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Behavior of Short Span Composite Beams Strengthened with CFRP Strips

Dr. Sabih Z. Al-Sarraf*, Dr. Jian Yang**
& Ahmed F. Kadhum

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Abstract

The experimental program in this paper is divided into two groups: the first one consists of seven composite beams; six of them were strengthened with one and two CFRP strips and with three different percentages of full beam length (40%, 60%, and 100%). The second group consists 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%).

The analytical investigation included the use of three dimensional nonlinear finite elements to model the performance of the composite beams using (ANSYS 8.0) computer program.

سلوك العتبات المركبة القصيرة الفضاء المقواة بأشرطة الياف الكربون فايبر

الخلاصة

البرنامج العملي في هذا البحث يقسم الى قسمين: القسم الأول يتكون من سبعة عتبات مركبة ستة منها مقواة بشريط واحد و شريطين من اشرطة الياف الكربون و بنسب اطوال مختلفة (40% ، 60% و 100%). اما الجزء الثاني فيتكون من خمسة عتبات مركبة مقواة في سطح الشفة السفلى للعتبة الحديدية باشرطة الياف الكربون و مثبتة ببراغي حديدية مع نسب طول (60% و 100%) من الطول الكلي.
اما التحليل النظري فيتضمن استخدام برنامج العناصر المحددة اللاخطي لتمثيل العتبات المركبة بأستخدام برنامج الحاسبة (ANSYS 8.0).

Introduction

Fiber reinforced polymer (FRP) has been found to be successful for flexural and shear strengthening of concrete flexural members as well as the ductility enhancement of concrete compression members [1]. Recently, research has been conducted to investigate the use of carbon fiber reinforced polymer (CFRP) materials to address this need.

A research of experimental program by Rizkalla et al., 2003 [1], consists of three phases. The first phase of testing was conducted to determine a suitable resin for the wet lay-up of unidirectional carbon fiber sheets bonded to steel. The second phase of the experimental program is designed to determine the

*Building and Construction Engineering Department., University of Technology, Baghdad
** Civil Engineering Department, University of Birmingham/Birmingham, UK

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

development length of the sheets used for the wet lay-up process as well as the development length for bonded CFRP laminates. For this phase of the program, a super-light beam (SLB) section was used with an additional steel plate welded along the length. The third phase of the program consists of testing composite steel-concrete beams scaled from typical steel bridge girders in composite action with the concrete deck slab. The tests were designed to determine the overall performance of the strengthening system. A paper by Al-Saidy et al., 2007 [2], presents the results of an experimental study on the behavior of strengthened steel-concrete composite girders using Carbon Fiber Reinforced Polymer (CFRP) plates. Strengthening was achieved by attaching the CFRP plates to the bottom flange and in some beams the CFRP plates were also attached to the beam web. The test results showed that using lightweight CFRP plates could enhance the strength and stiffness of steel-concrete composite girders up to 45% of the normal strength.

This research presents experimental tests whereby twelve composite steel-concrete beams have been investigated. Each composite beam consists of concrete slab with steel I-beam strengthened with carbon fiber strips at the bottom flange. Also an analytical investigation using ANSYS 8.0 computer program is carried out. The increase in the strength is (42%) as in the composite beam which strengthened with 100% of full beam length with two of CFRP strips and stiffeners in the web.

Material Properties

The investigation on the behavior of a composite beam depends on many parameters such as the strength of concrete, steel reinforcement, steel profile in addition to the CFRP strips which may be used to strengthen the beams. The properties of materials used in this study are determined by conducting standard tests according to the American Society for Testing and Materials (ASTM) and the Iraqi specifications. They are presented in the following sections:

Concrete

A concrete mix was designed according to the British Standard Method [4] using water/cement ratio of (0.47) and 1:1.5:3.5 mix proportion. Six concrete cube specimens measuring (150×150×150) (mm) were cast and cured for each beam under normal laboratory conditions for 28 days, then tested for compressive strength. The results of these tests are listed in Table 1.

Test Coupons

The physical properties of the metallic components of the test specimens were determined using test coupons. Coupons were prepared and tested at the Dept. of production and Metallurgy Engineering-University of Technology.

Reinforcing Bars (Rebars)

The reinforcement used in this investigation was square wire mesh with an average 4 mm diameter with yield stress f_y = 510 MPa and ultimate strength f_u = 638 MPa and modulus of elasticity = 196154 MPa.

