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Civil Engineering Journal

Vol. 5, No. 3, March, 2019

Enhancing the Behavior of One-Way Reinforced Concrete Slabs by Using Laced Reinforcement

Ali Faiq Hallawi [a*], Ali Hussein Ali Al-Ahmed [b]

[a] *University of Baghdad, College of Engineering, Department of Civil Engineering, Baghdad, Iraq.*

[b] *Assistant Professor, University of Baghdad, Collage of Engineering, Department of Civil Engineering, Baghdad, Iraq.*

Received 31 December 2018; Accepted 05 March 2019

Abstract

This paper studies experimentally the behavior of laced reinforced concrete one-way slabs under monotonic load. The experimental program included testing three simply supported one-way slabs of dimensions (1500 mm length, 600 mm width, and thickness 130mm. One of these slabs was the control specimen which was designed without lacing reinforcement steel and the other two specimens designed were with two variable lacing reinforcement ratio (0.27% and 0.52%). All specimens were cast with normal of 22 MPa compressive strength. Specimens were tested under two equal line loads applied at the third parts of the slab (monotonic load) gradually applying up to failure. The specimens showed an enhanced in ultimate load capacity up to 40% as a result of increasing the lacing steel ratio to 0.52 %. Also, decreasing in deflection at service and at ultimate load levels by 42% and %57 respectively. In addition, the results showed that specimen with lacing reinforcement are more ductility than specimen without lacing reinforcement so using of lacing steel reinforcement leads to significant improvements in ductility index which reached to about 49% with increasing the lacing steel ratio to (0.52%).

Keywords: One-Way Slab; Lacings; Ductility Index.

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1. Introduction

In the past two decades, considerable researches have been carried out to study how to increase the ductility levels of structural elements. The ductility and shearing capacity of the traditional Reinforced Concrete (RC) beams were enhanced with the existence of conventional vertical stirrups. However, RC slabs were suffered from flexural-shear cracks under bending [1]. Laced reinforcement was considered as an alternative to traditional stirrups in concrete structural elements to reduces these cracks and enhance the integrity of the structure which exposed to dynamic loads such as blast and earthquake. Moreover, the cost of Laced Reinforced Concrete (LRC) construct technique is higher than conventional stirrups. LRC elements consist of an equal steel reinforcement on both faces (tension and compression) and tied by cross rod with continues inclined reinforcement, which transferring forces and holding the lacing in its position. Lacing bars which are connected to the top and bottom longitudinal reinforcement by the cross rod will be in tension or compression and the resistance to compression is also provided by concrete strut [2]. Lacing bars lets the structural element to give large deflections before failure since the strain hardening region is improved. Laced element allows maximum deflection reach to $12^0$of support rotation; in compared with an element with single leg stirrups which is limited to 6^0 of support rotation, thus the using of laced reinforcement significantly effects in improving the ductility of flexural element [3].

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* Corresponding author: ali.faiq.eng@gmail.com

http://dx.doi.org/10.28991/cej-2019-03091282

The advantages of laced reinforcement system contributions in the structural element are listed in the following points [3]:

- Fully development of the strain hardening zone and ductility of the flexural reinforcement.
- Maintenance of concrete integrity between the flexural reinforcement layers despite a lot of cracking.
- Restriction of compression reinforcement from buckling.
- Controlling the speed and quantity of material fragmentation in post-failure and limited fragmentation after yield range.
- Large support rotation can be obtained than the traditional stirrup reinforced concrete elements.
- High shear resistance rather than conventional stirrup reinforced concrete elements under transient blast loading.
- Structural integrity is also enhanced by using lacings reinforcement.
- Linking the two principal reinforcement mesh together leads to improve the performance of LRC beam in the large–deflection zone

Extensive experimental investigations on (RC) and (LRC) beams were carried out by Parameswaran et al. (1986) [4]. Their results revealed that the angles of support rotations are varied between 3.5^0 to 7^0. The continuous lacing is normally inclined at 45^0 and 60^0 to longitudinal beam axis. The observation of large shear resistance in LRC beams leads to enhance the ultimate load capacity and the ductility of flexure element than the conventional beam that design without lacing steel reinforcement.

Numerical studies are approved by Thirumalaiselvi et al. (2014), on laced steel concrete composite (LSCC) slabs exposed to blast load by using finite element method which is adopted by ABAQUS computer program. Parametric studies were carried out on LSCC slab by changing steel plates thickness, concrete grade, diameter of lacing bars and cross rod to study their effect on the behavior of slabs exposed to blast loading. The results revealed that plate thickness is significantly effects the response of LSCC slabs than the diameter of the cross rod and lacing bar for same concrete grade used in the analysis. From the numerical analysis results. It conclude that the LSCC slab has great potential applications in the design of blast resistant structures [5].

Akshaya et al. (2015) presented experimental investigations on (LSCC) beams and fiber laced steel-concrete (FLSCC) beams under monotonic and reverse cyclic loads. The results showed that the FLSCC beams are higher load carrying capacity and ductility than the LSCC beams. Also, the ultimate load of LSCC was higher than of RC beams by about 22% [6].

