BEHAVIOR OF COMPOSITE ULTRA HIGH PERFORMANCE CONCRETE-STEEL BEAMS (EXPERIMENTAL AND FINITE ELEMENT ANALYSIS STUDIES)

سلوك العتبات المركبة من عتبة فولاذية وبلاطة خرسانية عالية الأداء (دراسات عملية وتحليل العناصر المحددة)

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Abstract:

The structural behavior of composite ultra-high performance concrete steel beam under static load had been investigated in this paper. The study was conducted by both experimental and theoretical parts. In the experimental part, seven composite beams were tested. These beams were divided into two groups depending on variable parameters, the first group contained four beams, one of them was the control beam, that designed to represent partial interaction and the other beams contained various number of shear connectors, the second group contained three beams depended on the different distribution of shear connectors; in shear zone only. In the theoretical part, the tested beams were numerically modeled, and then analyzed using the finite elements method. The numerical models were carried out in three dimensions by software package (ANSYS 12.1, 2009).The main concluded remarks obtained in this paper that; the ultimate load increased with increasing the shear connectors, and the measured end slip value, decreased when the degree of partial shear connection increased from 41.6% to 58.3% to 83.3% up to 100%. In addition to that, the results of the finite element analysis showed good agreement with the results of the experimental tests.

Keywords: composite beam, ultra-high performance concrete, steel fiber, ANSYS.

الخلاصة:

إن الهدف من هذا البحث هو تقصي السلوك الإنشائي للمنشآت المركبة ذات الخرسانة عالية الأداء تحت تأثير الأحمال الساكنة. ولهذا الغرض فإن الدراسة أجريت من خلال كلا الجانبين العملي والنظري .تضمن الجانب العملي من البحث فحص سبع عتبات مركبة. وقد تضمن هذا الجزء تقسيم العتبات المركبة ضمن مجموعتين , المجموعة الأولى تضمنت أربع عتبات مركبة من ضمنها نموذج المقارنة والذي صمم ليكون ذا ارتباط جزئي, والعتبات الثلاثة الباقية من اجل دراسة التغير في عدد روابط القص, والمجموعة الثانية تكونت من ثلاث عتبات مركبة من اجل دراسة تأثير توزيع روابط القص في منطقة القص فقط. وفي الجانب النظري من الدراسة تم تمثيل وتحليل النماذج بشكل رقمي باستخدام طريقة العناصر المحددة وتكوين النماذج الرقمية ثلاثية الأبعاد باستخدام برنامج الكتروني (ANSYS 12.1, 2009).من الاستنتاجات الرئيسة التي تم التوصل إليها في هذا البحث , زيادة في حمل الفشل مع زيادة عدد روابط القص. و نقصان في قيمة زحف الربط عند زيادة درجة الربط بين البلاطة الخرسانية والمقطع الحديدي من 41.6% إلى 58.3% الى83.3% إلى 100%. بالإضافة إلى ذلك أظهرت نتائج التحليل الرقمي تطابق جيد مع النتائج العملية.

1-INTRODUCTION

Steel-concrete composite beams have been used for a considerable time in bridge and building construction. A composite beam consists of a steel section and a reinforced concrete slab interconnected by shear connectors, as shown in Figure (1). It is common knowledge that concrete is strong in compression but weak when subjected to tension, while steel is strong in tension but slender steel members are susceptible to buckling while under compressive forces. The fact that each material is used to take advantage of its positive attributes makes composite steel-concrete construction very efficient and economical (1).

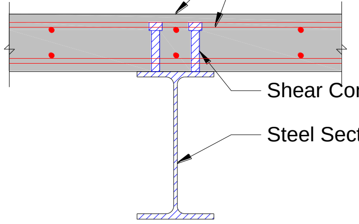


Figure (1) Composite Beam with Solid Slab

Seven model high- strength concrete (HSC) composite beams and one normal-strength concrete (NSC) beam were tested under monotonic loading by **Jianguo et al** (2), considering the strength of concrete flange, and flange width were the variable parameters. All beams were designed for a full shear connection between the steel beam and the concrete flange using shear studs. It was identified that the HSC composite beams had higher initial stiffness and very distinct post-yielding characteristics compared with the NSC beam. Test results of the HSC specimens also showed several favorable design aspects such as a larger margin beyond the steel yielding and greater ultimate deformability. Analysis based on the current design codes can provide a reasonable estimation to the flexural initial stiffness and ultimate flexural capacity of the HSC composite beams.

Abbas (3)investigated the structural behavior of composite beams in which a slab of concrete was joined together with a steel I-beam by means of headed stud shear connectors. The study consisted of two parts; the first part was to investigate experimentally ten composite beams in which the number of connectors was varied in order to change degree of partial shear connection. The type of loading, single concentrated and two point loads, and the region of bending moment, sagging and hogging, were also altered to explore the effects of these variables on the composite beams behavior. The second part dealt with the analysis of the tested beams theoretically. One-dimensional finite element program, coded by using FORTRAN77, was developed to conduct this analysis. Also an attempt was made to use the available ANSYS 5.4 code to simulate the concrete-steel composite beams. Some of his conclusions are, at the same load level, the deflection increased when the degree of partial shear connection decreased from 100 % to 33.3 %. This was true for both types of loading action, sagging and hogging bending moments. The deflection values for beams under sagging bending moment were smaller than those for beams under hogging bending moment.

Al-Sarraf et al (4) presented an experimental program contained two groups: the first one consisted of seven composite beams; six of them were strengthened with one and two CFRP strips with three different percentages of full beam length (40%, 60%, and 100%). The second group consisted of five composite beams strengthened at the face of the bottom flange with CFRP strips fastened to the steel section by steel bolts with two different length proportion of CFRP strips to beam soffit (60%, and 100%).Therefore, they used three- dimensional nonlinear finite elements to represent the model of the composite beams using (ANSYS 8.0) computer program. They concluded that the composite beams strengthened with CFRP strips in general showed a significant increase in the ultimate load, the amount of deflection for the composite beams strengthened with stiffeners and CFRP strips decreased with the increase of CFRP amount, and there was good agreement between the experimental and the analytical load-deflection curves at the mid-span and at the left edge of composite beams.

A new generation of Ultra High Performance Concrete (UHPC), named Reactive Powder Concrete (RPC) has been developed recently, and received great attention in recent years all over the world, due to its superior mechanical properties such as; high strength, high ductility, high durability, limited shrinkage consequences, high resistance to corrosion and abrasion. Therefore, UHPC used in this study to improve the behavior of composite beam. **Graybeal**(5), defined UHPC is a cementitious composite material composed of an optimized gradation of granular constituents, a water-to-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement. The mechanical properties of UHPC include compressive strength greater than (150 MPa) and sustained post-cracking tensile strength greater than (5 MPa).