Steel Girder

The typical cross-section of the tested beams was **IPEA200** (I-shaped member) 200 mm deep and 100 mm wide. The test specimen has average yield strength of 356 MPa and a modulus of elasticity of 206976 MPa.

Shear Connector (Stud)

There are many types of shear connectors in use. The headed stud is the most widely used type of connector in composite construction. The same type is used in this study (which was fabricated from bolt at Al-Sinak Region in Baghdad). The specimen of the studs used in this research was 50 mm in height, 9.5 mm in diameter of shank, and had 15mm diameter of head with f_y = 430 MPa.

CFRP Composites

A Sika CarboDur S512 carbon fiber fabric strengthening system supplied by Sika Near East, Beirut–Lebanon. Sika CarboDur S512 is described as rectangular strips of carbon fiber fabric with 50 mm in width and 1.2 mm in thickness. According to the manufacturer (Sika Data Book Construction Building with a Safe System) [6], the mean value of tensile strength is 3050 MPa and the modulus of elasticity is 155000 MPa while the elongation at break is 1.7%.

Adhesive (Sikadur-30)

A two-component epoxy paste (Sikadur-30) was used to bond the carbon fiber to the tension face of the composite beam specimens. The mixing ratio of component (A) (white paste) and component (B) (gray paste) is (3:1) by weight (A: B). The tensile strength and modulus of elasticity of the adhesive are 4 MPa and 12800 MPa according to the manufacture (Sika Data Book Construction Building with a Safe System) [6].

Experimental Program:

The experimental work presented in this paper is divided into two main test series:

Series A: Investigation of the influence of the number of CFRP strips, on the composite beams behavior.

Series B: Investigation of the influence of percentage (development) length of CFRP strips on the composite beams behavior.

The CFRP strip effect on the ten composite beam specimens was determined. In the following sections the aim of each test series along with the variables investigated are described ,detailed descriptions of the test specimens and procedures of testing are also given.

Description of Test Specimens

Twelve composite beams were tested to ultimate state under two-point loads. All composite beams had an I-shaped steel member of (200 mm) deep and (100 mm) flange width, and a concrete slab (80 mm) thick and (300 mm) wide. The studs (shear connectors) (9.5 mm) are distributed in pairs at (145 mm) pitch along the beam. The overall dimensions and details of the test specimens are shown in Figure 1.

Two composite beams without strengthening were tested as control beams and were designated as CB0 and CB01. In order to study the effect of the number of CFRP strips and the development length of the CFRP strip to the total specimen length, which was taken as a percentage (40, 60, and 100) % respectively on the flexural capacity of the strengthened beams, ten composite beams, were tested.

The first five beams are designated as CCB1, CCB3, CCB5, CCB7 and CCB9 with *one* CFRP strip. The first three have 40%, 60%, and 100% strip proportion while the last two have 60% and 100% of the original beam length, the only difference in the last two, is that their CFRP strips were fastened with bolts. The other five beams have the same prportion of length and the same method of fastening the CFRP strips in the five beams listed before, but the number of strips were *two*. These beams are designated as CCB2, CCB4, CCB6, CCB8, and CCB10. The holes in the CFRP strips were done using caustic bar to achieve the required hole diameters.

Specimen Identification and Strengthening Schemes

In order to identify a test specimen with different strengthening schemes, the following designation system is used:

- Number of CFRP strengthening strips: 1 or 2.
- Proportion of CFRP strengthening length to the specimen length.

Table 2 listed the details of the tested specimens.

All of the CFRP strips were installed to the bottom flange of the steel beam using the same resin (Sikadur 30) epoxy [52].

The loading was transferred to the beam by two steel rods 200 mm apart at the midspan, as illustrated in Figure 2.

Test Results, Analysis and Discussion

The behavior and failure load of the specimens were obvious in reflecting the results by the testing machine on the load-deflection and load-strain curves. The first crack for each specimen was noticed, and the load at which the CFRP strip had detached was recorded. The accuracy in detecting the first crack and the CFRP strip separation relies entirely on visual observation.