Allawi and Jabir (2016), studied the behavior of nine simply supported (LRC) one-way slabs subjected to static load up to failure. From the results it indicated that using of lacing steel ratio of 0.65% lead to increase the load carrying capacity about 57% compared with slab without lacing reinforcement .And also, it is increased by 104% when reducing the span to depth ratio by 31.25%. Analytical study was provided for static and repeated loading specimens through using of ANSYS computer program, the results show a good agreement with experimental results with difference of 7% [7].

1.1. Ductility index

Ductility is known as the member's ability to deform without obvious loss of its strength. Using the ductility factor method to determine the amount of ductility was expressed by the ultimate to the yield deflection ratio [7]. One of the methods that used in expression of ductility index is the displacement ductility factor (μ). Which is defined by Equation 1.

$$\mu = \frac{\Delta_u}{\Delta_y} \tag{1}$$

Where:

Δ_u: Mid span deflection at ultimate load.

Δ_y: Mid span deflection when yield is first reached.

According to previous studies, there is limited studied on LRC structures. Most of these studies focuses on studying the structural behavior of such beams under static load or one- way slab under blast and impact load. So, this paper is aim to study experimentally the behavior of LRC one-way slabs subject to monotonic load up to failure in terms of cracking, load-deflection and ductility index.

2. Research Methodology

To know the effectiveness of using laced reinforcement on the behavior of one- way RC slabs. Also, a better understanding of the contributions of the laced reinforcement which allow designers to compare the benefits of using (or not using) laced reinforcement. So that, the monotonic response of laced one- way RC slabs under four-point bending test is experimentally studied in this paper. The tests is focused on the influence using of variable lacing reinforcement ratios.

3. Mechanical Properties of Materials

The materials used in the experiments of test in this study are described as below:

3.1. Concrete

Ordinary Portland cement (Type I) was used. This cement was tested chemically and physically and are complying with the ASTM C150 for Portland cement [8]. Coarse aggregate (crushed gravel) with a maximum size of 10 mm is used. While, natural sand brought from Badra region (Iraqi city) was used in concrete mix after drying out and sieve analysis is made according to ASTM C33 [9]. In order to improve certain properties. All specimens were cast by a trick mixer to give a normal density concrete with average cylindrical strength of 22 MPa.

3.2. Steel Reinforcement

All steel rebars used in the experimental part of this research were new and deformed. The size of steel bars, yield stress are 6mm and 720 MPa respectively. The modulus of elasticity for all steel reinforcement is assumed to be (Es = 200000 MPa). Same steel bar diameter is used for lacing reinforcement. The lacing configurations angle of 45°were selected in order to achieve a correct bending according to the requirements of the UFC 3-340-02, (2010) [3], which states that the bending diameter is four times the diameter of the bar table with simple element using as shown in Figures (1and 2).

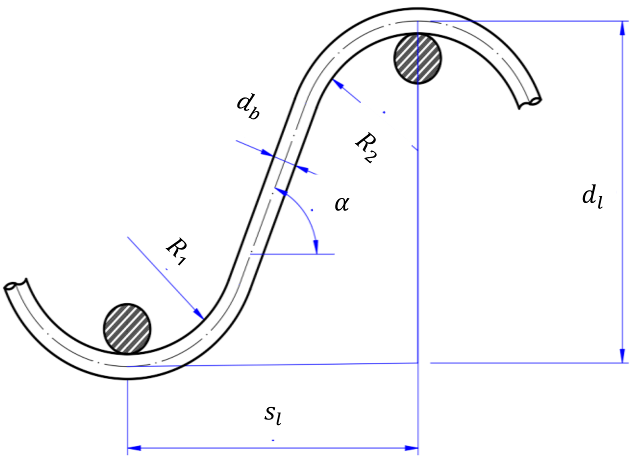


Figure 1. Lacing bar details [3]

Where;

d_b= diameter lacing bars ,R_1, R_2= bending radius , α=angle of lacing bar ,s_l=spacing of lacing in the direction parallel to the main reinforcement,d_l=distance between center lines of adjacent lacing bends measured normal to flexural reinforcement.

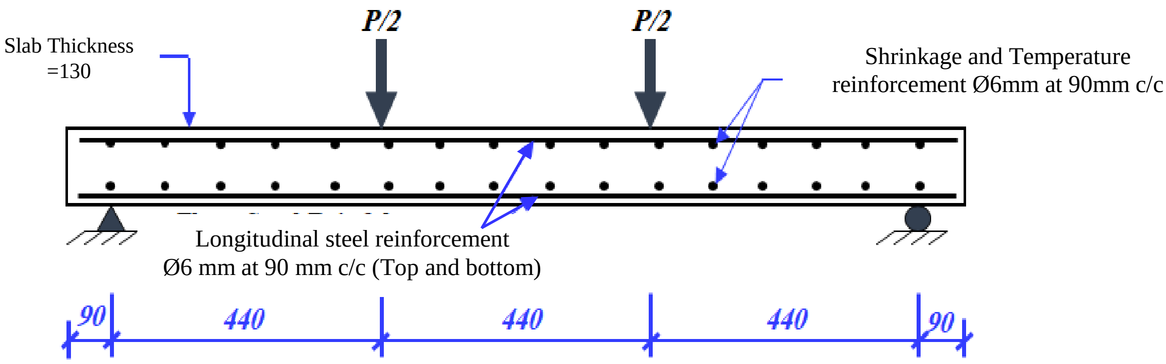
Figure 2. Photograph of Lacing Bars Fabrication