Orgass and Klug(6) investigated the influence of short steel fibers and a fiber mix of short and long fibers on the mechanical properties of Ultra-High Performance Concrete (UHPC) especially regarding the ductility and the size effect. In this regard the fiber contents changed between 0, 1 and 2 Vol.-%.Numerous tests were performed to study the flexural strength as well as the post cracking behavior of the investigated concrete. Experiments were carried out on specimens with different geometries. It was observed, that highest compressive and flexural strength was obtained on smallest specimens (prism). In vibrated concrete the compressive strength decreased with the increase of the specimen slenderness. This phenomenon was not observed in self-compacting ultra-high performance concrete.

Wille et al(7)described the development of aUHPC with a compressive strength exceeding 200 MPa, obtained using materials commercially available in the U.S. market and without the use of any heat treatment, pressure,or special mixer. The influence of different variables such as type of cement, silica fume,sand, and high range water reducer on compressive strength was evaluated. The test results showed that the spread value, measured through a slump cone test on a flow table, is a good and quick indicator to optimize the mixture packing density and thus its compressive strength.

2-THE EXPERIMENTAL WORK:

The experimental program included casting and testing seven composite beams under two point load, four of these beams contained different number of shear connectors and the other beams contained different number of shear connectors in shear zone only, which were of overall length (2m) consisted of concrete slab, (0.07 m) thickness and (0.4 m) width, and steel section (180mm * 90mm), connected together by shear connectors. The experimental work was carried out in the Materials Laboratory of the College of Engineering/ University of Karbala. The material properties of concrete are investigated through test the three cylinders of diameter 150 mm and height 300 mm to know the compressive strength and modulus of elasticity, three cubs of dimension 50mm to till known the compressive strength, three cylinders of diameter 100 mm and height 200 mm to know the splitting strength, and three prisms of dimension (100 mm*100 mm*500 mm) to know the flexural strength.

2-1 Material:

2-1-1 Ultra High Performance Concrete

Sulfate resisting Portland cement manufactured in Iraq with trade mark of (Al-Mass) has been used throughout this investigation. The very fine sand with maximum size 600μm (0.6mm) using for UHPC according to Iraqi SpecificationNo.45(8). Densified micro silica fume (Grade 85 D) from **LeycoChem LEYDE-Iraq** has been used as a mineral admixture added to the mixtures of the research. The used percentage is 25% as replacement of cement.

A high performance concrete superplasticizer (or named High Range Water Reduction Agent HRWRA) was used in this study, which is known as SikaViscocrete-5930. It is imported from Sika Company in Egypt. Also, the steel fibers used in this test program were straight steel fibers manufactured by the Ganzhou Daye Metallic Fibres Co., Ltd. The fibers have a nominal diameter of 0.2 mm and a nominal length of 13 mm which is brought from China.

2-1-2 Steel Section

The Ukrainian steel I-section beam with parallel-faced flanges, was used to represent the structural steel beam. This section has 180 mm height, 90 mm flange width and 19 kg/m weight. The flange and web thickness are 8 and 6 mm, respectively. To determine the mechanical properties of the steel material, a total number of six tensile samples were taken from the flanges and the webs of all the specimens. The samples fabricated according to ASTM-A370 (9), as shown in Plate (1), were tested by using tensile testing machine available in Strength of Materials laboratory at the College of Materials Engineering/University of Babylon. The average values of yield stress (316.67 MPa) and ultimate strength (453.33 MPa).

(A)Specimens before Testing

(B)Specimens after Testing

Plate (1) Photos of Tensile Test Specimens Taken from Steel Section

2-1-3 Properties of Shear Connectors

Headed stud shear connectors of diameter 10 mm and overall length 55 mm with a head of diameter 17 mm and height 5 mm were used in each test specimen. To resist the longitudinal shear at the interface between steel section and concrete slab, and to prevent the vertical separation between them. The shear connectors were connected to the upper top flange by using welding. The average values of yield stress (640.2MPa) and ultimate strength (787.033MPa) obtained from testing of three specimens were chosen randomly and tested under direct tension.

2-2 Mixes:

The high performance of UHPC mix design was based on the following vital factors: a low w/cm ratio, a high density which was done by a high content of cement, fine sands with a maximum particle size (600 µm), and micro silica fume. This is major to fill on the voids between the solid particles. The superplasticizer has been used in an appropriate ratio to give flowable concrete. To guarantee a sufficient ductility thin, steel fibers were added.

Many mix proportions were tried, in this investigation, to get maximum compressive strength according to (ASTM C109) (10).The details of the chosen mix are shown in Table (1).

Table (1) Mix Proportions of Concrete

Mix	Cement kg/m^3	Sand kg/m^3	S.F %	S.F kg/m^3	w/cement itious	S.P. %	Steel Fiber %	Steel Fiber kg/m^3
M1	880	970	25	220	0.175	5	1	78

2-3 Description of the Tested Specimens:

The composite members were constructed from UHPC slab of 400 mm width and 70 mm depth attached to a steel I-section of 180 mm x 90 mm x 19 kg/m, by headed stud shear connectors of 10 mm diameter and 55 mm length welded to the top flange of steel section.

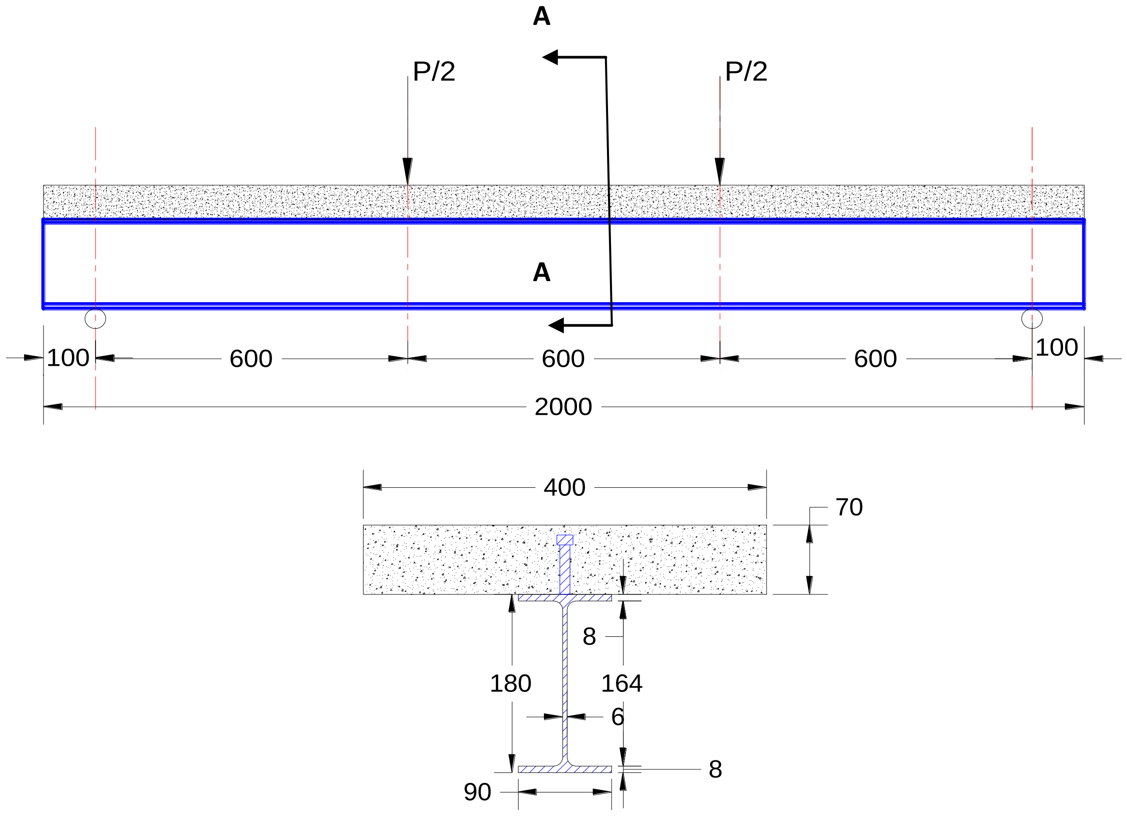
All beams were simply supported and tested under two point loads as shown in Figure(2). Each beam had a total length of 2000 mm and center to center span between supports of 1800 mm. No reinforcement used in the concrete slab and the distribution of shear connecters in one row in the longitudinal direction. The degree of connection was provided according to AISC Design Specifications (11) and push-out test results. The test beams were divided into two groups depending on variables parameters as explained in Table (2).