From Figures (3 to 9) as example for the tested beams, it can be noticed that the existence of CFRP had no significant effect on the first crack appearance in the concrete slab, while failure of the composite beams happened after an interval from the CFRP separation because of the yielding of the steel section. This delayed behavior was due to the difference in the modulus of elasticity of the steel (206,976 MPa) in one side and the CFRP and the epoxy (155,000 MPa, and 12,800 MPa respectively) from the other side.

The value of failure load ranged from 360 kN for the reference beam and 430 kN for CCB6, with an increase in strength by about 20%. The other beams had a failure value of 390 kN, 400 kN, 420 kN, 420 kN, and 420 kN for CCB1, CCB2, CCB3, CCB4, and CCB5 respectively as shown in the figures below so an appreciated effect of the CFRP strips can be noticed when used as a percentage of 60% and 100% of length with one and two strips.

For the load-deflection plots, it can be noticed firstly that the failure load was 370 kN for the beam CB01 (with no CFRP) and the failure load increased to 440 kN for CCB7 (with one CFRP strip) with an increase in the strength by about 22.22% and similarly 23.6%, 40.27%, and 41.27% for CCB8, CCB9, and CCB10 respectively. Secondly the overall behavior of the beams tends to be nonductile and there is a type of interlocking between the behavior of the steel section and the attached CFRP strips which affect on the overall behavior of the composite beam.

Table 2 shows the ultimate load with failure type for each specimen and the percentage of increase in the strength.

Finite Element Results and Discussions

The present section sheds light on the nonlinear behavior of composite beams using (ANSYS software computer program release 8.0). ANSYS is a program intended for solving practical engineering problems.

All tested beams in the experimental program of this paper were analyzed. Comparison of the load-deflection curves, and the ultimate load carrying capacity obtained from finite element (ANSYS) analysis and the laboratory tests is made.

The composite beams which were tested by ANSYS program can be divided into two groups; composite beams without stiffeners and composite beams strengthened with stiffeners against local buckling and distortion:

The idealization of the beam is done by subdividing the structure into a number of elements as shown in Figure 10. The equivalent force at each edge node has half the value of the interior node. The word *loads* in ANSYS terminology includes boundary conditions and externally or internally applied forcing functions for example: loads, displacements U_x, U_y, and U_z (DOF constraints), forces, pressures.

For the tested beam in this study the displacements (DOF constraints) U_x and U_y = 0 to represent the hinge end, while the other end is a roller so just U_y= 0. It is worthy to mention here that for the edge nodes $U_z = 0$ against transverse slip.

A comparison between the analytical and experimental results of the central and left edge deflections is shown in the Figures below.

According to these Figures (11 to 13) as example for the analyzed composite beams in this research it can be noticed that the beams that gave good agreement between the experimental and analytical results are: CB0, CCB9, and CCB10.

For the beam CB0 the calculated ultimate load is 360 kN which is the same value of the experimental results, and for the beam CCB9 and CCB10 the analytical and the experimental ultimate load is 505 kN and 510 respectively.

Conclusions

The conclusions drawn from the experimental and analytical results of using CFRP strips to strengthen the composite beams are listed as follows:

1. The composite beams strengthened with CFRP strips in general showed a significant increase in the ultimate load by about 41.7 % with steel bolts being used for fastening the CFRP strips to the bottom flange. For the composite beams strengthened with CFRP strips without stiffeners the increase in the ultimate load was to 19.5%
2. In general the amount of deflection for the composite beams strengthened with stiffeners and CFRP strips decreased with the increase of CFRP amount, with 60% of CFRP length proportion deflection reduced by 33.6% and with 100% of CFRP the decrease was 34%.
3. An increase in the ultimate load occurred with one CFRP strip of 60% of full beam length. The increase was 16.7% for the composite beams without stiffeners and 22.2% for the same composite beams but with steel stiffeners.
4. The ultimate strength of composite beams reached a maximum limit; after this limit there was no advantage of strengthening the steel sections as the concrete slab was the critical part in sustaining the ultimate load.
5. The three-dimensional finite element (ANSYS 8.0) models used to represent the composite beams are found efficient in simulating these composite beams. The concrete crushing, steel section failure, CFRP strips separation, and the ultimate loads predicted were close to the experimental results, most of the composite beams achieved a coincidence between the analytical and the experimental. The maximum difference in the ultimate load is (3.4%) as in the composite beam which was strengthened with 60% of full beam length with one of CFRP strip.

