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BEHAVIOR OF SIMPLY SUPPORTED COMPOSITE CONCRETE-STEEL BEAM WITH CORRUGATED WEB UNDER VERTICAL LOADS

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This paper presents the behavior of simply supported concrete-steel composite beams with corrugated web under vertical loads using the commercial finite element (FE) software ANSYS. The three-dimensional (FE) model is used to simulate the overall flexural and shear behavior of simply supported composite beams with corrugated web subjected to vertical loads. This study covers: load deflection behavior and load strain curve. The reliability of the model is demonstrated by comparison with experimental results test carried out by author and others. Two identical composite beams with corrugated web were tested to failure under vertical loads. The comparison shows good agreement. A parametric study was undertaken using the validated model performed using finite element program. The parametric analysis was executed to study the effect of web thickness on the behavior of concrete-steel composite beam under vertical loads. The comparison between concrete-steel composite beam with corrugated and flat web was introduced in this paper. From this study, it can be concluded that, the corrugation in web increases the stiffness and ductility for composite beam. The increasing of corrugated web thickness increases the ultimate load and enhances the shear behavior of concrete-steel composite beam.

KEYWORDS: *Experimental tests, finite element analysis, composite beam, corrugated steel web, nonlinear analysis.*

1. INTRODUCTION

Steel girders have been used for many years; new generation of optimized steel girders was developed by the advances in structural and fabrication technology. One of the developments in structural steel during the past few years has been the availability of corrugated web I-beams. Economical design of steel girders normally requires thin webs. The use of corrugated webs is a possible way of achieving adequate out-of-plane stiffness without using stiffeners. Engineers have long realized that corrugation in webs increases their stability against buckling and can result in economical design. The web corrugation profile can be viewed as uniformly distributed stiffening in the transverse direction of the beam. When girders with corrugated webs are compared with those with stiffened flat webs, it can be found that trapezoidal corrugation in the web enables the use of thinner webs without transversal stiffeners which eliminate the cost and time [1]. Also these beams have 9 to 13% less weight than current traditionally stiffened girders with flat webs [1]. Several previous studies [2-10] had been concerned on steel girders with corrugated webs. Most of these were about the shear and bending behavior of simply supported beams. Composite action between two materials enhances structural efficiency by combining the structural elements to create a single composite section. Composite beam designs provide a significant economy through reduced material, more slender floor depths and faster construction. Moreover, this system is well recognized in terms of the stiffness and strength improvements that can be achieved when compared with non-composite solutions. Therefore, the objective of this research is to study theoretically the influence of web corrugation on the structural behavior of concrete-steel composite beam under vertical loads. In order to use steel-concrete composite beam with corrugated web in practice, their behavior under shear load needs to be investigated. These beams are used in bridges and large span structures. In order to achieve economical design, the thickness of the web should be as small as possible. However for thin webs, shear buckling is very likely to happen. For steel-concrete composite beam with flat web, use of stiffeners in the web or increase the web thickness is an effective way to increase the shear capacity. By the adoption of corrugated web, thin web panel can also be used effectively and shear buckling can be avoided. Corrugated web composite beams offer several advantages over the stiffened flat web. The corrugations not only provided enhanced shear stability, but they also eliminate the need for transverse stiffeners, thereby offering the potential for improved fatigue life.

2. THEORETIACL APPROACH AND FINITE ELEMENT MODELING

It is widely known that laboratory tests require a great amount of time, are very expensive and, in some cases, can even be impractical. Also it is well known that, the finite element method becomes, in recent years, a powerful and useful tool for the analysis of a wide range of engineering problems. A comprehensive finite element model permits a considerable reduction in the number of experiments. Nevertheless, in a complete investigation of any structural system, the experimental phase is essential. Taking into account that numerical models should be based on reliable test results, experimental and numerical / theoretical analyses complement each other in the investigation of a particular structural phenomenon. In order to obtain reliable results up to failure, finite element models must properly represent the constituent parts, adopt adequate elements and use appropriate solution techniques. As the behavior of composite beams presents significant nonlinear effects, it is fundamental that the interaction of all different components should be properly modeled, as well as the interface behavior. Once suitably validated, the model can be utilized to investigate aspects of behavior in far more detail than is possible in laboratory work. For instance, it permits the study of the sensitivity of response to variability of key component characteristics, including material properties and shear stud layout. The present investigation focuses on the modeling of concrete-steel composite beams with corrugated web under vertical loading using the Finite element program ANSYS. A three dimensional model is proposed, in which all the main structural parameters and associated nonlinearities are included (concrete slab, steel beam and shear connectors). An eight-node solid element, SOLID65, was used to model the concrete. Each solid element has eight nodes with three degrees of freedom at each node – translations in the nodal x, y, and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing.

LINK8 element was used to model the steel reinforcement. Two nodes are required for this element. Each node has three degrees of freedom, – translations in the nodal x, y, and z directions. The element is also capable of plastic deformation.

The finite element elastic-plastic shell (SHELL43) was considered for steel section. The element SHELL43 is defined by four nodes having six degrees of freedom at each node. The deformation shapes are linear in both in-plane directions. The element allows for plasticity, creep, stress stiffening, large deflections, and large strain capabilities.

A nonlinear spring (COMBIN39) was used to represent the shear connectors. The element COMBIN39 is defined by two node points and a generalized force–deflection curve has longitudinal or tensional capability. The longitudinal option is a uniaxial tension–compression element with up to three degrees of freedom (translations) at each node.

In order to avoid numerical problems, the values measured in the experimental tests for the material properties of the steel components (webs and flanges) are used in the finite element analyses.

Displacement boundary conditions are needed to constrain the model to get a unique solution. To ensure that the model acts in the same way as the experimental beam boundary conditions need to be applied at the supports and loadings exist. The support was modeled in such a way that a roller was created. A single line of nodes on the plate were given constraint in the UY, and UZ directions, applied as constant values of zero. By achievement this, the beam will be allowed to rotate at the support. The force applied at ten nodes each node on the plate is one tenth of the actual force applied to eliminate the effect of located strain in each node. Figure 1 illustrates the applied loads and boundary condition for meshed composite concrete-steel beam.