4. Test Specimens

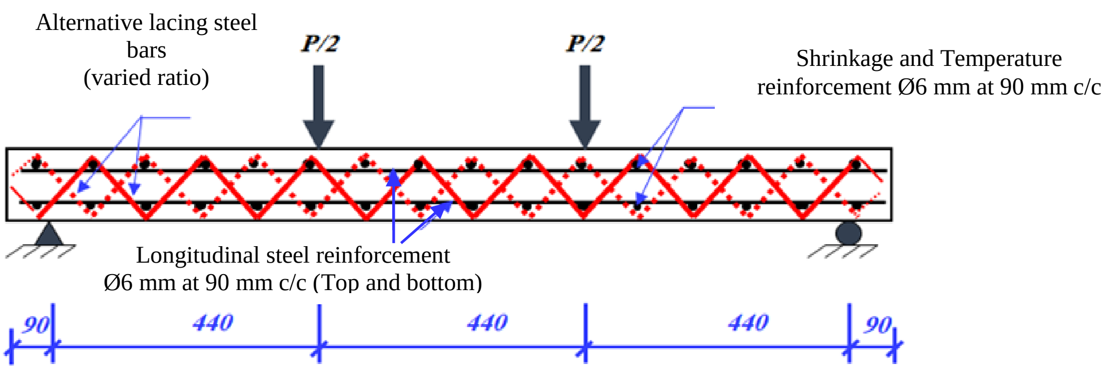
Three slabs were designed to reflect the interaction of the lacing bars with the other primary parameters. All slabs were designed to be simply supported conditions. The dimensions and steel reinforcement were selected according to ACI 318M-2014 [10] Code, and to satisfy and meeting with the UFC 3-340-02, 2010 [3] requirements for the laced reinforced concrete structures. All specimens having were the dimensions of 1500 mm length, 600 mm width and 130 mm thickness with clear span of 1320 mm. The test variable is the ratio of lacing reinforcement steel (0.27%and 0.52%). Constant ratio of flexural reinforcement ratio of 0.31% is adopted for all specimens and the reference specimen is designed without lacing reinforcement. The cover of concrete of all specimens was 20 mm, so the effective depth was 107 mm as shown in Figure 3. Table 1 show the details of tested specimens. All specimens were cast by the trick mixer to give a normal density concrete with average compressive Strength of 22 MPa.

Table 1. Details of test specimens

Specimens designation	Lacing steel spacing and designation	Ratio of lacing steel bars	Flexural longitudinal steel spacing and designation	Ratio of flexural steel reinforcement
0-S	0	0	7Ø6mm at 90mm c/c	0.31%
5-S	5Ø6mm at 114mm c/c	0.27%	7Ø6mm at 90mm c/c	0.31%
9-S	9Ø6mm at 60mm c/c	0.52%	7Ø6mm at 90mm c/c	0.31%



(a) Specimen (0-S) (control specimen) (without lacing reinforcement)



(b) Specimens (5-S) and (9-S) (with lacing reinforcement)

Figure 3. Details of the test specimens (all dimension are in mm)

4.1. Instrumentation

The instrumentations used during the experimental test are strain gauges and LVDTs (Linear variable differential transformer). While strain gauges used for both steel and concrete are foil strain gauges of (120 Ω) resistance from TML Japan. Two strain gauges are located at both tension and compression faces at mid-span of the specimens to measuring the tensile and compressive train at these locations respectively. While one strain gauge is used to measure the strain in longitudinal bottom steel bar as shown in Figure 4. In addition, three LVDTs were used to measure the deflection at mid-span and at two-thirds part of the tested slabs. The research includes measuring the strain in steel reinforcement and deflection of specimens connected to data logger. An Australia data logger DT85 smart model was model number DTBSG and serial number of 100777 is used as shown in Figure 5. While, Figure6 shows the testing machine with specimens and other instruments that used in the test.

