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Civil Engineering Journal

Vol. 5, No. 12, December, 2019

Structural Behavior of High Strength Laced Reinforced Concrete One Way Slab Exposed to Fire Flame

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Received 31 July 2019; Accepted 18 October 2019

Abstract

In this study, an experimental investigation had conducted for six high strength laced reinforced concrete one-way slabs to discover the behavior of laced structural members after being exposed to fire flame (high temperature). Self-compacted concrete (SCC) had used to achieve easy casting and high strength concrete. All the adopted specimens were identical in their compressive strength of ($f_c' \approx 60$ MPa), geometric layout 2000×750×150 mm and reinforcement specifics except those of lacing steel content, three ratios of laced steel reinforcement of (0.0021, 0.0040 and 0.0060) were adopted. Three specimens were fired with a steady state temperature of 500℃ for two hours duration and then after the specimens were cooled suddenly by spraying water. The simply supported slabs were tested for flexure behavior with two line loads applied in the middle third of the slab (four-point bending test). The average residual percentage of cubic compression strength and splitting tensile strength were 57.5% and 50% respectively. The outcomes indicated that the residual bending strength of the burned slabs with laced ratios (0.0021, 0.004, 0.006) were (72.56, 70.54 and 70.82%) respectively. However; an increase in the deflection was gained to be (11.34, 14.67 and 17.22%) respectively with respect to non-burned specimens.

Keywords: Laced Reinforced Concrete; One-Way Slab; Fire Flame; High Temperature; SCC.

1. Introduction

Normal reinforced concrete (NRC) is known to have bounded ductility and confinement of concrete, NRC can be enhanced by appropriate amendment in materials of concrete and by considering suitable alteration in the reinforced details. Laced bars are reinforcing bars that extend in a direction parallel to the main reinforcement, they are bending into a diagonal manner between top and bottom reinforcement. Laced bars usually enclose temperature reinforcement bars which are placed outside the main reinforcement. Laced member is reinforced with two identical mats of steel bars for tension and compression. Through truss behavior, laced bars tied the two principal reinforcement and bounded the concrete between the reinforcement by truss action, they are also placed in a reciprocal way to encompass all transverse reinforcement as shown in Figure 1. Laced reinforcement for concrete members improves the ductility and produces better confinement for concrete [1]. Recently, considerable researches have studied the behavior of laced element under static and dynamic loads, in addition the use of laced reinforcement for blast resistant structures that leads to an urgent need to study the behavior of laced reinforced members exposed to fire flame.

Slab members have a significant effect by fire because of its large surface that exposed to fire relatively to its depth. Besides, fire may be exposed from one side of the member; which produced a gradation in temperature over slab thickness. An experimental program was carried out by Moss et al. (2008) [2], to study the behavior of two way reinforced concrete slab affected by fire. Moss concluded that concrete and reinforcement on the bottom of the slab were

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http://dx.doi.org/10.28991/cej-2019-03091446

heated well prior the top reinforcement and concrete. When the main reinforcement in the bottom reached 300℃, the yield strength of the main reinforcement started to decrease, that's way bending moment and membrane strength decrease. Ghoreish et al. (2010) [3], indicated that the existence of imposed load during the burning process lead to a bad effect on slab behavior. Harada et al. (1972) [4], found that the residual compressive strength of concrete at a temperature 300℃ to reference specimen was 60%, and the residual of steel concrete bond was 44%. Experimental test was done by Izzat et al. (2012) [5] to investigate the behavior of one-way reinforced SCC slab under fire flame effect, concluded that the residual flexural strength of the slab that cooled gradually was (81.5%, 75%, 62.3%) for fire temperature (300℃ , 500℃ , 700℃) respectively. Also, it was concluded that increasing the compressive strength decrease the residual flexural strength percent and sudden cooling is more effective to the residual flexural strength than gradual cooling while the deflection was increased with the increasing of burning temperature. Another study presented by Mohammed and Fawzi (2015) [6] investigated the structural behavior of SCC beams under the effect of repeated load after being exposed to fire flame of steady state temperature (200,300,400 and 500) ℃ and two different methods of cooling, sudden and gradual. The results showed that number of cycles that's required to vanish the residual deflection was directly proportion with the burning temperature and sudden cooling method. It was also noticed that the failure mode changed to be combined shear-flexure instead of pure flexure due to the drop of the compressive strength amount.

The main purpose of using shear reinforcement is to enhance the behavior of structural members in large deflection stage by connecting the two main reinforcement. In the design of traditional structures, the essential purpose of shear reinforcement is to prohibit formation and spread of inclined tension cracks [7]. A wide range of experimental investigations conducted on (RC) and (LRC) beams by Parameswaran et al. (1986) [8], indicated that the support rotation angles range from 3.5^o to 8^o. The extended laced steel bars inclined from the horizontal plane at an angle 45^o and 60^o. The main objective of the investigations is the using laced steel reinforcement leads to improve the ductility and the load carrying capacity the beams compared with the beams traditional shear reinforcement.

A test study was executed by Keshava Rao et al. (1992) [9] to investigate the effect of blast load on the laced reinforced concrete members. It was concluded that the laced reinforcement increases the strength of the member by 25% under blast loading. A test programme presents by Akshaya et al. (2015) [10] to investigate the effect of monotonic and cyclic loads on the behaviour of laced steel-concrete composite beams with 60^o lacing with and without fiber (LSCC) and (FLSCC). Their results revealed that load carrying capacity and ductility index for (FLSCC) beams was higher than (LSCC) and RC beams. The increasing in load carrying capacity was about 46% and 22% for (FLSCC) and (LSCC) respectively with respect to RC beams.

Experimental study was carried out by Allawi and Jabir (2016) [11] to study the behavior of one-way laced reinforced concrete slab under static load. Nine specimens were test for flexural behavior with three parameters of laced steel ratio, tension steel ratio, and clear span to effective depth ratio (L/d). The results indicated that specimen with laced steel ratio of (0.0065) gives an increase in ultimate load by about 57% with respect to specimen without laced ratio, also the decreasing (L/d) ratio by (31.25%) lead to increase failure load by about (103.57%) with respect to control specimen.

Al-Ahmed and Hallawi (2019) [12], studied the influence of laced reinforcement on the behaviour of one way-slab under monotonic load. The test results showed that the cracking load and ultimate load increased by about (28% and 45%) and (16% and 40%) respectively for lacing ratio of (0.0026 and 0.0052) with respect to specimen without laced reinforcement. Also the ductility factor increased by about 33% and 49% for laced ratio 0.0026 and 0.0052 with respect to specimen without laced reinforcement.

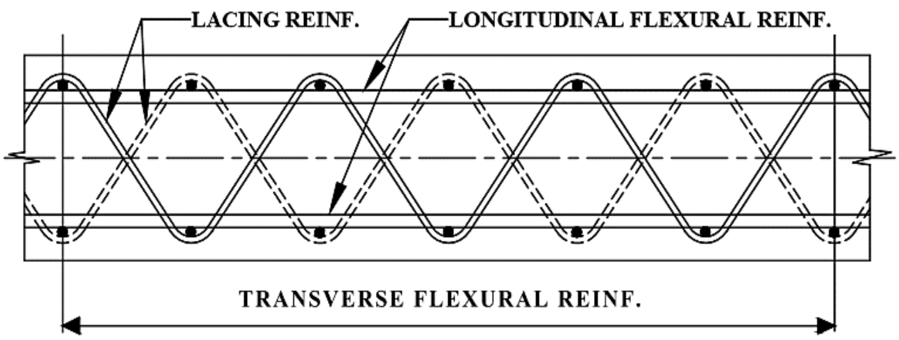

Figure 1. Lacing Reinforcement [1]

2. Experimental Program

2.1. Materials

Ordinary Portland cement (Type-I), a natural sand of maximum size 4.87 mm, crushed gravel of (10mm) maximum size, tap water, a very fine pozzolanic material (Microsilica) as additives (pozzolanic material) and ViscoCrete-5930 (product of Sika) were used in the adopted concrete mix to produce SCC for all the specimens. The results of sieve analysis test for fine and coarse aggregate are presented in Table 1 and 2. The adopted concrete mix was designed according to EFNARC (2005) [13] to satisfy fresh properties of SCC and to match the expected compressive strength. Materials proportion for SCC are shown in Table 3, and tests for fresh SCC were complied with the limit of EFNARC (2005) [13] as shown in Table 4.

