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Experimental Behavior of Laced Reinforced Concrete Beams under Static Loading

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Abstract: ***This paper provides results of an investigation to study the influence of lacing reinforcement on the flexural performance of reinforced concrete beams under static load. A twelve reinforced concrete beams with and without lacing reinforcement are tested under four points bending loading with displacement control. Three test parameters are used, which are: the diameter of lacing bar (4mm, 6mm, and 8mm), inclination angle of lacing bar with longitudinal beam axis ($30^\circ, 45^\circ, and\ 60^\circ$), and number of lacing bar in the longitudinal face of the beam (lacing steel ratio). Flexural capacities of laced reinforced concrete (LRC) beams are founded to be more than the reinforced concrete (RC) beams. Flexural capacity of such beam is increased by using large lacing bar diameter, $30^\circ and\ 45^\circ$ angle of inclination lacing bar, and maximum lacing steel ratio, while the deflection decreases.***

Keywords: RC beam**,** laced reinforcement, ductility, crack, static loading

1. Introduction

Reinforced concrete elements (RC) are known to have limited ductility and concrete confinement tendencies. The RC structural element properties can be amendment by modification in the concrete components and by given an appropriate detail for reinforcements. Symmetrical reinforcement (compression and tension reinforcement is the same) has been used in a laced element. The main flexural reinforcement bars on both face of the element and the concrete components are bind together throw the influence of the truss action of lacing reinforcement as illustrate in **Figure 1**. The ductility and concrete confinement are enhancing by lacing technique **[1]**. The main objective of the use of shear reinforcement (stirrups or lacing bars) is to improve the performance of the structural element in the large deflection zone of response, shear forces resistance, and to prevent the diagonal tension cracks from forming and spreading **[2].**

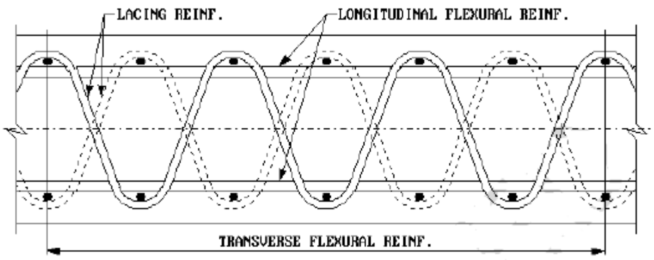

Figure 1: Lacing Reinforcement, [1].

Large deflections and the development of reinforcement in strain hardening zone can be achieved by lacing reinforcement technique. The laced element possible to achieve a maximum deflection about to 12° support rotation. The support rotation of single leg stirrups is limited to 6° under the action of flexural or 12° under the action of tension membrane **[1]**.**Rao, P. S. et al.[3]** introduced experimental investigation on 23 LRC cantilever beams having various forms of lacing with$40^\circ and\ 60^\circ$ inclination,90° rectangular lacing and single leg lacing using normal and fiber reinforced concrete. There results indicated that the inclined lacing give better response than the other shape of lacing. **Anandavlli N. et al.[4]**, proposed a new approach for finite element modeling of reinforced concrete element under flexure. Their modeling approach assumes the RC and LRC as a homogenous material with stress-strain relationship derived from the moment curvature relationship of structural element component. **Anandavlli N. et al. [5],**studied the behavior of two laced steel concrete composite (LSCC) beams subjected to monotonic loads. LSCC systems contains two layers of thin plate with holes through which the lacing ($45^\circ and\ 60^\circ$ inclination) enters and connects with the cross bar and the poured concrete interspersed the two plates. Their results revealed that the maximum support rotation $13^\circ and\ 16^\circ$ achieved for LSCC beams with$45^\circ and\ 60^\circ$ inclined lacing respectively. And noticed that the two beams have the same strength response. **Madheswaran C.K. et al.[6]**, describe the ductility performance of laced reinforced geopolymer concrete beam (LRGPC) under monotonic loading. It was indicated that the ductile failure is not possible to achieve for reinforced concrete beam with 2.5 span/depth ratio. Therefore they developed ductile failure of such beams by suitable reinforcement detail with laced bar (45° inclined angle to horizontal).

2. Research Significance

Knowledge of the effectiveness of using lacing bars on the performance of reinforced concrete beams and to understand the benefit of using shear reinforcement (stirrups or lacing bar) under static load. The experimental behaviors of laced reinforced concrete (LRC) beams under four point's static load are studied.

3. Test Beams

The study focused on the influence of different bar diameter, inclined angle with longitudinal axis, and number of lacing reinforcement in both longitudinal faces of beam (lacing steel ratio). All beams are designed according to **ACI 318M-** code **[7]**, and meeting with **UFC 3-340-02 [1]**, requirements for the laced reinforced concrete structures. Details of the tested RC and LRC beams are describe hereafter. The cross section dimensions are $(160mm \times 300mm)$ and 3000mm in length. Two reinforced concrete beams used as control beam and the rest ten beams are a laced reinforced concrete beams that used to study the influence of various bar diameter, inclined angle and number of lacing bar in both longitudinal faces of beam as shown in **Figures 2 to5**. All beams (6SRC, 8SRC, 6SLRC-S-30°, 8SLRC-S-30°, 6SLRC-S-45°, 8SLRC-S-45°, 8DLRC-S-45°, 6SLRC-S-60°, 6DLRC-S-60°, 8SLRC-S-60°, 8DLRC-S-60°, 4SLRC-S-60°) are tested under static load. The beam symbols can be defined as follows. The first symbol announce to stirrup or lacing bar diameter, the second denote to type of shear reinforcement (stirrups for reinforced concrete beam, single or double lacing reinforcement for laced concrete beam), the third symbol after slash indicate loading type (static load), and final symbol announce to the angle of inclined lacing bar with beam axis. The parameters of LRC beams are listed in **Table 1**. The steel reinforcement properties are: $\varnothing16$mm steel bars are used for compression and tension reinforcement, $[f_y = 564.147\ Mpa]$, $\varnothing10$mm steel bars are used for cross bars, $[f_y = 562.7\ Mpa]$, $\varnothing8\ mm, \varnothing6\ mm\ and\ \varnothing4mm$ steel bars are used for shear reinforcement with yield stresses [f_y =492.39 Mpa, 456.24 Mpa and 545.24 Mpa, respectively]. The beams are constructed using a normal per-casting concrete with a compressive strength of 39.225MPa.

