and (c) an alternative SCS sandwich construction

2. LITERATURE REVIEW

It is known that the degree of interaction between steel and concrete influences the shear flow and strain distribution. Also, it has an impact on the structural performance such as strength, stiffness, and failure mode. The degree of interaction in steel–concrete composite systems can be evaluated as full-interaction, partial-interaction, and no-interaction (Veljkovic, 1996; Oehlers et al., 2000). The assumption of full-interaction may result in an overestimation of the structural performance while the assumption of no-interaction may cause an underestimation of the structural performance. Therefore, the partial-interaction assumption and analysis with a degree of interaction becomes more practical and seems to be essential for a precise prediction of behavior. Actually, the steel–concrete composite members generally show partial-interaction due to the deformation of shear connectors and slip at the interface under the applied loads (Johnson, 1994; Dogan, 1997; Roberts and Dogan, 1998; Oehlers and Bradford, 1999; Jeong et al., 2005; Ranzi et al., 2006; Gara et al., 2006; Queiroza et al., 2007; Ranzi and Bradford, 2007; Jeong, 2008; Ranzi, 2008; Girhammar et al., 2009; Sousa Jr. et al., 2010). In many situations, slip and its influence on the structural behavior of steel-concrete composite systems may be small enough to be neglected in the analysis (that is, full interaction). However, in some cases it may be feasible to use either fewer connectors than are required for complete shear connection or connectors which possess a relatively low stiffness. In such situations the influence of slip may not be negligible and result in reduced stiffness of the system (that is, partial interaction). In general, the stiffness of the connectors has a significant influence on both the slip and deformations of a composite beam. The stiffness of the shear connectors may be determined experimentally from so called push-shear tests.

Analysis of the influence of slip in composite beams, assuming both linear and non-linear material and shear connector behavior (Knowles, 1973; Yam, 1981; Newmark et al., 1951; Yam and Chapman, 1968; Yam and Chapman, 1972; Johnson, 1975; Johnson, 1981) has generally been based upon an approach attributed to Newmark et al. (1951). The equilibrium and compatibility equations for an element of the beam are reduced to a single second order differential equation in terms of either the resultant axial force in the concrete or the interface slip. Solutions for the axial force or interface slip are substituted back into the basic equilibrium and compatibility equations, which can then be solved to give displacements and strains throughout the beam.

Newmark et al. (1951) presented the results of tests and analysis for evaluating the load deflection behavior of simply supported, partially interactive, composite concrete and steel T-beams. The theoretical analysis was based upon the assumption that a continuous imperfect connection existed between the two elements. A second order differential equation expressing the relationship between the longitudinal forces, transmitted through the shear connection from the concrete slab to the steel beam, and the applied bending moment, was derived and solved for the case of a beam loaded with a concentrated load.

Newmark et al. (1951) approach has been developed by Yam and Chapman (1968, 1972) and Yam (1981) to incorporate on-linear material and shear connector behavior. The resulting non-linear differential equations were solved iteratively and the influence of slip on the ultimate flexural strength of composite beams was studied.

An alternative approach to the analysis of composite beams with partial interaction has been presented by Roberts (1985), in which the basic equilibrium and compatibility equations are formulated in terms of the displacements of the layers. The resulting differential equations are then solved simultaneously by expressing the displacement derivatives in finite difference form. The development of this approach to incorporate non-linear material and shear connector behavior has been described by Al-Amery and Roberts (1990). The resulting non-linear differential equations are expressed in finite difference form and solved iteratively.

3. CASE STUDY

In this paper, experimental investigations were carried to find the behavior of sandwich beams in bending. The experimental work included testing of four beams; first beam is control beam (CB) with dimensions (150 mm width, 300 mm depth and 1300 mm length) , second beam is steel-concrete-steel beam with stud connecters with normal ends without connected top and bottom steel plates (SCS1), third beam is steel-concrete-steel beam with stud connecters with wide ends without connected top and bottom steel plates (SCS2) and fourth beam is steel-concrete-steel beam with stud connecters with wide ends with connected top and bottom steel plates (SCS3) , the last three beams with dimensions (150 mm width, 250 mm depth and 1300 mm length)

The longitudinal reinforcement for control beam are consists of three No.16 bars (16 mm dia.) in tension, two No.12 bars (12 mm dia.) in compression and No.12 bars at 100 mm stirrup.