Table 1. Grading of the fine aggregate

Sieve Size mm	Passing by Weight %	Cumulative Passing % Limit of Iraqi Specification No. 45/1993			
		Zone 1	Zone 2	Zone 3	Zone 4
10	100	100	100	100	100
4.75	91	90-100	90-100	90-100	95-100
2.36	75.5	60-95	75-100	85-100	95-100
1.18	56.5	30-70	55-90	75-100	90-100
0.60	39.4	15-34	35-59	60-79	80-100
0.30	10.9	5-20	8-30	12-40	15-50
0.15	2.5	0-10	0-10	0-10	0-15

Table 2. Grading of the coarse aggregate

Sieve Size (mm)	Cumulative Passing %	Limit of Iraqi Specification No.
37.5	100	100
19	100	95-100
14	---	---
9.5	95.7	30-60
4.75	5.6	0-10

Table 3. Mix proportions of the used SCC mix

Materials	Proportion
Cement	600 (kg/m^3)
Sand	760 (kg/m^3)
Gravel	900 (kg/m^3)
SF*	4%
w/b	0.27
SP**	2

* Replacement by weight of cement
** Liter / 100 kg of cemen

Table 4. Tests for Fresh SCC

Property Measured	Test Method	Test Values	EFNARC Limits
Flowability	Slump Flow	690 mm	600-850 mm
Flowability	T_{500}	4 Sec	2-5 Sec
Passing Ability	L-Box	0.84	$\geq$ 0.75

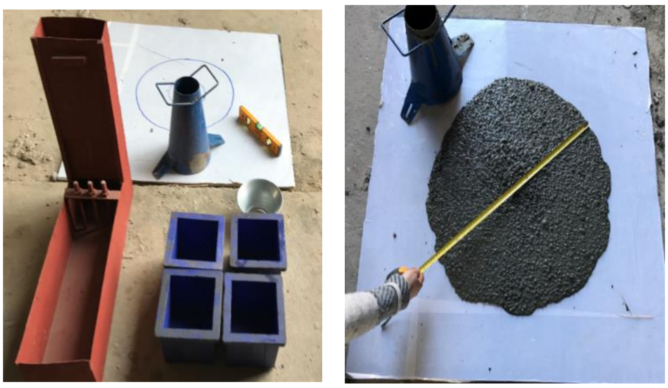

Figure 2. Fresh concrete tests

2.2. Test Specimens

Six simply supported laced reinforced SCC one-way slabs were cast and cured. All the specimens had the same geometrical layout, compressive strength and reinforcement specifics except laced steel ratio. The specimens were designed according to ACI 318M-2014 [14] and accepted with UFC 3-340-02, 2008 [1], for laced reinforcement details. The specimens had divided into three pairs, each pair had different laced steel ratio (0.0021, 0.0040 and 0.0060). For each pair, one slab was burned with steady state fire temperature 500℃ for a duration of two hours and the other was not. The considered cooling method was sudden cooling by spraying water. Then after, all specimens had tested under monotonic load of two parallel line load till the failure. The slab details and dimensions are shown in Figure 3. All specimens had the same reinforcement for compression and tension of 8 mm diameter deformed rebar at 100 mm c/c spacing and temperature reinforcement of 8 mm diameter deformed rebar at 120 mm c/c spacing for top and bottom. The characteristics of the tested slabs are illustrated in Table 5.

Figure 4 shows the positions of the strain and dial gauges. Two dial gauges were used, one was installed in the central of the slab and the other near to support. Three strain gauges (5 mm length) were installed in tension, compression, and lacing steel bars in the mid span. Two strain gauges (30 mm) were fixed at top and bottom concrete face in mid span. The used strain gauges were of (120Ω) resistance made in japan for TML. Strain gauges for steel bar hadn't used for burning specimens because it will be destroyed by fire. An instrument consists of thirteen metal plates of different thickness ranging from 0.05 to 1.0 mm was used to measure the width of cracks. Thermocouple was used for measuring the temperature of the furnace and the specimen. Dial gauge was used during the burning process to measure the central deflection of slabs. Figure 5 shows the testing rig and specimen position.

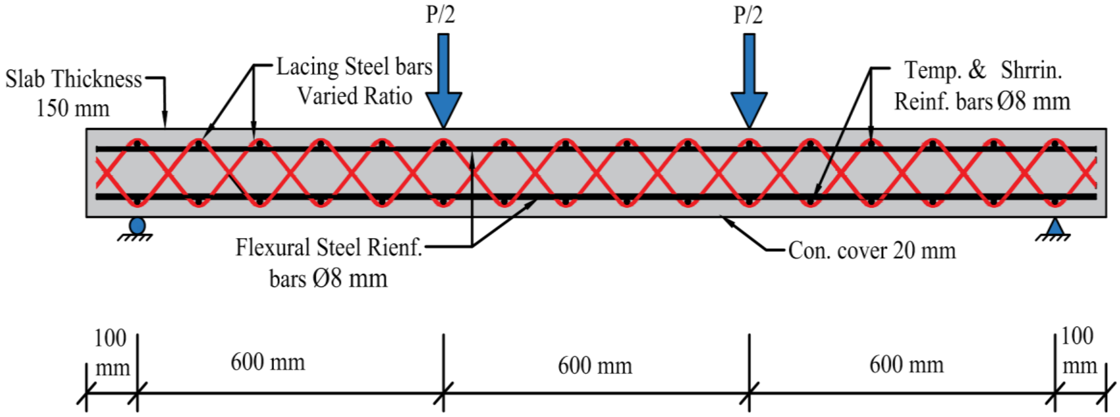

Figure 3. Details and dimensions of test slab specimens

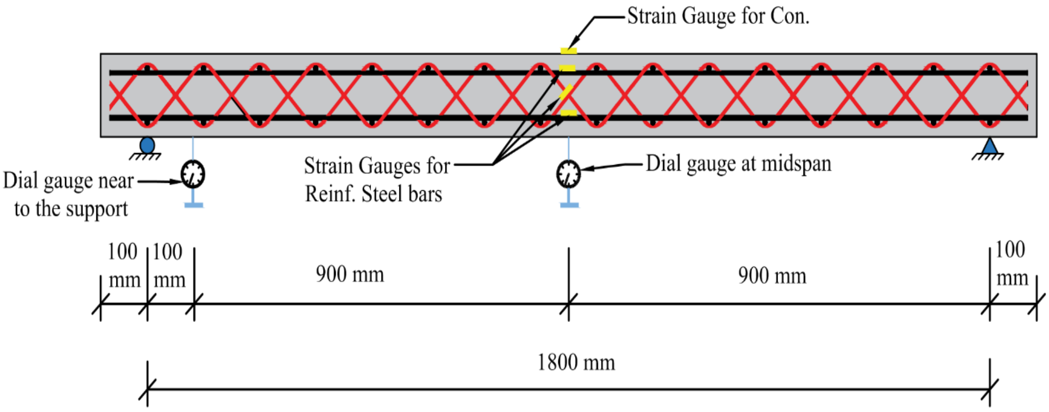

Figure 4. Instrumentation detailed and position

Table 5. Characteristics of the tested slabs

No.	Specimens Designation	Tension steel ratio (ρ_t)	Laced steel ratio (ρ_s)	Laced angle (θ)	Temp. (℃)	Laced steel details
1	S42/21NB	0.0042	0.0021	45°	30	Ø6 mm at 110 mm c/c
2	S42/40NB	0.0042	0.0040	45°	30	Ø6 mm at 60 mm c/c
3	S42/60NB	0.0042	0.0060	45°	30	Ø8 mm at 70 mm c/c
4	S42/21B	0.0042	0.0021	45°	500	Ø6 mm at 110 mm c/c
5	S42/40B	0.0042	0.0040	45°	500	Ø6 mm at 60 mm c/c
6	S42/60B	0.0042	0.0060	45°	500	Ø8 mm at 70 mm c/c

