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Response of Laced Reinforced Concrete Beams to Fatigue Loading

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Abstract: ***In this paper, experimental investigation of laced reinforced concrete beams (LRC) under fatigue loading is produced. Six simply supported beams are subjected to highloading frequency(10 Hz) with displacement control to study the effect of lacing reinforcement on the fatigue performance of LRC beams. Three parameters are used in fatigue test, which are: lacing bar diameter (6mm and 8mm), lacing bar inclination to beam axis (30, 45 and 60), and lacing steel ratio. Mid-span deflections for LRC beams are compared. From comparison results, it is observed that the deflection is decreased with increasing of lacing bar diameter, lacing bar inclination and lacing steel ratio.***

Keywords: RC beam**,** laced reinforcement, fatigue 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].**

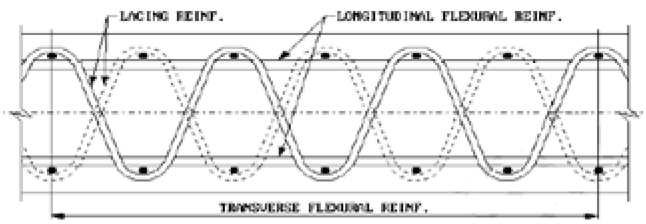

Figure 1: Lacing Reinforcement, [1]

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]**. **Lakshmanan et al [3]** proposed a mathematical model to calculate the support failure rotation of twenty six reinforced concrete beams. Their results indicated that the major failure mode is the rupture of tension steel bar and others failed by buckling of compression steel bar. Some of beams exposed to reversed cyclic loads and it was failed by buckling of the compression steel bar under negative loads. **Rao, P. S. et al. [4]** introduced experimental investigation of twenty three cantilever reinforced concrete beams with different form of lacing with or without steel fiber under monotonic and reversed cyclic load. Their results revealed that the beams with inclined shear reinforcement bars response better rather than other forms of shear reinforcement. The behavior of lacing reinforcement concrete beams with or without steel fiber under negative and positive cyclic shear loading introduced by **Lakshmanan et al. [5]**. Their results showed that the shear response was improved and increased by adding steel fiber and also found that the ductility of laced reinforced concrete beams under cyclic loading is lower rather than those under static loading. **Anandavlli, N. [6]** investigated the response of laced steel concrete composite (LSCC) beams with45°, *and* 60°inclination of lacing bar to horizontal under monotonic and reversed cyclic loads. The results of tested beams showed that the LSCC technique prevent the concrete spallation and fragmentation. And found that the energy absorption during the first cycle was more than the second and third cycles.

Number of authors studies the behavior of reinforced concrete elements under fatigue loads. Many factors affected on fatigue strength of concrete such as loading range and rate, history of load and material properties which can be found in **ACI Committee 215 [7]**. Fatigue of material defines as an internal change of materials properties as a result of exposure to frequent loading until failure. Fatigue of concrete has occurred when concrete gets larger strain and micro cracking appearance more than under static load and fatigue of reinforcement steel bar define as the appearance of fatigue crack at the long side especially at the connection area with one of stirrups (transverse lugs), **ACI Committee 215 [7].**Previous studies mentioned that the failure of reinforced concrete beams under fatigue loading was not always the same as the failure mechanism of such beam under static loading **[8]**. Graf O. and Brenner, E. **[9]** and **[10]**studied the effect of loading frequency on the fatigue life, their results showed that the fatigue life slightly effected by loading frequency range between (4.5Hz-7.5Hz). Moreover, they recorded that the fatigue life of such beams was decreased when the frequency was lower than 0.16Hz. Other researchers **[7]** and **[11]** recorded that the fatigue life was simply effected by loading frequency range between (1Hz-15Hz) with maximum stress level less than 75% of the static compressive strength (f_c'). This paper investigated the influence of high loading frequency (10Hz) with lower stress level on the behavior of laced reinforced concrete beams.

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 (lacing bar) under fatigue load. The experimental behavior of laced reinforced concrete (LRC) beams under four point's fatigue loading with high frequency is studied.

3. Test Beams

The study focused on the influence of different bar diameter, inclined angle with longitudinal axis and lacing steel ratio. All beams were designed according to **ACI 318 M-code[12]**, and meeting with **UFC 3-340-02, [1]**, requirements for the laced reinforced concrete structures. Details of the tested LRC beams are described hereafter. The cross section dimensions are $(160mm \times 300mm)$ and 3000mm in length. Six beams are used to study the influence of various bar diameter, inclined angle and lacing steel ratio as shown in **Figures 2 to 4**. All beams (6SLRC-F-30°, 8SLRC-F-30°, 6SLRC-F-45°, 8SLRC-F-45°, 6SLRC-F-60°, 8SLRC-F-60°) are tested under high fatigue load. The beam symbols can be defined as follows. The first symbol announce to lacing bar diameter, the second denote to type of shear reinforcement (single lacing reinforcement in lacing reinforced concrete beam), the third symbol after slash indicate loading type (fatigue load), and final symbol announce to the angle of inclined lacing bar with beam axis. The details of tested beam are listed in **Table 1**. The steel reinforcement properties are: Ø16mm steel bars are used for compression and tension reinforcement, $[f_y = 564.147\ Mpa]$, Ø10mm steel bars are used for cross bars, $[f_y = 562.7\ Mpa]$, $\emptyset 8\ mm, \emptyset 6\ mm\ and\ \emptyset 4mm$ 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 were constructed using a normal per-casting concrete with a compressive strength of 39.225Mpa and tensile strength 3.6Mpa at 28 days.

