Strengthening Of R.C. Beams By External Steel Plate Using Mechanical Connection Technique

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Abstract:

The volume of the infrastructure that needs upgrading, strengthening and/or repair is growing worldwide. A strengthen method that was used quite extensively during the mid 1970s is steel Plate Bonding, this method has gained renaissance in the last decades. This paper presents experimental test data with theoretical analyses on the effect of replacing internal tension bars by externally steel plate on its cracking pattern, structural deformations and ultimate strength of concrete beams reinforced with external using mechanical connection technique. The traditional method use the epoxy glues for interfaces bonding while the idea of this new technique is connection the internal shear reinforcement with the external steel plate mechanically. The experimental work includes flexural testing of $100 \times 150 \times 1500mm$ concrete beams. The test variable included the percentage of replacing the internal reinforcement with external steel plate. Theoretical analyses implemented by ANSYS finite element program for all beams also presented. The results show that beams reinforced with external steel plate behave as a composite action right up to ultimate load and the mode of failure occurs by yielding of external plate not by separation of plate. Replacing the internal by external steel restrains the central deflection with considerable increasing of ultimate moment capacity. The ratio of steel replacement with 33%, 67% and 100% leads to deflection drop with 12.5%, 7.7% and 4.6% respectively. Results show good agreement between the experimental and theoretical output data.

Keywords :Steel plate, external reinforcement, replacing, mechanical connection, composite action, RC beams, bond failure, tension face, replacement ratio

تقوية العتبات الخرسانية المسلحة بواسطة الصفائح الحديدية الخارجية باستخدام تقنية الربط الميكانيكي

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الخلاصة:

لا يزال حجم منشـآت البنـى التحتيـة والفوقيـة بحاجـة مسـتمرة ومتزايـدة لإعـادة التأهيـل وإجـراءات التقويـة والصيانة مع مرور الوقت وتعتبر طريقة تقوية العتبات الخرسانية المسلحة بصفائح فولاذية خارجية من الطرق الشـائعة بالرغم من بعض العيوب. يقدم هذا البحث دراسة عملية ونظرية على تأثير استبدال تسليح الشد الداخلي بصفائح فولاذيـة

خارجية على التشقق ، التشوهات الإنشائية و المقاومة القصوى لها وذلك باستخدام تقنية جديدة عن طريق ربط حديد القص الداخلي بالصفائح الخارجية بطريقة ميكانيكية تختلف عن الأسلوب التقليدي في ربط الصفائح الخارجية بسطح العتبة الخرسانية باستعمال المواد الأيبوكسية اللاصقة .

تتضمن هذه الدراسة فحص الانثناء لأربع عتبات خرسانية (100 ˟ 150 ˟ 1500ملم) للتحقق من تأثير زيادة سمك الصفيحة وتأثير نسبة استبدال التسليح الداخلي بالصفيحة الفولاذية الخارجية تم إجراء التحليل النظري لهذه العتبات باستخدام برنامج العناصر المحددة ANSYS . أظهرت نتائج هذه الدراسة انه باستخدام أسلوب الربط الميكانيكي بين العتبة الخرسانية و الصفيحة الفولاذية يتصرف العنصر الإنشائي كوحدة واحدة الى حد الحمل الأقصى ويكون طور الفشل بخضوع حديد الصفائح الخارجية ولا يحدث عزل بين العتبة والصفيحة إطلاقا . استخدام الصفائح الفولاذية كحديد تسليح خارجي أظهر تقييد في الإزاحات المقاسة في مركز العتبة وأدت الزيادة في سمك الصفيحة الى زيادة في قابلية تحمل المقطع . إن نسب استبدال حديد التسليح الداخلي 33 % ،67 % و 100 % أدت الى نقصان في الهطول بنسب 12.5 %، 7.7 % و 4.6 % على التوالي وأظهرت الدراسة تقارب جيد بين النتائج العملية والنظرية .

Notation :

b_c: width of RC beam.

b_p : width of steel plate.

c: neutral axis distance from top fiber.

d: effective depth of concrete section.