6. In general it can be said that there was good agreement between the analytical and the experimental load-deflection curves at the midspan and at the left edge of the composite beams. As in midspan deflection, a composite beam without strengthening gave a percentage of analytical to the experimental values of 82.5% and for composite beam with strengthening with two of CFRP strip with 60% of full beam length the percentage is 107.8% while for left edge deflection the percentage for a composite beam with one of CFRP strip with 60% of full beam length is 93% and for composite beam with two of CFRP strip with 100% of full beam length is 94.4%.

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[6]Sika Data Book Construction "Building with a Safe System".

Table(1) Properties of concrete specimens

Beam No.	Compressive strength, f_{cu} (MPa)	Compressive strength, f'_c (MPa)*	Tensile strength, f_{ct} (MPa)*	Modulus of elasticity, E_c (MPa)*
CB0	39	33.15	2.3	27,061
CB01	37	31.45	2.24	26,358
CCB1	40	34	2.33	27,405
CCB2	41	34.85	2.36	27,746
CCB3	39.5	33.58	2.32	27,236
CCB4	36	30.6	2.21	26,033
CCB5	40.5	34.43	2.35	27,578
CCB6	41	34.85	2.56	27,746
CCB7	41.5	35.28	2.38	27,916
CCB8	39	33.15	2.3	27,061
CCB9	37.5	31.88	2.26	26,537
CCB10	40	34	2.33	27,405

*Calculated as: $f'_c = 0.85\, f_{cu}$ and $f_{ct} = 0.4\sqrt{f'c}$ [4], and $E_c = 4700\sqrt{f'c}$ [5]

Table (2) Details of the tested specimens

Specimen No.	CFRP No. of strips	CFRP width (mm)	Percentage of CFRP length (%)	Fastening
CB0	Without CFRP Fabric			
CB01	Without CFRP Fabric But With Stiffeners			
CCB1	1	50	40	-----
CCB2	2	50	40	-----
CCB3	1	50	60	-----
CCB4	2	50	60	-----
CCB5	1	50	100	-----
CCB6	2	50	100	-----
CCB7	1	50	60	Bolts Φ5 mm
CCB8	2	50	60	Bolts Φ10 mm
CCB9	1	50	100	Bolts Φ5 mm
CCB10	2	50	100	Bolts Φ10 mm

Table (3) Percentage of strength increase and type of specimens' failure

Specimen	Failure load (kN)	Percentage of increase	Type of failure
CB0	360	---	Local Buckling + Longitudinal Shear Failure
CB01	370	---	Concrete Transverse Shear Failure
CCB1	390	8.33	CFRP Separation + Local Buckling + Concrete Crushing
CCB2	400	11.11	CFRP Separation +Local Buckling
CCB3	420	16.66	CFRP Separation +Local Buckling +Conc. Longitudinal Shear Failure
CCB4	420	16.66	CFRP Separation +Local Buckling + Conc. Longitudinal Shear Failure
CCB5	420	16.66	CFRP Separation +Local Buckling + Conc. Longitudinal Shear Failure
CCB6	430	19.44	CFRP Separation +Local Buckling + Conc. Longitudinal Shear Failure
CCB7	440	22.22	Concrete Transverse Shear Failure
CCB8	445	23.6	Concrete Transverse Shear Failure
CCB9	505	40.27	Concrete Transverse Shear Failure
CCB10	510	41.67	Concrete Transverse Shear Failure