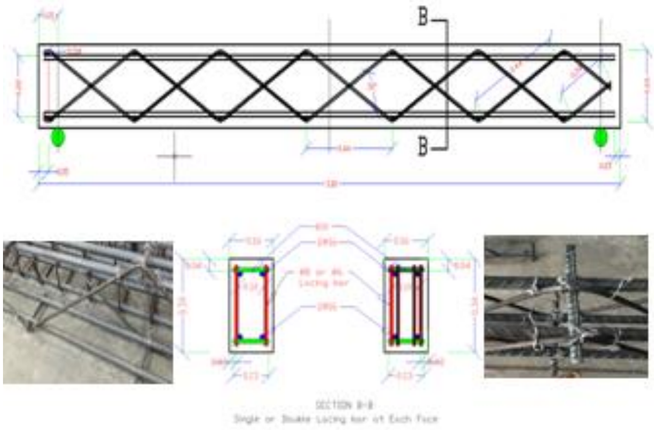

Figure 2: Laced Reinforced Concrete Beams with 30 Laced inclined angle to Horizontal

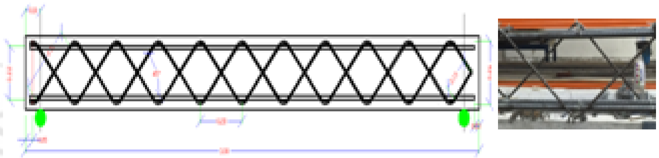

Figure 3: Laced Reinforced Concrete Beams with (6mm or 8mm) Lacing Bar and 45° Inclined Angle to Horizantal

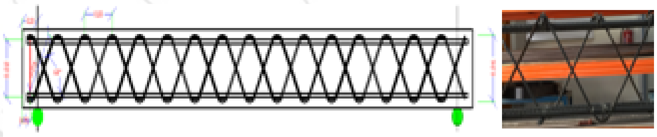

Figure 4: Laced Reinforced Concrete Beams with (6mm or 8mm) Lacing Bar and 60° Inclined Angle to Horizantal

Table 1: Parameters of Six Reinforced Concrete Beams under Fatigue Loading

Beam symbols	Ratio of lacing reinforcement			Diameter of Lacing Bar (mm)
	Angle of inclined lacing bar to horizontal			
	30°	45°	60°	
6SLRC-F-30	0.00124	-	-	6
8SLRC-F-30	0.00219	-	-	8
6SLRC-F-60	-	-	0.00302	6
8SLRC-F-60	-	-	0.00537	8
6SLRC-F-45	-	0.00194	-	6
8SLRC-F-45	-	0.00345	-	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 load is applied at four points of the beam as shown in **Plate 1**. The two supports are rollers types to ensure that the fatigue load is evenly applied during fatigue test, **Papakonstantinou, C.G. [13]**.Constant amplitude fatigue loading tests forsix beams are conducted in two stages. First, at the first cycle, a preload is applied until the required maximum cycle load (P_{Max}) is reached and stopped manually. Then sine signal fatigue loading is used as shown in **Figure 5**. High cyclic loading (10 Hz) is used by imposed displacement control with lower stress level, this process lead to consuming time and the stress-strain relationship for the material will be within the elastic range, the maximum load should be less than the yield load within the elastic range. The fatigue test parameters are fatigue life limit N_f, maximum cycle load (P_{Max}), minimum cycle load (P_{Min}), mean fatigue load(P_m), amplitude fatigue load (P_a), fatigue load range (P_r), load ratio (R), maximum stress (σ_{max}), minimum stress (σ_{min}) and stress range (σ_r).**Table 2** illustrated the loading parameters of high cyclic frequency.At specified cycle, the deflection, load and strain in steel reinforcements (flexural and lacing bars) are recorded and the cracks are marked carefully.

Plate1: Simply Supported Beams under Fatigue loading.

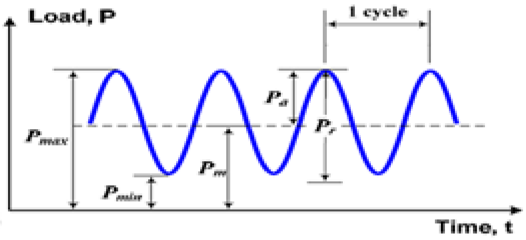

Figure 5: The Parameters of Cyclic loading.

Table 2: Fatigue Loading Parameters

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
N_f	2×10^6 Cycles	P_m	19 kN	R	0.8	σ_r	1.68 Mpa
P_{Max}	21 kN	P_a	2 kN	σ_{max}	8.85 Mpa		
P_{Min}	17 kN	P_r	4 kN	σ_{min}	7.15 Mpa		

6. Test Results and Discussion

6.1 Crack Patterns

A few cracks are appeared at mid span in the tension zone. Failure did not occurred in all tested laced reinforced concrete beams and these beams are remained within the elastic range; this is because the stress range in each cycle did not exceed the tensile strength limit of the concrete,**Rabbat, B.G. et al. [14]**. The shape of the cracks is parallel and vertical along the depth of beams at mid span.**Plates 2-a** to**2-f** shows the crack pattern of the tested beams.

a: Beam 6SLRC-F-30. b: Beam 8SLRC-S-30.

c: Beam 6SLRC-F-45. d:Beam 8SLRC-S-45.

e: Beam 6SLRC-F-60. f: Beam 8SLRC-F-60.