3 .VERVICATION OF THE COMPUTER PROGRAM (ANSYS)

The accuracy of the computer program (ANSYS) used in this study was checked by comparisons against Chapman and Balakrishnan tests [10], as well as against results of experimental work.

3.1. Chapman and Balakrishnan tests [11]:

The tests performed by Chapman and Balakrishnan successfully illustrate the behavior of the composite system which is being investigated. The beams spanned 5490 mm with an I-shaped steel member 305 mm deep and a concrete slab 152 mm thick ×1220 mm wide. The slab was longitudinally reinforced with four top and four bottom 8 mm bars. The transverse reinforcement incorporated top and bottom bars of 12.7 mm @ 152 mm centers and 12.7 mm @ 305 mm centers, respectively. The yield tensile strength, the Young's modulus and the Poisson's ratio of the reinforcing steel bars were 320 N/mm^2, 205 000 N/mm2 and 0.3, respectively. A full description of these beams is presented in Fig.2.

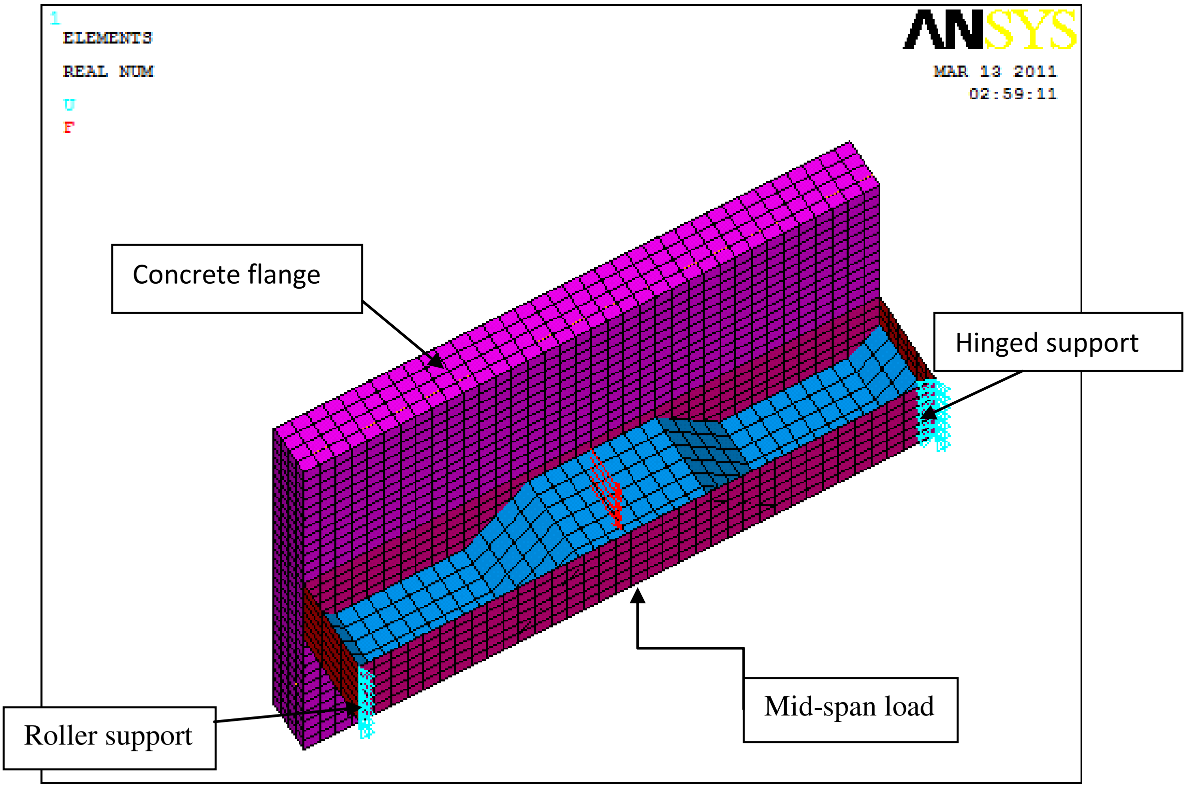

Fig. 1: Applied load and boundary condition mesh for composite concrete –steel beam.

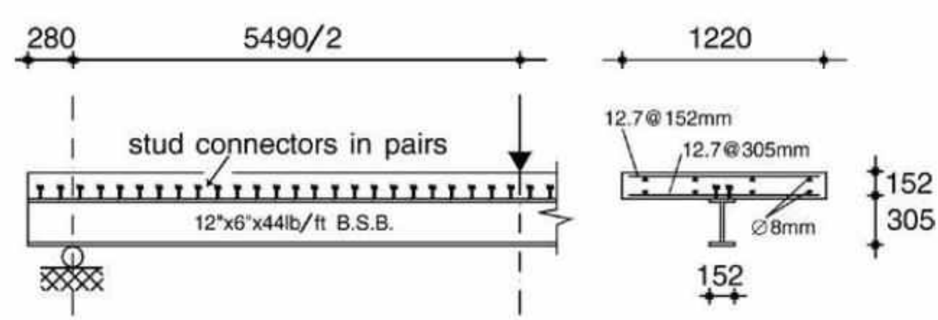

Fig. 2: Simply supported beam layout (dimensions in mm)

The load-deflection curve of the composite beam obtained by finite element model is compared with that obtained by experiments in Figure. 3. It can be observed from Figure.3 that the initial stiffness of the composite beam predicted by the finite element model is the same as that of experimental one. The ultimate load obtained by finite element model was 494 kN. This is equal 95.3% of the experimental value. The nonlinear finite element analysis conformed the experimental observation that the composite beam failed by crushing of the top concrete slab at mid-span. It can be concluded that the finite element model used herein is reliable and little conservative in predicting the ultimate strength of composite beams.