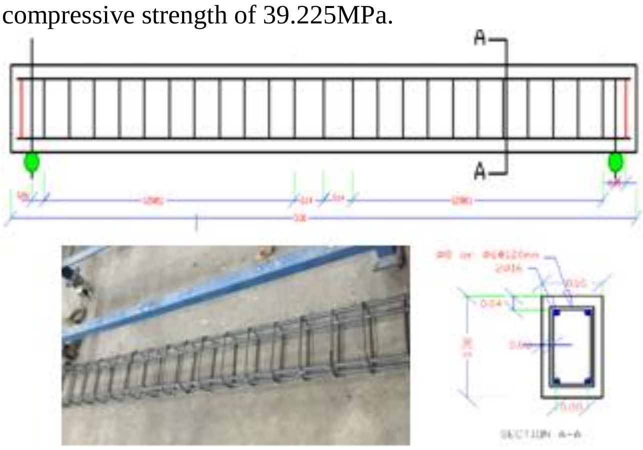

Figure 2: Control Beams with stirrups (6mm or 8mm)

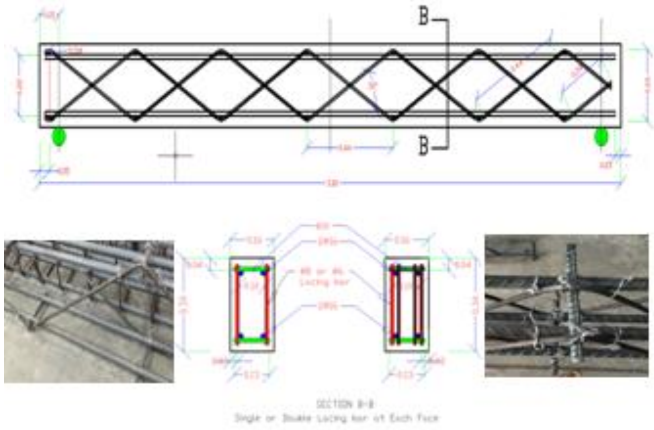

Figure 3: Laced Reinforced Concrete Beams with 30 Laced inclined angle to Horizontal

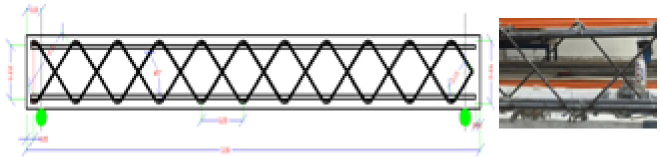

Figure 4: Laced Reinforced Concrete Beams with (6mm or 8mm) Lacing Bar and 45° Inclined Angle to Horizantal

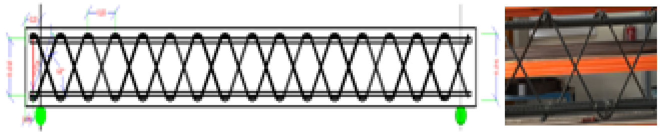

Figure 5: Laced Reinforced Concrete Beams with (6mm or 8mm) Lacing Bar and 60° Inclined Angle to Horizantal

Table 1: Parameters of Twelve Reinforced Concrete Beams under Static Load

Beam symbols	Ratio of lacing reinforcement Angle of inclined lacing bar to horizontal			Diameter of stirrup and Lacing Bar (mm)
	30°	45°	60°	
6SRC	-	-	-	6
8SRC	-	-	-	8
6SLRC-S-30	0.00124	-	-	6
8SLRC-S-30	0.00219	-	-	8
6SLRC-S-60	-	-	0.00302	6
6DLRC-S-60	-	-	0.00604	6
8SLRC-S-60	-	-	0.00537	8
8DLRC-S-60	-	-	0.0107	8
4SLRC-S-60	-	-	0.00134	4
6SLRC-S-45	-	0.00194	-	6
8SLRC-S-45	-	0.00345	-	8
8DLRC-S-45	-	0.0069	-	8

4. Measuring Instruments

The instrumentation is used in testing the beams for recording strains and deflections, and also it's used to obtain and realize the behavior of the laced reinforced concrete beam.120Ω resistance of Strain gauges (made in Japan for TML), are used to measure the strain in steel reinforcement at mid span. LVDT (Linear variable deferential transformer) is used to measure the deflection at mid span, and it is attached to bottom surface of beams.

5. Test Procedure

All beams are tested using the hydraulic actuators of 300 kN capacity which available in school of engineering at Monash University/Malaysia. The beams are a simply supported as shown in **Figure6.** Four points bending test are carried out by displacement control at rate of 0.05mm/sec. At each increment stage, the deflection, load and strain in steel reinforcements (flexural and lacing bars) are recorded. At each stage of the test progress, the cracks are marked carefully.