Figure 5. Test set-up

2.3. Burning and Cooling

Three specimens were burnt in a furnace made for this purpose with fire flame. The specimens were installed on two supports in the furnace and a uniform load was applied to the specimen of 10.64 kN/m^2. Blocks of net mass around 50 kg were distributed uniformly on slab to obtain uniform load during the fire test duration. Burning test was according to ASTM E119 (2000) [15]. The specimens were burned for two hours of steady state temperature 500℃. The required time to reach 500℃ was 5 minutes. Both deflection and specimen's temperature were recorded during the fire test duration. The cooling method was sudden cooling by spraying water to slab after burning time. The burning process details were the same for the three slabs. Figure 6 shows the furnace and the slab position.

Figure 6. Flame Furnace

3. Results And Discussions

3.1. Non-burned Specimens

The experimental program included testing three reinforced concrete one-way slabs that non-burned to study the effect of laced reinforcement on one-way slab. The mode of failure for all the tested slabs were flexure. The first flexural crack was firstly appeared in the middle third of the tension face for the slab where maximum moment occurred. As the load increased further, additional flexural cracks were generated and extended in the bottom surface of the slab parallel to the initial crack and the supports direction. Then, the cracks were grown to the sides of the slab and reached to the top edge of the slab at failure stage. There was noticed that the cracks located in the middle third of the slab and no cracks were observed near the supports. Eventually, the failure of the specimens happened due to the extensive yield of tensile steel bars. The test results regarding the initial crack loads and ultimate loads are illustrated in Table 6.

Table 6. Cracking and ultimate loads for non-burned specimens

Specimens	Ultimate Load (*Pu*) (*kN*)	First Crack Load (*Pcr*) (*kN*)	Load at the (0.4mm) Crack Width (*kN*)	% Increase in (0.4mm) Cracking Load with Respect to Ref.	*Pcr/Pu* %	% Increase in Ultimate Load with Respect to Ref.
S42/21NB	143.22	33.35	89.6	Ref.	23.29	Ref.
S42/40NB	155.98	33.35	92	2.67	21.38	8.9
S42/60NB	177.56	33.35	116.24	29.73	18.78	23.97

The first crack occurred for all specimens that non-burned in the same load (33.35 kN) that's belong to the similarity in the characteristics of compressive strength and main reinforcement ratio and also indicated that increasing laced reinforcement do not effect on the first cracking load. Cracks width behavior and load increments are shown in Figure 7; it can be detected from this figure that the increasing rate of crack width is highly sensitive after yielding stage. Generally, it is obvious from the results that increasing laced steel ratio increased the failure load, the increasing was (8.9%, 23.97%) for specimens (S42/40NB, and S42/60NB) with respect to the specimen (S42/21NB). The deflection for specimens were discussed at service load and ultimate load. Tan and Zhao, 2004 [13], indicated that service load is about (70-75%) of the ultimate load. In this study the service load was taken to be 70% of the ultimate load. The results of this study show that, the increasing of the laced ratio is directly proportion with the ultimate deflection as shown in Figure 8, also from this figure the load-deflection curve for the non-burned specimens had the same behaviour and diverge after yielding of tension reinforcement. The increasing in the deflection at ultimate load was (5.03% and 21.7%) for specimens (S42/40NB and S42/60NB) with respect to (S42/21NB).

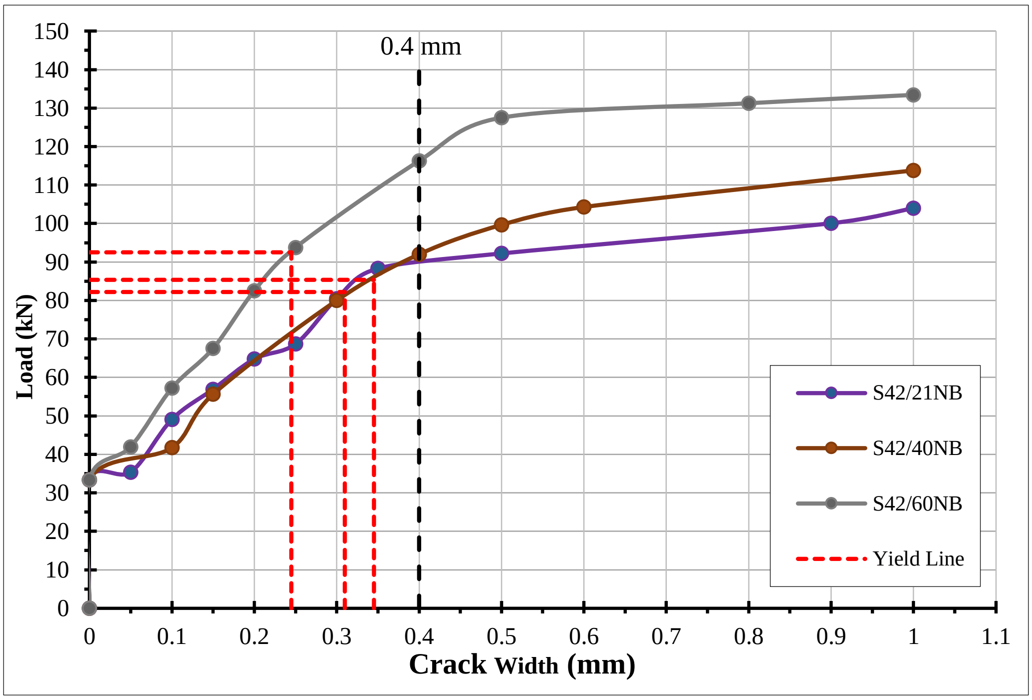

Figure 7. Effect of lacing ratio on crack width behavior for non-burned specimens