2-4 Specimen Preparation and Testing:

At the duration end of curing, all beams and material specimens were taken out from the water tank, left to dry, and then all beams were cleaned and painted with white color, so that cracks can be easily detected. Each beam was placed on simple supports at 10 cm from each end in the machine with a clear span between two supports of 180 cm.

The machine of 2000 KN capacity, which was used in the test of beams. All beams tested under two points load by using a steel beam over the beam with clear span of (600)mm, which allowed dividing the total applied load on two steel rods with a cross section of (25) mm applied on steel plates to avoid stress concentration on the slab flange, as shown in Plate (2).

The load was applied by successive increments of approximate 13.848 KN in each step of loading. At each increment load, the deflection at center of beam and slip at each end of beam using a dial gauge of (0.01mm) sensitivity, strain values reading in mid-span using demec point and extensometer with gauge length of 200 mm, that recorded and marked the cracks and the value of load at each crack were written.



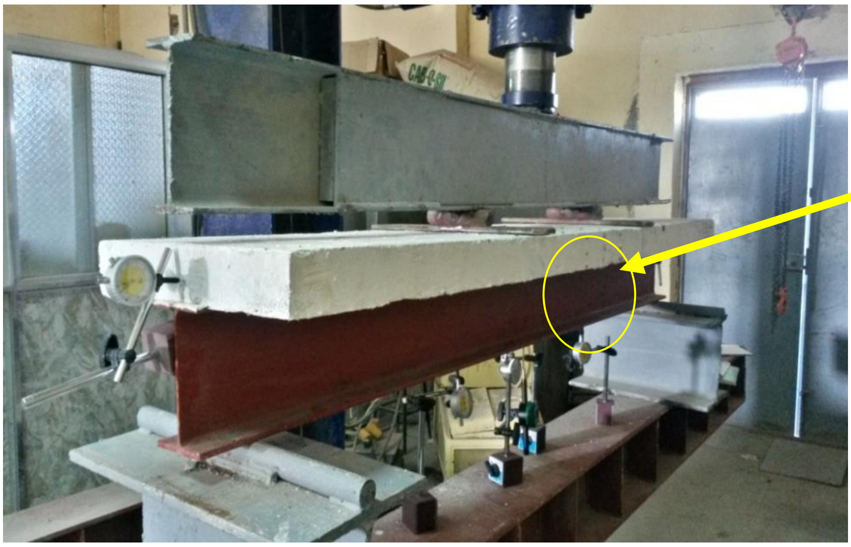
(Section A-A)

Figure (2): Dimensions of Composite Beam Specimens (all dimensions in mms.)

.Table (2) Details of All the Test Beams in the Present Study

Group No.	Parameter	Beam	Shear Connectors				
			No. / beam	Interaction , %	Spacing, mm	Length of SC	Location
1	Change the number of shear connector	CB11	10	41.6%	200	55	Uniformly Distribution
		CB12	14	58.3%	138.46	55	Uniformly Distribution
		CB13	20	83.3%	94.74	55	Uniformly Distribution
		CB14	24	100%	78.26	55	Uniformly Distribution
2	Change the arrangement of shear connector	CB21	10	41.6%	120	55	In Shear Zone
		CB22	14	58.3%	85.71	55	In Shear Zone
		CB23	20	83.3%	60	55	In Shear Zone

**SC: shear connectors



Position of Demec Point

Plate (2) Testing Composite Beam

3- EXPERIMENTAL RESULTS AND DISCUSSION:

3-1 Mechanical Properties of (UHPC):

The average results of test control specimens for UHPC mix at 28 days showing in the Table (3).

Table (3) UHPC the Mix Average Structural Properties

Mix	Steel fibers V_f %	Silica fume content SF%	f_{cu}, MPa.	fc′, MPa.	f_{sp}, MPa.	fr, MPa.	Ec, MPa.
M1	1	25	118	103.56	12.54	15.37	46507

3-2 Composite Beams Test:

3-2-1 Load-Deflection Relationship

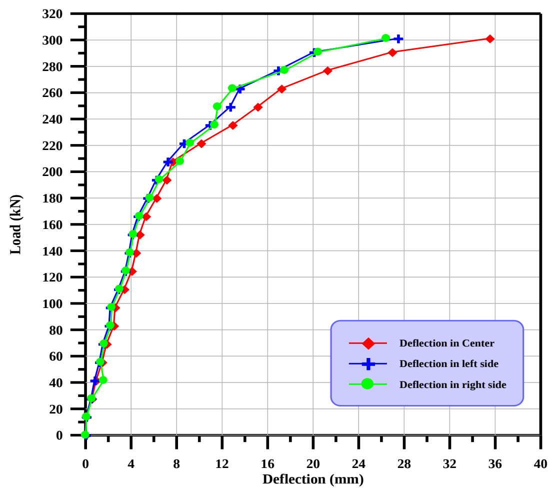
The vertical deflection for the test beams were recorded at each increment of load in the center of beam under the bottom flange of steel beam in three positions:

- The center of beam under the bottom flange of steel beam.
- The left of center of beam under point load.

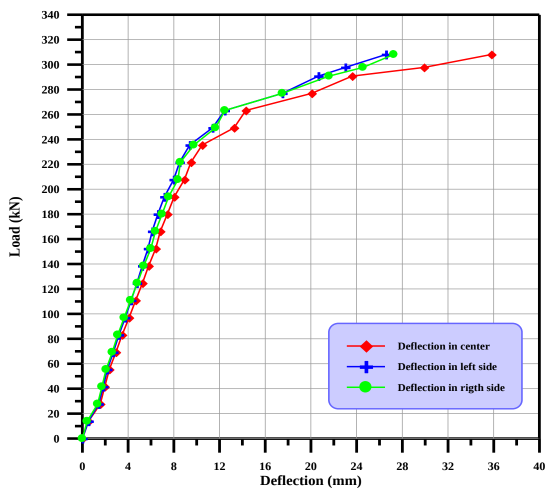
The right of center of beam under point load.