E_c, E_s: modulus of elasticity of concrete and reinforcement.

f'_c, f_r: compressive and flexural strength of concrete.

f_y, f_{yp}: yield stress of internal steel bars and external steel plate respectively.

t_p: plate thickness.

t_{pb}: plate thickness at balance condition.

t_{pmax} : max. plate thickness.

Φ: diameter of internal steel bars.

1. Introduction

Different rehabilitation techniques have been proposed for civil structures to overcome deficiencies associated with the aging process, increased loading, change in use, and deterioration. External strengthening gives a practical and cost suitable solution when compared to other traditional rehabilitation methods. Use of steel plates bonded to the tension surface of the concrete structure was the first mode of external strengthening methods. The introduction of advanced composite materials, particularly fiber reinforced polymers (FRPs), in structural engineering, was a second mode of externally bonded retrofit materials. Retrofit of structures using glass-FRP (GFRP) and carbon-FRP (CFRP) has been studied extensively over the past decade [1].

Although the applications of FRPs are becoming wider and popular, the cost of material is still relatively high. A new mechanical strengthening technique had been proposed in this work. External tension steel plates connected with the internal shear steel reinforcement

mechanically to overcome the two main older problems result from the high cost of strengthening materials and the weak of adhesion bonding forces with the prepared concrete surface.

2. Object and Scope

The main aim of this work is to compare the two techniques of replacing internal tension bars by external steel plate. The first technique carried out by bonding the external steel plate to the beams by epoxy (glue) which was implemented by Awadh E. Ajeel et al. The second technique provided by bonding the external steel plate to the beams using mechanical connection which was the main difference than the study by the above researchers. The beams were tested up to the failure by subjection two points load on the top surface.

Theoretical analysis using ANSYS program implemented to compare the theoretical and experimental results. The study presents tests results on the performance of plate bonding when used instead of internal reinforcement. The effect of reinforcement ratio on mode of failure and ultimate strength is intended to discuss.

3. Basic Concepts

Concrete and steel are considered to be the prime two construction materials in most countries around the world. The number of buildings, bridges, pipelines and other concrete components of the infrastructures that have deteriorated in service and in need of repair and maintenance is large and ever increasing. Deterioration or damage to structures may result from different sources, including faulty design and construction practices that ignore the environmental impact, overloading, fire, blast loading, and corrosion of steel. On the other hand, some of these buildings, bridges, pipelines and other components were originally designed for small size vehicles, lighter loads, and lower traffic volumes than are common today. Rehabilitation can be defined as an operation to bring a structure (or a structural component) that is deficient in design demand to the desired specific performance level. Depending upon the state of the structure and the desired post intervention performance level, rehabilitation can be divided into two categories: repair and strengthening. Repair is the rehabilitation of a damaged structure or a structural component with the aim of restoring the original capacity of the damaged structure. Strengthening, on the other hand, is the process of increasing of the existing capacity of a non-damaged structure (or a structural component) to a specified level [2].

4. Rehabilitation Using Steel Plates

The method of rehabilitation using steel plates has considerable potential in the rehabilitation field, and has already been used to strengthen both buildings and bridges in

many countries around the world. The major attractions of this technique are the relative simplicity of the implementation, the speed of application, and the relatively small consequential change in structural size. In recent years, extensive experimental investigations on the factors influencing the structural performance of plated concrete beams have been reported. The results of these investigations have shown that the bonding of thin steel plates to the tension faces of concrete beams can lead to a significant improvement in structural performance, under both service and ultimate loading conditions [2,3,4] .

The shortcoming of the strengthening method with steel plates is the possibility of corrosion at the epoxy-steel interface, which may adversely affect the bond strength. The effect of this factor had been neglected in this work.