Figure 6: Simply Supported Beams with four point bending test

6. Test Results and Discussion

6.1 General Behavior and Crack Patterns

The first flexural cracks are appeared at the tension zone within the mid-portion of the beams at which the maximum bending isoccurs. With farther loading, the cracks growth and additional vertical flexural micro-cracks are form in the middle part and extended to the compression zone and became wider and inclined shear cracks appeared near of the support. Then horizontal surface cracks are appeared under loading area that lead to crush the concrete and failure. The mode of failure for all beams is characterized as flexural-shear failure mode. **Figures 7-a to 7-l** shows the crack pattern of the tested beams. The test results for cracking and ultimate loads of all beams are given in **Table 2**.

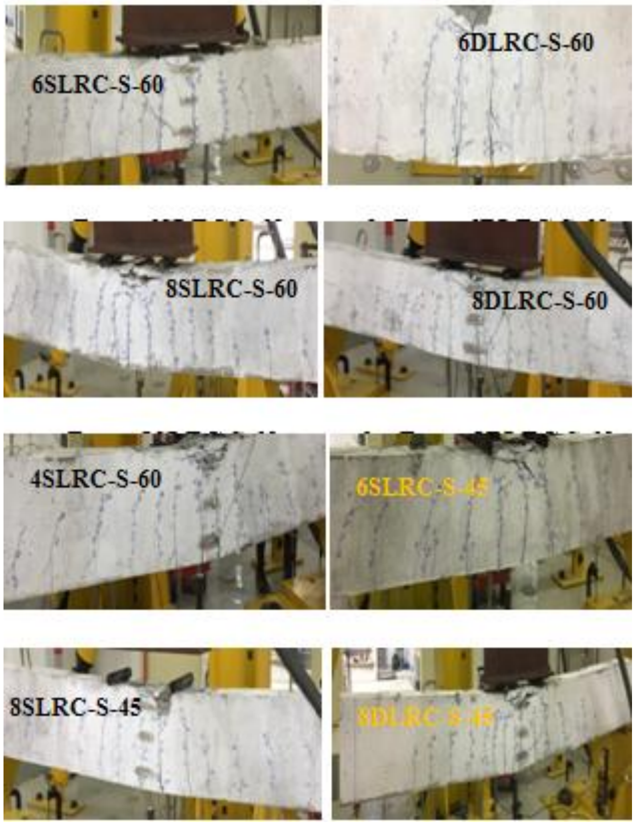

Figure 7: The Cracks Pattern of the Tested Beams

Table 2: Experimental Results (cracking and ultimate loads) for Twelve Reinforced Concrete Beams under Static Load

Beam symbols	Cracking load (P_{cr})kN	Ultimate load(P_u) kN	$\%P_{cr}/P_u$	% increasing in first cracking load respect to control	% increasing in ultimate load respect to control
6SRC	13	85.14	15.27	Ref.	Ref.
8SRC	13	86.72	14.99	Ref.	Ref.
6SLRC-S-30	16	90.25	17.73	23.07	6.002
8SLRC-S-30	17	92.17	18.44	30.77	6.28
6SLRC-S-60	17	85.25	19.94	30.77	0.13
6DLRC-S-60	18	93.1	19.3	38.46	9.35
8SLRC-S-60	20	88.14	22.69	53.85	1.64
8DLRC-S-60	22	93.6	23.5	69.23	7.93
4SLRC-S-60	16	91.12	17.56	*	*
6SLRC-S-45	19	88.97	21.36	46.15	4.5
8SLRC-S-45	20	100.61	19.88	53.85	16.02
8DLRC-S-45	24	101.7	23.59	84.62	17.3

*without Ref.

Generally it is notice that the growth of cracks within the beam depth is increased with test progress. The shape of the cracks is parallel and vertical along the depth of the section up to failure for the control beams. While the cracks in beams with lacing reinforcement take form of a semi-curved near support and vertical shape in the middle of beam. From the results, observed that the first cracking load increase with using of lacing steel reinforcement and specially for angle range between (30-45) by about 23.07%, 30.77%, 46.15%, 30.77%, 53.85%, and 53.85% for beams 6SLRC-S-30, 6SLRC-S-60, 6SLRC-S-45, 8SLRC-S-30, 8SLRC-S-60, and 8SLRC-S-45 respectively, with respect to reference beams

6SRC and 8SRC, respectively. Comparisons have been done between the laced reinforced concrete beams (LRC) to study the influence of lacing bar diameter, inclined lacing angle and lacing steel ratio at the appearance of the first cracking load as follows: it is observed that the first cracking load increased with increasing of lacing bar diameter by about 6.25%, 17.65% and 5.26% for beams 8SLRC-S-30, 8SLRC-S-60 and 8SLRC-S-45 respectively, with respect to beams 6SLRC-S-30, 6SLRC-S-60 and 6SLRC-S-45 respectively, and it is increased with increasing of inclined lacing angle by about 6.25%, 18.75%, 17.65% and 17.65% for beams 6SLRC-S-60, 6SLRC-S-45, 8SLRC-S-60 and 8SLRC-S-45 respectively, with respect to references beams 6SLRC-S-30 and 8SLRC-S-30 respectively. And also it is increased with using of doubly lacing reinforcement in each face of beam (increasing lacing steel ratio), by about 38.46%, 69.23%, and 84.62% for beams 6DLRC-S-60, 8DLRC-S-60 and 8DLRC-S-45 respectively, with respect to reference beams 6SRC and 8SRC, respectively.