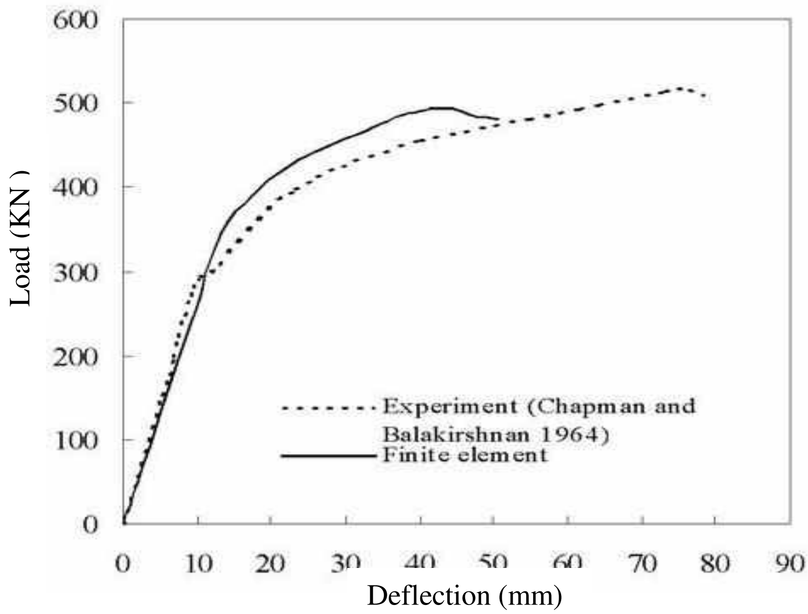

Fig. 3: Comparison of finite element modeling result with experimental result [11]

3.2 EXPERIMENTAL WORK

3.2.1 Details of Beams:

Two identical specimens were tested, (B1and B2). Each beam consists of three parts with 3 m total length. The middle was unstiffened with corrugated web, while the two outer parts were compacted sections and built up with stiffened flat webs. The middle part and the two outer stiffened parts were connected together using 10mm thickness plate and six bolts M 16 grade 10.2. The middle part consists of steel flanges of 150mm width and 10 mm thick where the web was corrugated and had 130 mm height and 2mm thickness. The composite action was performed using 8cm top reinforced concrete slab connected with the top steel flange using shear connector. The shear connectors were angles 40x40x4mm with length of 150mm. The angles were welded continuously to the top steel flange; it was spaced at distance equals to 20cm as shown in Fig 4. The concrete slab contained welded mesh of reinforcement at mid-depth. The mesh reinforcement was consisted of 10 mm diameter high tensile steel bars spaced at a distance equals to 150 mm in the longitudinal direction and 178 mm in the transversal direction. The outer stiffened parts were stiffened enough to ensure that, the failure occurs at the middle tested part. The stiffened part was built up section bare steel beam with overall depth of 250mm. Each stiffened part was consisted of bottom and top steel flange with 150mm width, 28mm depth and flat web with 194mm height and 10mm thickness. Four steel plate stiffeners (194x50x5) mm were used in every part as shown in Fig 4.The stiffened and medial parts were connected together by bolted connection. The parts are to be disassembled changes in connections are quite simple because of the bolted removal. The bolted connection’s components were detailed in Fig (4).

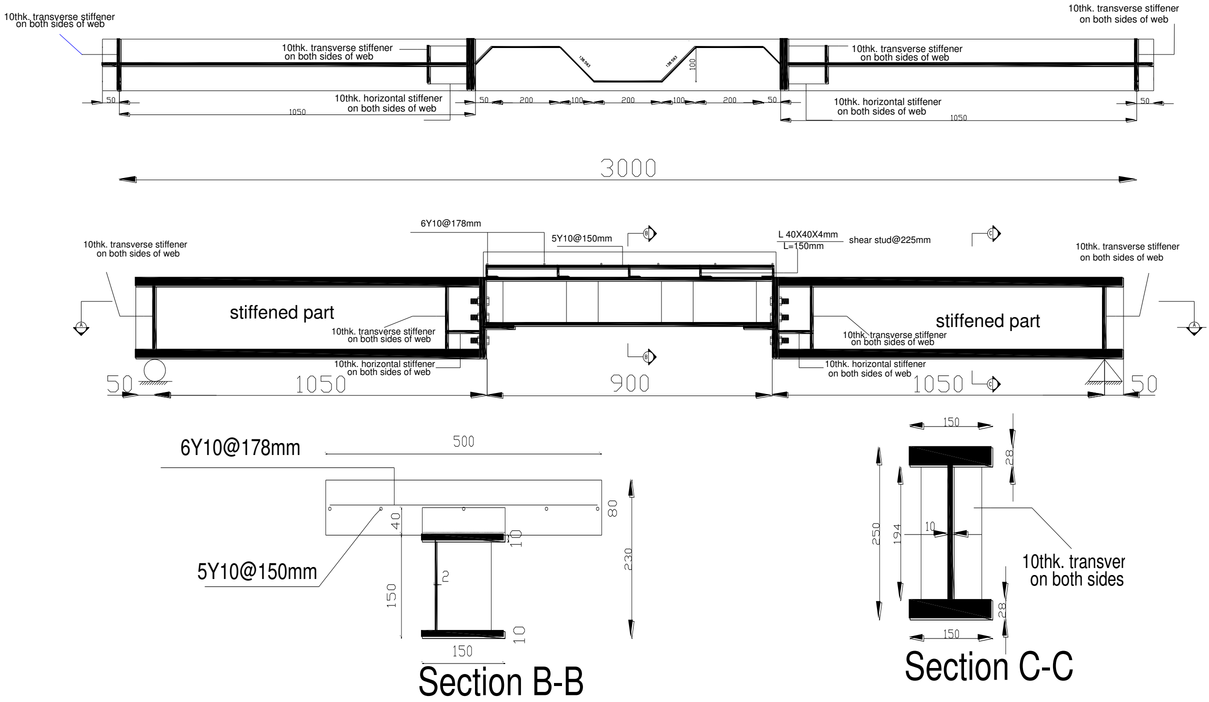

Fig. 4: Details of test specimens B1and B2 (all dimensions are in mm)

3.2.2 Materials:

- Concrete mix design was made to produce concrete having a 28 day cube compressive strength of about 27.5 N/mm^2.
- High strength deformed bars 10 and 12 mm diameters were used in reinforced concrete flange. Table (1) gives a summary of mechanical properties for used steel.