Plate 2: The Cracks Pattern of the Tested Beams**.**

6.2 Load-Deflection and Mid Span Deflection- Cycle Responses

The load-deflection and mid-span deflection curves of six beams at identified number of cycles (N= 10^3,10^4,10^5,10^6 and 2×10^6) are recorded and drawn in **Figures 6** to **11**. At the first stage of load-deflection curves, the slope of the ascending curve is changed until it is reached the maximum cycle load (P_{Max}). The ascending curve is taken this slope because of the applied load is exceeded the cracking load. For the rest cycles, straight lines with minimum slope and additional deflection are formed due to the fatigue loading. The response of mid-span deflections is divided in two stages appears in progress of deflection. First stage, the deflection for all beams still a constant before 10 cycles except beam 6SLRC-F-30; the deflection remains a constant before 10^3 cycles. Second stage, the deflection is increased gradually up to 2×10^6 cycles.

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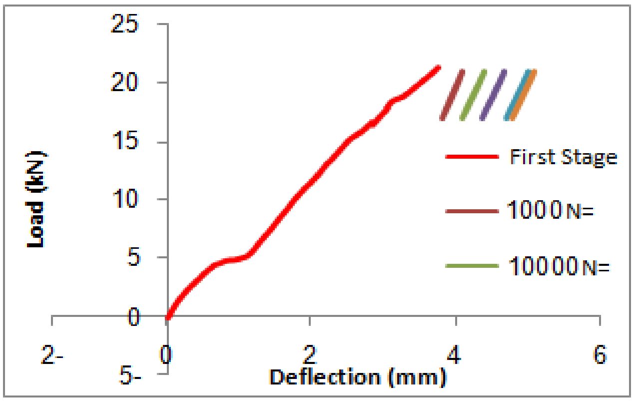
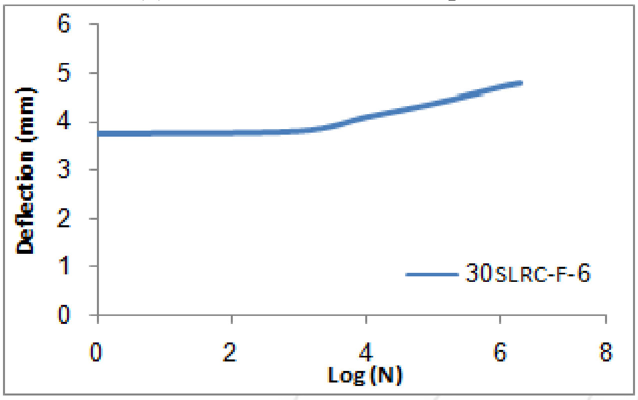
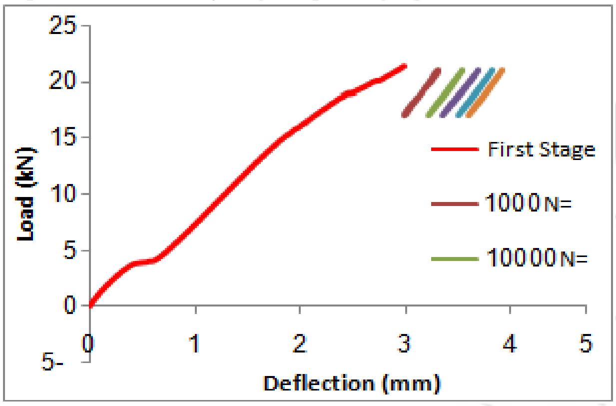


(a): Load vs. Deflection Response

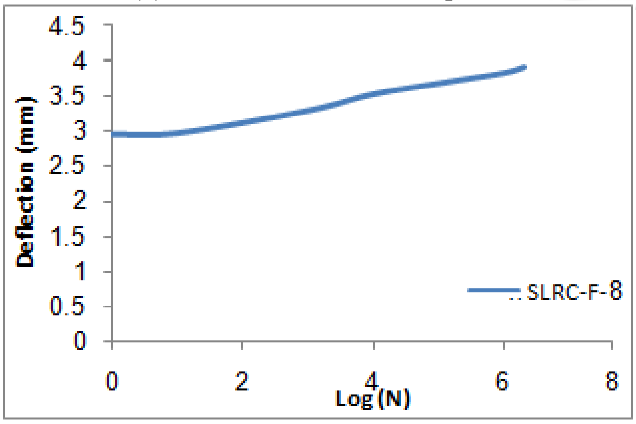


(b): Deflection vs. Log Number of Cycles Response.

Figure 6: Laced Reinforced Concrete Behavior under Fatigue Loading; (a) Load-Deflection Response; (b) Mid Span Deflection-Cycles Response for Beam 6SLRC-F-30.