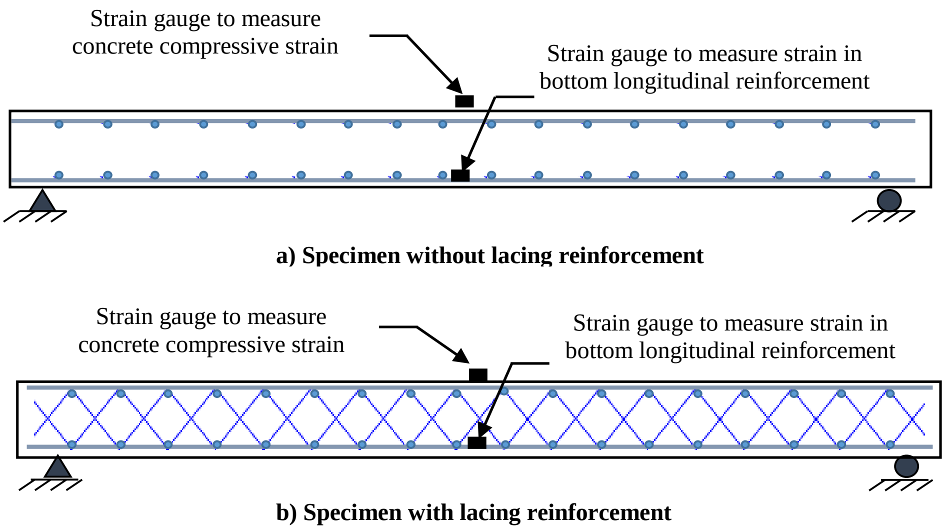


Figure 4. Location of the strain gauges used in the experimental test

Figure 5. Photograph for Data Logger

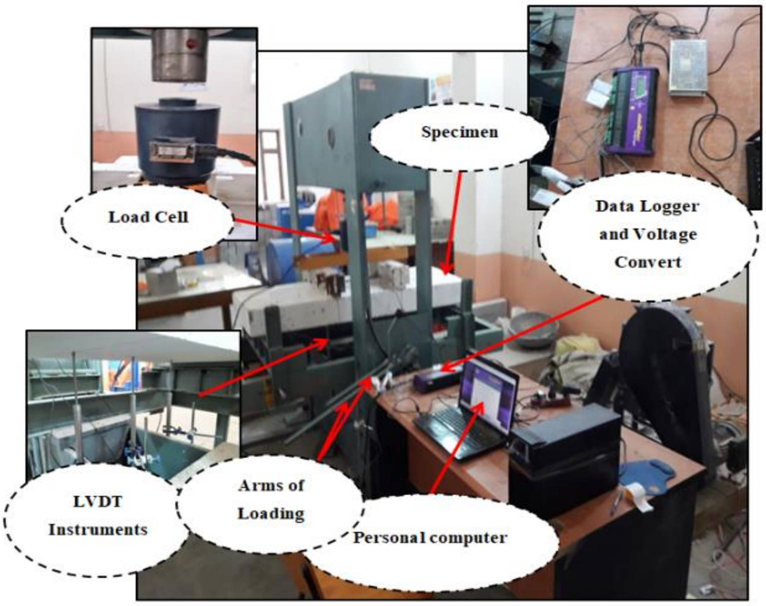


Figure 6. Setup of a typical tested slab

5. Test Procedure

All specimens were tested up to failure by using hydraulic testing machine as shown in Figure 7. Four point bending test (i.e. two line load) were adopted to give more indication about the behavior of the specimens under testing as shown in Figure 8. The one-way slabs were restrained as simply supported with a clear span of 1320 mm. Hydraulic jack with 500 KN capacity is used to apply a gradually load until failure of specimens. The load of hydraulic jack transfer to two line load by I-section beam with suffusion to amount of stiffeners were positioned under the load cell. Finally, the load cell and the LVDTs tools were connected to a data-logger that was connected to computer and set to read results at each second during testing time.