5. Steel Plate Dimensions

The width of plate so the interface layer is limited by the size of concrete section and is considered equal to the concrete beam width:

$$b_p = b_c \tag{1}$$

The thickness of the plate (as it taken by Awadh E. Ajeel et al) must be equal to / or less than the plate thickness at balance load conditions and the maximum plate thickness to ensure a ductile flexural failure .

$$\mathbf{t_{p\,max}} \ \pounds \ \mathbf{t_{pb}} = \frac{\mathbf{(b1c_b(0.85f\acute{c})b_c - A_S f_y)}}{\mathbf{b_p f_{yp}}} \tag{2}$$

Two tentative design criteria are suggested to ensure the full flexural capacity of the beam and ductility at failure [5,6]:

$$\frac{\mathbf{b_p}}{\mathbf{t_p}} \ni \mathbf{50} \quad \textbf{(for mild steel)} \tag{3}$$

$$\frac{\mathbf{c}}{\mathbf{d}} \ \pounds \ \mathbf{0.4} \tag{4}$$

6. Experimental Work

Four beams of 100 x 150 mm cross section and 1500 mm long were tested up to failure by two point loads. All beams were reinforced with 2Φ8mm in compression and tension reinforcement. The shear spans were provided with Φ 6mm links at 60mm center to center. The first beam was made without external steel plate while the other three beams were made with external steel plates have thickness of 0.5mm, 1mm and 1.5mm. All beams have

constant width of 100 mm and length of 1500mm as shown in Figure (1). The sufficient thickness and equivalent area of external steel plate substitute the tension steel bars strength in each beam. The present technique adopted in this work was the mechanical connection to achieve adequate bonding and composite action between concrete beam and external steel plate. The common and traditional technique of bonding external plates with concrete beam is by epoxy (glue). The main idea of mechanical connection based on connecting the internal and external steel by screws, washers and nuts. The vertical stirrups were machinery screwed to the required design diameter.   Also, two rows of circular holes with suitable diameters were made in the steel plate with the same position of stirrups to ensure of penetrating each rod in the corresponding hole. The main advantages of this technique are the very low cost of providing screwed stirrups without needing of any other expensive materials and lobar and achieving a full bonding between the R.C beam and steel plate during loading test up to the failure. **Figure (2)** illustrates the mechanical connection technique. The details of the main variables in the test are shown in **Table (1).**
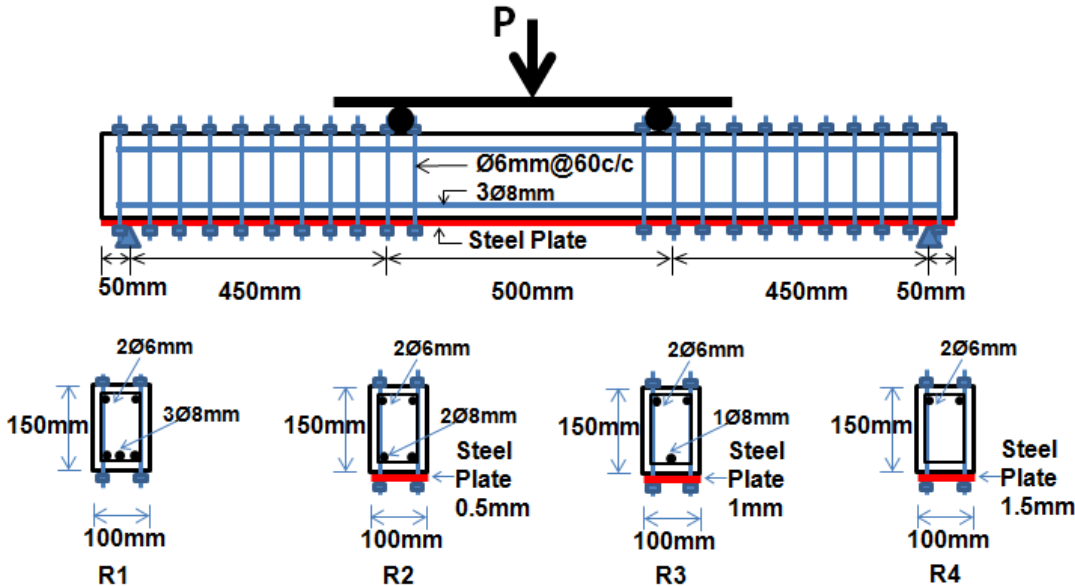