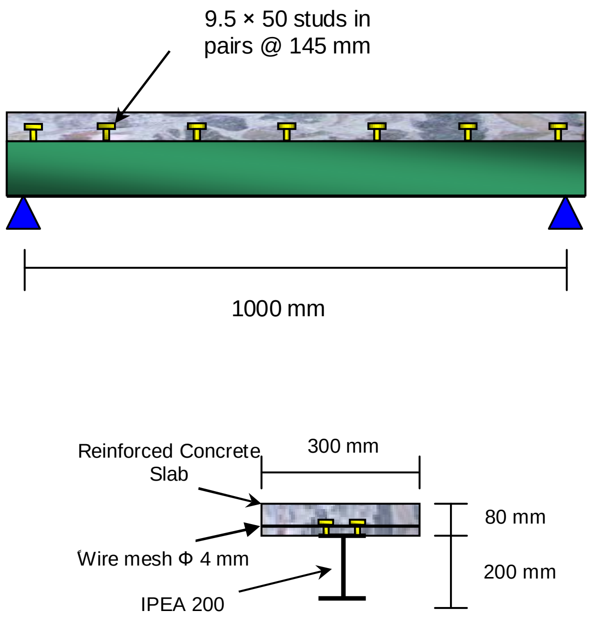

Figure (1) Geometrical characteristics of simply supported beam specimen

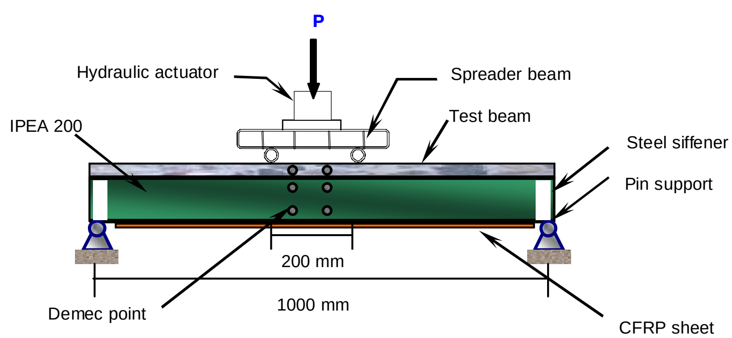

Figure (2) Side view of composite beam under applied load

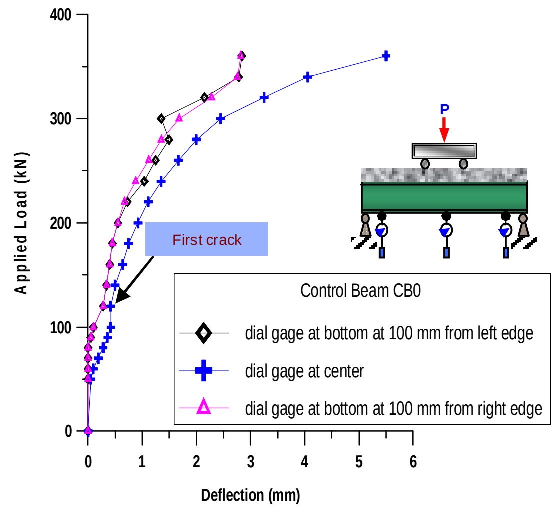

Figure (3) Load-deflection curves for the composite beam (CB0 with no CFRP)

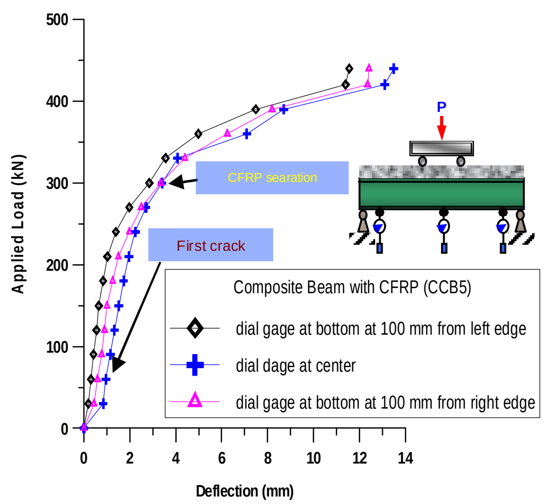

Figure (4) Load-deflection curves for the composite beam (CCB5 with one CFRP strip / 100% of beam length)

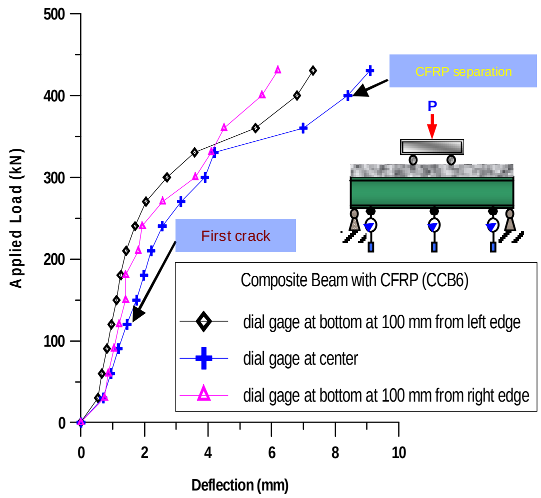

Figure (5) Load-deflection curves for the composite beam (CCB6 with two CFRP strips / 100% of beam length)