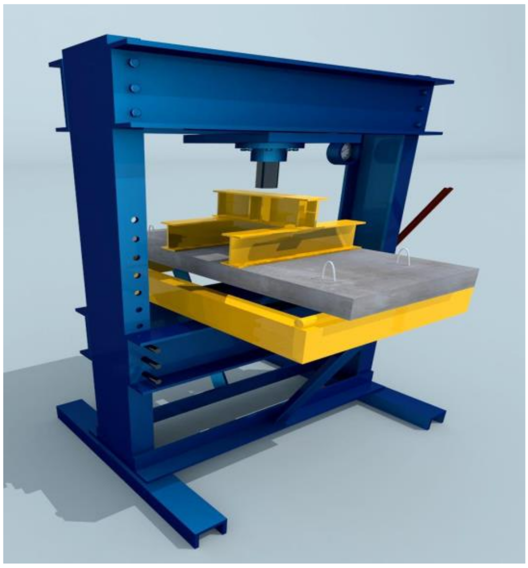


Figure 7. Hydraulic testing machine

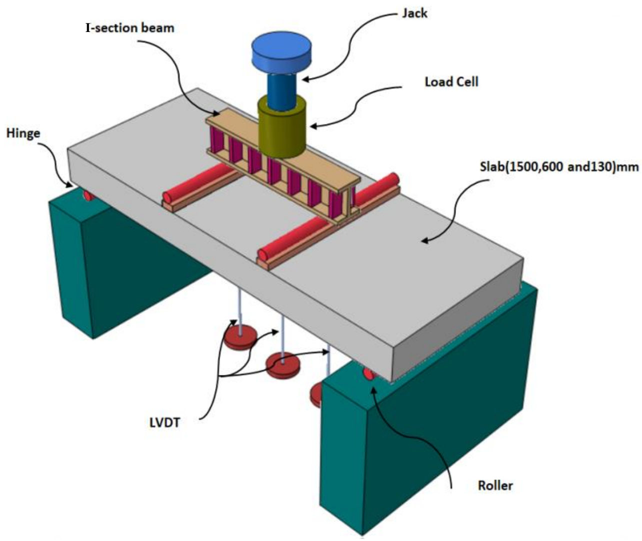


Figure 8. Test set up

6. Experimental Results

6.1. First Cracking and Ultimate Load Capacities

The experimental results of first cracking and ultimate loads for the three specimens are summarizes in Table 2. The initial cracks for the three specimens were ranged between of (14.5-21) kN and it occurred at a load range of (29.9%-33.2%) of their ultimate load capacities. The first initial cracks appeared at the middle third of the span where the maximum moment occurred at the bottom face of slabs where tension stress is maximum. According to Table 2, the first crack (flexural) for control one-way slab 0-S occurred at load (14.5) kN. While, for specimen with of 0.27% lacing ratio (specimen 5-S) the first cracking load is increased to18.6 kN. For specimen 9-S (i.e., lacing ratio=0.52%) the first cracking load is 21 kN. So that increasing the ratio of lacing reinforcement leads to improve the resistance of the specimens for cracking. The percentage increasing in first cracking leads with respect to control specimens is (28.3% and 44.8%) for slabs 5-S and 9-S respectively.

When the load was increased, the first initial crack for specimens growth slowly across the width of slabs and many cracks accrued and developed at this region. It noticed that when increasing the load for specimen 0-S the cracks separated and kept to develop across the width of the slab and slowly propagated throughout the thickness of the slab until the plastic hinge occurred. While, specimens 5-S and 9-S showed that the cracks at the tension face needed more load to occur the plastic hinge and these cracks were curved and connected to gather at bottom tension face .Also when the load was increased, cracks for side face of the specimens with lacing reinforcement were curved and connected through the slab thickness .Figures 9 and 10 show the cracks pattern for both bottom and side face of the tested specimens.

Also it is clear from Table 2 that the load capacity (ultimate load) for the control is equal to 48.5 kN. While, using lacing reinforcement of 0.27% and 0.52% (specimens 5-S and 9-S) the ultimate loads were 56kN and 68kN respectively. So that a good enhancement in the ultimate load capacity of 15.5% and 40.2% is occurred due to using lacing ratio of (0.27% and 0.52%) respectively compared to solid slab without lacing reinforcement.

Table 2. Cracking and ultimate loads of specimens

Specimens	%Lacing ratio (ρ_s)	First cracking load (P_{cr}) (kN)	% Increases in first cracking load	Ultimate load(P_u) (kN)	% Increases in ultimate load	$(P_{cr}/P_u)\times 100$
0-S	0.0	14.5	Ref.	48.5	Ref.	29.9
5-S	0.27	18.6	28.27	56.0	15.46	33.21
9-S	0.52	21.0	44.83	68.0	40.21	30.88