Fig .(1) RC Beams Reinforced Externally by Steel Plate

Fig .(2) Mechanical Connection Technique

Table (1) Details of the Beams

Beam Symbol	Tension Bars	Plate Thickness	Area of Plate	Ratio of Replacement
R1	3 Φ 8	-	0	0
R2	2 Φ 8	0.5	50	33
R3	1 Φ 8	1.0	100	67
R4	-	1.5	150	100

Figures (3) and (4) show the beam reinforcement with steel mold and reinforced concrete beams after casting.

Fig .(3) Beam Reinforcement with Steel Mold

Fig .(4) Reinforced Concrete Beams after Casting in the Mold.

7. Materials Properties

The same materials properties with the same mix proportions used by Awadh E. Ajeel et al had been used to ensure a true comparison between the two techniques however the mechanical properties of concrete show a small difference. Ordinary Portland cement type (I) was used. The coarse aggregate was 14mm maximum size crushed gravel and the fine aggregate was natural river sand (AL-Ukhaider), zone (2) according to IQS:45 1984 with 2.71 fineness modulus. Cylinders and prisms for control tests were cast and stored with each beam and then tested when the beam was tested. The mix proportions and the average results of cylinder strength f'c, modulus of rupture f_r for all beams are given in **Table (2).**

Table (2): Mix Proportions and Mechanical Properties of Concrete

Mix Properties	Weight Constituent kg/m^3					Mechanical Properties MPa		
	Ceme	Sand	Gravel	Water	SP	f'$_c$	f$_r$	†f$_r$
	430	645	1289	129	6.5	30.8	3.81	3.88

† $f_r = 0.7\sqrt{f'c}$

Deformed steel bars of diameter 8mm were used for the main reinforcement and steel bars of diameter 6mm were used for stirrups. Steel plates with different thicknesses of 0.5, 1.0 and 1.5 mm were used as external reinforcement instead of the same area of tension reinforcement. Properties of the steel bars and the plates are shown in **Table (3).**

Table (3): Properties of Steel Reinforcement

Reinforcement	Bar Diameter	Plate Thickness	Yield Stress (f$_y$)	Ultimate Stress	Modulus of Elasticity
Steel Bars	6	-	383	545	200
	8	-	424	602	200
Steel Plates	-	0.5	283	351	200
	-	1.0	280	347	200
	-	1.5	280	347	200

8. Test Method

The beams were tested simply supported on a pivot bearing on one side and a roller bearing on the other, over a span of 1400mm and loaded at the third points. Load was applied, by means of a hydraulic jack, with increments of 5kN throughout the test. Central deflection was measured at each load increment and concrete cracks were detected and

drawn on the face of the tested beam and their width observed. Testing was continued until the beam showed a drop in load carrying capacity with increasing deflections.

9. Theoretical Work

The nonlinear finite element approach can be used to predict the behavior of plated beam structure at elastic stage, plastic stage, cracking load, post-cracking stage and ultimate load. The finite element models used in the current study was described by using the available elements in the ANSYS program for the materials representation and the structural members. The reinforced concrete beams are simulated by SOLID65 element. This element is capable of following cracking in tension, crushing in compression, and plastic deformation with (2x2x2) integration points. It also has the capability of dealing with reinforcement whereby the rebars can be defined within the concrete element itself. In other words, the 3-D solid element is used to model the concrete while the rebar capability is available for modeling the reinforcement behavior. Thus, the most important aspect of this element is the treatment of nonlinear material properties. The SOLID65 is defined by eight nodes having three degrees of freedom at each node as a translation in the x, y and z-direction. The shear reinforcement bars modeled separately from SOLID65 by using an element called LINK8. This element is a 3-D spar and uniaxial tension-compression element with three degrees of freedom at each node and is assumed to be smeared throughout the solid element. The external steel plate had been represented by SHELL63element. SHELL63 has both bending and membrane capabilities. Both in-plane and normal loads are permitted. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. Stress stiffening and large deflection capabilities are included [7].