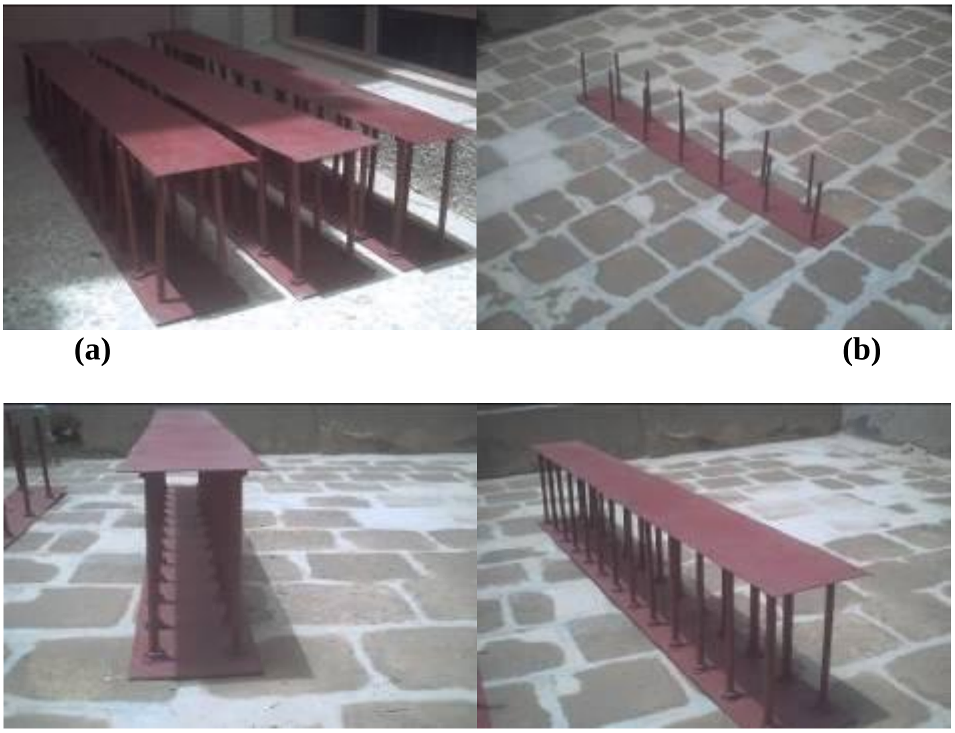
The steel plate equivalent to longitudinal reinforcement for SCS1, SCS2 and SCS3 are plate thickness 4 mm with 150 mm width in tension, plate thickness 1.5 mm with 150 mm width in compression and No.12 bars at 100 mm stirrup. The clear span between the two simply supports was 1100 mm.

The titles of specimens where chosen according to the classification listed in table (1)

Table 1- Classification of Beams

The Symbol	The name of beam
CB	control beam
SCS1	steel-concrete-steel beam with stud connecters with normal ends with connected on either top or bottom steel plates
SCS2	steel-concrete-steel beam with stud connecters with wide ends with connected on either top or bottom steel plates
SCS3	steel-concrete-steel beam with stud connecters with wide ends with connected top and bottom steel plates

The figure (2) shown sandwich beams in experimental work.



(a) **(b)**

(c) **(d)**

Figure 2. Sketch of (a, b, c and d) the model of specimen.

4. MATERIALS AND MIX USED

Ordinary Portland cement was used for all the beams. The Fine Aggregate used for casting was clean river sand. The specific gravity of fine aggregate was 2.7. The coarse aggregate used was broken granite stone of size 14 mm. The specific gravity of coarse aggregate was 2.8. Bore well water available in the Structural Engineering laboratory was used for casting all specimens of this investigation.