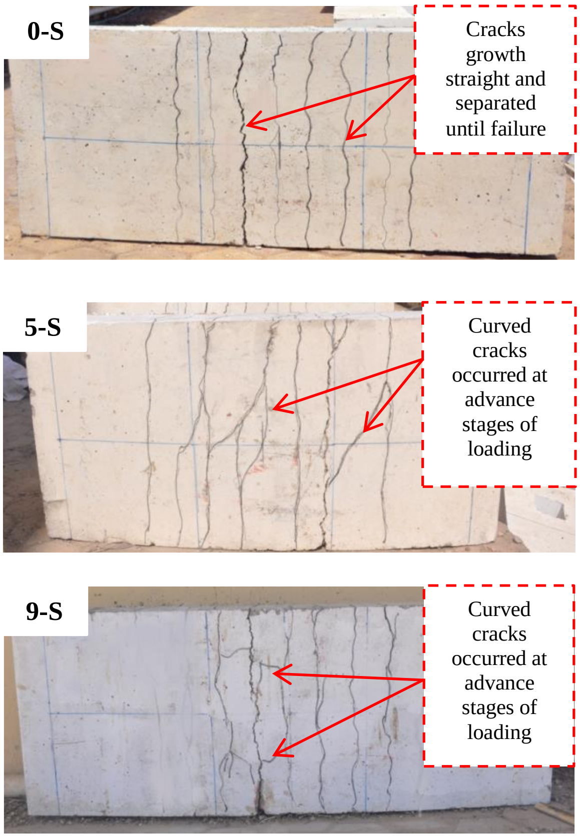


Figure 10. Cracks pattern for tension face of specimens

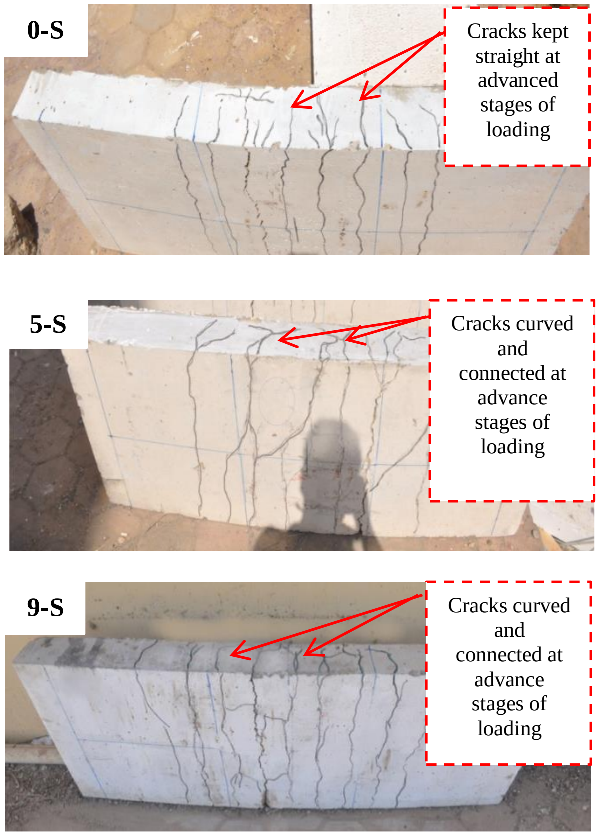


Figure11. Cracks pattern for side face of specimens

6.2. Load-Deflection Response

Vertical deflection is measured at the middle of the specimens by using LVDT instruments and data logger that set up to record the deflection and load every one second during the load test. The behavior of specimens with lacing reinforcement are compared with the control specimen at two load stages.

Stage one: Service load stage .It worth to mention that the limit of the service load is about (70-75%) of the maximum load according to Tan and Zhao, (2004) [11]. So that the service load is taken, as 70% of the peak load of control specimen (0-S). The influence of using lacing steel bars on the reducing the deflection at service load is relatively adequate where the reduction in deflection is 21.8% and 41.8% for specimens 5-S and 9-S respectively compared with the control specimen **0-S** at same load level of the control specimens.

Stage two: Ultimate load stage, when load was increased, the deflection increases rapidly after initiation of first crack and when the cracks developed, the deflection keeps to raise without an appreciable increment in load until failure as showed in Figure 12.

Using of lacing reinforcement for enhancing one –way slabs reduces the deflection corresponding to ultimate load level of the control specimen about 43.3% for specimen 5-S and 56.7% for specimen 9-S in comparison with the reference slabs Table3 summaries the results of the central deflection of specimens at service load and ultimate load stages.

Table 3. Central deflections of specimens at service and ultimate load stages

Specimens	%Lacing ratio (ρ_s)	Deflection at service load level of the control specimen (mm)	%Decreasing in deflection at service load level of the control specimen	Deflection at ultimate load (mm)	Deflection at ultimate load level of the control specimen (mm)	%Decreasing in deflection at ultimate load of the control specimen
0-S	0.0	5.5	Ref.	15.0	15.0	Ref.
5-S	0.27	4.3	21.8	20.0	8.5	43.3
9-S	0.52	3.2	41.8	24.0	6.5	56.7

