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Response of Laced Reinforced Concrete Beams subjected to Repeated Loading

Dr. Abbas AbdulMajeed Allawi[1], *Dr. Arshad Nadhom Mohammed Ali Shubber[2]

1) Assist Prof., Civil Engineering Department, Baghdad University, Baghdad, Iraq.
2) Lecturer., Civil Engineering Department, Al-Mustansiriyah University, Baghdad, Iraq.

Abstract: In this research, the structural behavior of Laced Reinforced Concrete T-beam of cross sectional dimensions (300mm × 80mm) flange and (150mm × 220mm) web under monotonic loadings was studied experimentally. Two types of lacing reinforcement with inclination angle of 45^{o} and 60^{o} with respect to the longitudinal reinforcement and 6 mm and 8 mm diameters for each type were used. During monotonic loading tests, the load deflection values at different locations of the tested specimens were recorded in addition to determination of the ultimate load. Also, the support rotation and the ductility ratio for each tested beam were calculated. The study of inclination angle of lacing reinforcement shows that lacing reinforcement of 60^{o} inclination angle has more deflection than that of 45^{o} inclination angle, also the ultimate load of first type above is more about 6% than other type. The results show that beams with lacing reinforcement are stiffer than beams with conventional stirrup reinforcement. Results have shown that specimens with lacing reinforcement are more ductile than beams without lacing (conventional vertical stirrups) and the ductility factor of laced reinforced beams ranges from 1.73 to 11.7, while it is 1.6 for unlaced (stirrups) beams. Also, the support rotation of laced reinforced concrete beams is about five times higher than that of conventional reinforcement.

Keywords: *Lacing Reinforcement, Monotonic Loading, T-beam, Reinforced Concrete.*

السلوك الانشائي للعتبات الخرسانية ذات المقطع T وبتسليح متعرج تحت الاحمال المتكررة باتجاه واحد

الخلاصة: ان السلوك الانشائي للعتبات الخرسانية ذات المقطع (T) وبتسليح متعرج وبابعاد مقطع (300 ملم * 80 ملم) للجزء العلوي المستعرض و(150 ملم * 220 ملم) الجزء السفلي الوترة وتحت تاثير الاحمال المتكررة باتجاه واحد تم دراستها عمليا. نوعين من التسليح المتعرج بزاوية ميلان ^{o} 60 و^{o} 45 نسبة الى اتجاه الحديد الطولي و باقطار 8 ملم و 6 ملم لكل نوع تم استخدامها. من خلال تسليط الاحمال المتكررة باتجاه واحد تم قياس قيم الاحمال والهطول المصاحب لها عند اماكن معينة اضافة الى تعيين قيم الاحمال القصوى. كذلك تم حساب زاوية دوران المسند ونسبة المطيلية لكل عتبة تم اختبارها. تبين ان حديد التسليح المتعرج بزاوية ميلان^{o} 60 نسبة الى اتجاه الحديد الطولي تمتلك هطول اكبر من حديد التسليح المتعرج بزاوية ميلان ^{o} 45 نسبة الى اتجاه الحديد الطولي بينما مقاومة النوع الاول اعلاه هي حوالي 6% اكبر منها لحديد التسليح المتعرج بزاوية ميلان^{o} 45. بينت النتائج انه العتبات ذات حديد التسليح المتعرج اكثر جساءة من العتبات ذات التسليح الاعتيادي الحلقي. النتائج بينت ان العتبات ذات التسليح المتعرج اكثر مطيلية من العتبات ذات التسليح الاعتيادي الحلقي حيث ان نسبة المطيلية لعتبات التسليح المتعرج كانت 1.73 و 11.7 بينما كانت 1.6 للعتبات ذات التسليح الاعتيادي الحلقي. وكذلك فان قيم دوران المسند للنوع الاول اكبر بحدود خمسة مرات منها للنوع الثاني.

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*Corresponding Author arshadnadhom@gmail.com

1. Introduction

Laced construction is familiar in steel framed structures. In reinforced concrete structures, the inclined reinforcement are used as special reinforcement.