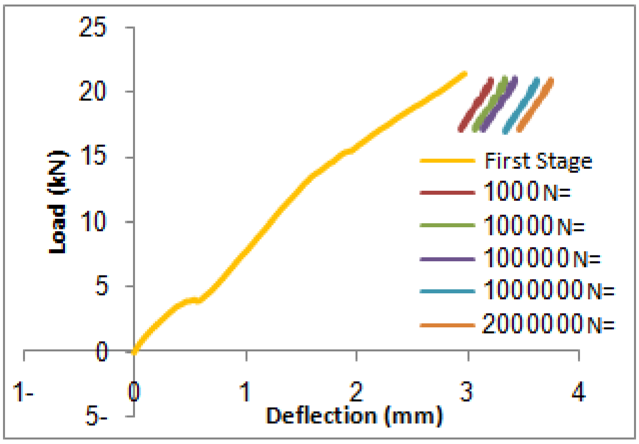


(a): Load vs. Deflection Response.

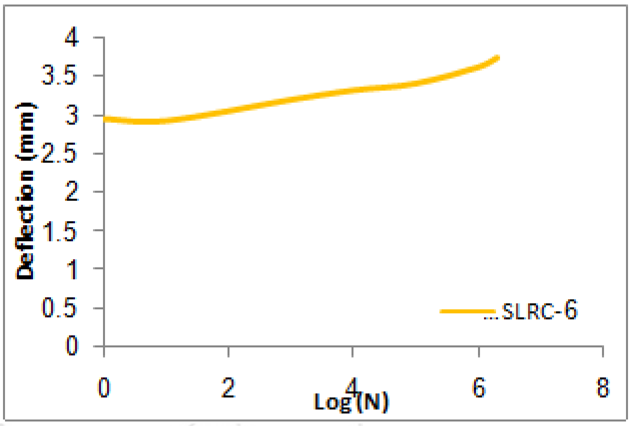


(b): Deflection vs. Log Number of Cycles Response.

Figure 7: Laced Reinforced Concrete Behavior under Fatigue Loading; (a) Load-Deflection Response; (b) Mid Span Deflection-Cycles Response for Beam 8SLRC-F-30.

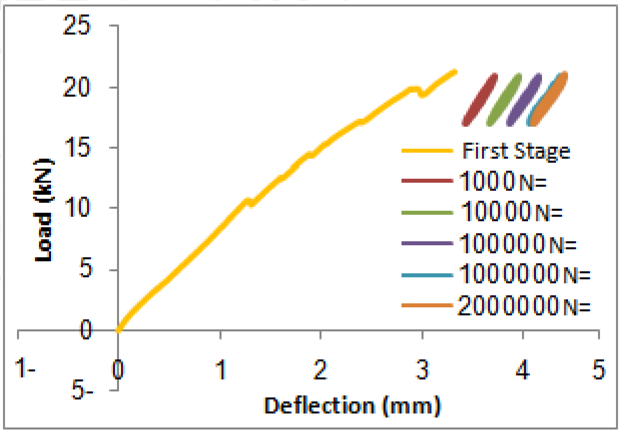


(a): Load vs. Deflection Response

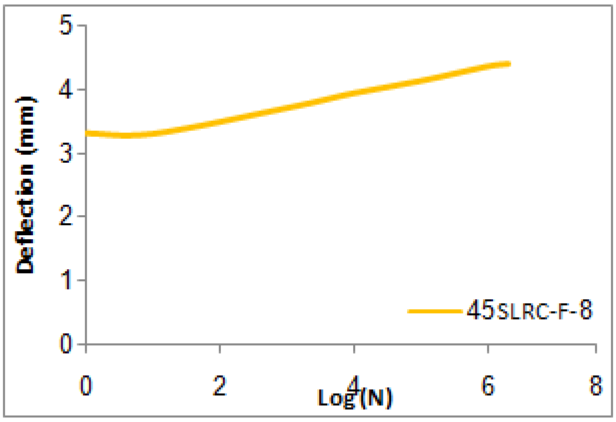


(b): Deflection vs. Log Number of Cycles Response.

Figure 8: Laced Reinforced Concrete Behavior under Fatigue Loading; (a) Load-Deflection Response; (b) Mid Span Deflection-Cycles Response for Beam 6SLRC-F-45.

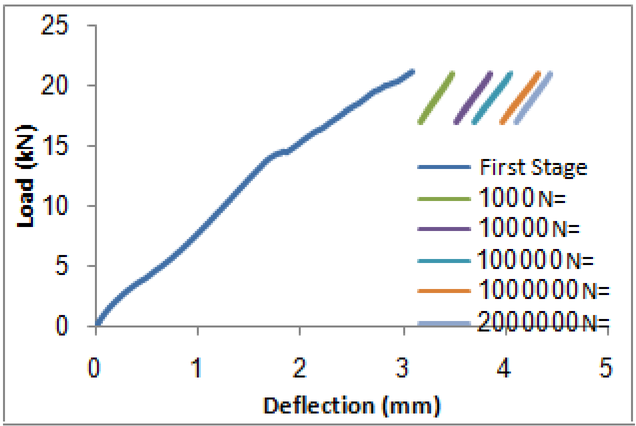


(a): Load vs. Deflection Response.