The load-deflection curves for the beams in group one are shown in Figures.(3) to (6), this group consisted of four specimens with variable in degree of partial shear connection, as its (41.7%, 58.3%, 83.8%, 100%). The beam with a (41.7%) degree of partial shear connection, considered as a control beam. And the load-deflection curves for the beams in group two are shown in Figures.(7) to (9). This group consist of three beams are (CB21, CB22, and CB23).

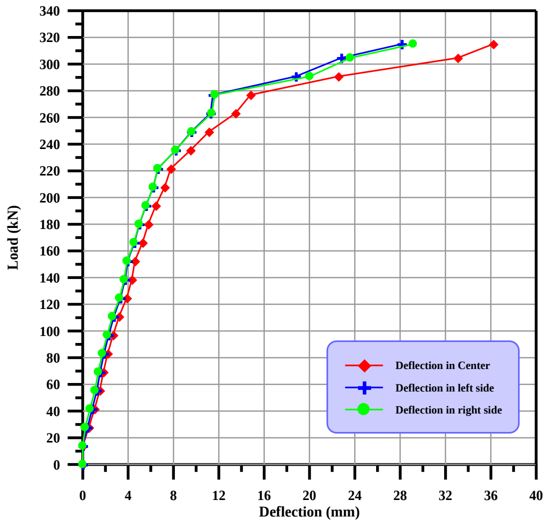
Through the following Figures.(10) and (11), the effect of each parameter, in the present study, on the tested beams behavior is studied. These figures are concerned with the deflection at mid-span which is almost the maximum deflection.



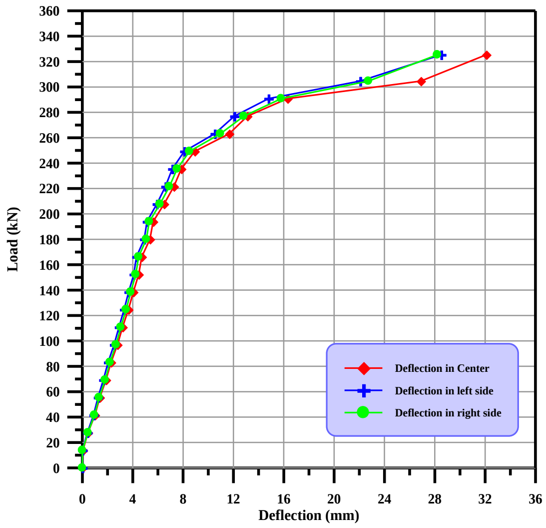
Figure(3) load-deflection Curve for Beam (CB11)



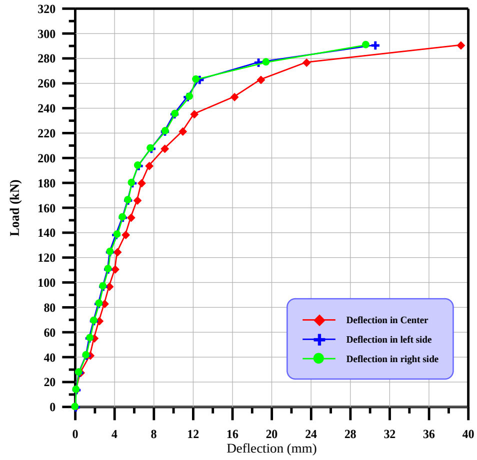
Figure(4) load-deflection Curve for Beam (CB12)



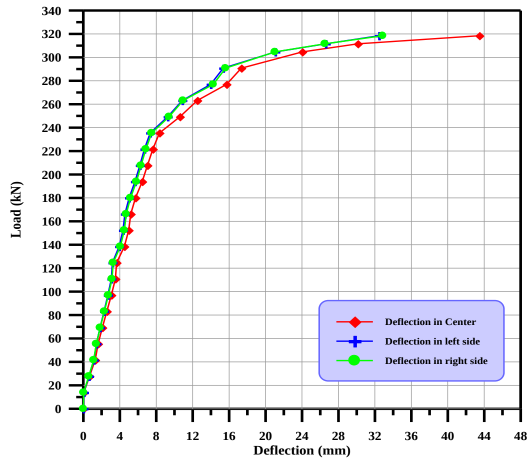
Figure(5) load-deflection Curve for Beam (CB13)



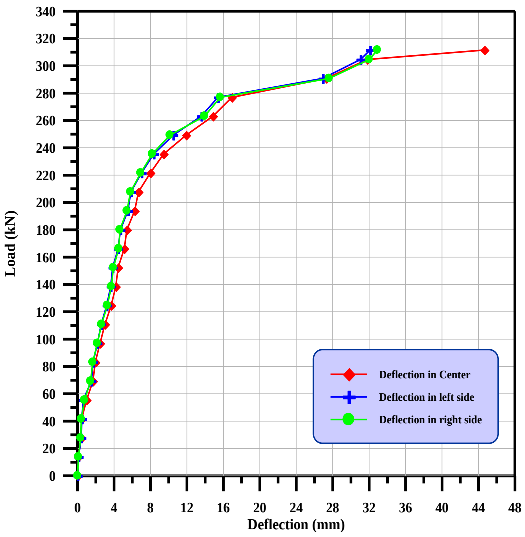
Figure(6) load-deflection Curve for Beam (CB14)



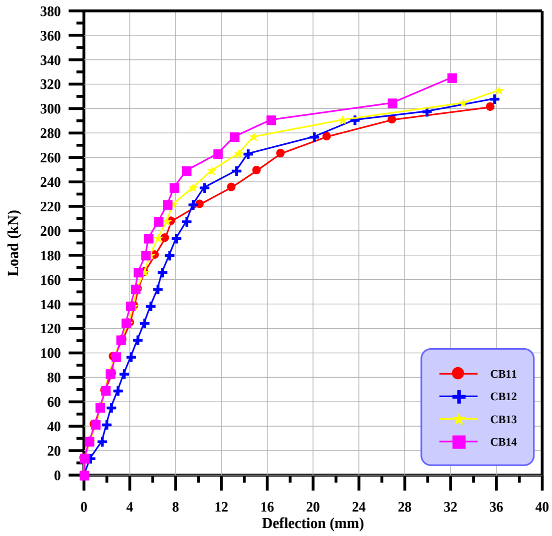
Figure(7) load-deflection Curve for Beam (CB21)



Figure(8) load-deflection Curve for Beam (CB22)



Figure(9) load-deflection Curve for Beam (CB22)