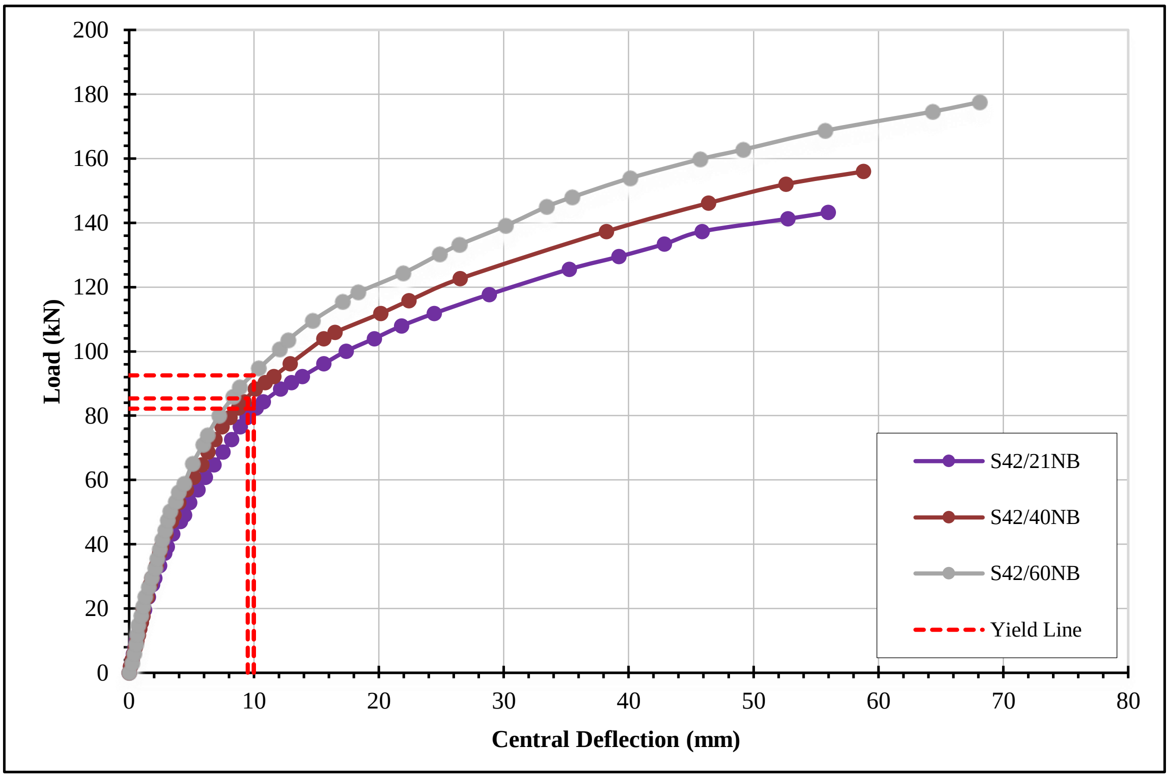

Figure 8. Effect of lacing reinforcement on load-deflection behavior

The central deflections at ultimate and service loads are given in Table 7. Increasing laced steel ratio decreases the deflection at ultimate load of reference specimen about 22% and 42% for specimens (S42/40NB and S42/60NB) with respect to (S42/21NB). The absorbed deflection-load curves were matched up to yield stage then after they spaced to produce a different level of absorbed energy to be (6021, 6887, 9133) for the specimens (S42/20NB, S42/40NB and S42/60NB) respectively. Ductility factor was calculated for all the specimens as illustrated in Table 6, which is the rate of central deflection at failure load to the central deflection at yield point. It was obvious from this table that increasing laced steel ratio increases the ductility factor. Load-strain behavior for laced bars is shown in Figure 9, which illustrates that small strains were recorded in the first but after yielding of the tension steel bars the strain increasing rapidly, also it can be noted that the yielding of the central laced bar at failure stage. Also load-strain for tension steel bar and top fiber of concrete was recorded as shown in Figures 10 and 11. In general, it is obvious that the influence of laced reinforcement was to prevent the tension reinforcement strain during its strain hardening region. At failure the strain at concrete top fiber was between (4438 and 3332) micro-strain.

Table 7. Central deflection at service and ultimate loads for non-burned specimens

Specimens	Deflection at Service Load (mm)	% Decrease in Deflection at Service Load	Deflection at Ultimate Load of Ref. Specimen	% Decrease in Deflection at The Ultimate Load of Ref. Specimen	Ultimate Deflection (mm)	% Increase in Deflection at Ultimate Load
S42/21NB	17.48	Ref.	55.99	Ref.	55.99	Ref.
S42/40NB	18.51	5.6	43.66	22.02	58.81	5.03
S42/60NB	21.94	25.5	32.45	42	68.14	21.7

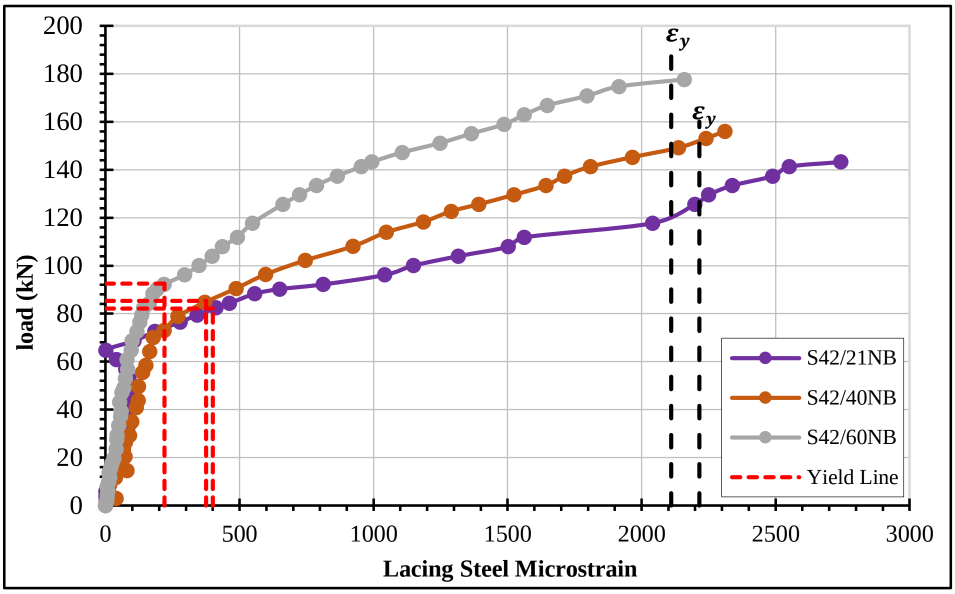

Figure 9. Effect of lacing steel ratio on lacing strain behavior for non-burned specimens

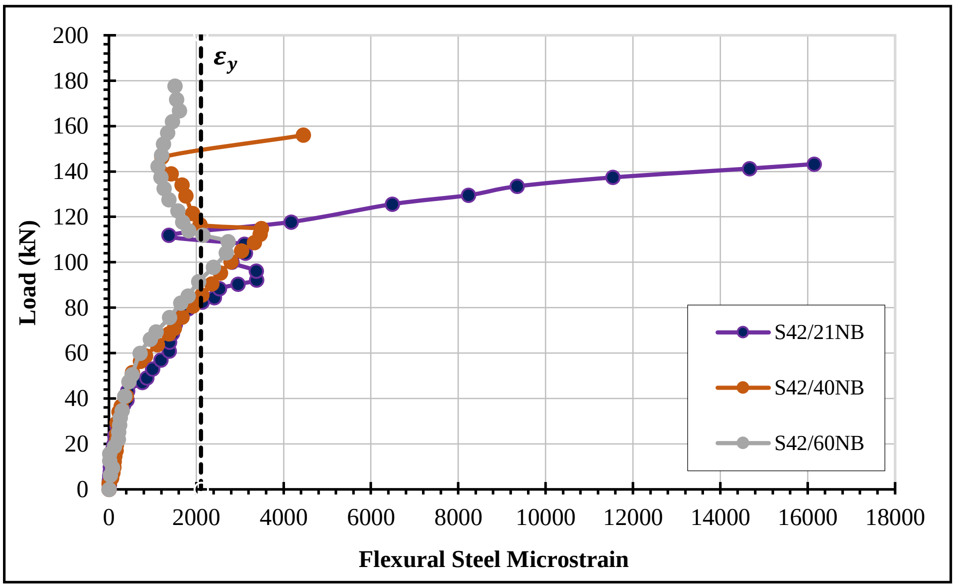

Figure 10. Effect of lacing steel ratio on the tension steel strain of non-burned specimens