All steel rods of 415 N/mm2 yield strength were used as the tension and compression reinforcement.

Concrete mix of 1 (cement): 1.5(F.A): 3 (C.A.) with water cement ratio by weight of 0.50 was used for making the composite sandwich concrete beams.

Cement and sand were first mixed then coarse aggregate was added and the materials were mixed thoroughly until uniformity was achieved. Then the required quantity of water was added slowly and wet mixing was done.

three cubes were tested after 28 days measured from date of casting to obtain the standard compressive strength of concrete and three cubes and cylinders were tested at date of testing the beams to obtained the compressive strength and the splitting tensile strength of concrete at time of testing as shown in table (2).

Table 2- Compressive and tensile strength of concrete

Cubic compressive strength (f_{cu}) at 28 days (MPa)*	Compressive strength (f'_c) at 28 days (MPa)**	Cubic compressive strength (f_{cu}) at time of testing (MPa)*	Compressive strength (f'_c) at time of testing (MPa)**	Modulus of elasitcity (E_c) (MPa)***	Tensile strength at time of testing (MPa)****
28.15	22.52	29.46	23.57	22818	2.11

* Average of three cubes

** $f'_c=0.8\times f_{cu}$ (1)

*** $E_c=4700\ [f'_c]^{(1/2)}$ (where f'_c is compressive of strength at time of testing) (2)

**** Average of three cylinders

5. THE COMPOSITE ACTION EFFECT ON ELASTIC STIFFNESS OF COMPOSITE SANDWICH BEAMS

The composite beam with partial composite action: partial composite action section, strain distribution along sectional height, and internal forces are shown in figure (3 and 4).

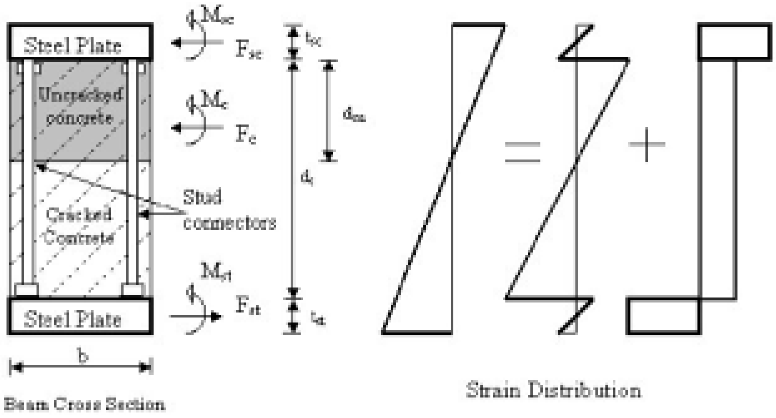


Figure 3. Internal forces and strain distribution over the depth of a SCS section for full interaction

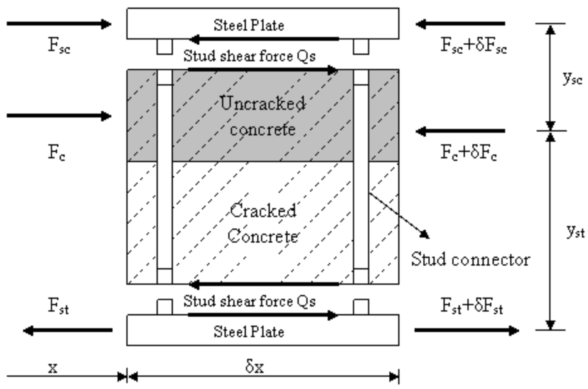


Figure 4. Interface shearing forces of a SCS beam.

The figure (5) shows the support location and location of loading points.