Table (1): properties of steel reinforcement

properties	**Diameter of used steel(mm)**	
	10	**12**
Yield Strength (***Fy***) t /cm^2	280 N/mm^2	290 N/mm^2
ultimate strength(***Fu***) t /cm^2	320N/mm^2	320 N/mm^2
elongation %	12.73%	14.3%

- The structural steel that used in web and flange of steel beam was tested to determine its mechanical properties. These properties are listed in Table (2).

Table 2: Mechanical properties of specimens as obtained from tension test

Coupon type	**(Fy) N/mm^2**	**(Fu) N/mm^2**	**(E) N/mm^2**	**Elongation %**
Flange& Web	310	390	200000	19.6

3.2.3 Test procedure and Instrumentation:

All beams were tested simply supported and the loads were applied as third points loads as shown in Fig (5). Instrumentation was provided to measure central deflection and the induced strain in both concrete and steel at mid-span using electrical strain gauges. Crack patterns and failure modes were carefully observed.

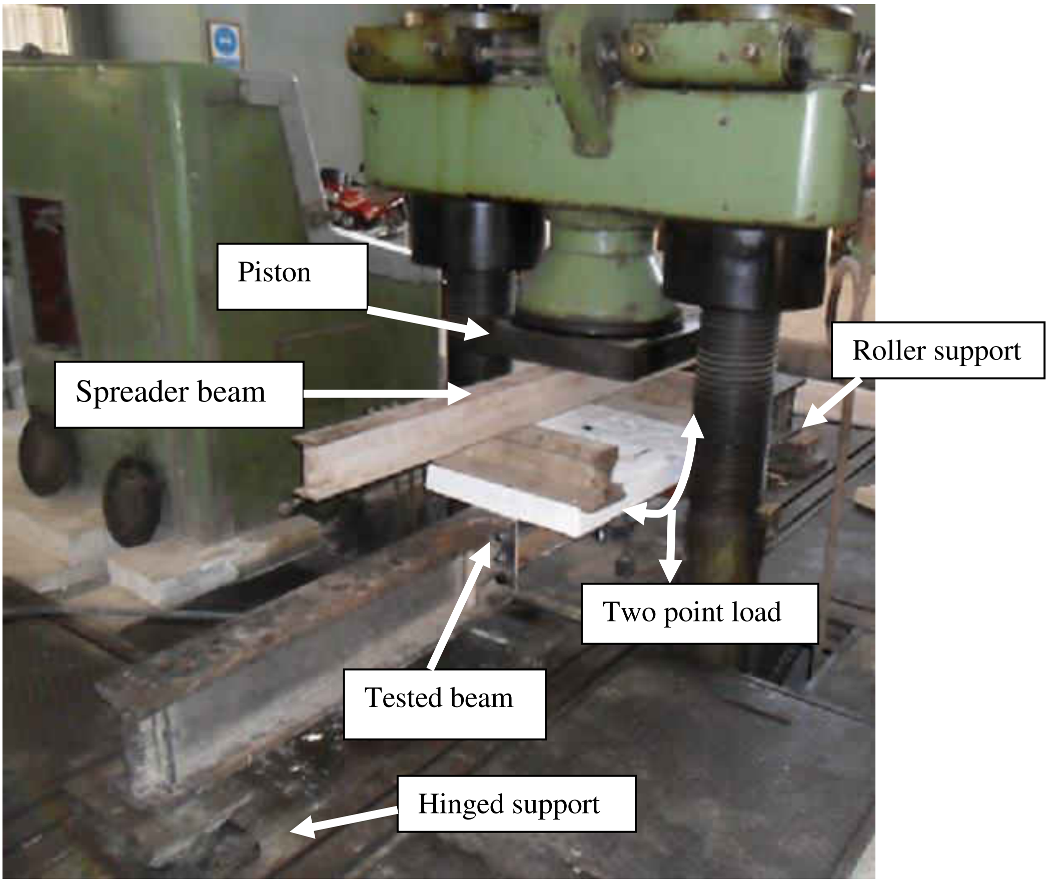

Fig. 5: Test set-up

4. TEST RESULTS AND DISCUSSION

4.1 Failure Mode:

The initiation and propagation of cracks for the tested beams was observed visually with a magnifying glass. The first crack appeared at the bottom side of concrete slab near the concrete-steel interface under the point load position and propagated upward. This crack appeared at corresponding load 80 kN for **B1**and 60 kN for **B2**. As the load increased, other cracks formed and become wider and propagate in an inclined direction toward the top surface of the concrete slab. The formed cracks reached the top surface of the concrete slab with increasing the load. The appearance of the formed cracks on the top surface of the concrete slab was in the same time near the two point loads position. As the load increased, the cracks became wider to form two big major cracks at each side of the concrete slab. The propagation of the major cracks was toward the mid span and inclined with approximately 30 ° on the longitudinal center line of the concrete-steel composite beam. New minor cracks were observed with increasing the load. The new formed cracks were neighbor and parallel to the major cracks. The minor cracks were appeared at corresponding load equal to 120 kN for B1 and 100 kN for B2.Then the propagation of cracks stilled in the same manner with increasing of load until failure load that was 170 kN for the two beams B1andB2. Fig (6.a) and Fig (6.b) show the failure modes of the two tested composite beams B1, B2. A summary of significant information regarding B1 and B2 is provided in Table 3.

Table 3: Summary of test results of beams (B1 & B2)

beam No	f_{CU} **kN /mm^2**	P_{cr} **kN**	P_u **kN**	P_u/P_{cr}	**Mode of failure**
B1	27.5	80	170	2.12	Flex. Comp. (ductile)
B2	27.5	60	170	2.83	Flex. Comp. (ductile)

Fig. 6-A: Failure mode and cracks pattern for B1

Fig. 6-B: Failure mode and cracks pattern for B2
Fig. 6: Cracks pattern and shape of failure.