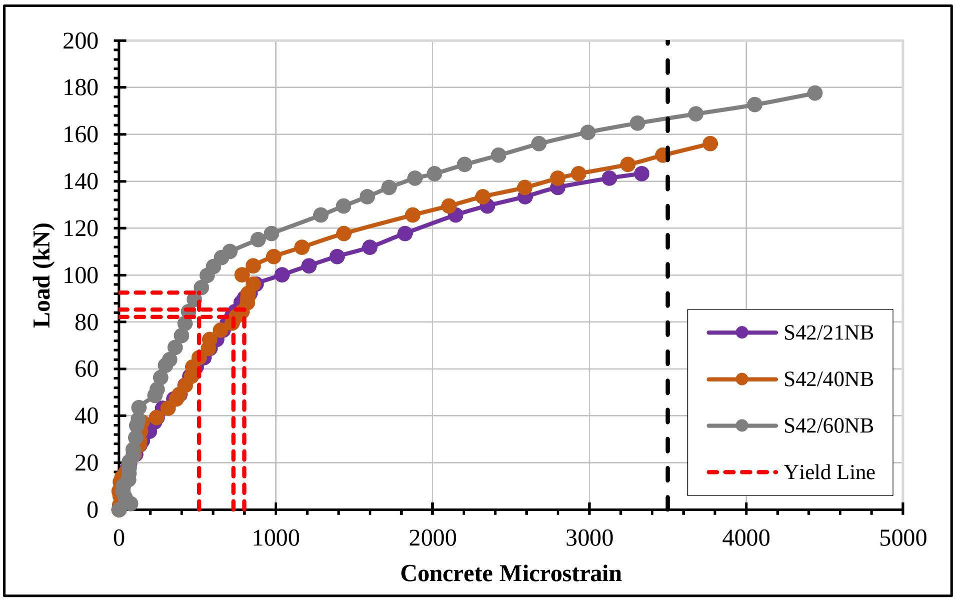

Figure 11. Effect of lacing steel ratio on concrete compression strain

3.2. Burned Specimens

The results for burned specimens indicated that cracks were spread on the surfaces of the slabs after firing and cooling process, also flexural cracks were appearing due to fire and imposed load in the bottom and sides of the slabs. Concrete compressive strength for testing cubes after burning and cooling showed that the compressive strength is decreased. The residual compressive strength was (57%, 59%, 57%) for specimens (S42/21B, S42/40B and S42/60B) respectively. Also the residual splitting tensile strength for testing cylinders after burning and cooling was (50%, 52%, 49%) for specimens (S42/21B, S42/40B and S42/60B) respectively. The deflection of the specimens during the burning process increased at a faster rate in the first twenty minutes, after that the deflection approximately remains constant and returned to decrease in the second hour of burning as shown in Figure 12. After completion the burning and cooling process the specimens were tested under static load of two line loads. Flexural failure was occurred for all the slabs. Firstly, the cracks were generated at the bottom of the slab (new cracks), also, grew from fire cracks in the bottom of the slab. The crack width-load behavior is shown in Figure 13. The outcomes indicated that the deflection and load at the failure stage increase as laced reinforcement is increased, Table 8. And the deflection behavior is shown in Figure 14. Also strain-load behavior for concrete compression face for burned slabs are shown in Figure 15.

Table 8. Ultimate load and deflection of burned specimens

Specimens	Ultimate Deflection (mm)	Ultimate load (kN)	% Increase in ultimate deflection	% Increase in ultimate load l
S42/21B	62.34	103.92	-	-
S42/40B	68.92	110.03	5.03	5.88
S42/60B	82.32	125.76	21.89	21.02

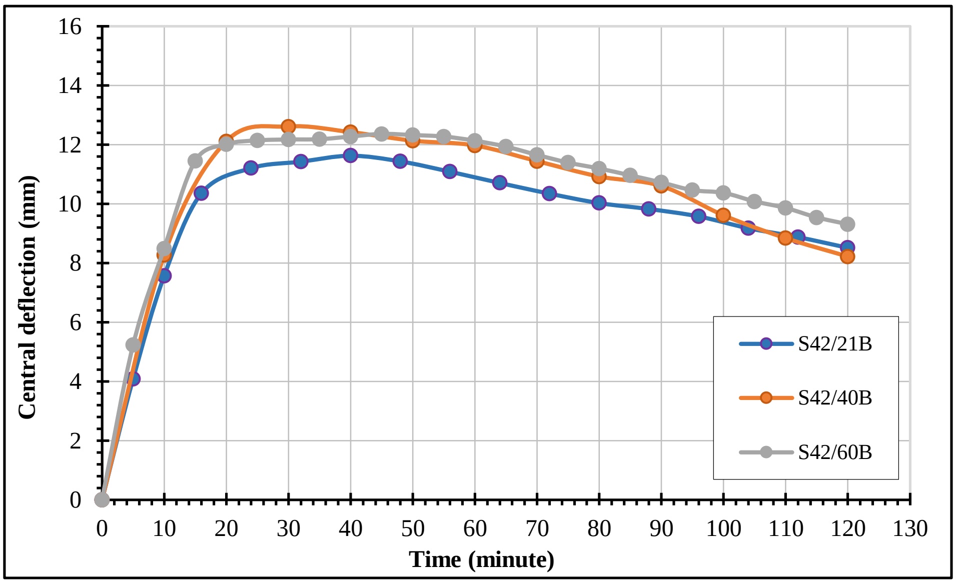

Figure 12. Central deflection-time history for burned specimens for non-burned specimens

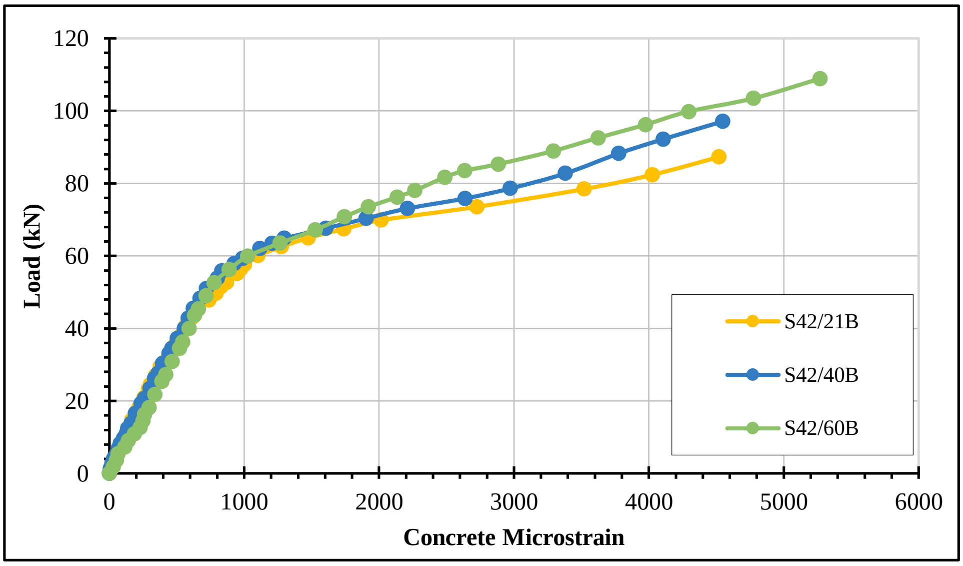

Figure 13. Load–Strain Relation for Concrete Top Surface at Mid–span for Burned Specimens