Figure(10) Effect of Number of Shear Connectors on Load-Deflection Curve

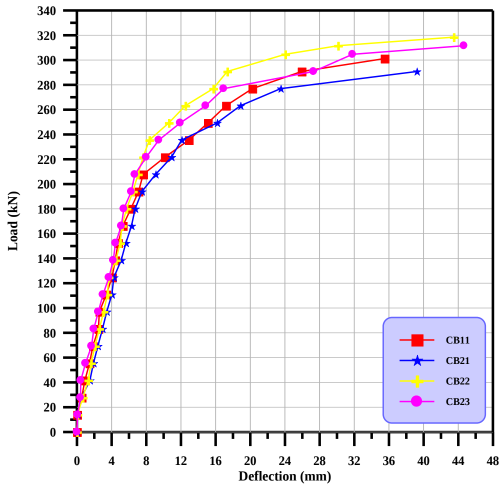


Figure (11) Effect of Distribution of Shear Connectors on Load-Deflection Curve

Reviewing the curves of load-deflection which are presented in Figures (10) and (11) which indicates the following two points:

1) The increase in the number of shear connectors has small effect on maximum deflection, while has clear effect in the ultimate load,so that increase the number of shear connectors led to an increase in the ultimate load with maximum percentage 8% for the number of shear connectors (20).
2) The omitting of shear connectors in the middle zone for CB21 beam, which is due to the decrease in the ultimate load and the increase in the deflection compared with CB11 beam, as shown in Figure(11). It can be noted that the increase in the ultimate load and deflection for CB22 and CB23 compared with CB21, while it shows no significant effect between CB22 and CB23 beams for the ultimate load and deflection. It concluded that the decrease in the spacing of shear connectors to minimum has no effected.

3-2-2 Failure Load and Crack Pattern:

Generally cracks in concrete are formed at regions where the tensile stresses existed and exceeded the specified tensile strength of concrete. For the UHPC has large tensile strength than the normal strength concrete; therefore, in this study crack appeared later.

Table (4) shows the ultimate load recorded for each sample, the load of first crack formed in the concrete slab, and the ratio between the two along with the type of failure. As shown in Plate (3), cracks initiate at bottom face of concrete slab then up wards in thickness of concrete flange. The number beside the crack refers to the load when the crack penetrated the concrete upwards.

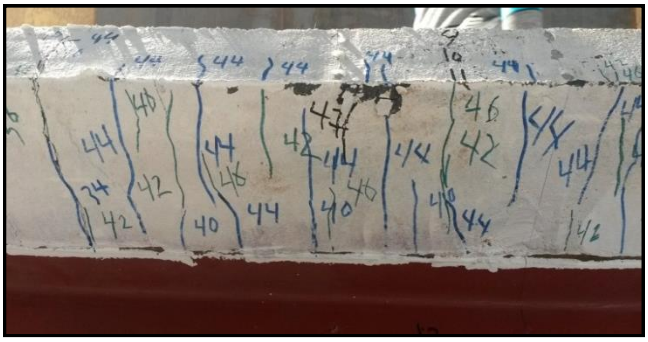
3-2-3 Horizontal Slip:

The measured values of the end slip between the steel beam and concrete slab with each increment of loading are presented in Figures (12) and (13) for every tested beams.

Table (4) Ultimate Load and First Crack Load

Group	Specimens	First Crack Load Pcr (kN)	Ultimate Load Pu (kN)	Pcr / Pu (%)	Type of Failure
One	CB11	207.72	301.194	68.97	Yielding of the steel beam
	CB12	221.568	308.118	71.9	Unsymmetrical web buckling
	CB13	249.264	315.042	79.12	Yielding of the steel beam and unsymmetrical web buckling
	CB14	235.416	325.428	72.34	Yielding of the steel beam
Two	CB21	180.024	290.808	61.9	Web buckling
	CB22	207.72	318.504	65.22	Yielding of the steel beam and start web buckling
	CB23	207.72	311.58	66.67	Yielding of the steel beam

CB13



CB14

Plate (3) Cracks Pattern for Test Specimens (Continue)

CB23

Plate (3) Cracks Pattern for Test Specimens (Continued)

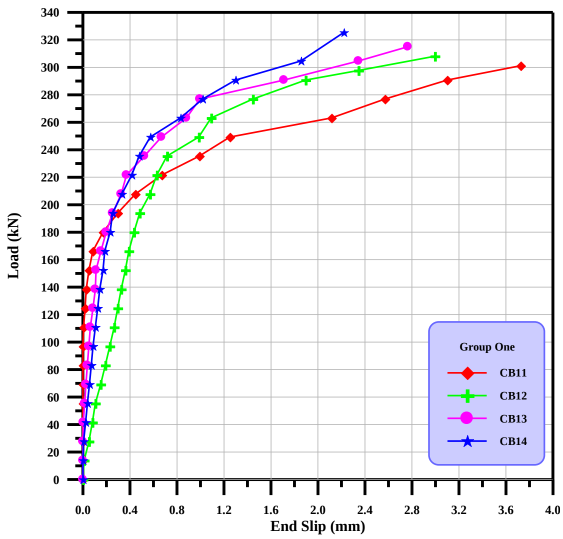


Figure (12) load-Slip Curve for Beams in Group One

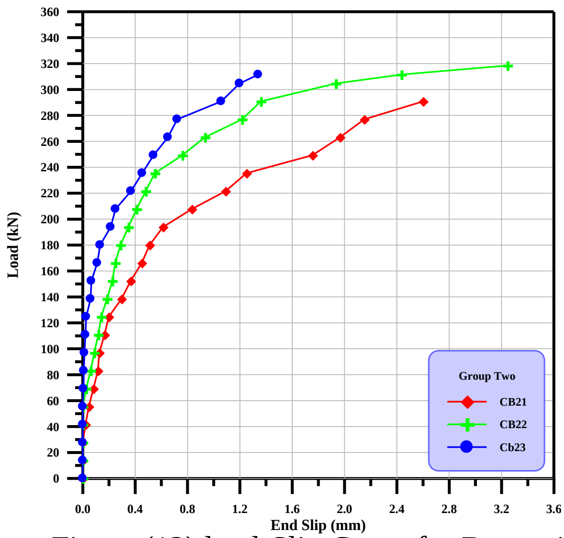


Figure (13) load-Slip Curve for Beams in Group Two

From the above Figures (12) and (13), the following are concluded:

1) It is obvious, that the decrease of the measured end slip value when the degree of partial shear connection increased from 41.6% to 58.3% to 83.3% to 100%.
2) The increase in the number of connectors in the ends increased the slip stiffness of the beam. The reason behind that is the increase in the number of shear connectors at the ends which are the zones of higher shear force.

3-2-4 Distribution of Normal Strain:

Figures (14) and (15) show the relationship between the longitudinal strain and load through the depth of the composite beam (CB13 and CB23) at mid-span for different load levels, including failure load. The strain was measured at seven levels across the depth of composite beam.