Laced reinforced concrete could be used for special type of structures like blast resistant structures. Considering dynamic action load nature, continuous inclined reinforcement (lacing) is provided in two parallel faces along the longitudinal reinforcement and lied with traverse cross rod.

Ductility of reinforced structures is a property where resistance to brittle failure during flexure is required to ensure structural integrity. Ductile behavior of a structure can be enhanced through the use of plastic hinges positioned at specific locations throughout the structural frame. These frames are designed to provide reasonable ductility to resist structural collapse after the yield stress of the material has been achieved. The available ductility of plastic hinges in reinforced concrete is determined based on the shape of the moment-curvature relations. Ductility may be defined as the ability to undergo deformations without a substantial reduction in the flexural capacity of the member (Park & Ruitong 1988)[1].

Extensive experimental works were carried out by Parameswaran et al (1986)[2] on Laced Reinforced Concrete members with deformed bars. Based on these studies, the value of support rotation in Laced Reinforced Concrete LRC members for blast resistant structures has been recommended. On a simply supported beam, this means a failure deflection of the order of 1/25 to 1/30 of span.

In the study done by Stanley C. Woodson (1994)[3] in the US Army Engineer Waterways Experiment Station (WES), sixteen one way reinforced concrete slabs were statically loaded. All slabs were designed to be loaded in a clamped (laterally and rotationally restrained). Each slab had a clear span of 600mm, a width of 600 mm, and an effective depth of 60 mm, maintaining the L/d ratio at a value of 10. The values of shear reinforcement ratio are identical when compared between a laced slab and a slab with stirrups. The main conclusion from the experimental program is that lacing and stirrups contribute to the ductility of a one way slab in a similar manner and magnitude. Failure modes were nearly identical for the slabs comparing the two types of shear reinforcement.

Behavior of laced reinforced concrete LRC and its application for blast resistant design has been discussed in detail by Lakshmanan (2008)[4]. Response of laced reinforced concrete LRC beam under low shear span to depth ratio is also presented. It was also observed that cyclic ductility is significantly lower than static ductility for these beams. Inclusion of fibers was found to increase the performance substantially under reversed shear cyclic loading. The versatility of laced reinforced concrete LRC under blast loading was demonstrated by full scale testing.

P. Srinivasa Rao, B.S. Sarma, and et al (1998)[5] made research on laced reinforced concrete beams in order to describe their ductility behavior. Many types of lacing has been introduced such as inclined welded lacing, inclined tied lacing, rectangle lacing and single leg lacing using normal and fiber reinforced concrete while keeping the longitudinal reinforcement and cross section of beam as the same. The on-line data acquisition device has been used in order to define the plastic hinge zone and obtain the shear and flexural behavior. Based on the experimental data obtained, they proposed the ductility indices and a new damage model has been introduced. Test results shows that lacing reinforced concrete beams even with high tension steel can reduce brittle failure so large ductility and sustained loading over large yield plateau can be ensured.

Anandaralli, et al (2012)[6] proposed a new system of laced steel -concrete composite (LSCC). The LSCC system is consisted of a thin steel cover plates provided with perforations, in which reinforcements in the form of lacing are fixed in position with the presence of transverse bars, then concrete is filled in between the two cover plates. The maximum support rotation of conventional reinforced concrete (CRC), laced reinforced concrete (LRC) and laced steel-concrete composite (LSCC) beams had been estimated to be 3.5^o, 7^o, and 15^o, respectively. The comparison between laced steel-concrete composite (LSCC) and steel-concrete composite (SCC) in terms of support rotation indicates that LSCC beams have relatively high support rotations.

Allawi, A. A. and Jabir, H. A. (2016a, 2016b)[7,8] studied the behavior of reinforced concrete one way slab with lacing reinforcement under both static and repeated loading. They tested eight slabs under static loading and nine slabs under repeated loading. All the tested slabs were designed to investigate the effect of the lacing reinforcement on the flexural behavior of one way slabs. The parameters were the lacing steel ratio, flexural steel ratio and span to the effective depth ratio. All specimens were tested under four point loading up to failure.