4.2 Load Deflection Curve:

Figure 7 shows the load- deflection curve for the two tested beams. It can be seen that the high rigidity of the concrete-steel composite beams. Elastic-plastic behavior was studied in the composite beam; in elastic stage the concrete and steel act as one element that is reflected on the rigidity of the concrete-steel beam as shown in Fig7. Also it can be noted that, the deflection curve is liner until cracking and beyond this limit the mid-span deflection increased at higher rate. The contribution of the concrete in resistance was gradually decreased with increasing of cracking until the end of plastic stage. The maximum deflection at failure was approximately 26mm for B1 and 27mm for B2.

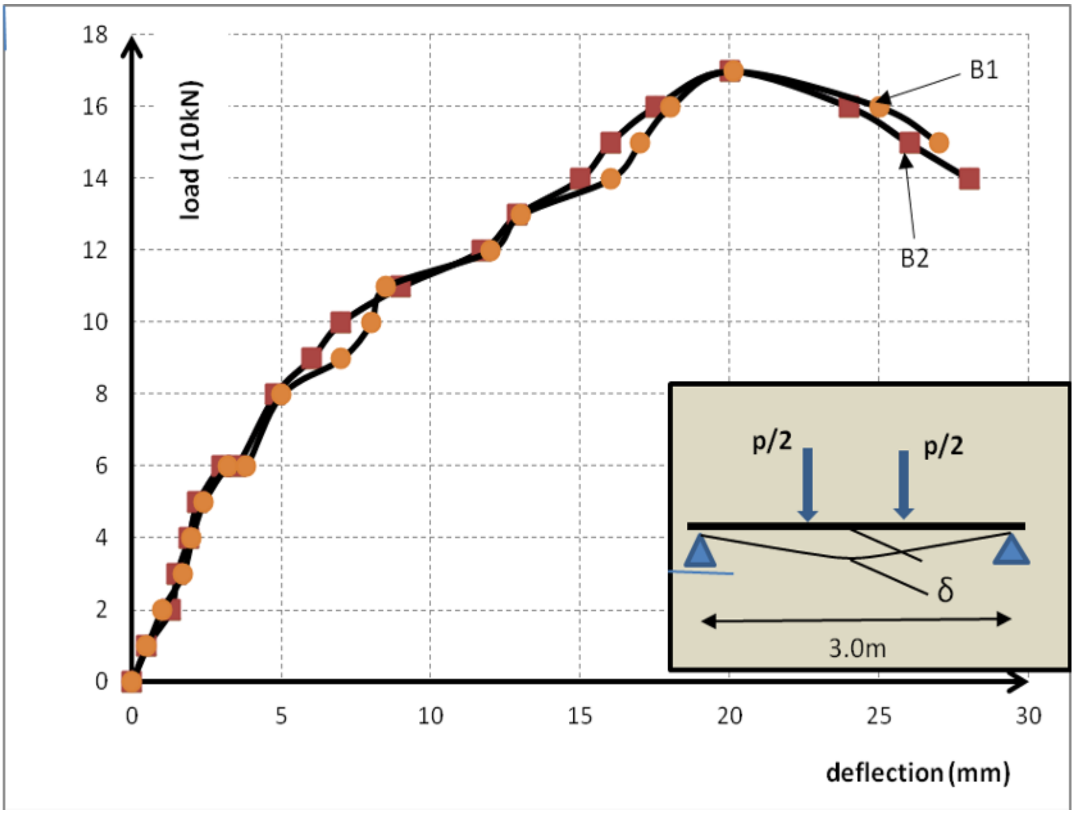

Fig. 7: Load –Mid span Deflection Curve for B1 and B2 at mid-span.

4.3 Strain Distribution:

In order to point out the contribution of the concrete slab and steel beams during the test procedure; the induced strain in both concrete and steel at mid-span were measured. The strains are plotted against load for different stages of loading in order to study the behavior of the tested beams as shown in Fig 8. It can be noted that there are four regions of the load-strain curves. In the first region, the strain increased linearly according to the load. Then the strain increases rapidly while the applied load increases in low rate. This region began with the appearance of the cracks in the concrete slab. In the third region, the strain increases faster again linearly, according to the applied load. In the last region, the strain is stopped in the concrete flange by the new formed cracks and the development of the earlier cracks. On the other hand the strain in steel beam increased quickly when the load is stable. This region corresponds to the failure of the concrete-steel composite beam.