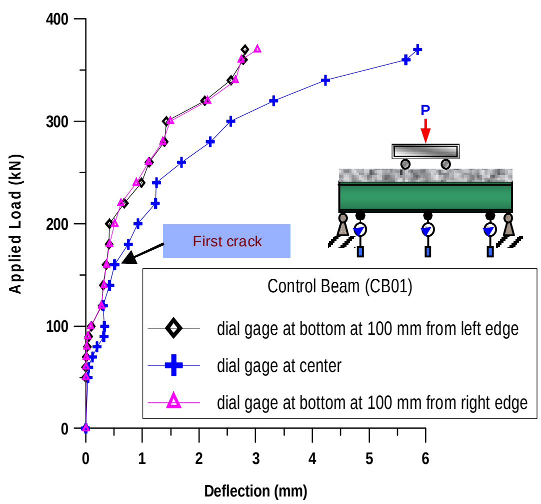

Figure (6) Load-deflection curves for the composite beam (CB01 with no CFRP)

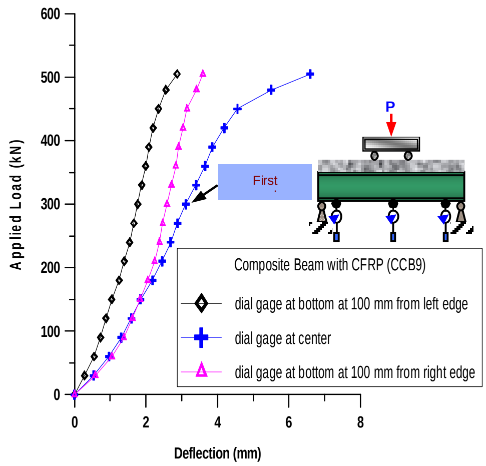

Figure (8) Load-deflection curves for the composite beam (CCB9 with one CFRP strip / 100% of beam length, with bolts)

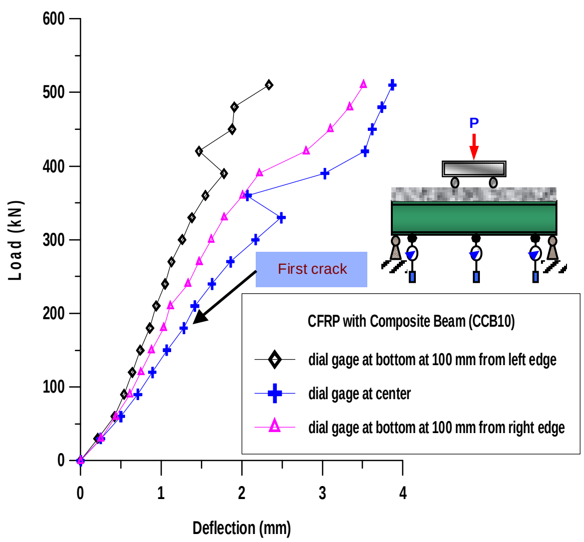

Figure (9) Load-deflection curves for the composite beam (CCB10 with two CFRP strips / 100% of beam length, with bolts)