Recently, Allawi A, A. and Shubber, A, N. (2017)[9] studied the behavior of laced reinforced concrete beam under static Load. They tested five laced reinforced concrete T-beams of cross sectional dimensions (300mm × 80mm) flange and (150mm × 220mm) web with different lacing angles. Test results indicated that. the lacing reinforcement of 60^o inclination angle with respect to longitudinal reinforcement has more stiffness, i.e., less deflection than lacing reinforcement of 45^o inclination angle with respect to longitudinal reinforcement.

2. Objective Of The Work

The overall objective of this work is to develop and conduct an experimental investigation comparing the effects of conventional stirrup reinforcement and lacing reinforcement on behavior of reinforced concrete T-beams under monotonic loads.

Also, to obtain a good understanding of the role of shear reinforcement in enhancing the ductility of reinforced concrete T-beams subjected to monotonic loading.

3. Static Versus Monotonic Loading

Static loadings as an opposite to dynamic loadings are specified by their time-independent nature like the self-weight of structures and superimposed dead loads. In this study this type of load has been applied gradually from rest at a pre-specified rating load (steps of 5kN each) till the failure occurs.

Monotonic loading which is also a static load but it's characterized by the manner of applying the loads. In monotonic loading the load has been increased from rest at a pre-specified rating load until reaching the first loading stage and the releasing the load to rest. The second loading stage has been reached also, from rest and at the same previous rating load till reaching the second stage value. Then releasing the loadings to rest as in the first stage.

This procedure of loading in an increasing manner in each step and re-loading to rest has been repeated until failure of the specimen.

The monotonic loading (one-directional loading) is often referred as an opposite to cyclic loading (two-directional loadings).

4. Experimental Program

The experimental program was conducted in the laboratory of the Civil Engineering Department at College of Engineering at the University of AL-Mustansiriyah. The experimental program involves five laced reinforced concrete T-beams under monotonic loading. Lacing reinforcement of 6 mm and 8 mm diameter with 45^o and 60^o inclination angle with longitudinal main reinforcement have been used for beams. Also, conventional shear reinforcement (vertical stirrups) have been used for the remaining beam.

The detailed explanation has been shown in Table (1).

Table (1) T-beams used in experimental work.

Beam symbol	Type of shear reinforcement	Diameter (mm)	Inclination angle (^{o})	Type of loading
Conv.-M	stirrup	8	-	monotonic
L-6-45-M	lacing	6	45	monotonic
L-6-60-M	lacing	6	60	monotonic
L-8-45-M	lacing	8	45	monotonic
L-8-60-M	lacing	8	60	monotonic

The following abbreviations have been adopted in this research:

M: monotonic;
L: laced reinforcement;
Conv.: conventional shear reinforcement (stirrup).

The dimensions of T-beams used as testing specimens are as follows:

Length of the T-beam is 2450 mm, effective span length of T-beam is 2250 mm, flange width is 300 mm, flange thickness is 80 mm, depth of web is 220 mm and width of web is 150 mm as shown in Fig. (1).

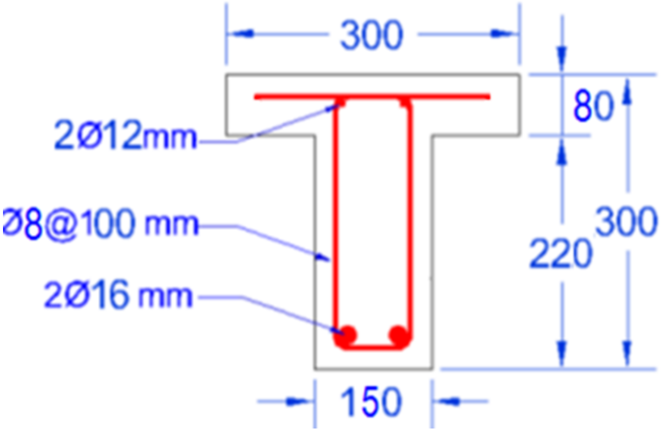

Fig. (1) Dimensions of testing T-beam specimens.