Element real constants are properties that depend on the element type. For SOLID65, reinforcing bar specifications were input as real constants; which include the material number of reinforcing bar, the volume ratio which was defined as the reinforcing bar volume divided by the total element volume, and the orientation angles in two directions. The link element needs to input the cross section area while the shell element needs to input the thickness at each node as real constants.

The model consists of two main materials; reinforced concrete and structural steel. The rectangular beam made of reinforced concrete and the external steel plate and steel reinforcement were made of steel. The reinforced concrete is defined as a nonlinear inelastic material while the steel is defined as a linear elastic material.

The ANSYS program provides a graphical user interface to create any geometry by a sequence of commands. **Figure (5)** shows set of output pictures for the four tested beams.

10. Failure Mode

The comparison conducted between the old technique of beam strengthening by steel plate using epoxy glue and the new technique in this work by mechanical shear connection shows that the failure mode of the beams in the first technique take place by separation of

steel plate that occur before the beam reach its load capacity as shown in the **Figure (6).** The beams connected with external steel plates behave as a one structural unit and the mode of failure in the present technique is always by yielding of external steel plate and crashing of the concrete with showing of significant increasing in the beam load capacity. No splitting or pullout of shear reinforcements occurs under low and high loading. **Figure (7)** illustrate the failure mode in the present work. **Table (4)** shows the experimental failure load of the beams. Some pictures of beams under loading machine illustrate in **Figure (8).**
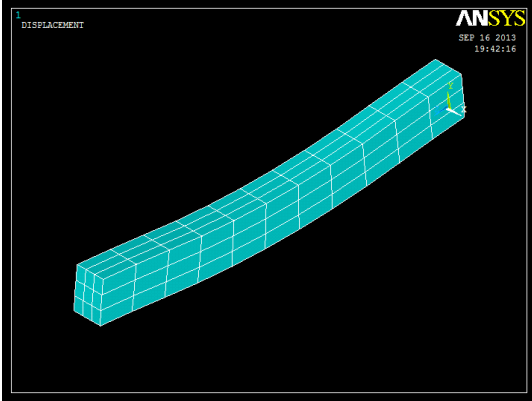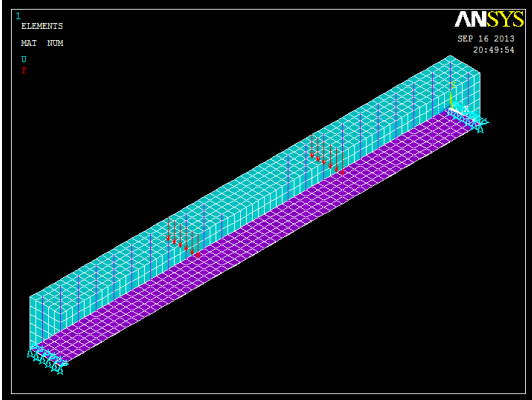
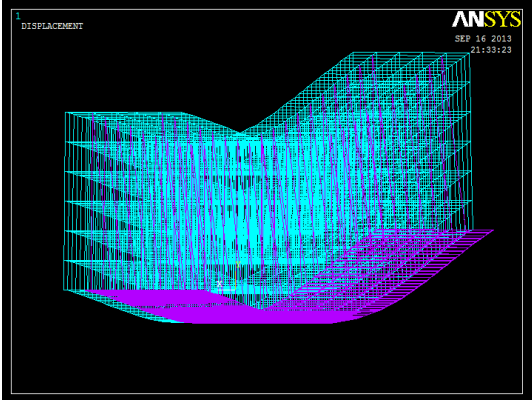