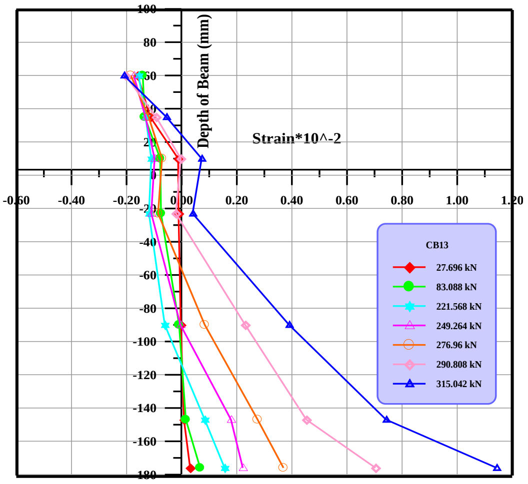


Fig.(14) Strain Distribution at Mid-Span of Beam (CB13)

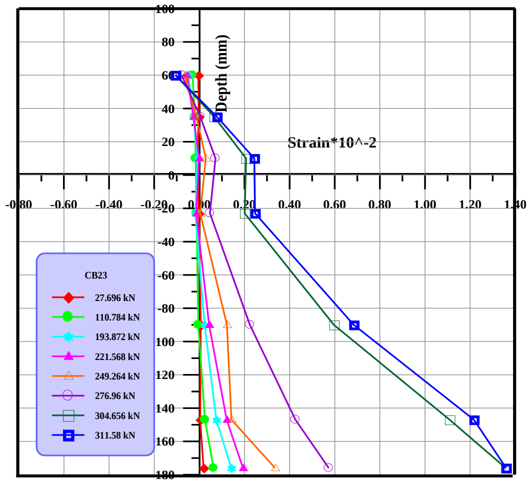


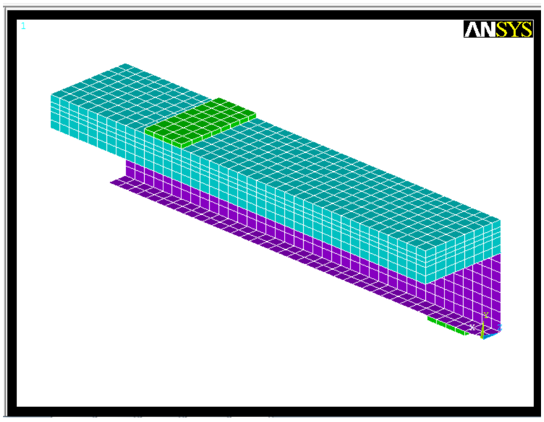
Fig.(15) Strain Distribution at Mid-Span of Beam (CB23)

4-NUMERICAL ANALYSIS:

The numerical analysis by using finite element method was used for analyzing the UHPC composite beams subjected to static load of two points, which is presented in this section. The nonlinear analysis has been conducted using ANSYS computer software Release12.1.

In this section the verification is done to check the validity and accuracy of the finite element procedure. Verification was done by comparisons between the numerical results and experimental results consisted of the load-deflection results and the load-slip results.

By taking advantages of symmetry, a quarter was used for finite element analysis in the present study, as shown in Figure(16) this path reduces computational time and the computer disk space requirement significant.The types of element considered in the analysis model are shown in Table (5).



Figure(16) Geometry of the Quarter Model

Table (5) Types of Element used in This Study

Material type	ANSYS element
Concrete	SOLID 65
Steel plate	SOLID 45
Steel section	Shell 43
Shear connector	LINK 8 to resist uplift Combine 39 to resist slip
The interface	Contact 52- point to point contact

4-1 Load-Deflection Relationship:

The load-deflection curve for each beam acquired from the analysis of finite element together with the experimental curves are presented and compared in Figures (17) and (18).

4-2 Load-Slip Relationship:

Due to partial interaction, slip always takes place between concrete slab and steel beam, so that this phenomenon is represented in the numerical analysis by interface model. The comparison between the numerical and experimental for the end slip results is shown in Figures. (19) and (20).

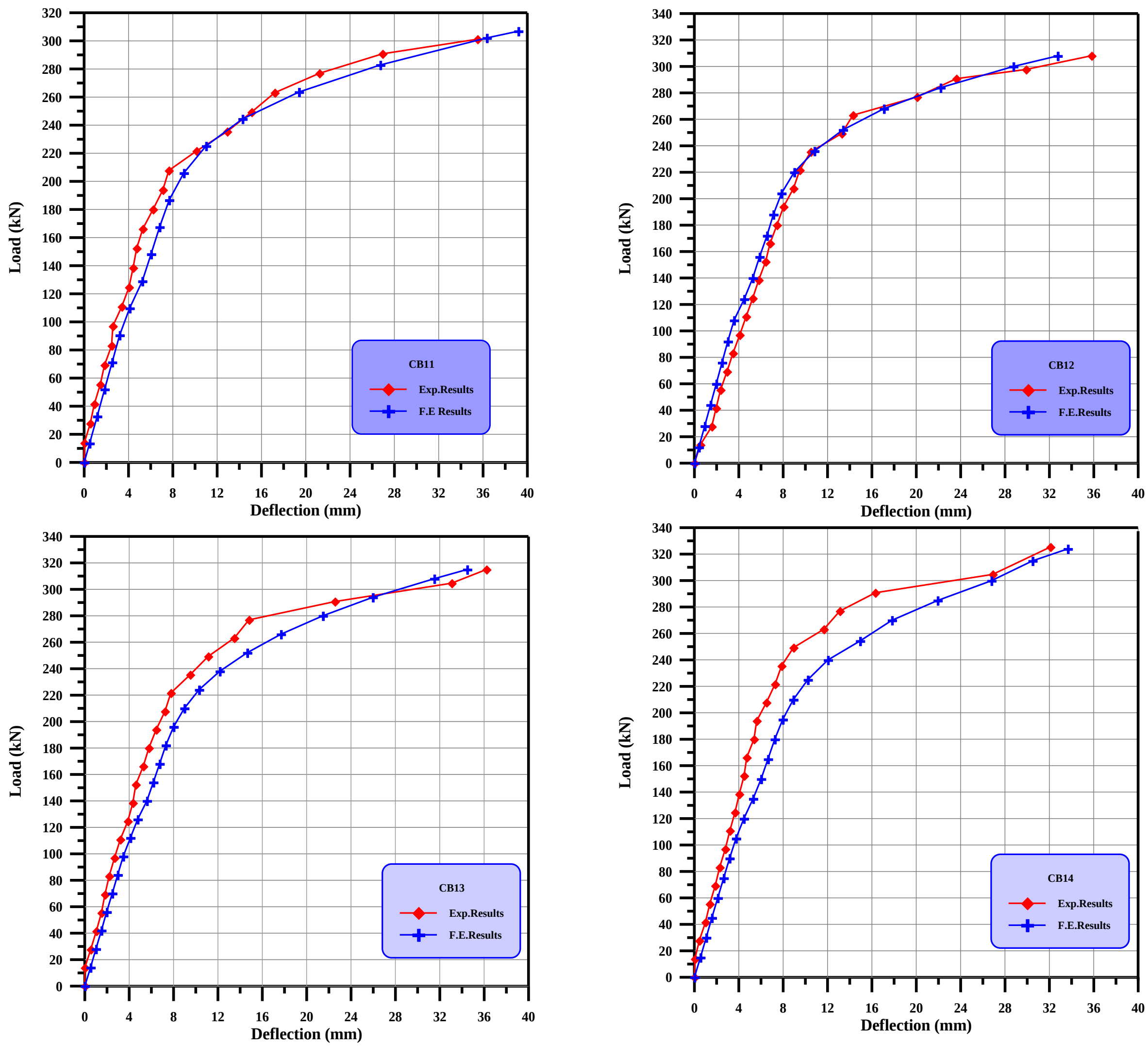


Figure (17) Load-Deflection Relationship of Beam in Group One.