The steel reinforcement which is used for lacing reinforcement are of two diameter sizes, namely, 6 mm diameter and 8 mm diameter. Each one of them has been inclined at 45^o and 60^o with flexural (longitudinal) reinforcement.

The schematic details as shown in Fig.(2).

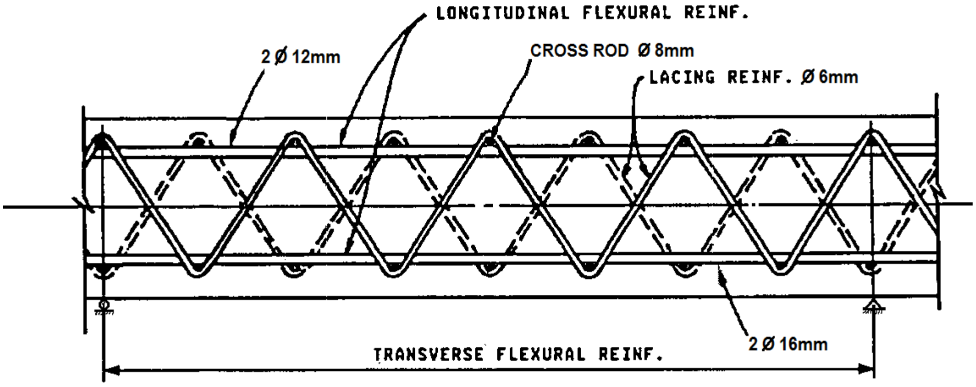

Fig.(2) Laced reinforced element.

The fabrication and construction of laced reinforcement to the required shape and dimension have been done by universal press machine in industrial zone in Shaikh Omar in Baghdad, as shown in Fig.(3).

Fig. (3) Lacing reinforcement fabrication.

Fig. (3): continued

5. Material

5.1 Steel Reinforcement

For longitudinal reinforcement in both tension and compression zones, deformed steel bars of diameter 16 mm and 12 mm respectively have been used. While for conventional shear reinforcement (stirrups), we used deformed steel bars of 8 mm in diameter. Deformed steal bar of 8 mm diameter was also used as a cross rod to tie both sides of laced reinforcement over the longitudinal reinforcement.

Three specimens of 500 mm length for each deformed bar have been tested in the Consulting Engineering Bureau/ Collage of Engineering/ University of Baghdad.

The results of these tests are shown in Table (2).

Table (2) Mechanical properties of steel bars.

Nominal diameter, mm	Measured diameter, mm	Yield stress Fy, MPa	Tensile strength fu, MPa	Elongation, %
6	6.0	415	574	5
8	8.0	425	605	4
12	12.0	600	730	8.5
16	16.0	620	755	12.5

5.2 Cement

For all test specimens, Ordinary Portland Cement (Type-I) which is product of the United Cement Company for Cement Production (UCC) was used.

The chemical analysis and physical test results of the cement are given in Tables (3) and (4), respectively. They conform to the Iraqi Standard Specification (IQS) No. 5/1984.

Table (3) Chemical composition of cement.

Compound composition	Chemical composition	% Weight	IQS No.5/1984 limits
Lime	CaO	61.19	-
Silica	SiO2	21.44	-
Alumina	Al2O3	4.51	-
Iron oxide	Fe2O3	3.68	-
Magnesia	MgO	2.31	5*
Sulfate	SO3	2.70	2.8*
Loss on ignition	L.O.I	2.39	4.0*
Insoluble residue	I.R	1.18	1.5*
Lime saturated factor	L.S.F	0.87	0.66-1.02
Bogue's Potential Compound			
Tricalcium aluminates	C3A	6.06	-
Tricalcium silicate	C3S	Not available	-
Dicalcium silicate	C2S	Not available	-
Tricalcium aluminate ferrite	C4AF	Not available	-

Table (4) Physical composition of cement

Physical properties	Test Results	IQS No.5/1984
Fineness using Blain air permeability apparatus(m2/kg)	405	230**
Soundness using autoclave method	Not available	0.8%*
Setting time using Vicat's instruments		
Initial(min.)	135	45**
Final(hr)	3:25	10*
Compressive strength for cement Paste Cube(70.7mm) at:		
3days(MPa)		
7days(MPa)	24.4	15**
28days(MPa)	32.3	23**
	47.2	

*Maximum limit

**Minimum limit

5.3 Fine aggregate

AL-Ukhaidher natural sand of (4.75mm) maximum size was used throughout this work. Grading of the sand conforms to the Iraqi Standard Specification (IQS) No. 45/1984, as shown in Table (5).