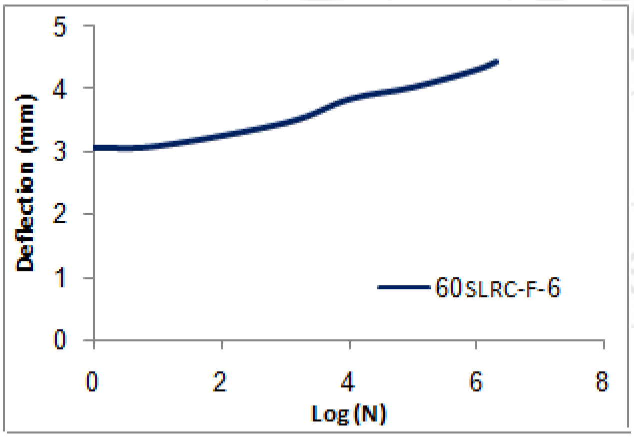


(b): Deflection vs. Log Number of Cycles Response.

Figure 9: Laced Reinforced Concrete Behavior under Fatigue Loading; (a) Load-Deflection Response; (b) Mid Span Deflection-Cycles Response for Beam 8SLRC-F-45.

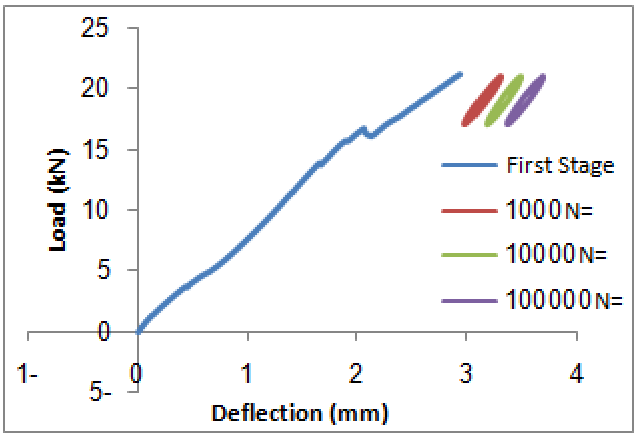


(a): Load vs. Deflection Response.

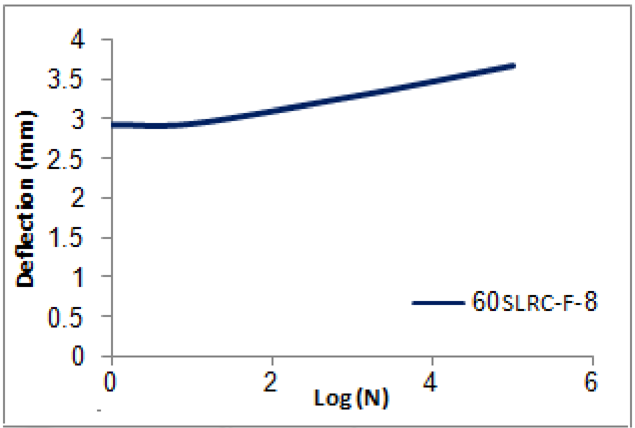


(b): Deflection vs. Log Number of Cycles Response.

Figure 10: Laced Reinforced Concrete Behavior under Fatigue Loading; (a) Load-Deflection Response; (b) Mid Span Deflection-Cycles Response for Beam 6SLRC-F-60.



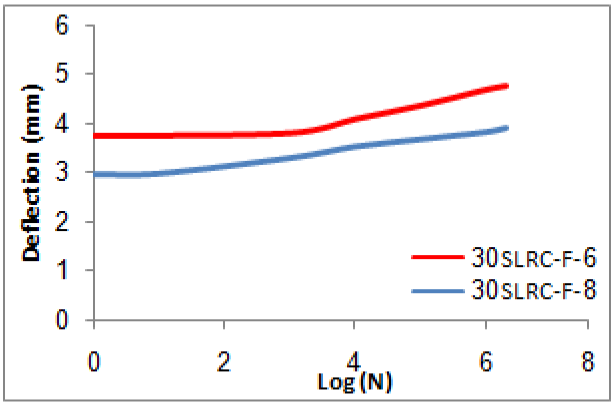
(a): Load vs. Deflection Response.



(b): Deflection vs. Log Number of Cycles Response.

Figure 11: Laced Reinforced Concrete Behavior under Fatigue Loading; (a) Load-Deflection Response; (b) Mid Span Deflection-Cycles Response for Beam 8SLRC-F-60.

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 magnitude of the deflection with cycles as follows: when the cycling is increased it is observed that, the deflection is decreased with increasing of lacing bar diameter and lacing steel ratio by about 18.45% and 17.45% for beams 8SLRC-F-30, and 8SLRC-F-60, respectively, with respect to beams 6SLRC-F-30 and 6SLRC-F-60 respectively. Except beam 8SLRC-F-45, the deflection is increased by 17.65% from beam 6SLRC-F-45 as shown in **Figures 12**, **13** and **14**.