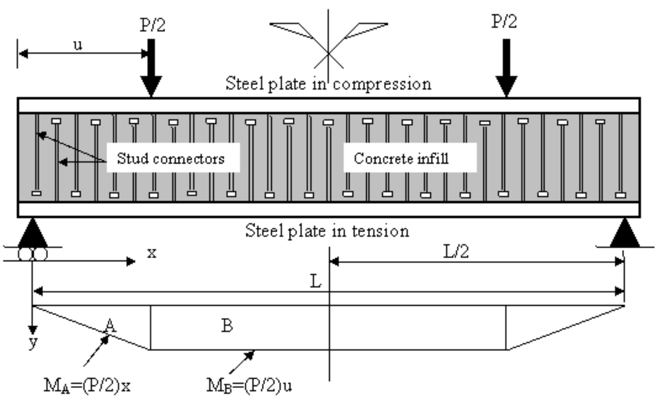
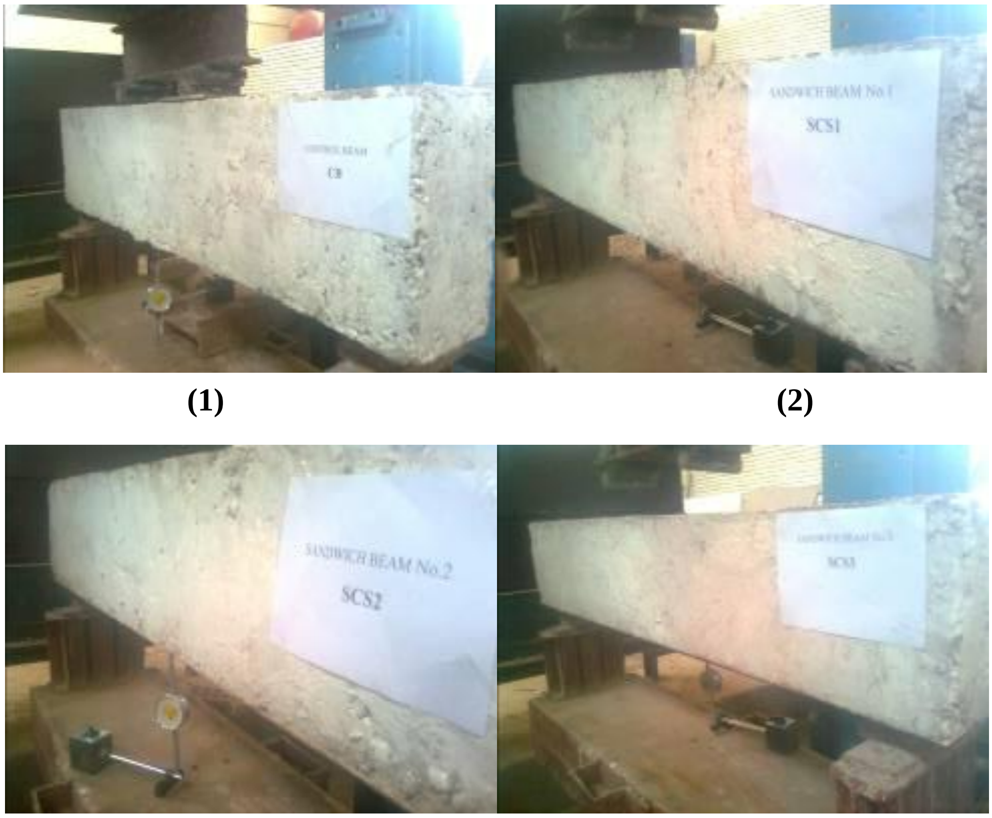


Figure 5. Geometry of laboratory

6. EXPERIMENTAL RESULTS

The main objective of the current research work is to investigate the effect of behavior changing the longitudinal main reinforcements in tension and compression zone by equivalent steel plate and load currying capacity of sandwich beams.

The experimental program consists of testing of four cases of beams. The experimental program variables include the method of connected the top and bottom of steel plate with together. The photograph of tested beams is shown in figure (6) prior to testing.



(1) **(2)**

(3) **(4)**

Figure 6. Tested beams before testing

Figure (7) below shows the pattern of failure of the sandwich beams under two point load, the type of failure is shear model and separation the top steel plate in location of point load and separation of bottom steel plate in position of support.