5.4 Coarse Aggregate

Graded Crushed gravel of a maximum size of 10mm brought from AL-Niba'ee fields was used throughout this work. Table (6) shows the grading of the aggregate which conforms to the limits specified by the Iraqi Standard Specification (IQS) No. 45/1984.

Sieve analysis for fine and coarse aggregate was performed in the Material Laboratory at the College of Engineering, Al-Mustansiriya University.

Table (5) Grading of fine aggregate

No.	Sieve (mm)	% Passing	
		Fine aggregate	IQS No.45/1984Zone(2)
1	5	100	90-100
2	2.36	83.75	75-100
3	1.18	63.84	55-90
4	0.6	35.84	35-59
5	0.3	8.84	8-30
6	0.15	0.64	0-10

Table (6) Grading of coarse aggregate.

Sieve size (mm)	% Passing	
	Coarse aggregate	IQS No.45/1984 limits
14	100	100
10	89	85-100
5	5	0-25
2.36	1	0-5

5.5 Water

Tap water was used for both curing and mixing procedures. For concrete mixing, the water cementitious material ratio (w/c) was (0.5).

6. Concrete Mixing

The mixing proportion [cement: sand: coarse aggregate] was (1: 1.5: 3) by weight and the water cementitious material ratio was (0.5) in order to produce concrete with average cylindrical compressive strength of 27 MPa. It is evident that the w/cm is relatively high since the mixing was done in June (when temperature at the laboratory was about 45°C and the evaporation of water was in a high ranges). The mix contents for (1 m^3) of concrete are given in Table (7).

Table (7) Mix proportions for (1 m3) of concrete

Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	w/cm ratio	Water (lit/m^3)
400	600	1200	0.5	200

7. Test Results

7.1 Load Deflection Relationship

The deflections have been measured at mid-span (designated as mid) and under left and right applied loads (designated as L and R respectively).

The load-deflection curves have been plotted for each tested beam, as shown in Fig.(5-1).

It is noticed that the residual deflections have been occurred after each load step and the residual deflections have been increased rapidly as load approaches the ultimate load.

Maximum vertical deflection at mid span and beneath applied load, about 90 mm at mid-span and 75 mm beneath the load is obtained for specimen L-8-60. While in the specimen of conventional vertical stirrup the value are about 12 mm and 98 mm respectively, as shown in Figs.(4).