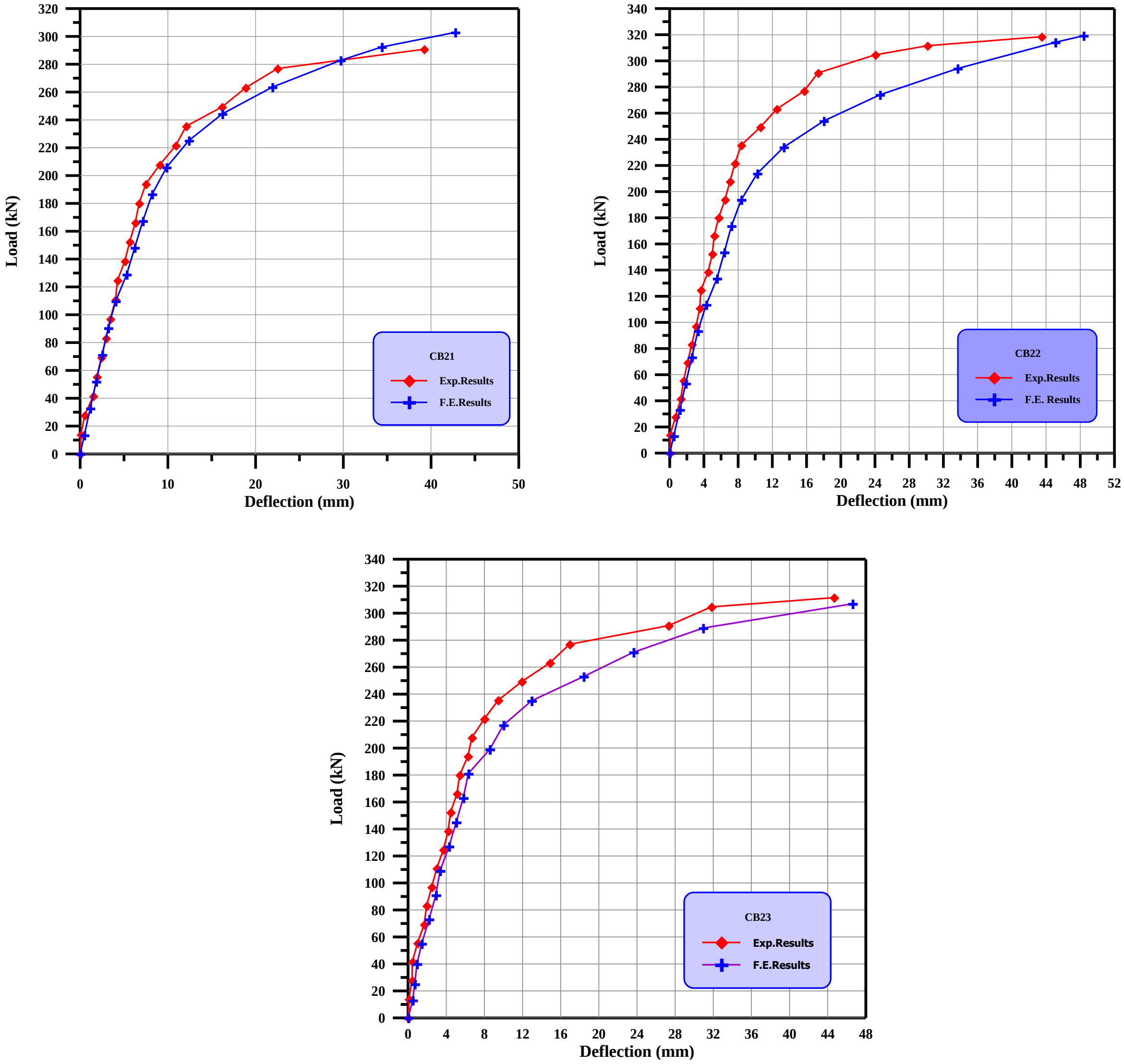


Figure (18) Load-Deflection Relationship of Beam in Group Two

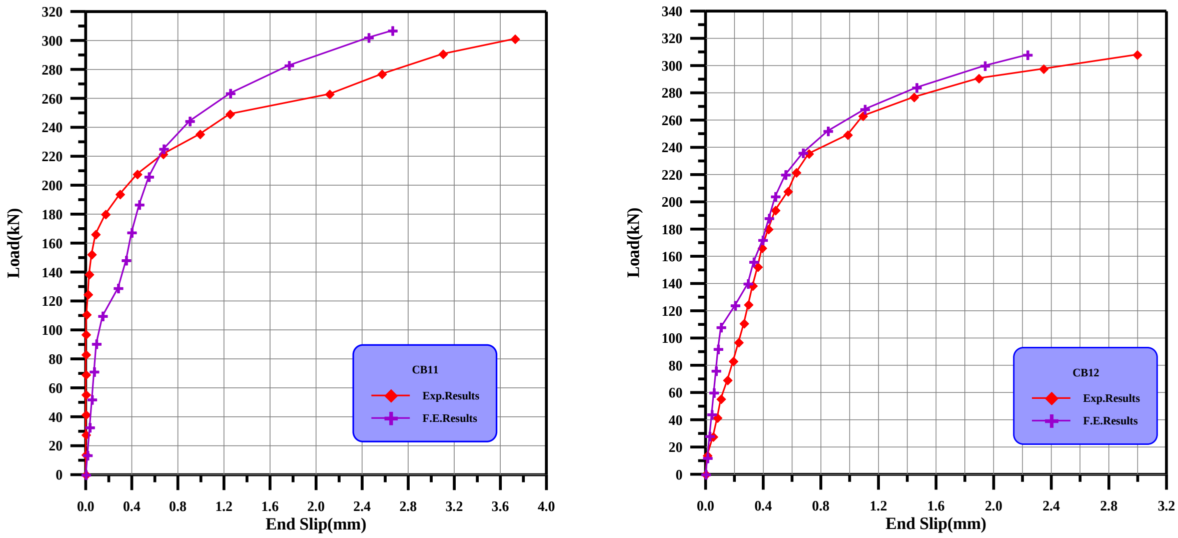


Figure (19) Load-Slip Relationship of Beam in Group one (Continue)