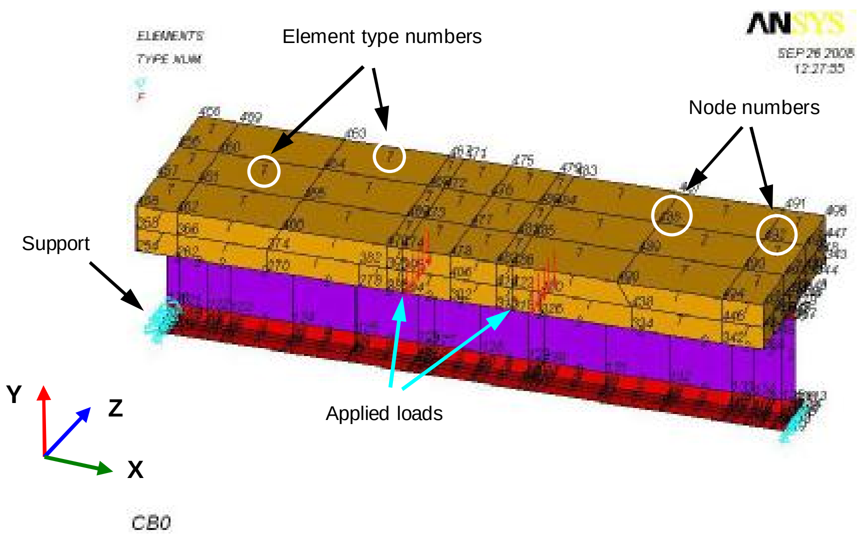

Figure (10) ANSYS mesh of the composite beam CB0

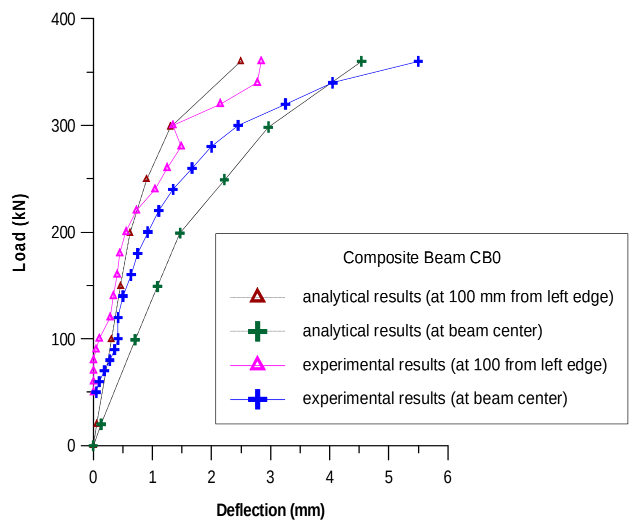

Figure (11) Load-deflection relationship: analytical-experimental comparison of beam CB0

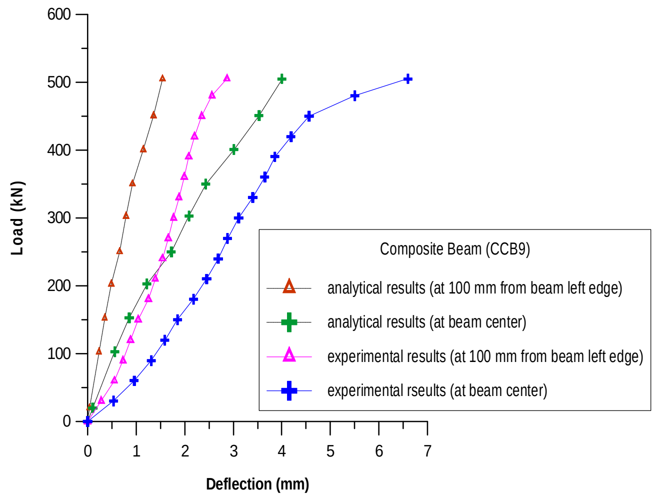

Figure (12) Load-deflection relationship: analytical-experimental comparison of beam CCB9

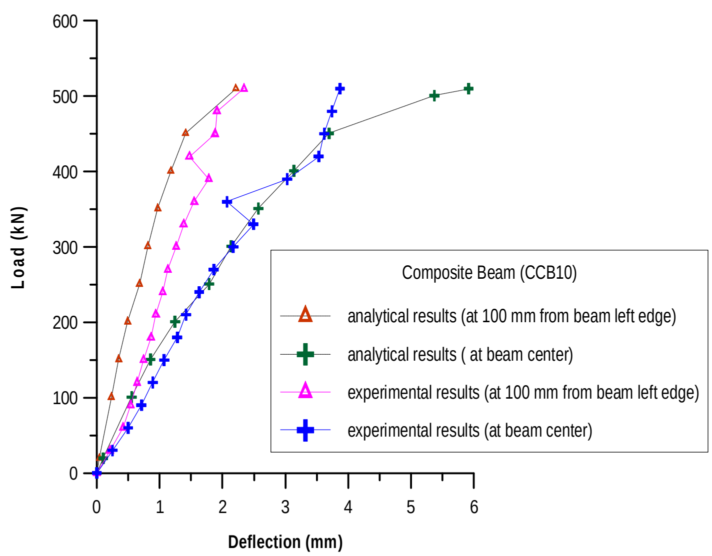

Figure (13) Load-deflection relationship: analytical-experimental comparison of beam CCB10