(a): Deflection vs. Log Number of Cycles Response

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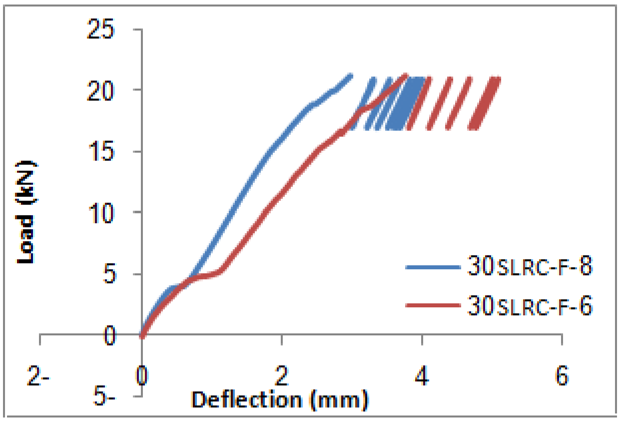
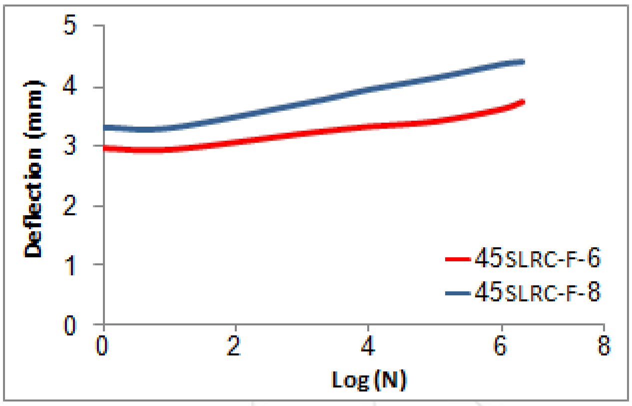
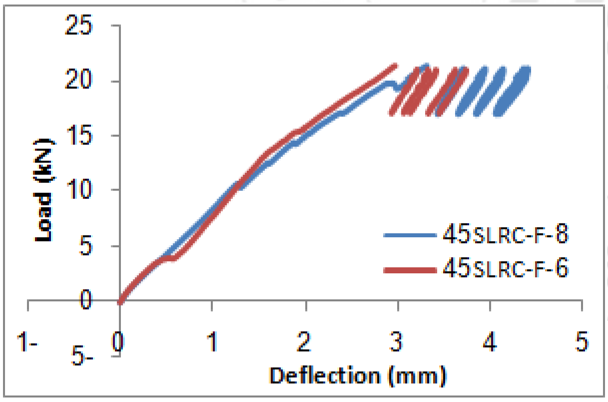


(b): Load vs. Deflection Response.

Figure 12: Influence of Lacing Bar Diameter and Lacing Steel Ratio on: (a) Mid Span Deflection-Cycles Response; (b) Load-Deflection Response for Beams with Inclined Lacing Angle 30.

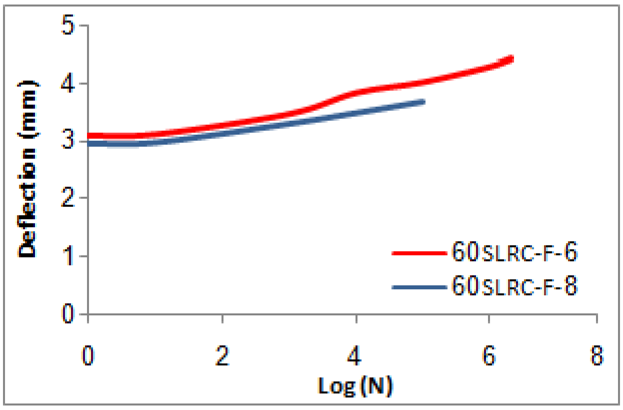


(a): Deflection vs. Log Number of Cycles Response

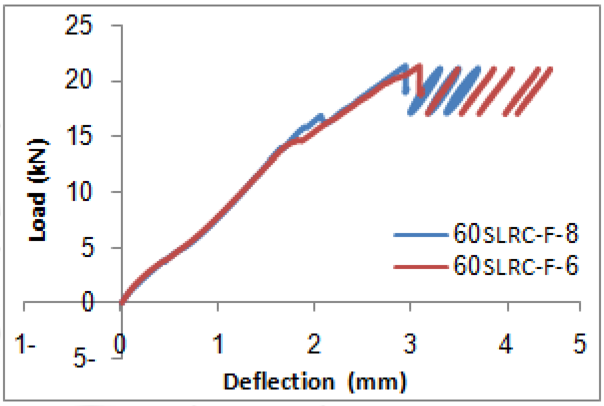


(b): Load vs. Deflection Response

Figure 13: Influence of Lacing Bar Diameter and Lacing Steel Ratio on: (a) Mid Span Deflection-Cycles Response; (b) Load-Deflection Response for Beams with Inclined Lacing Angle 45.