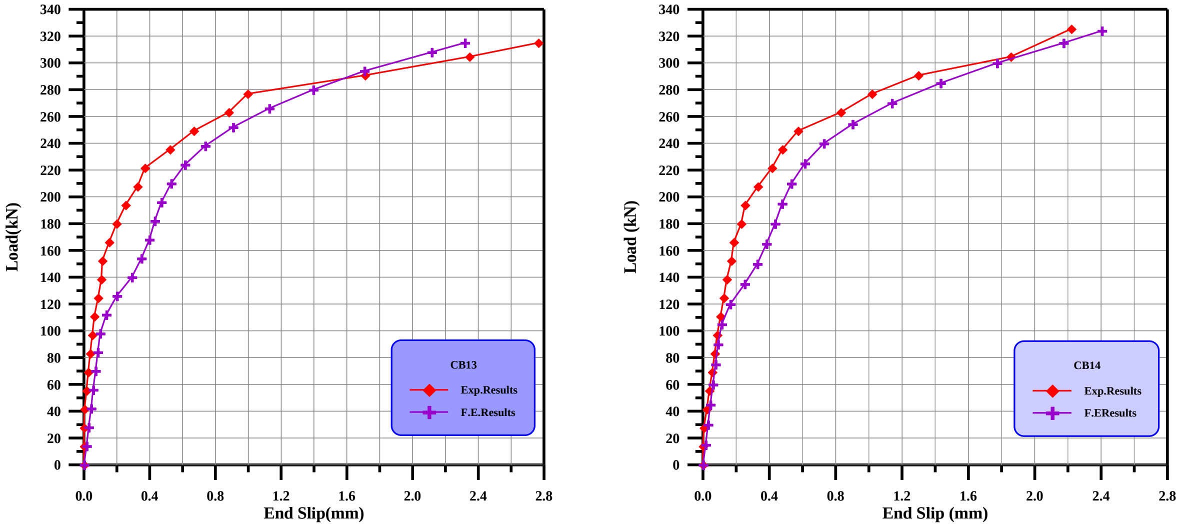


Figure (19) Load-Slip Relationship of Beam in Group one (Continued)

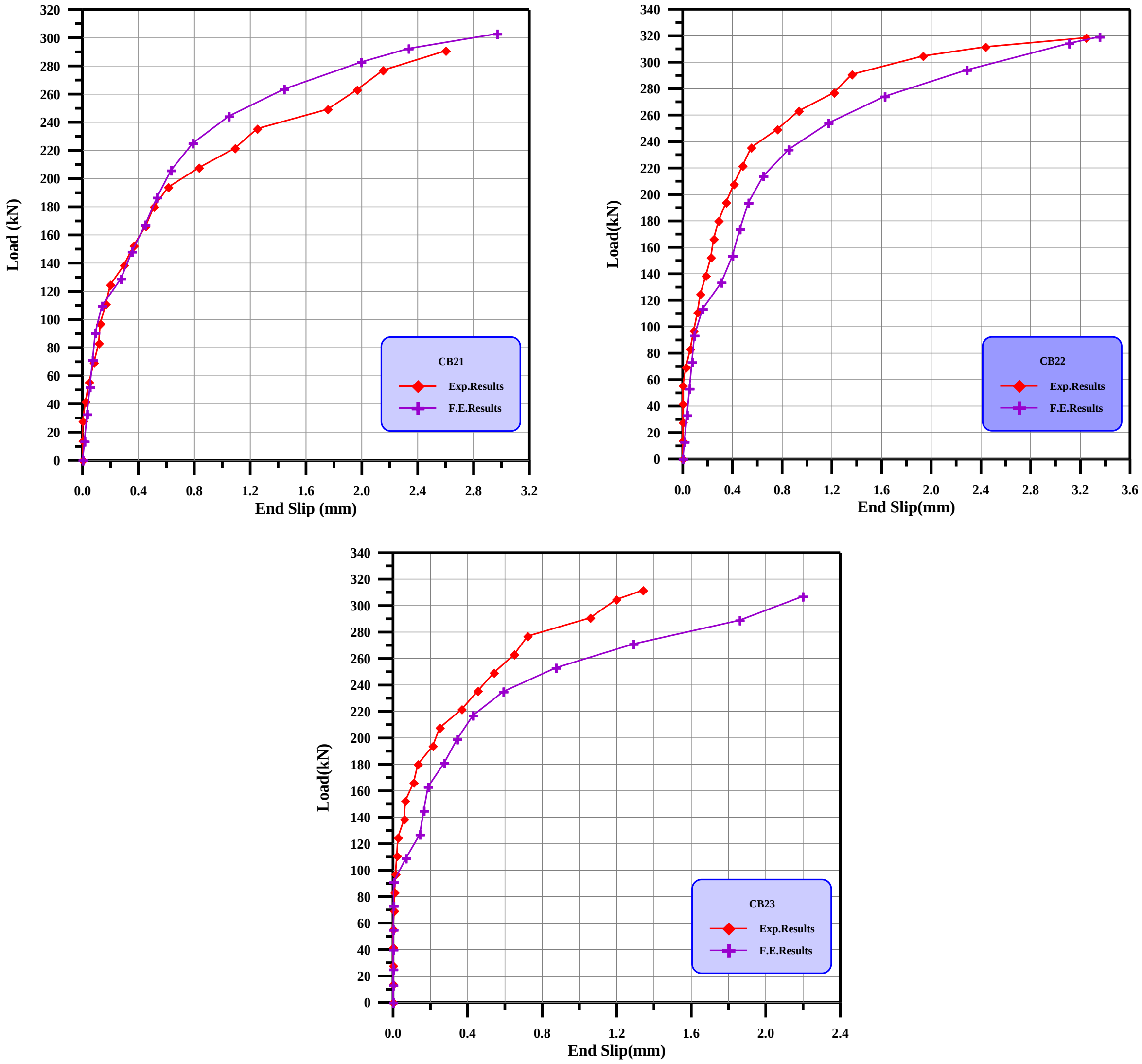


Figure (20) Load-Slip Relationship of Beam in Group Two

5-CONCLUSIONS:

From this study the following conclusions has been drawn:

1) The use of steel fiber with the UHPC provides some improvement in material properties, consisted of cube and cylinder compressive strength, splitting tensile strength, modulus of rupture and modulus of elasticity.
2) The increase in the number of shear connectors had small effect on maximum deflection, while there was a clear effect in the ultimate load, so that increase the number of shear connectors resulted an increase in the ultimate load with maximum percentage 8% for the number of shear connectors (20).
3) It can be noted that the increase in the ultimate load and deflection for CB22 and CB23 compared with CB21, while it shows no significant effect between CB22 and CB23 beams for the ultimate load and deflection. It concluded that the decrease in the spacing of shear connectors to minimum has no effected.
4) The decrease of the measured end slip value when the degree of partial shear connection increased significantly up to 100%.
5) The increase in the number of connectors in the ends increased the slip stiffness of the beam. The reason behind that is the increase in the number of shear connectors at the ends which are the zones of higher shear force.
6) The general behavior of models of finite element represented in the load deflection and the load-slip plots showed good convention with the data of test from the experimentally tested composite beams.
7) The predicted failure loads from numerical analysis were very close to those measured during experimental testing. The minimum and maximum deference in ultimate loads for beams were (0.038% and 4.16%) respectively.

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