Figure 7. Pattern of failure of the sandwich beams

Figure (8) show the load versus mid-span deflection curves for experimental test of sandwich beams which was constant of the control beam BC and three sandwich beams SCS1, SCS2 and SCS3.

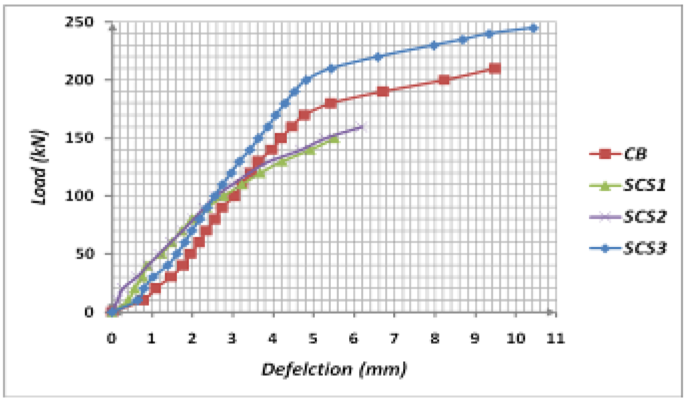


Figure 8. Load-deflection curves for experimental test of sandwich beams

7. MODELING OF TESTED BEAMS FOR ANSYS COMPUTER PROGRAM

In the *ANSYS* computer program, there are three steps to be considered before modeling the beam.

1- Choosing element type for each material used.
2- Defining real constants for these choosing elements.
3- Defining material properties for the choosing element.

The element type for each material used in the analysis in chosen off. In this study, three elements were used, these element are ***solid65***, ***solid45*** and ***link8*** to represent concrete, steel plate and steel reinforcement, respectively.

The real constant used for solid65 element with smeared reinforcement in the three direction x, y and z, while the reinforcement is treated as discrete representation. Therefore, this real constant set to zero to turn off smeared representation for reinforcement.

The real constant used for link8 element. Input data for cross sectional area.

By taking advantage of symmetry of the tested beam, only one quarter of beam was used for modeling as shown in figure(8).

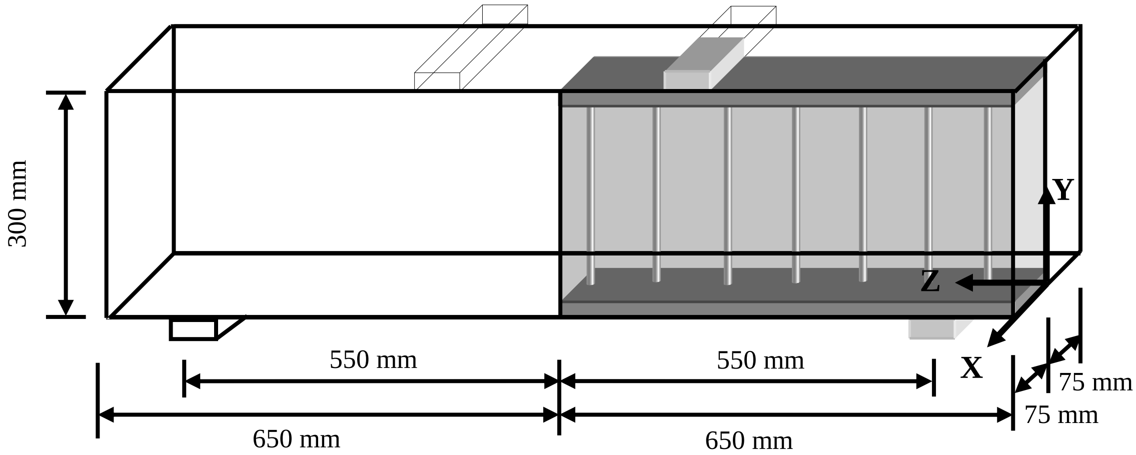


Figure 8. One quarter of deep beam used for analysis

Figure (9) shows the modeling and analysis of the sandwich beams by *ANSYS* software program.