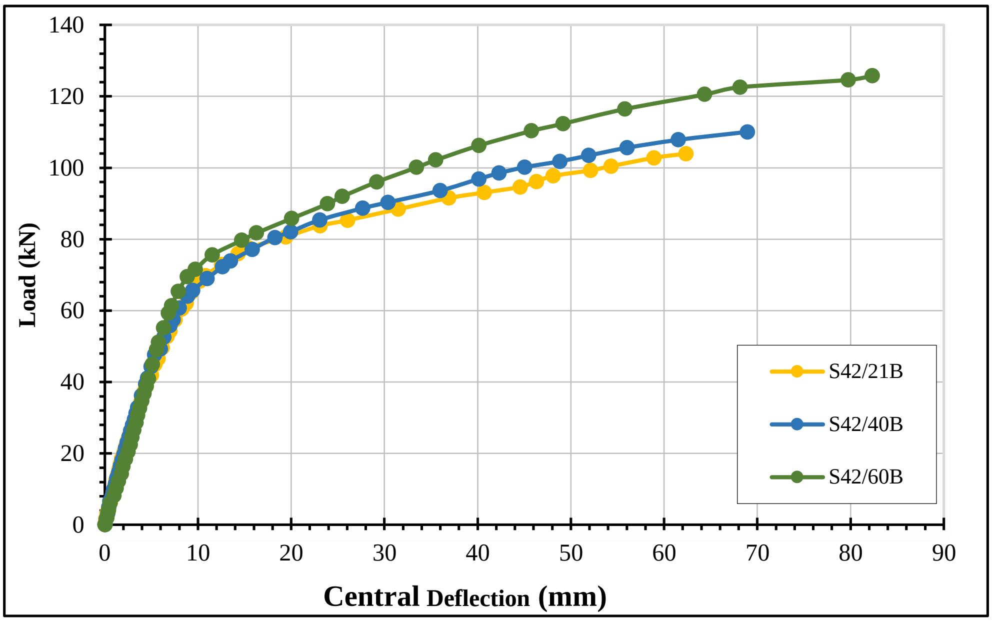

Figure 14. Central deflection-load behavior for burned specimens

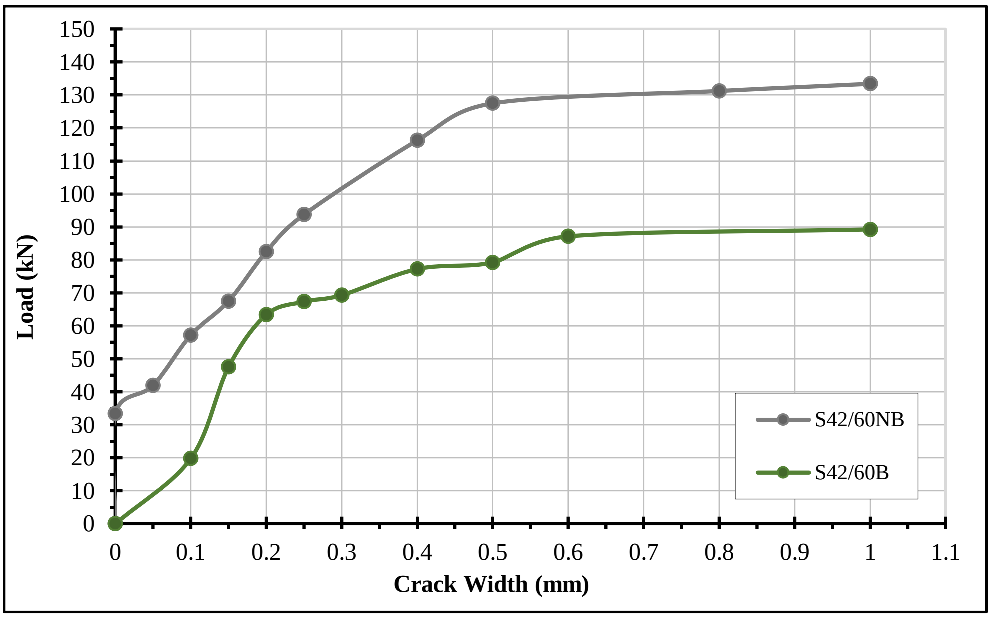

Figure 15. Cracks width behavior for burned specimens

3.3. Comparison between Burned and Non-Burned Specimens

Cracks width behavior for the burned and non-burned specimens are shown in Figures 16 to 18. It is clear that crack width- load curves for burn and non-burn state had two stages which represents two intervals (before and after yield stage). The results also indicated that cracks pattern are similar for all the tested specimens as shown in Figure 19. Flexural failure was occurred for all the specimens due to the yield of the tension reinforcement and excessive deflection. The failure loads for all the tested slabs in this study are given in Table 9. It is obvious that fire decreases the ultimate load of the slab, the residual ultimate loads were (72.56, 70.54 and 70.82%) for specimens (S42/21B, S42/40B and S42/60B) with respect to reference specimens. The ultimate deflection increases for specimens affected by fire with respect to non-burned specimens, the increasing was (11.34, 14.67 and 17.22%) for specimens (S42/21B, S42/40B and S42/60B) respectively with respect to the reference specimens as shown in Figure 20. The recorded strain - load for concrete compression top fiber indicated that the strain at failure stage was (5270, 4518) microstrain for burned specimens as shown in Figure 21. It is more than the strain recorded for non-burned specimens. Concrete crushing at failure load was happened to burned specimens while there was no crushing observed for non-burned specimens. Table 10 illustrates the results for all specimens.

Table 9. Ductility factor for the non-burned specimens

Specimens	Steel Yielding Load (kN)	Yield Deflection (mm)	Ultimate Deflection (mm)	Ductility Factor
S42/21NB	82.17	10.12	55.99	5.53
S42/40NB	85.33	9,46	58.81	6.22
S42/60NB	92.5	9.83	68.14	6.93

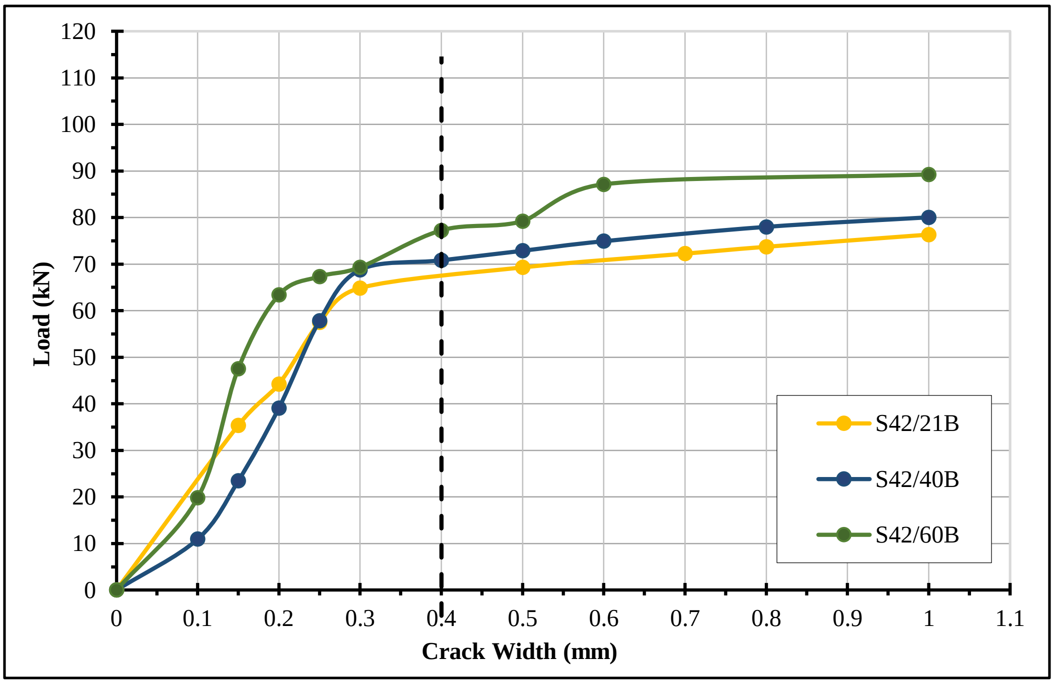

Figure 16. Influence of Burning and Cooling on the Cracking Behavior for Specimen with Laced Ratio (0.0060)