6.2 Load-Deflection Response

The behavior of the beams is compared to the behavior of control beam at service load and ultimate load stage as listed in **Table 3**. The limit value of the service load is taken within range of 70% to 75% of the ultimate load **Tan, K.G. and Zhao, H. [8].** In this research, the service load is taken as 70% of the ultimate load of control beam. From the results, load-deflection responses are founded to be linear up to the point of yield of RC and LRC beams, after that the behavior will be nonlinear until failure of beam and it is noticed that the ultimate load carrying capacityis increased in beams with lacing reinforcement and by about 6.002%, 0.13%, 4.5%, 6.28%, 1.64%, 16.02%, 9.35% 7.93% and 17.3% for beams 6SLRC-S-30, 6SLRC-S-60, 6SLRC-S-45, 8SLRC-S-30, 8SLRC-S-60, 8SLRC-S-45, 6DLRC-S-60, 8DLRC-S-60 and 8DLRC-S-45 respectively, with respect to beams 6SRC and 8SRC as listed in **Table 2**, on the other hand, the deflection at service load stage is reduced by 8.06%, 13.9%, 12.53%, 11.46%, 0.978%, 0.356%, 4.89%, 9.87%, and 5.78% for beams 6SLRC-S-30, 6SLRC-S-60, 6SLRC-S-45, 6DLRC-S-60, 8SLRC-S-30, 8SLRC-S-60, 8SLRC-S-45, 8DLRC-S-60 and 8DLRC-S-45 respectively, with respect to control beams 6SRC and 8SRC respectively.

At the ultimate stage, the deflection at the same load level of control beam is reduced by about 42.86%, 17.27%, 33.7% 53.5%, 23.25% and 53.98% for beams 6SLRC-S-30, 6SLRC-S-60, 6SLRC-S-458SLRC-S-30, 8SLRC-S-60 and 8SLRC-S-45 respectively, with respect to reference beams 6SRC and 8SRC respectively, Moreover, it is observe thatthe increasing of lacing steel ratio lead to an additional reducing in deflection by about 45.3%, 45.09%, and 55.77% for beams 6DLRC-S-60, 8DLRC-S-60 and 8DLRC-S-45 respectively, with respect to control beams 6SRC and 8SRC, respectively as shown in **Figures8 and 9**.

Table 3: Deflection Values for Tested Beams at Service and Ultimate Loads

Beam Symbol	Deflection at Service load of Control Beam (mm)	% Decrease in Deflection	Deflection at Ultimate Load (mm)	Deflection at Same Load Level of Ref. Beam (mm)	% Decrease in Deflection at Same Load Level of Ref. Beam
6SRC	13.09	Ref.	38.56	Ref.	Ref.
6SLRC-S-30	12.035	8.06	28.5	22.03	42.87
6SLRC-S-60	11.27	13.9	32.41	31.9	17.3
6SLRC-S-45	11.45	12.53	40.17	25.56	33.71
6DLRC-S-60	11.59	11.46	34.9	21.09	45.3
8SRC	11.25	Ref.	35.86	Ref.	Ref.
8SLRC-S-30	11.14	0.978	26.11	16.67	53.5
8SLRC-S-60	11.21	0.356	31.12	27.52	23.26
8SLRC-S-45	10.7	4.89	36.22	16.5	53.99
8DLRC-S-60	10.14	9.87	31.2	19.69	45.09
8DLRC-S-45	10.6	5.78	37.93	15.86	55.77
4SLRC-S-60	-	-	32.58	-	-

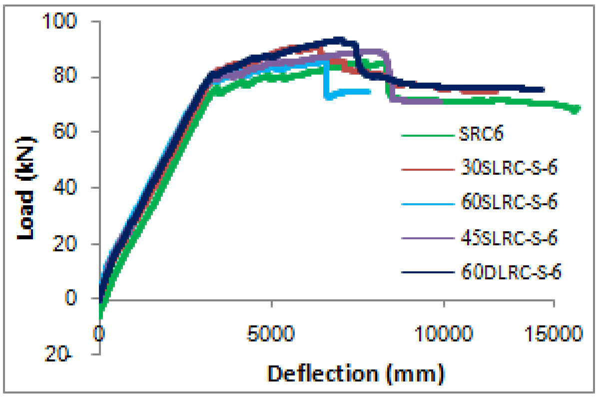

Figure 8: Comparison of 6SRC Beam to 6LRC Beams.

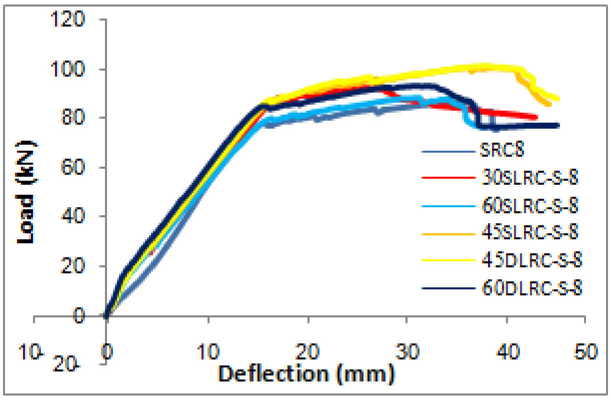

Figure 9: Comparison of 8SRC Beam to 8LRC Beams.

Comparisons have been done between the laced reinforced concrete beams (LRC) to study the influence of lacing bar diameter, inclined lacing angle and lacing steel ratio on the load-deflection response and discussed clearly as follow.