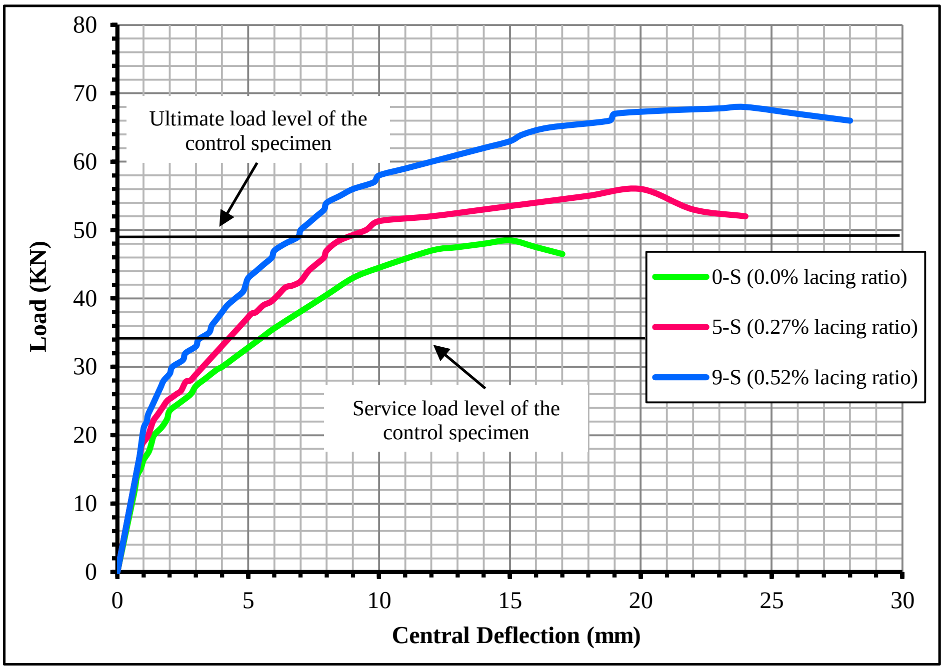


Figure 12. Load-Central deflection response for tested slabs

6.3. Load-Strain for Steels and Concrete

During applying load, the data logger record the measurement of strain in concrete and in main steel bars every one second of time escape .According to Figure.13, the strain in main steel bar for each specimen is plotted. It could be noticed that the effect of lacing reinforcement for reducing the strain of the flexural reinforcement especially when the flexure reinforcement exceed the yielding (i.e., plastic region) is sufficient. Furthermore, increasing the lacing ratio showed more reduction in main steel bar strain because the lacing reinforcement in tension zone would cooperate with main reinforcement.

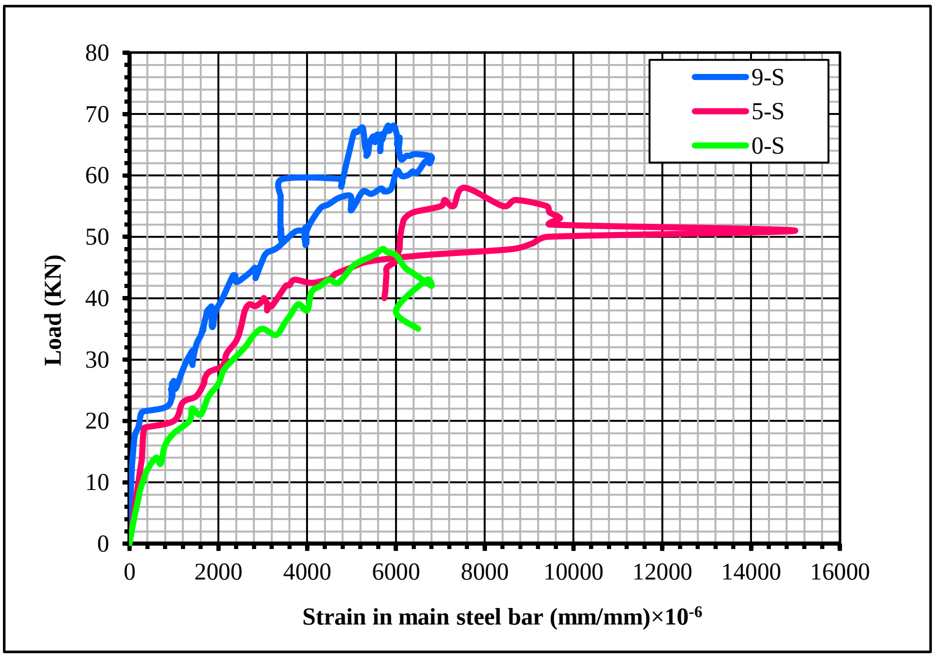


Figure 13. Load -Strain curves for tension steel reinforcement at mid-span

While, the concrete strain at compression face of the specimens is shown in Figure 14. This figure reveals that both of specimens 0-S and 5-S not reached the maximum compressive strain. While, specimen 9-S reached the concrete maximum strain. The maximum concrete compressive strain at the top surface was recorded as (1410) microstrain at ultimate load of specimen 0-S. While specimens 5-S and 9-S recorded (1900) and (3016) microstrain at ultimate load.