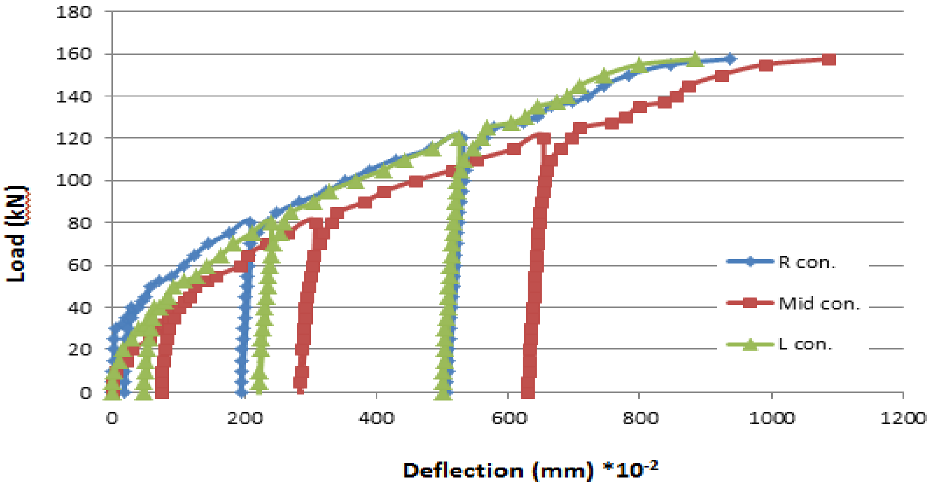

Fig.(4 a) Load-deflection relationship for beam with conventional stirrup

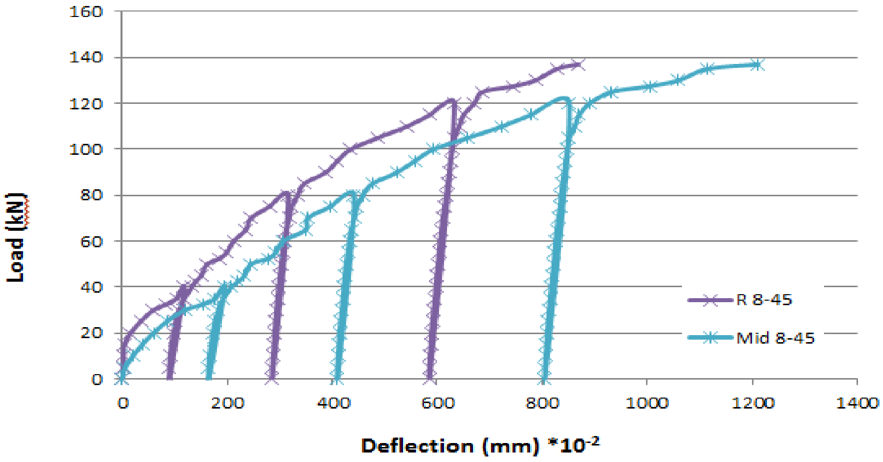

Fig.(4 b) Load-deflection relationship for beam L-8-45.