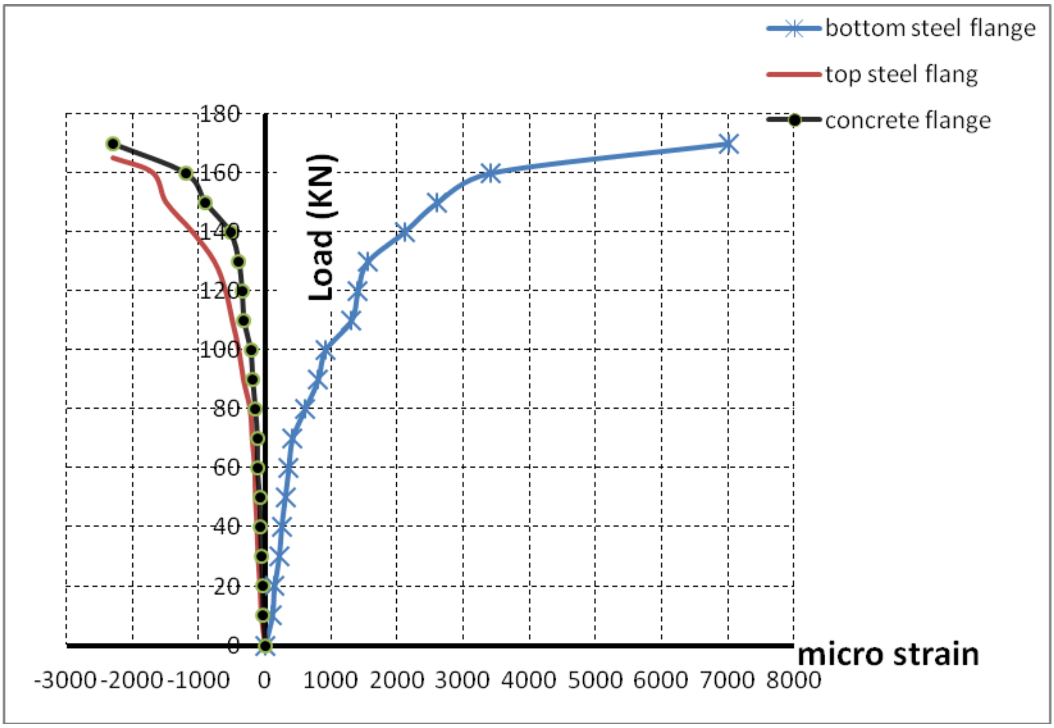

Fig. 8: Load-Strain curve

The distribution of the strain on the cross section is shown in Fig 9. It can be noted that the distribution was liner in the first stages up to the load corresponding to the cracking of concrete slab and the yield of the steel beam. The strain in the concrete slab and top steel flange is compression strain; that mean the neutral axis occur below the top steel flange. Also it can be seen that, the two curves which represent the strain in concrete, top steel flange are much closed and have similar slope. That confirms the combined action between the concrete slab and the steel flange which was provided by shear connectors. Due to the cracks that were created in concrete slab, the neutral axes moves downward as shown in Fig 9.

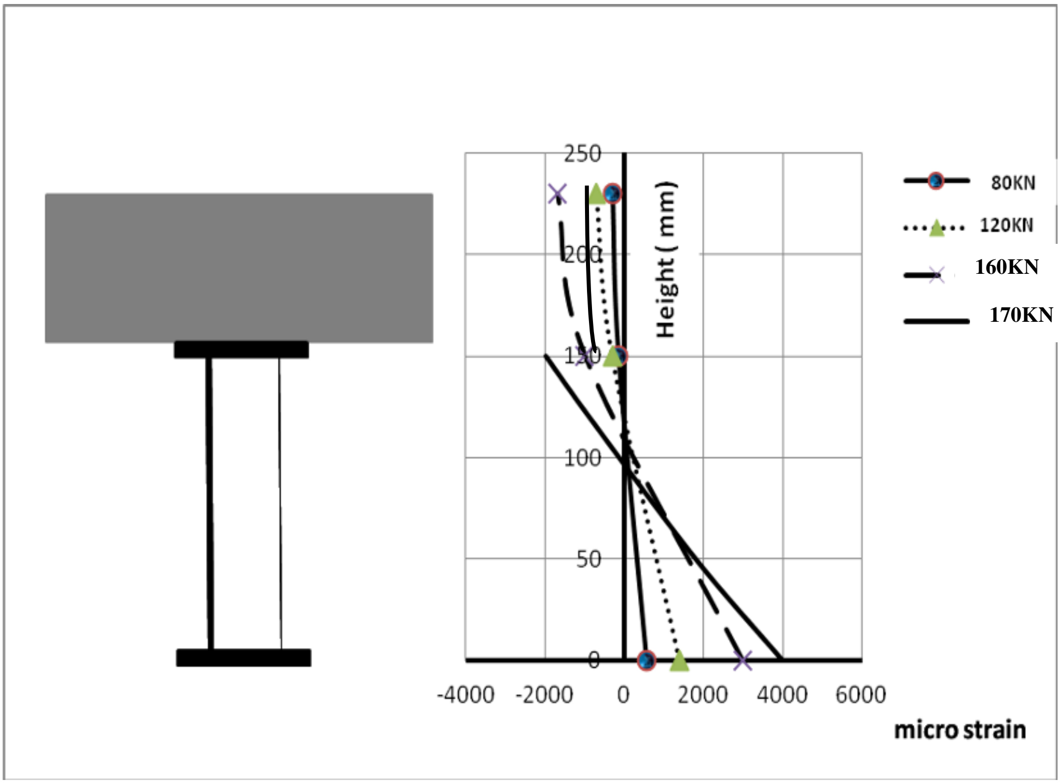

Fig. 9: Position of experimental neutral axis the mid-span

5. COMPARSION BETWEEN THE FINITE ELEMENT RESULTS AND THE EXPERIMENTAL RESULTS

Using finite element program (ANSYS), the central deflection was calculated. Figure 10 shows the load-deflection curves calculated using the finite element analyses and that from the test results. As shown in this figure the load-deflection curves obtained from the finite analyses agrees well with the experimental data for the composite concrete-steel beams. In the linear range, the load-deflection plot from the finite element analysis is approximately coincide with that from the experimental results. After the first cracking, the finite model becomes slightly stiffer than the actual beam. The higher stiffness in the finite element models may be due to Micro cracks produced by drying shrinkage and handling is present in the concrete to some degree. These would reduce the stiffness of the actual beams, while the finite element model does not include micro cracks. It can be observed from the curves that, the program stopped at lower deflection. This may be due to the crushing of the concrete under the applied load. The crushing of the concrete was due to the fact that there was high stress concentration at the nodes under the applied line load in the finite element model, which induced concrete crushing to occur at these locations. On the other hand, bearing plates help in distribute the load uniformly in actual test. Finely, the maximum deflection from the ANSYS was 24mm, while for the experimental data was 27mm.