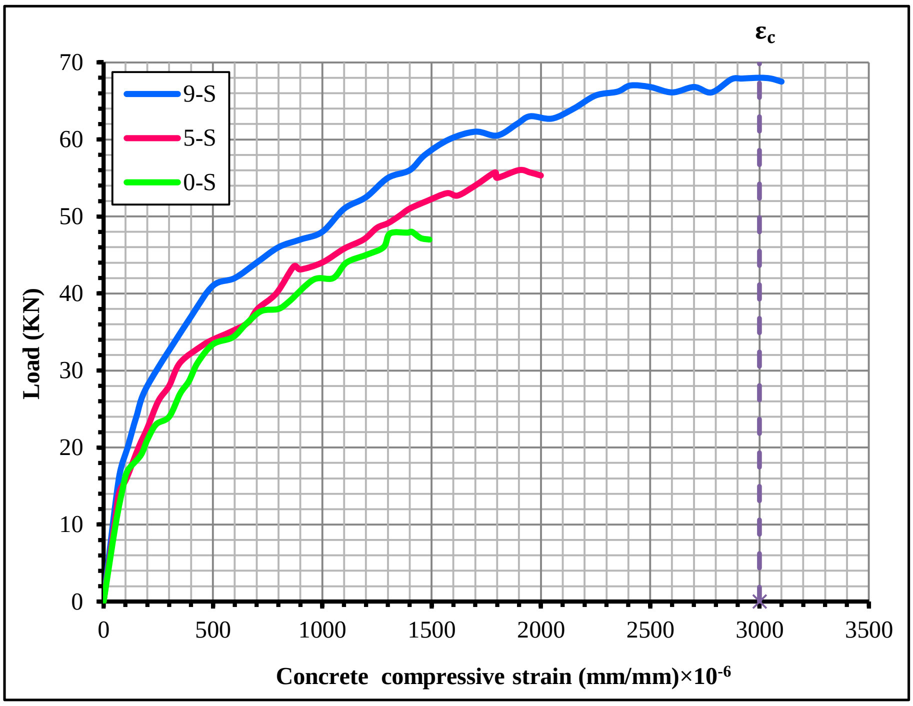


Figure 14. Load-strain curves for compression surface of specimens

6.4. Ductility Index

As mentioned before, the ductility index (μ) is calculated by divided the deflection at ultimate load to the deflection at first yielding of tension steel reinforcement. It is important to remember that the deflection at yielding of steel reinforcement can be measured from the curves plotted in the previous section .It could be noticed that ductility index increases as the ratio of lacing reinforcement increases compared with the specimen without acing reinforcement by 33.0% and 49.1% for specimens **5-S** and **9-S** respectively . All experiment of data used for calculating the ductility index is summarised in Table 4. Figure 15 shows how the ductility index increases with the increase of lacing reinforcement ratio.

Table 4. Ductility index of specimens

Specimens designation	Ultimate load (KN)	Deflection at ultimate load (mm)	Load (KN) at yielding of steel reinforcement	Deflection at yield load (mm)	Ductility index (μ)	% Increasing in ductility index
0-S	48.5	15	37	6.5	2.30	Ref.
5-S	56	20	42	6.7	3.06	33.0
9-S	68	24	49	7	3.43	49.1

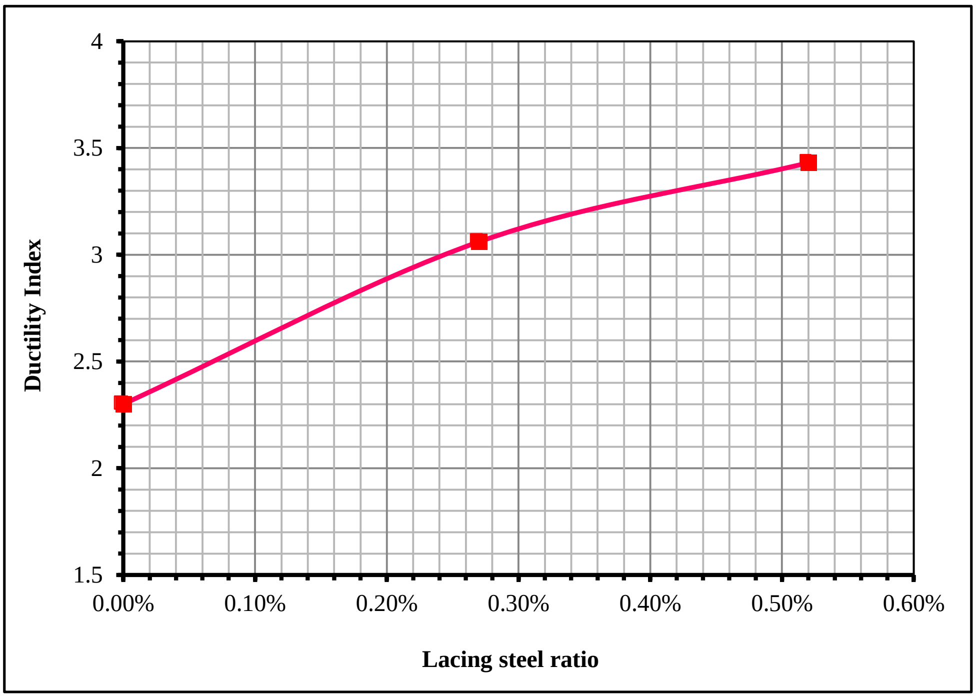


Figure 15. Ductility index versus lacing steel ratio

7. Conclusions

The conclusions based upon the results of the experimental test of solid slabs with or without lacing reinforcements under monotonic load are presented in this section.

- All tested specimen failed in flexural mode by reaching the reinforcement to its yield point.
- Increasing the ratio of lacing reinforcement lead to improve the resistance of the specimens for cracking by about (28% and 45%)for lacing ratios (0.27% and 0.52%) respectively compared with the specimen without lacing reinforcement.
- Using lacing steel bars for enhancing solid RC one-way slabs causes an increase in ultimate load capacity by about (16% and 40%) for lacing reinforcement ratios (0.27% and 0.52%) respectively compared with the control specimen. Also, reducing the deflection at ultimate load level of the control specimen by about 43% and 57% and at service load level by about 22% and 42% for same lacing ratios.
- The ductility index is increased with increasing the ratio of lacing reinforcement by about 33% and 49% for lacing ratio 0.27% and 0.52% respectively.

8. Acknowledgement

The authors wish to thank the University of Baghdad/Iraq for offering the financial support to complete this research and for the help to do the experimental test in the concrete laboratory at the Civil Engineering Department.

9. Conflicts of Interest

The authors declare no conflict of interest.

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