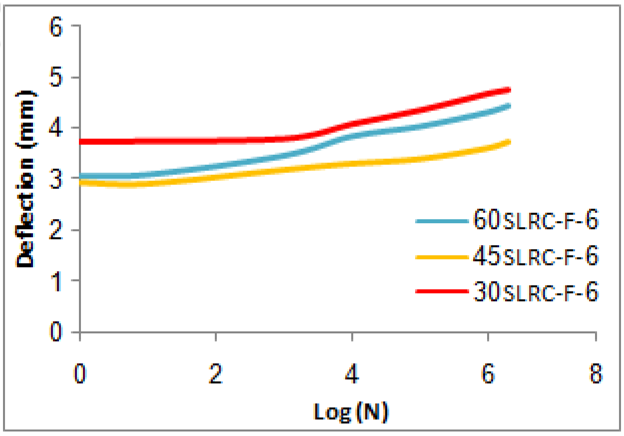
(a): Deflection vs. Log Number of Cycles Response



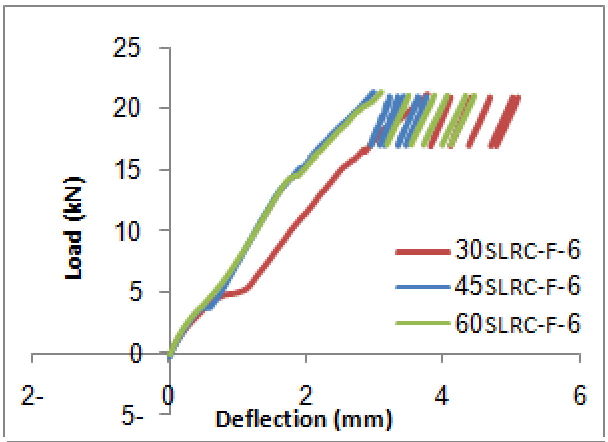
(b): Load vs. Deflection Response

Figure 14: Influence of Lacing Bar Diameter and Lacing Steel Ratio on: (a) Mid Span Deflection-Cycles Response; (b) Load-Deflection Response for Beams with Inclined Lacing Angle 60.

Also from the results it is noticed that the deflection is decreased with increasing of inclined lacing angle by about 7.34%, 21.95% and 6.17% for beams 6SLRC-F-60, 6SLRC-F-45, and 8SLRC-F-60 respectively, with respect to references beams 6SLRC-F-30 and 8SLRC-F-30, respectively. Except beam 8SLRC-F-45, the deflection increased by 12.6% from beam 8SLRC-F-30 as shown in **Figures 15** and **16**.

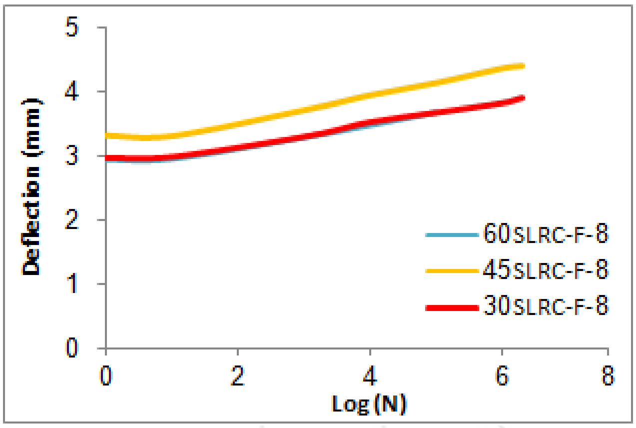


(a): Deflection vs. Log Number of Cycles Response.

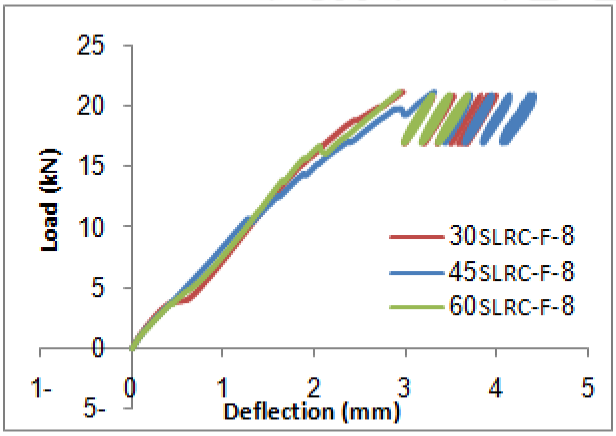


(b): Load vs. Deflection Response.

Figure 15: Influence of Different Lacing Inclined Angle on: (a) Mid Span Deflection-Cycles Response; (b) Load-Deflection Response for Beams 6SLRC.



(a): Deflection vs. Log Number of Cycles Response.



(b): Load vs. Deflection Response.

Figure 16: Influence of Different Lacing Inclined Angle on: (a) Mid Span Deflection-Cycles Response; (b) Load-Deflection Response for Beams 8SLRC.

6.3 The Strain-Cycles Response

The strain-cycles curves for steel reinforcement are recorded to get a clear concept for the influence of lacing reinforcement at the response of laced reinforced concrete beams under fatigue loading as shown in **Figures 17** to **20.** In this section the performance of strain of tension bar at the beginning of each cycle is presented. It is noticed that the flexural reinforcement sill in elastic range and the strain is recorded by about (197.19 $\mu\varepsilon$ -944.634 $\mu\varepsilon$). Two stages appearance in the test progression. First stage, the strain remains a constant before the cycles range (10^1-10^4). Second stage, the strain is increased gradually up to 2×10^6 cycles; except beam 8SLRC-F-45, the strain is increased gradually up to 10^5 cycles then it is decreased rapidly at 2×10^6 cycles. From the results it is noticed that although theuseof inadequate lacing steel percentage, fatigue did not occurs in the steel reinforcement (flexural and lacing bars) after the appearance of cracksas in beam 6SLRC-F-30and also it is noticed that the lacing steel bars still within the elastic range as listed in **Table 3**.