First, it is notice that the load carrying capacities increase with increasing of lacing bar diameter from 6mm to 8mm in each case of fixed inclined angle of lacing bar. The amount of the increasing is founded by about 2.13%, 13.07% and 0.017% for beams 8SLRC-S-30, 8SLRC-S-45 and 8SLRC-S-60 respectively, as compared with beams 6SLRC-S-30, 6SLRC-S-45 and 6SLRC-S-60, respectively. On other hand, the deflection of the beams is decreased with increasing of lacing bar diameter by about 21.63%, 54.5% and 15.09% for beams 8SLRC-S-30, 8SLRC-S-45 and 8SLRC-S-60 respectively, with respect to beams 6SLRC-S-30, 6SLRC-S-45 and 6SLRC-S-60,respectively at same load level as shown in **Figures 10, 11 and 12.**

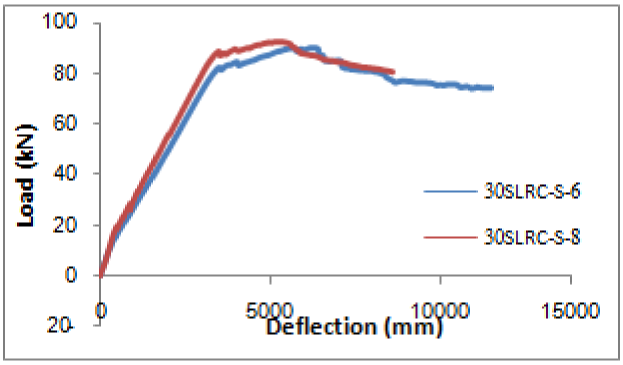

Figure 10: Influence of Lacing Bar diameter on the load-deflection response for beams with inclined angle 30

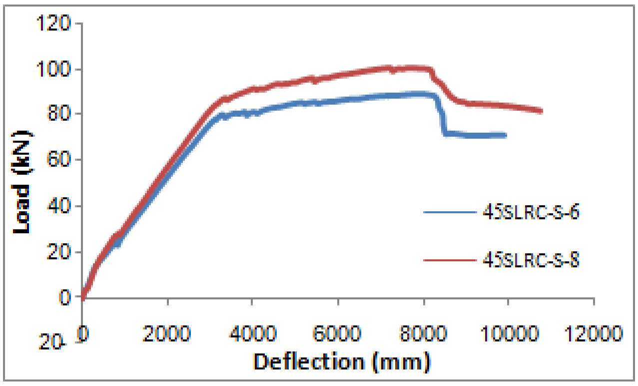

Figure 11: Influence of Lacing Bar diameter on load-deflection response for beams with inclined angle 45

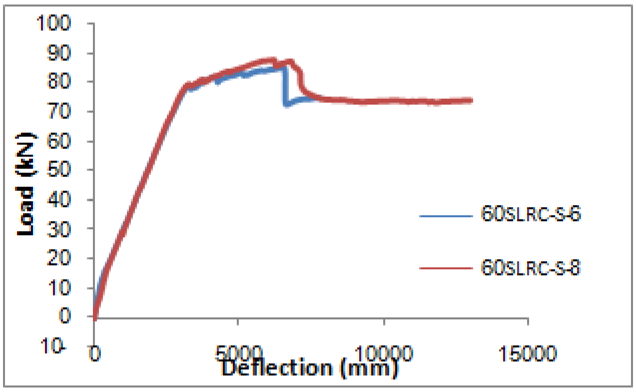

Figure 12: Influence of Lacing Bar diameter on load-deflection response for beams with inclined angle 60

Second, it is observe that the load carrying capacity is increased with using inclined angle of lacing bar (30 and 45) more than 60The percentages of the increasing in the ultimate load are estimated by 5.87%, 4.36%, 4.6%, 14.15% for beams 6SLRC-S-30, 6SLRC-S-45, 8SLRC-S-30 and 8SLRC-S-45, respectively, as compared with beams 6SLRC-S-60 and 8SLRC-S-60 respectively. On other hand, the deflection of the beams become smaller for beams of lacing bar angle between 30 and 45 more than 60 by about 31.72%, 20.55%, 39.36% and 42.99% for beams 6SLRC-S-30, 6SLRC-S-45, 8SLRC-S-30 and 8SLRC-S-45 respectively, with respect to beams 6SLRC-S-60, 8SLRC-S-60,respectively at same load level as shown in **Figures 13 and 14**.

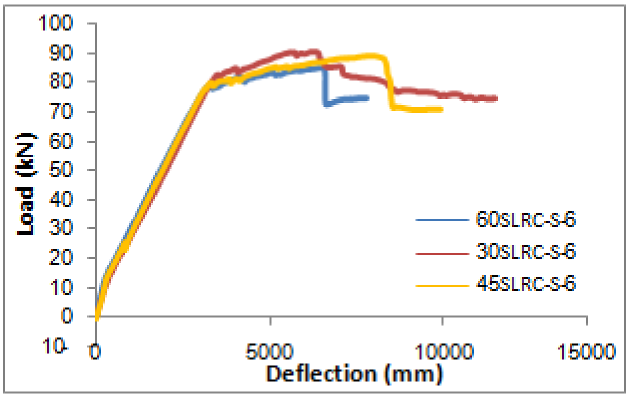

Figure 13: Influence of different Lacing inclined angle on load-deflection response for 6SLRC beams

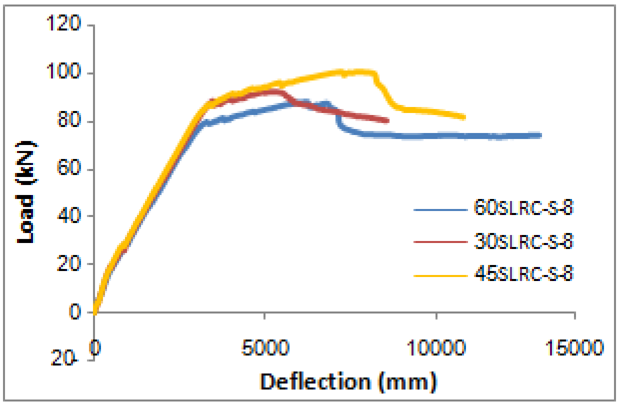

Figure 14: Influence of different Lacing inclined angle on load-deflection response for 8SLRC beams.