Deflected Shape (R1)
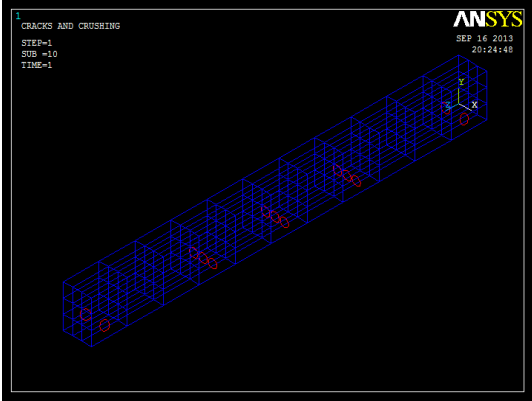
Concrete Cracking (R1)
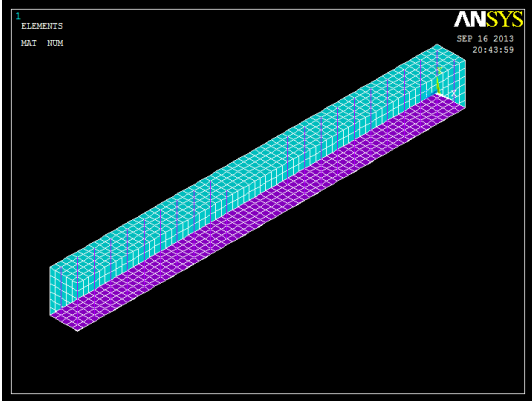
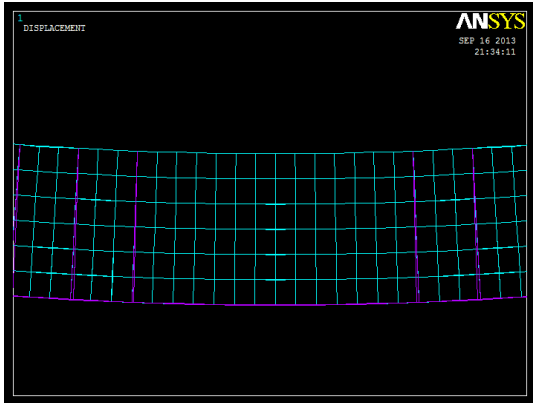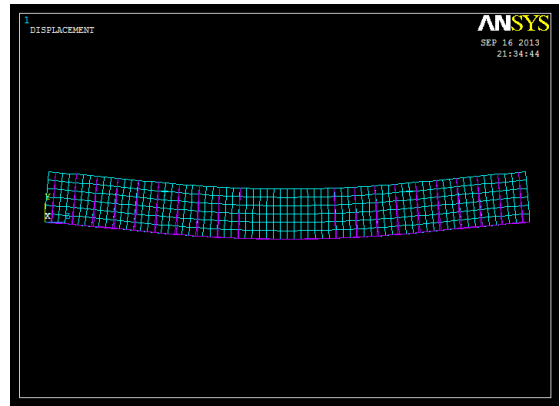**Elements Types (R2)**
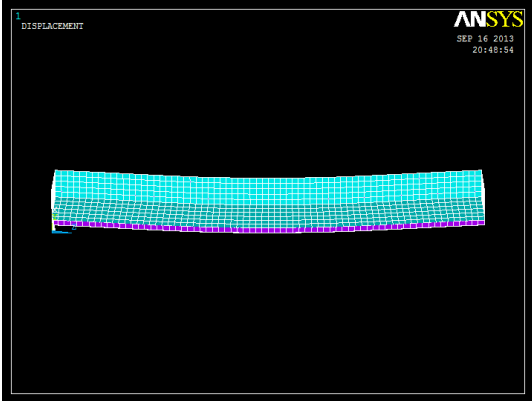
Deflected Shape (R2)

Loads and Boundary Conditions

Wireframe Elements Mode

Shear Reinforcement Without pull out

Shear Reinforcement Connected with Steel Plate

Fig .(5) Set of Output Pictures for the Four Tested Beams

Fig .(6) Failure Mode by Separating Steel Plate

Fig .(7) Failure Mode by Yielding of Steel Plate

Table (4) Experimental Failure Load

Beams	Experimental Failure Load kN	Experimental Failure Load* kN	Increment of Experimental Failure Load %	Theoretical Failure Load kN	Exp. Failure load / Theo. Failure Load	Mode of Failure
R1	37.5	22	41	35	1.07	Concrete cracking
R2	45	23	48	40	1.125	Steel plate yielding with
R3	52	21	59	47	1.106	Steel plate yielding with
R4	58	7	88	53	1.09	Steel plate yielding with