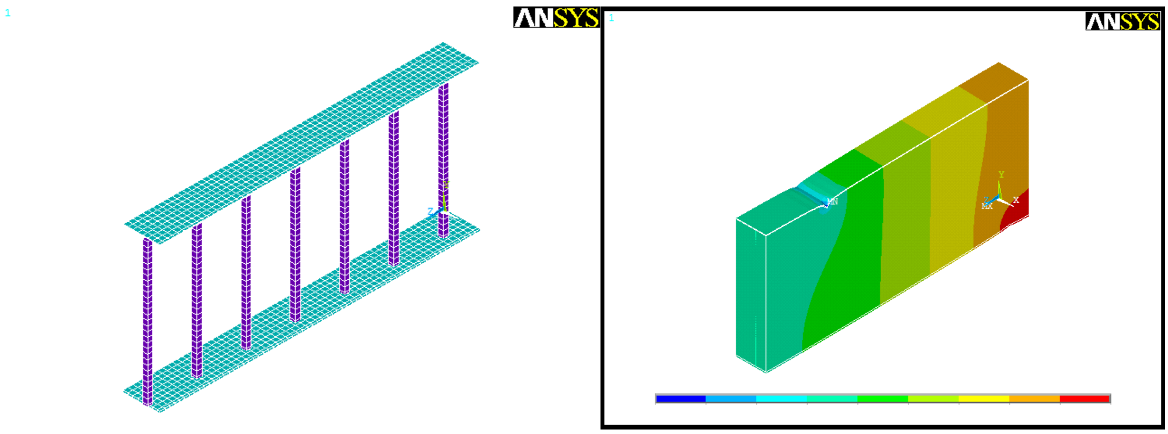


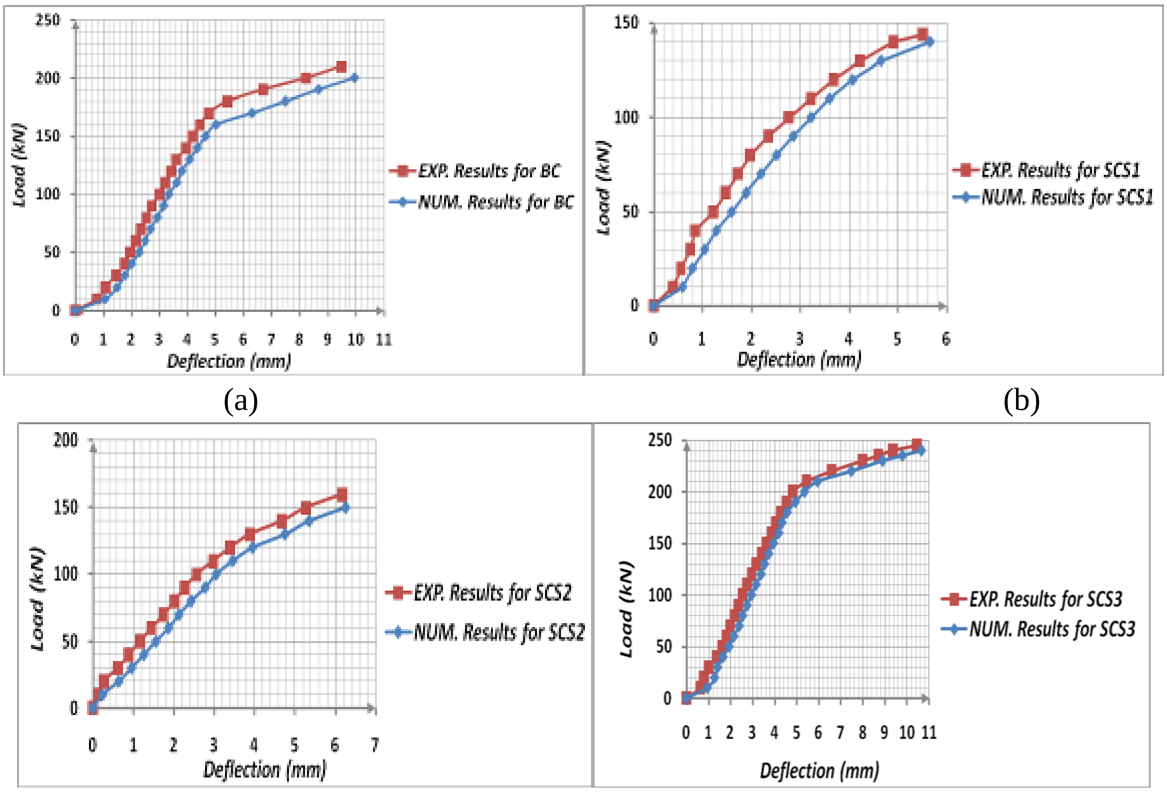
Figure 9. One quarter of deep beam used for analysis