Third, from comparing the results of the beams, it is observe that the load carrying capacity is increased with increasing of lacing steel ratio. The percentages of the increasing in the ultimate load are estimated by 9.2%, 6.19%, and 1.09% for beams 6DLRC-S-60, 8DLRC-S-60, and 8DLRC-S-45, respectively, as compared with beams 6SLRC-S-60, 8SLRC-S-60 and 8SLRC-S-45 respectively. On other hand, the deflection of the beams become smaller by about 35.6%, and 31.75% for beams 6DLRC-S-60, 8DLRC-S-60 respectively, with respect to beams 6SLRC-S-60, 8SLRC-S-60, respectively at same load level except beam 8DLRC-S-45, the deflection increased by 111.75% from 8SLRC-S-45 as shown in **Figures 15, 16 and 17**.

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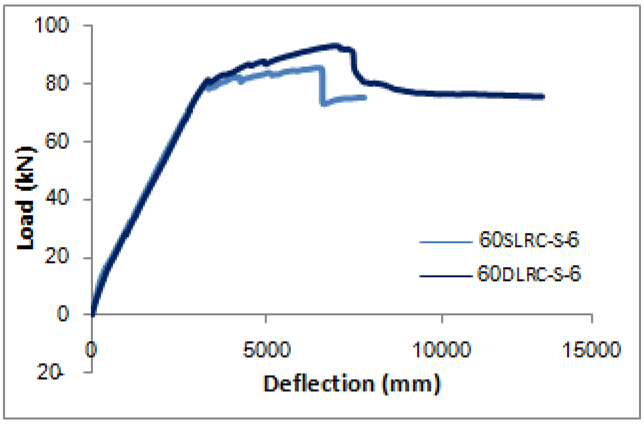

Figure 15: Influence of increasing lacing steel ratio on load-deflection response for beams 6LRC-60

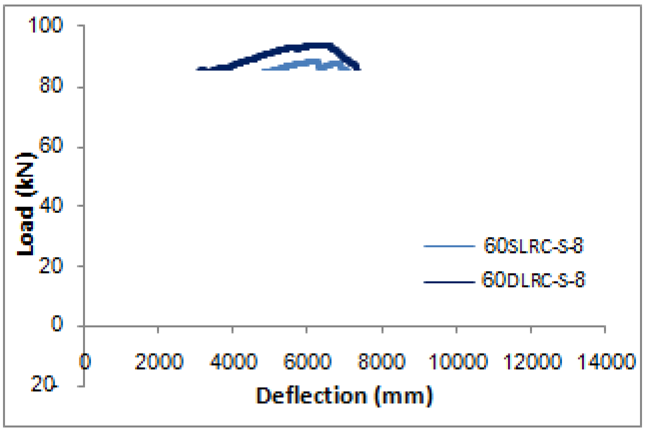

Figure 16: Influence of increasing lacing steel ratio on load-deflection response for beams 8LRC-60

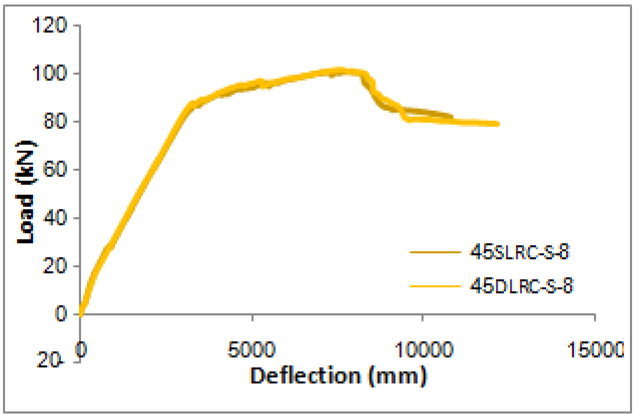

Figure 17: Influence of increasing lacing steel ratio on load-deflection response for beams 8LRC-45

From the results data for beams with minimum lacing steel ratio, it is observe that the load carrying capacity is increased with increasing lacing steel ratio. It is considered by 0.96% for beam 4SLRC-S-60 with respect to 6SLRC-S-30, on other hand, the deflection is decrease for beam with 30° inclined angle and large lacing bar diameter and estimated by 5.5% for beam 6SLRC-S-30 from 4SLRC-S-60 at same load level as shown in **Figure 18**.

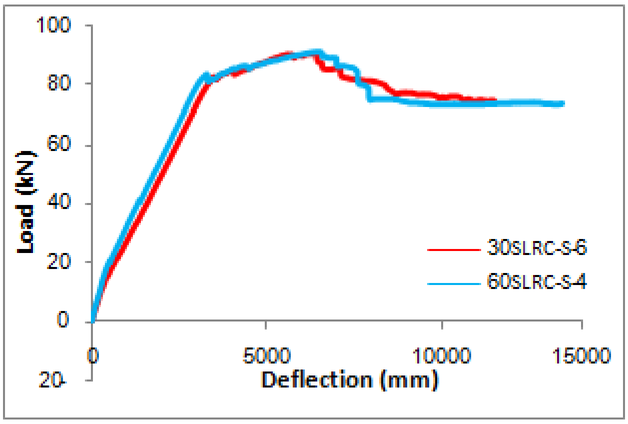

Figure 18: The influence of minimum lacing steel ratio for beams 6SLRC-S-30 and 4SLRC-S-60

6.3 Load- Strain Relations

The load-strain curves for steel reinforcement are recorded to get a clear concept for the response of laced reinforced concrete beams as shown in **Figures 19 and 20.** In this section the performance of strain of tension bar with load is presented.