*By Awadh E. Ajeel et al

Fig .(8) Beams under Loading Machine

11. Results

The results of deflection of all the beams had been drawn in the load deflection comparison curves. Generally, the experimental deflection results show small increments than the theoretical results at the beginning of loading which increase with increasing of loading. **Figure (9)** of load deflection relations shows good agreement between the experimental and theoretical results for the four beams. It is considered from the figures that the deflections of the beams decrease with replacing the internal tension steel by the external steel plate under the same load. The reference beam R1 with 150mm^2 of internal tension steel and no external

plate shows the largest central deflection while the beam R4 with no internal tension steel and 150mm^2 of external steel plate shows the smallest deflection. The external steel plate has larger effective depth than the internal steel tension bar and the moment of inertia of the composite section is also larger than the moment of inertia of the reinforced concrete section without of external plate, so the increase of bending effective depth increases the moment capacity of the beam section causing smaller deflection. The higher membrane forces resulting from constraining the internal and external steel reinforcements generate axial forces which prevent increasing of deformations. **Figures (10)** shows the central deflection comparison between the theoretical and experimental results independently. The results from these figures also support the above conclusions. The ratio of steel replacement of internal reinforcement by external steel plate with 33%, 67% and 100% leads to deflection drop with 12.5%, 7.7% and 4.6% respectively.
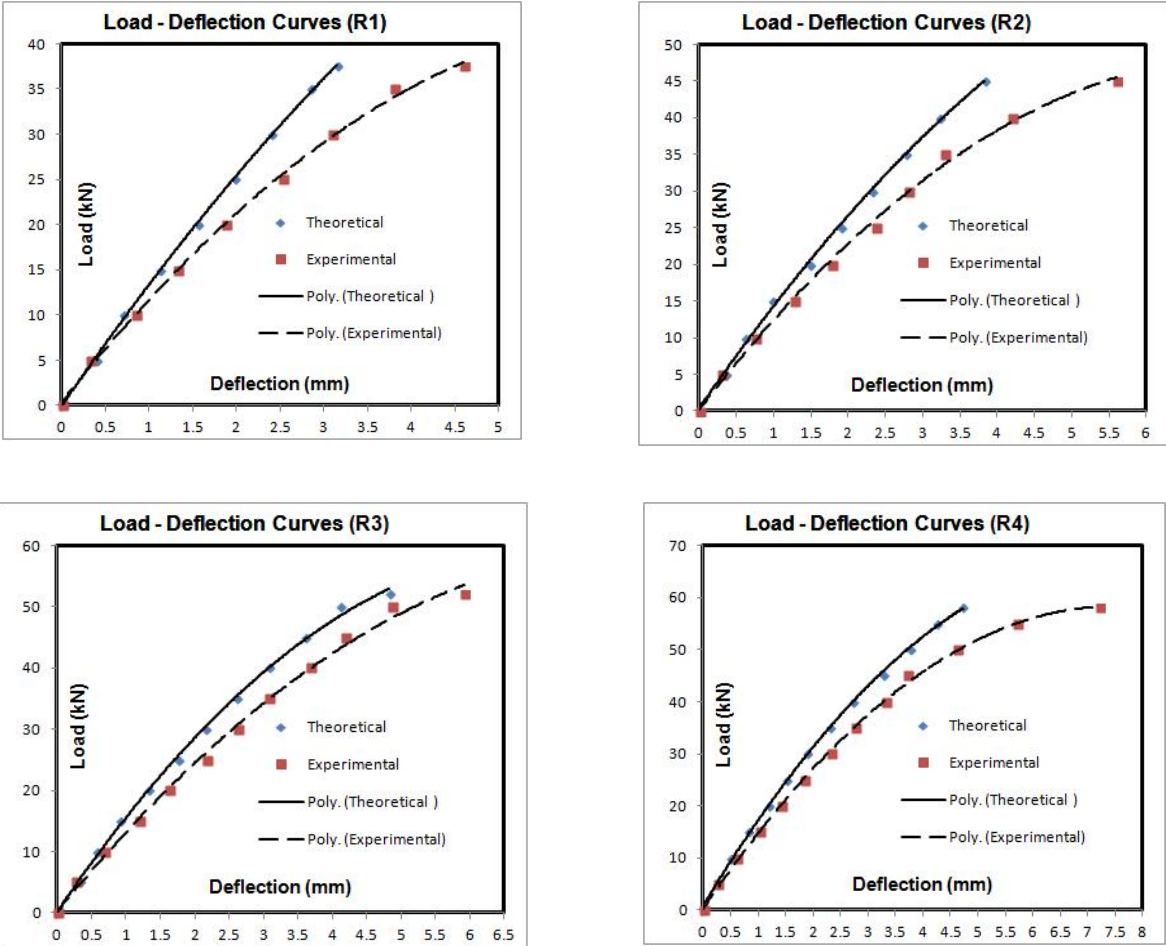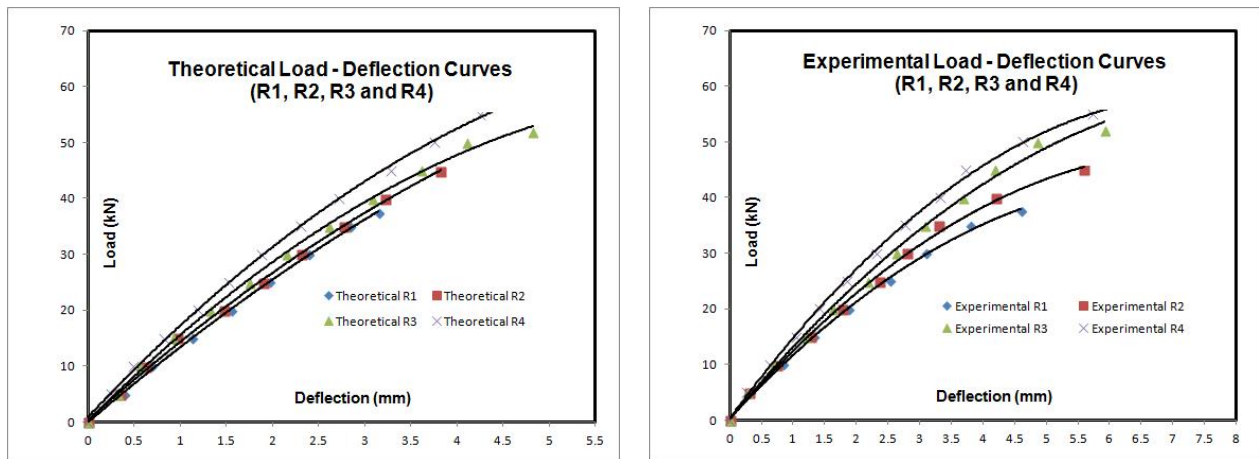

Fig . (9) Load Deflection Curves

Fig .(10)

Central Deflection Comparison between the Theoretical and Experimental Results

12. Conclusions

The present experimental work represents a preliminary study only and much more data are required before any conclusions can be made. The following remarks can be observed from current study:

- Full composite action exists between the plate and concrete and the beam failed by plate yielding.
- The very important conclusion was the obtaining the full bond between the RC beams with the external steel plate by using the new mechanical technique of shear connection without needing any surface bond materials.
- Very low cost of material and labor of the present technique comparing with the old technique.
- External plating has a considerable reducing effect on both flexural crack width and deflections.
- Increment of experimental failure load occurs when use the mechanical connection.
- The experimental failure load increase by 48%, 59% and 88% for the beams R2, R3 and R4 respectively with use the mechanical connection.

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