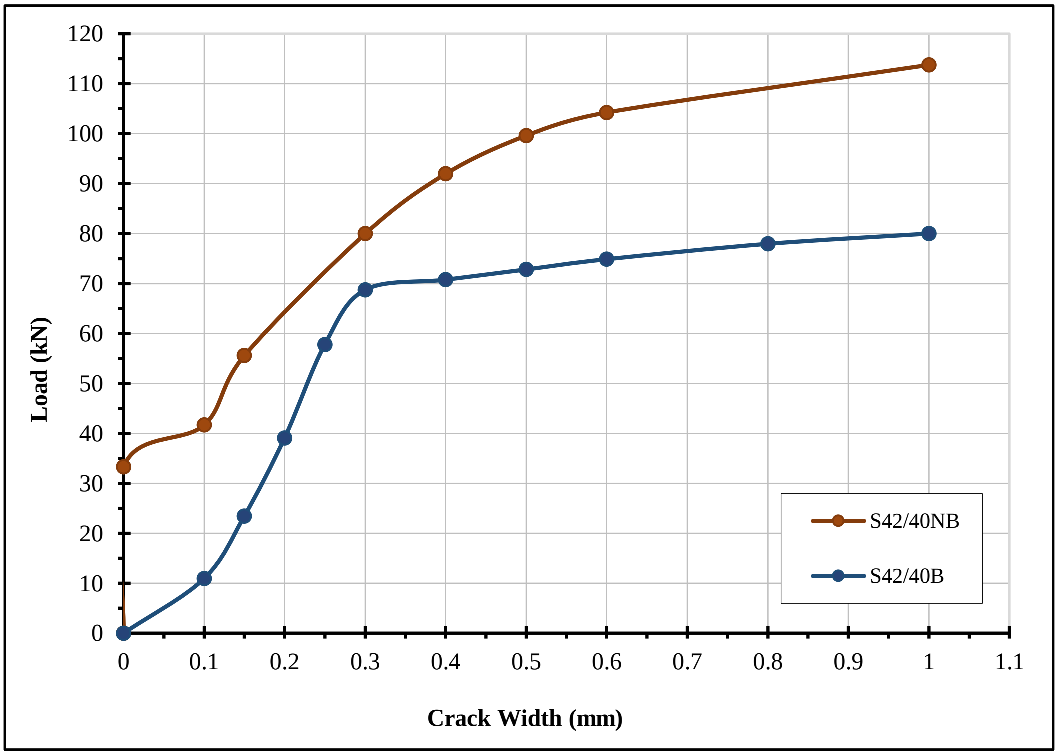

Figure 17. Influence of Burning and Cooling on the Cracking Behavior for Specimen with Laced Ratio (0.0040)

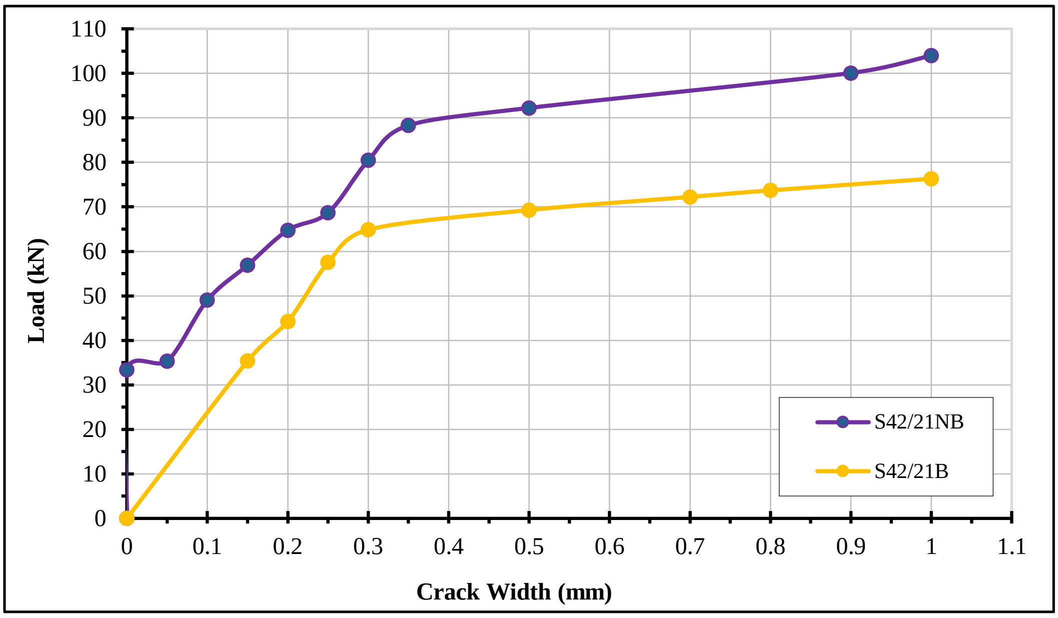

Figure 18. Influence of Burning and Cooling on the Cracking Behavior for Specimen with Laced Ratio (0.0021)