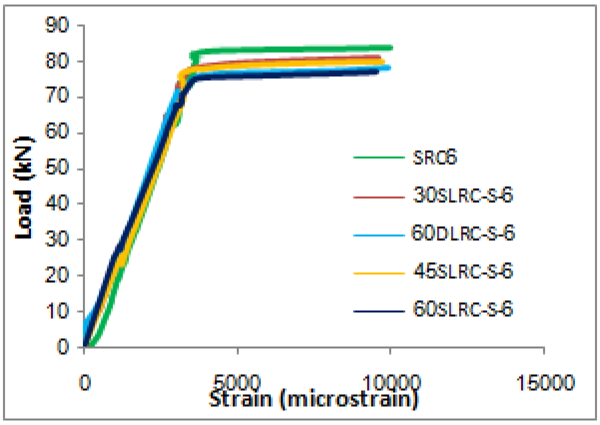

Figure 19: Load–strain response at the Tension steel reinforcement

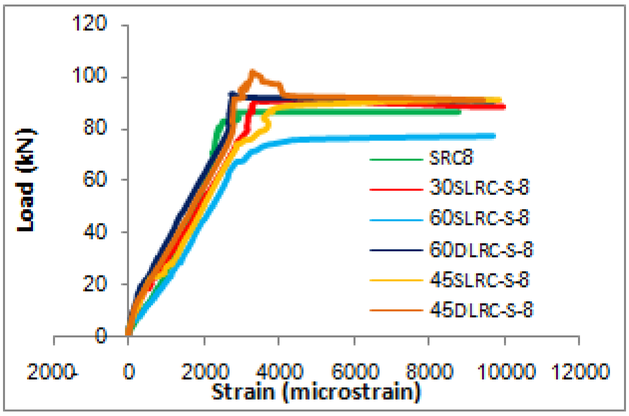

Figure 20: Load–strain response at the Tension steel reinforcement

In general, at service load stages, it is noticed that the flexural reinforcement sill in elastic range and the strainis recorded by about (2790 $\mu\varepsilon$ -2110 $\mu\varepsilon$) accept two beams (6DLRC-S-60 and 6SLRC-S-45), the tension bar is yielded at service load stage. Near the ultimate load limit, the flexural steel reinforcement is yieldedand the strainis recorded by about (7283.8 $\mu\varepsilon$ -9959.03 $\mu\varepsilon$). It is notice clearly that tension reinforced bar resist the yielding with increasing lacing bar diameter in same angle of inclined lacing bar as shown in **Figures21, 22 and 23**andalso this resistant is increased with increasing lacing steel ratio with the kept of same diameter lacing bar and inclined lacing angle as shown in **Figures 24, 25 and 26**.

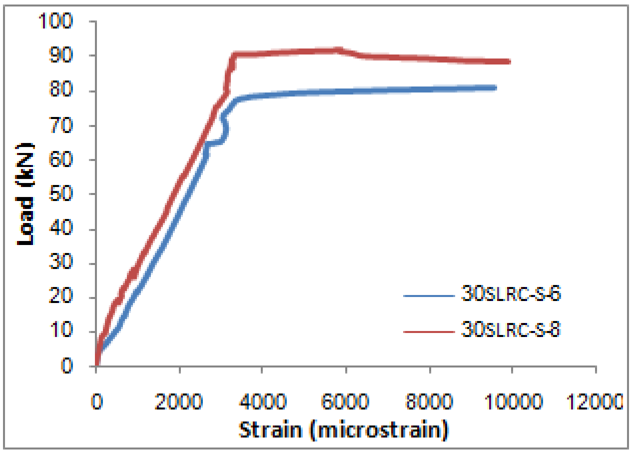

Figure 21: Influence of Lacing Bar diameter on load-strain response for beams with inclined lacing angle 30

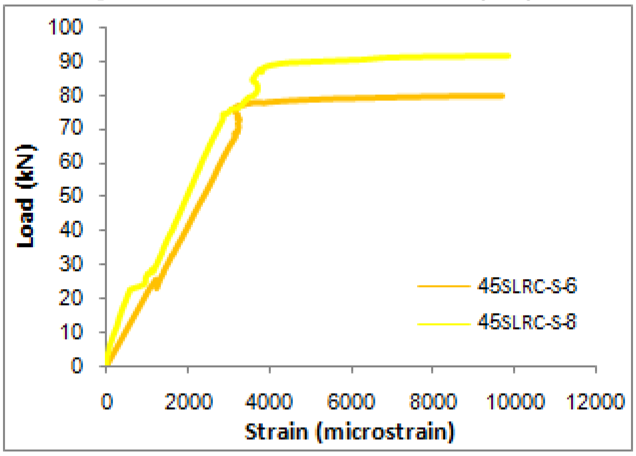

Figure 22: Influence of Lacing Bar diameter on load-strain response for beams with inclined lacing angle 45