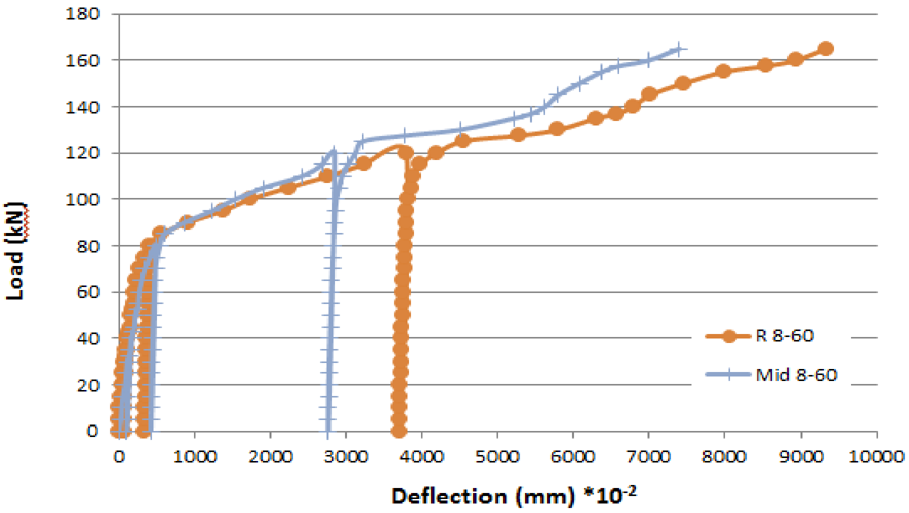

Fig.(4 c) Load-deflection relationship for beam L-8-60

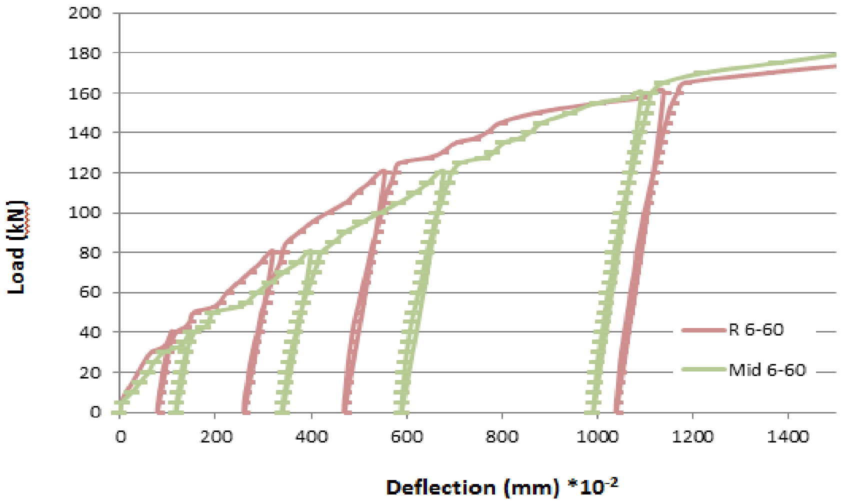

Fig.(4 d) Load-deflection relationship for beam L-6-60.

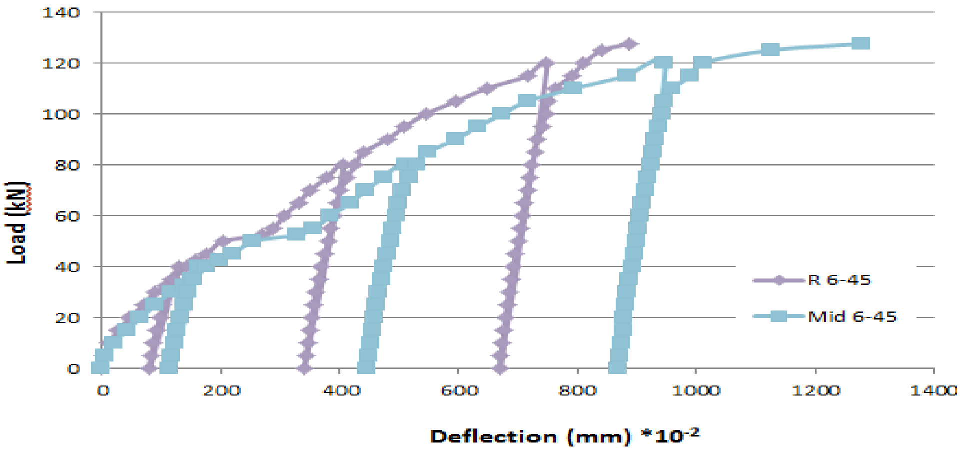

Fig.(4 e) Load-deflection relationship for beam L-6-45.

Fig.(5) demonstrates the vertical deflections at mid-span for all the tested specimens.

Specimen with lacing reinforcement L-8-60 experience more performance than other specimens due to the amount of lacing reinforcement included which is contributed with flexure reinforcement to resist the applied loading.

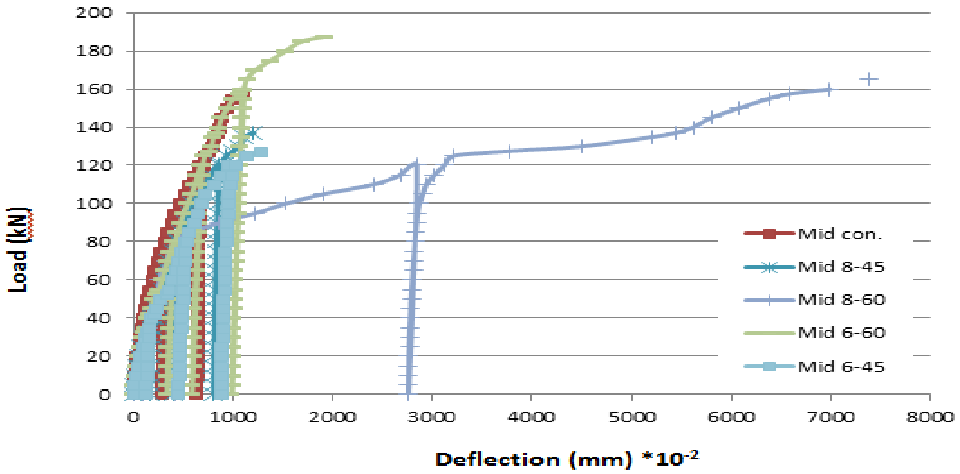

Fig.(5) Load- mid span deflection relationship for tested beams under monotonic loading.