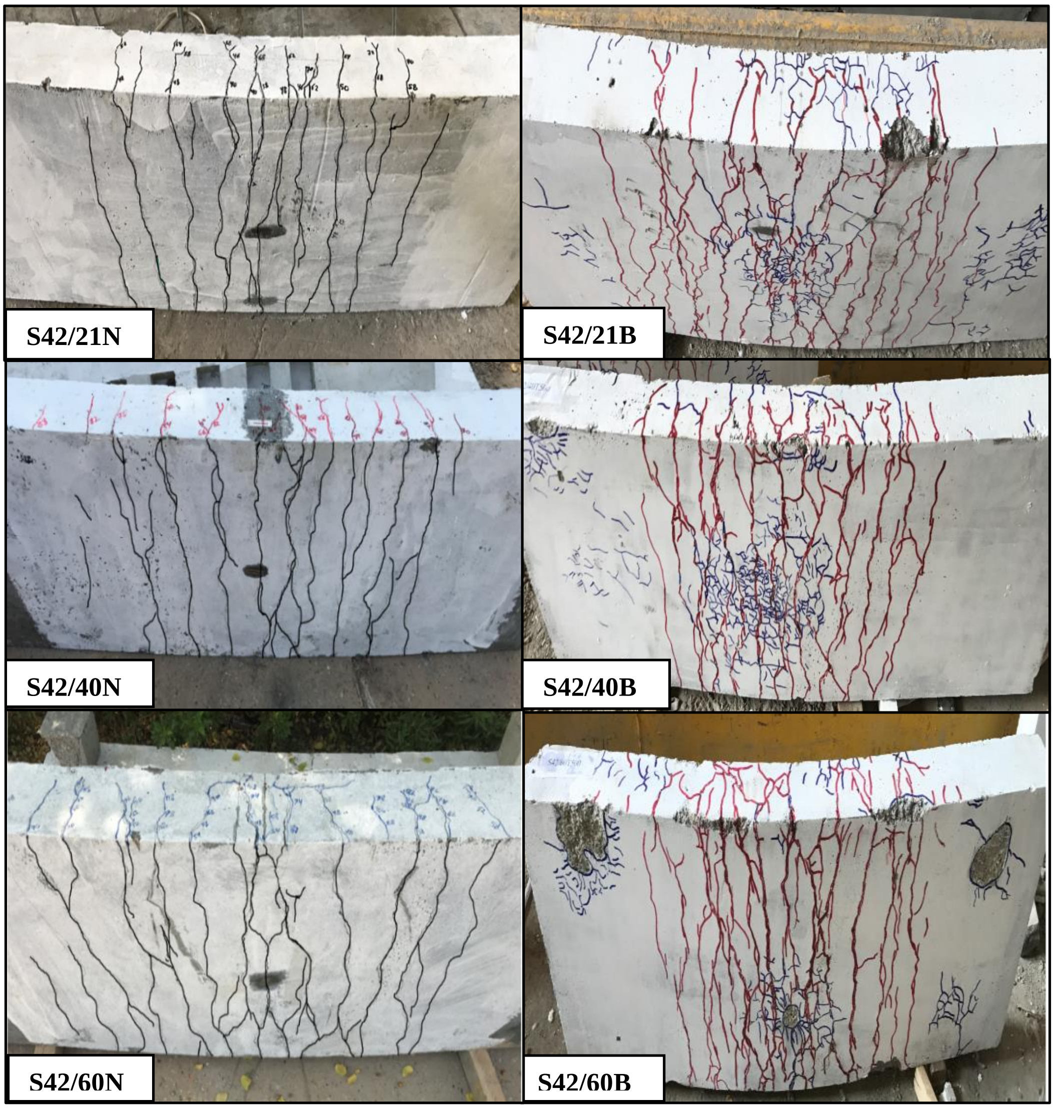

Figure 19. Cracks pattern for burned and non-burned specimens

Table 10. Data for burned and non-burned specimens

Specimens	Ultimate Load (P_u) (kN)	Ultimate Deflection (mm)	First Crack load (P_{cr}) (kN)	Residual strength	Compressive Strength (MPa) at 60 days	Inc. in ultimate deflection
S42/21NB	143.22	55.99	33.35	-	58.66	-
S42/40NB	155.98	58.81	33.35	-	61.56	-
S42/60NB	177.56	68.14	33.35	-	58.03	-
S42/21B	103.92	62.34	Precracking	72.56%	33.5	11.34%
S42/40B	110.03	68.92	Precracking	70.54%	30.75	14.67%
S42/60B	125.76	82.32	Precracking	70.82%	30.39	17.22%

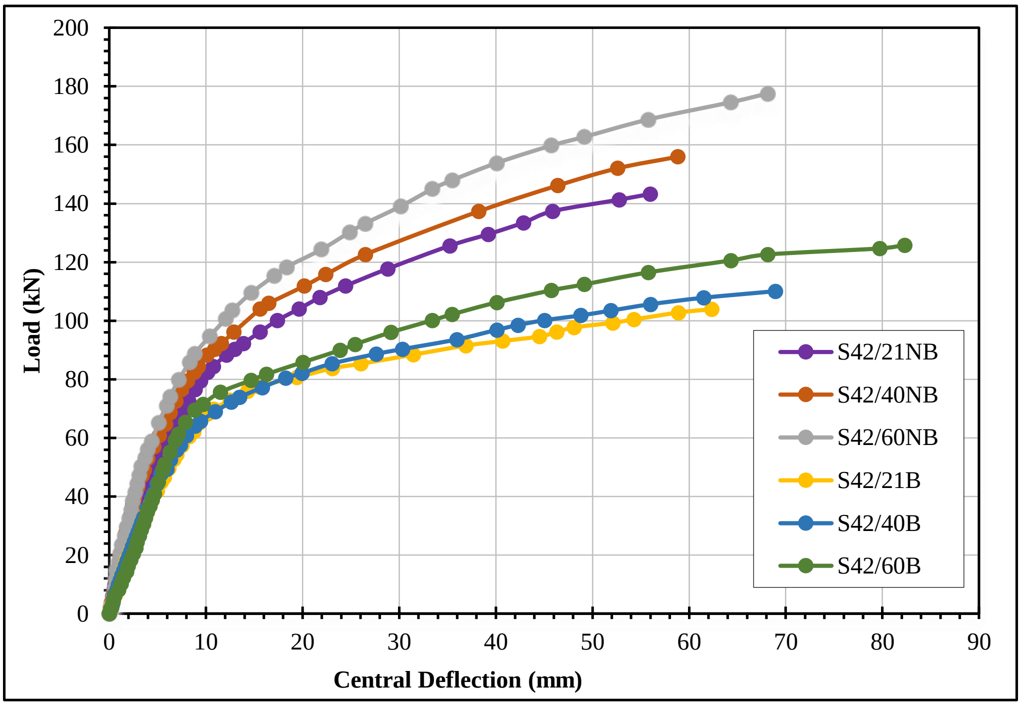

Figure 20. Central deflection-load behavior for burned and non-burned specimens

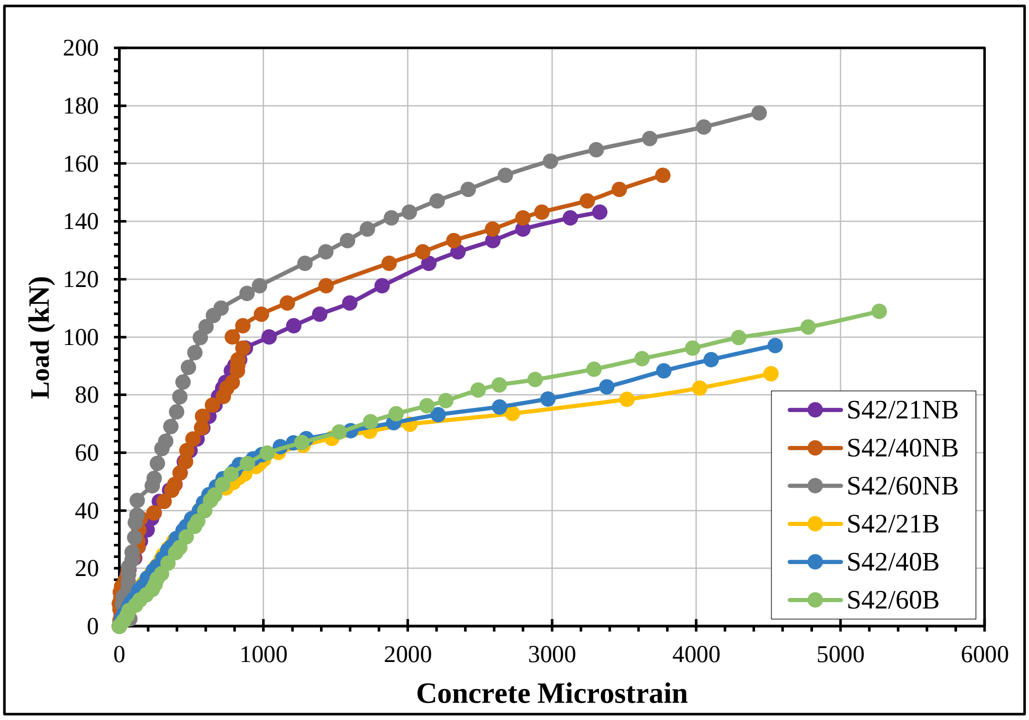

Figure 21. Load-strain behavior of concrete top fiber for burned and non-burned specimens

4. Conclusion

A test program was performed for six simply supported high strength reinforced concrete one-way slabs with reciprocal laced steel bars. As foresaw that flexural failure was occurred for all specimens by excessive deflection and the yield of tension steel bars, the flexural cracks for static test were located in the middle third of the bottom face for the slabs (constant moment). The cracks appeared after burning the specimens were distributed on the surface of the slab and approximately no cover spalling, also the deflection-time history of burned specimens indicated that the deflection decreased in the second hour. Increasing laced ratio for burned and non-burned specimens leads to an increasing in the failure load and ductility factor of the specimens, also the ultimate deflection and service deflection were increased. Load-strain curves improved that laced steel bars restricted tension reinforcement to strain in the strain hardening region, however concrete strain of the compression face was increased in a non-linear manner with load till the fail of the slab.

The compressive strength of concrete after exposure to fire flame was decreased, for 500℃ burning and sudden cooling the residual compressive strength percent was approximately (57.5%). Also, the failure load was decreased by about (28.7%). While the ultimate deflection was increased by about (14.41%).

5. Conflicts of Interest

The authors declare no conflict of interest.

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