8. ANALYTICAL RESULTS

A three-dimensional finite element model is adopted to examine the structural behavior of sandwich beams. The analytical results obtained using the nonlinear finite element program **(ANSYS Ver.11)**,with solid65, solid 45 and link8 elements have been used to represent concrete, steel plates and steel bars respectivly.

For all analyzed the sandwich beams numerical failure occures by diagonal shear crack similarly to the made of failure occurred in experimental work. ANSYS results reveal that the same sequence of behavior of behavior occurs at all stage of loading.

the comparison between the numerical and experimental load-deflection curves for the sandwich beams are shown in figure (10) ware constants of the control beam BC and three sandwich beams SCS1, SCS2 and SCS3.



(a) (b)

(c) (d)

Figure 10. Load-deflection curves experimental test of sandwich beams

The ratios of the perdicted finite element maximum deflections and ultimate loads to the corresponding experimental maximum deflections and ultimate loads of the analyzed sandwich beams are listed in table (3).

Table 3- A comparison between experimental and numerical results of the sandwich beams

Beam designation	Experimental results		Experimental results		$P_{nu}/P_{ex.}$	Load capacity ratio of beam with respect to CB
	Max. deflection (mm)	Ultimate load P_{ex} (kN)	Max. deflection (mm)	Ultimate load P_{nu} (kN)		
BC	9.49	211	9.95	200	0.948	1.000
SCS1	5.52	153	5.66	144	0.941	0.725
SCS2	6.18	161	6.25	153	0.951	0.763
SCS3	10.44	246	10.64	239	0.972	1.166

9. CONCLUSIONS

After making all of the experimental tests to the sandwich beams and the analytical analysis had been finished there were many phenomenon's and conclusions that can be extract from this research; further more discussing the reasons that led into the happening of this phenomenon.

The most important phenomenon that one can conduct from this research is:

1. In SCS1 and SCS2 beams a separation can be seen between the steel plate that replaces the longitudinal bars and the concrete, and when continuing the loading process a dent can be seen in the upper zone of the steel plate at the loading point and also at the lower zone on the beam supports; afterwards a slipping happens between the steel and concrete which continues until the occurrence of a wide and clearly seen crack, at that point the bearing capacity of the beam back down till failure.
2. In SCS3 beam the same phenomenon in the last beams can be seen and that is because of the existence of full bond between the two steel layer, and the tolerance continues for a while and then a sudden failure with a blast like sound will occurs and that is mainly happened because of the separation of the stirrups that connect the two steel ends after increasing the load applied on it.
3. It was observed that the difference is so little between the load capacity of SCS1 and SCS2 beams; where there is no such big influence because of the existence of the wide area at the end of stirrups at SCS2
4. The load capacity in SCS3 beam is larger than the load capacity of CB beam with a ratio of 1.166 and that is due to the following reason: the full correlations between the steel parts at both the tension and compression zones where the contribution part of the forming stresses at the tension area to the compression area which leads into lifting the neutral axis and increases the moments on the beam.
5. After making the numerical analysis using a well known program ANSYS an observation can be made that the nonlinear results for analyzing the beams is so close to the practical ones which indicate clearly the consistency between the practical and works.

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