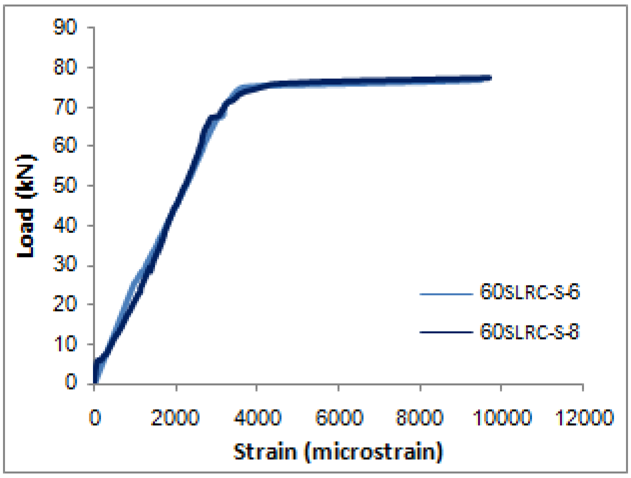

Figure 23: Influence of Lacing Bar diameter on load-strain response for beams with inclined lacing angle 60

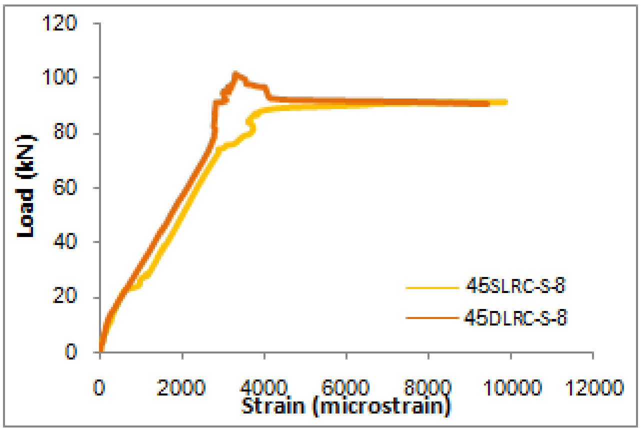

Figure 24: Influence of increasing lacing steel ratio on load-deflection response for beams 8LRC-45

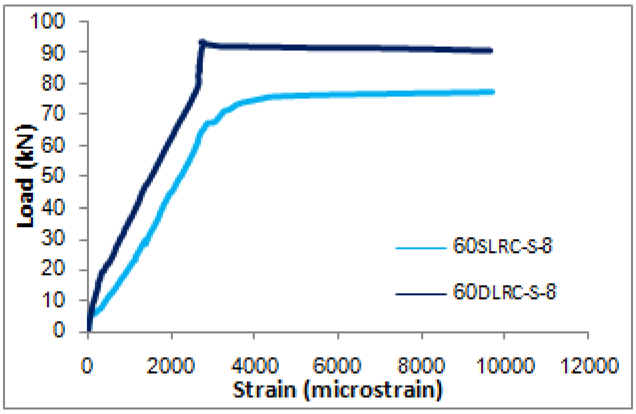

Figure 25: Influence of increasing lacing steel ratio on load-deflection response for beams 8LRC-60

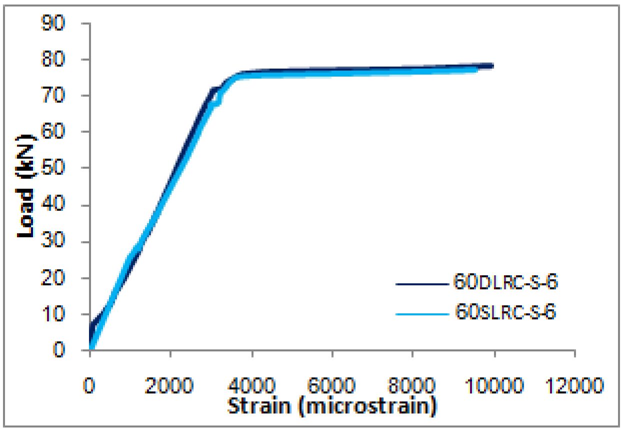

Figure 26: Influence of increasing lacing steel ratio on load-deflection response for beams 6LRC-60.

While the lacing steel bars still within the elastic range except beams 4SLRC-S-60, 6SLRC-S-45 and 8SLRC-S-45 show that the lacing steel bars yielding before failure load as listed in **Table 4**.

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Table 4: Maximum Strain Values in Lacing Steel Reinforcements at Mid-Span.

Location Beam Symbol	Pure Flexure Strain Gauges at Lacing Renf. ($\mu\varepsilon$)	Location Beam Symbol	Pure Flexure Strain Gauges at Lacing Renf. ($\mu\varepsilon$)
6SRC	479.8^T	6DLRC-S-60	969.05^T
8SRC	113.6^T	4SLRC-S-60	2726^T
6SLRC-S-30	1922.133^T	6SLRC-S-45	2280^T
8SLRC-S-30	damage	8SLRC-S-45	2462^T
6SLRC-S-60	866.7^T	8DLRC-S-45	1437^T
8SLRC-S-60	651.6^T	8DLRC-S-60	1416.95^T

7. Conclusions

A series of laboratory tests are carried out on twelve simply supported beams with and without lacing steel reinforcement under static load and concluded as follows:

- The mode failure for all beams is flexural-shear failure mode.
- The first cracking load is increased with using large diameter of lacing bar, and maximum lacing steel ratio.
- The load carrying capacities are increased with using lacing shear reinforcement and also they're increased with increasing of lacing bar diameter, and lacing steel ratio, while the deflection decreases.
- The load carrying capacity is increased with using inclined lacing angle 30 and 45 more than 60, on the other hand the deflection reduces.
- The load-strain behaviors for flexural steel reinforcement are resist the yielding in beams with maximum lacing steel ratio and large diameter of lacing bar as compared to beams with small lacing steel ratio and small diameter of lacing bar.

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