7.2 Calculations of Support Rotation

For a simply supported beam, two points loaded at each third length of the beam, the support rotation angle has been calculated according to the following equation:

$$\theta = \tan^{-1} (\Delta / L1) \qquad (1)$$

Fig.(6) shows a typical diagram for deflected shape of the beam.

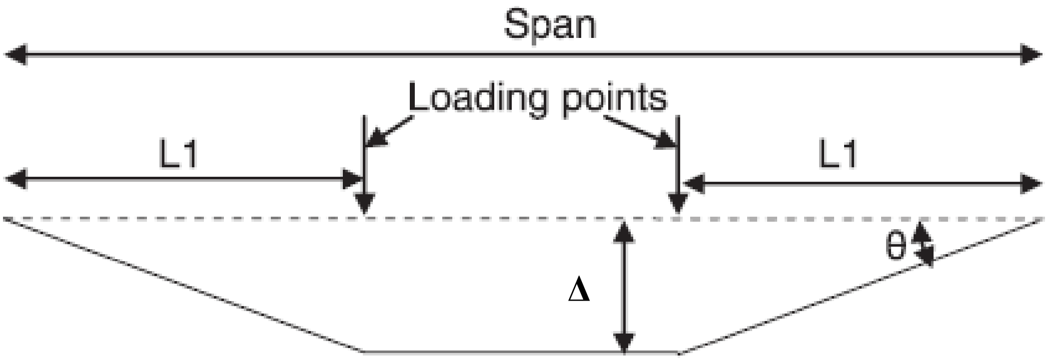

Fig.(6) Calculation of support rotation.

The maximum support rotation is obtained for specimen L-8-60 when the inclination angle 60° and size 8 mm of lacing reinforcement. While the minimum is 0,73 for specimen L-6-45 when the inclination angle 45° and size 6 mm of lacing reinforcement.

It can be demonstrated that lacing reinforcement of 45^o inclination angle has lowest support rotation due to a little amount of lacing reinforcement in the specimen.

Table(8) Summary of the calculated support rotation for each type of beam.

Beam symbol	Pu (kN)	Δ (mm)	Θ (deg.)
Ref.	160	15.74	1.2
L-6-45	130	9.56	0.73
L-6-60	190	28.27	2.16
L-8-45	140	9.83	0.75
L-8-60	160	89.36	6.79

7.3 Ductility Ratio

The displacement ductility ratio has been adopted for calculating the ductility ratio of beam specimens.

$$\text{Displacement ductility ratio } (\mu\Delta) = \Delta u / \Delta y \qquad (2)$$

where Δu is the ultimate displacement

Δy is the displacement when the tension reinforcement first reaches the yield strength.

Table(9) Displacement ductility factor of tested beams .

Beam symbol	Ultimate displacement (mm)	Yield displacement (mm)	Ductility factor
Ref.	15.83	9.90	1.6
L-6-45	14.46	6.73	2.15
L-6-60	22.34	9.43	2.37
L-8-45	14.88	8.61	1.73
L-8-60	69.91	5.95	11.7

Ductility factor ranges from 1.6 for specimen with conventional vertical stirrup (no lacing) to 11.7 for specimen with lacing reinforcement of 60^o inclination angle and 8 mm diameter size.

8. Conclusions

1. Support rotation of specimens with lacing is higher than that of specimens without lacing reinforcement.
2. Residual deflections occurred for specimens tested under monotonic loading and noticed to be increased as the loading level is increased.
3. Ductility factor for specimen with lacing reinforcement is higher than that for specimen with conventional vertical stirrup (no lacing).
4. Deflection of lacing reinforcement diameter size of 8mm is about 400% more than lacing reinforcement of 6mm diameter.

5. The strength capacity of 60o inclination angel LRC T-beam is 14% more than that of 45o inclination angle LRC T-beam.
6. The re-straining effect has been occurred for beams with laced reinforced concrete.

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