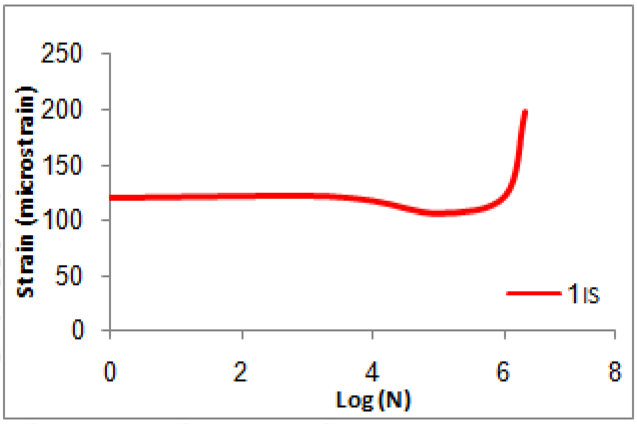


Figure 17: The Strain-Cycles Response for Beam 6SLRC-F-30

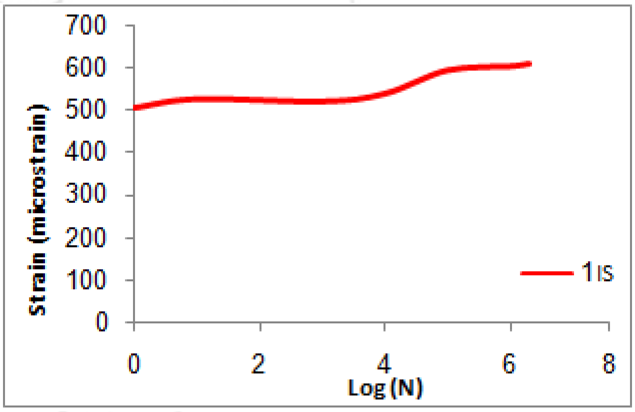


Figure 18: The Strain-Cycles Response for Beam 8SLRC-F-30

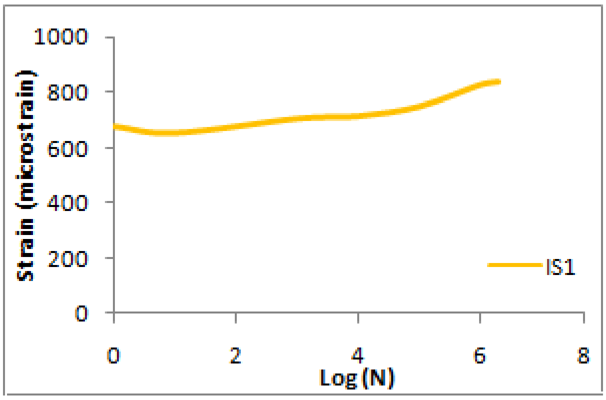


Figure 19: The Strain-Cycles Response for Beam 6SLRC-F-45.

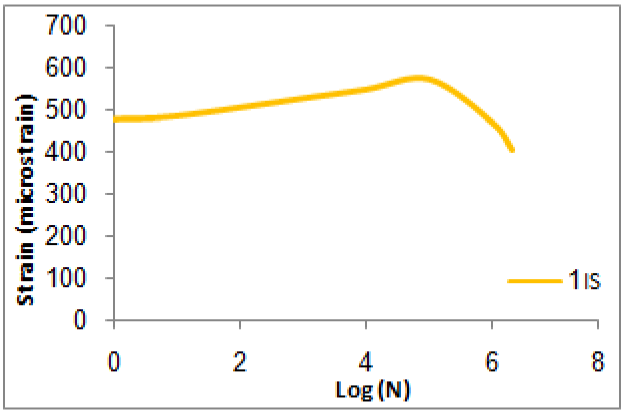


Figure 20: The Strain-Deflection Response for Beam 8SLRC-F-45

Table 3: The Strain Values at 2×10^6 cycles in Lacing Steel Bars at Mid-Span

Location	Pure Flexural
Beam Symbol	Strain Gauges at Lacing Renf. ($\mu\varepsilon$)
6SLRC-F-30	384.051
8SLRC-F-30	145.5
6SLRC-F-45	122.07
8SLRC-F-45	Damage
6SLRC-F-60	177.471
8SLRC-F-60	Damage

7. Conclusions

From the comparison results of the tested laced reinforced concrete beams under fatigue loading, the conclusions can be briefed as follow:

- Laced Reinforced Concrete (LRC) beams subjected to high frequency fatigue loading with low stress levelare exceed the limit of fatigue life and did not fail.
- The deflection of laced reinforced concrete beams is decreased with increasing of lacing bar diameter, inclined angle to beam axis, and lacing steel ratio.
- The steel reinforcement (flexural and lacing bars) response still within the elastic range when LRC beams subjected to high frequency fatigue loading with low stress level.

8. Acknowledgement

The authors wash to thank Professor Soon-Thiam KHU and Dr. Arashfor their invitation to test the beams in concrete lab at Monash University/Malaysia, and also thank Dr. Kong for his experimental assistance and Eng. Afiq.

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