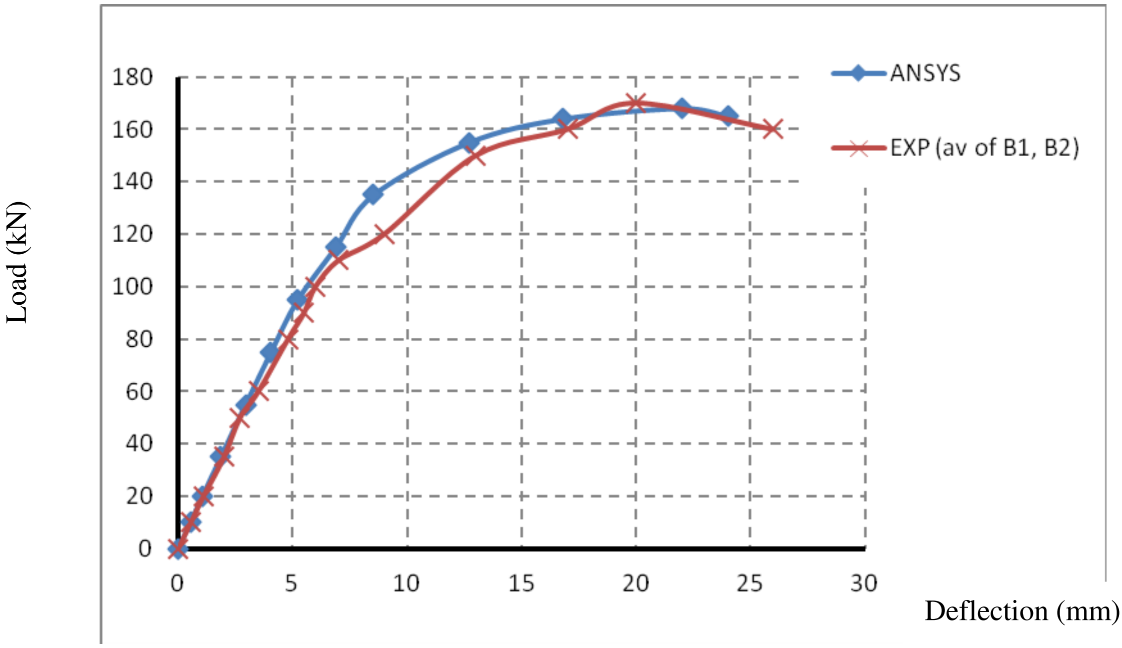

Fig. 10: Comparison of the finite element and the experimental load versus mid-span deflection behavior.

6 SHEAR BEHAVIORE OF STEEL-CONCRETE COMPOSITE BEAM WITH CORRUGATED WEB

In this section the behavior of simply supported steel-concrete composite beams under combined bending and shear are investigated by using the finite element method. A three dimensional finite element model which accounts for geometric and material nonlinear behavior of composite beam, is described in detail. The developed finite element model has been used to investigate the behavior of simply supported steel-concrete composite beams with different corrugated web thickness (1, 2 and 6 mm) under combined action of bending and shear. A point load was applied at mid-span of all models. The load-deflection curves obtained from the nonlinear finite element analysis are shown in Fig 11. It can be noted that the response of composite beams to applied loads is initially linear and the nonlinear load-deflection behavior is observed. Also it can be noted that the strength and stiffness of composite beam increase with an increase in the corrugated web thickness. For model with corrugated web thickness of 1mm, the ultimate load was 80 kN with maximum deflection equal to 2mm. however increasing the web thickness to 2mm, increases the ultimate load to 175 kN with maximum deflection equals to 3mm. For beam with corrugated web thickness of 6mm, the ultimate load was 200 kN and the maximum deflection was 4mm.

In general increasing corrugated web thickness enhances the ductility and the ultimate carrying capacity of the steel-concrete composite beam with corrugated web.

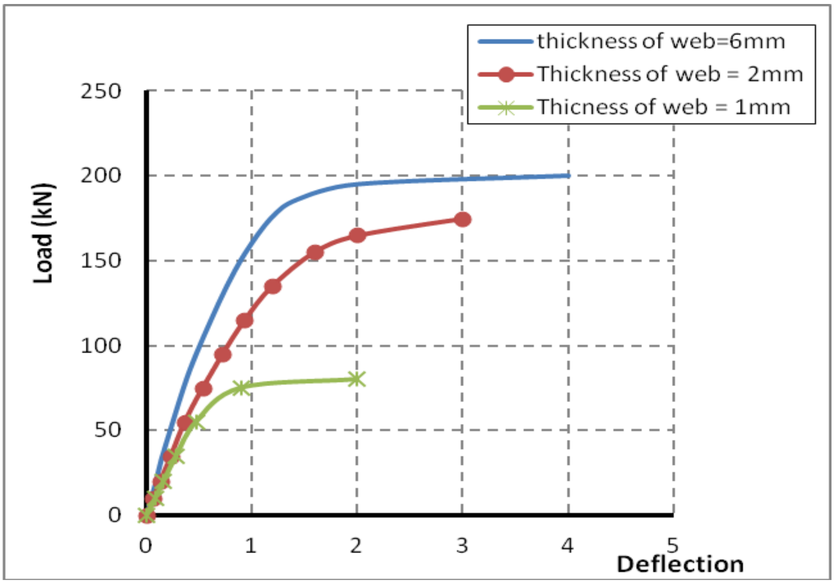

Fig. 11: load-mid-span deflection for composite beams with deferent corrugated webs thickness.

7. COMPARISON BETWEEN STEEL-CONCRETE COMPOSITE BEAMS WITH CORRUGATED WEB AND STEEL-CONCRETE COMPOSITE BEAMS WITH FLAT WEB USING FINITE ELEMENT PROGRAM

In order to investigate the effect of corrugated web on structural behavior of steel-concrete composite beams, another model had been developed. A three –dimensional finite element model has been developed to account for geometric and material nonlinear behavior of composite beams. The corrugated web in the previous model was replaced by flat web of the same thickness. Load-deflection curve for each case is shown in Fig 12. It can be noted that the corrugation web effect efficiency on strength and ductility behavior of composite beam. For steel-concrete composite with flat web, the ultimate load was 110 kN with maximum deflection equal to 4mm. On the other hand the ultimate load for steel-concrete composite beam with corrugated web was 180 kN with maximum deflection equal to 5mm. The increasing in ultimate load for steel concrete beam with corrugated web respect to steel-concrete composite beam with flat web was about 63%. The ductility index was calculated for each beam using under curve area method. The ductility index for steel-concrete composite beam with corrugated web was about 195% of the ductility index for steel-concrete composite beam with flat web. In general, corrugations in webs enormously increase their stability against buckling and can result in very economical designs. Therefore steel-concrete composite beam with corrugated web have the potential to eliminate many costly web stiffeners. In addition, the use of thinner webs results in fewer raw materials. Since the corrugation in the web provides the members with a higher resistance against bending over the weak axis and rotation thin corrugated webs act efficiently in shear resistance without needing to stiffeners.

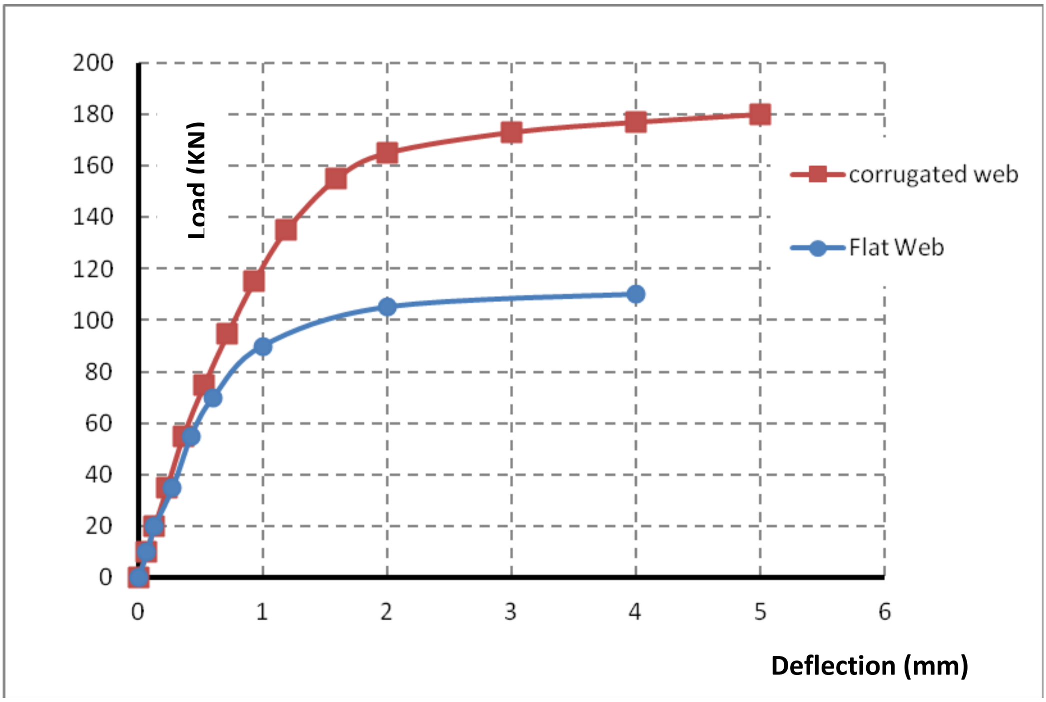

Fig. 12: Load-mid-span Deflection for Composite Beams with Corrugated web & Flat web.

CONCLUSIONS

Based on the results of theoretical and experimental studies on behavior of simply supported composite concrete-steel beam with corrugated web under vertical loads the following conclusions are made.

1. The FEA throw Ansys program can be used as a very useful tool in predicting the failure load of composite concrete-steel beams with corrugated web and can provide very detailed information for the distribution of stress / strain in composite beams with corrugated web.
2. The thickness of corrugated web has a very little effect on flexural behavior for composite concrete-steel beam with corrugated web.
3. There was clear increasing in ductility and ultimate load where corrugations in webs enormously increase their stability against buckling and can result in very economical designs.
4. The increasing in ultimate load for steel concrete beam with corrugated web respect to steel-concrete composite beam with flat web was about 63%.
5. Increasing of corrugated web thickness enhances the shear behavior of steel-concrete composite beam with corrugated web, increasing the ultimate load and maximum deflection.

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سلوك الكمرات المركبة من صلب وخرسانة ذات الاعصاب المعرجة تحت تأثير الاحمال الرأسية

يهدف البحث الي دراسة عملية ونظرية لسلوك الكمرات المركبة من صلب وخرسانة ذات الاعصاب المعرجة تحت تأثير الاحمال الرأسية حتي حدوث الانهيار.

تمت الدراسة بعمل نمازج نظريه لكمرتين بطريقة العناصر المحدده وباستخدام التحليل ثلاثي الابعاد اللاخطي بطريقة العناصر المحددة لتحديد الحمل الاقصي لتلك الكمرات. حيث تم دراسة السلوك الانحنائي والقصي لهذه الكمرات . وتم التحقق من فاعلية البرنامج المستخدم بمقارنة النتائج بتلك التي تم الحصول عليها من البرنامج العملي حيث تم اختبار كمرتين بنفس الابعاد في المعمل حتي الانهيار. وبالاعتماد علي فاعلية البرنامج ودرجة الدقة المقبوله تم دراسة تأثير سمك العصب علي سلوك الكمرات في القص وكذلك اجراء مقارنة بين الكمرات المركبة من صلب وخرسانة ذات الاعصاب المعرجة وتلك ذات الاعصاب المسطحه وذلك تحت تأثير الاحمال الرأسية

ومن اهم النتائج التي تم استنباطها من البحث مايلي:.

- سمك العصب له تأثير ضعيف علي السلوك الانحنائي للكمرات المركبة من صلب وخرسانة
- سمك العصب له تأثير ملحوظ علي سلوك الكمرات المركبة من صلب وخرسانة في القص. حيث انه بزيادة سمك العصب يزداد الحمل الاقصي اللازم لانهيار الكمره.
- بمقارنة النتائج التي تم الحصول عليها عمليا ونظريا ونسبة الحمل الاقصي العملي الذي تتحمله هذه الكمرات الي الحمل الاقصي الذي تم الحصول عليه من البرنامج وجدت انها لاتزيد عن 1.2 بالمائه.
- بدرجة دقه مقبولة يمكن استخدام البرنامج النظري لدراسة السلوك اللاخطي لمثل هذه الكمرات تحت تأثير الاحمال الرأسية وكذلك لدراسة المتغيرات التي قد تؤثر علي قيمة الحمل الاقصي الذي تتحمله هذه الكمرات مثل مقاومة الخرسانة وسمك العصب وعرض التعرج وزاوية التعرج وشكل التعرج.