

Steel Fiber Enhancement upon Punching Shear Strength of Concrete Flat Plates Exposed to Fire Flame

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Abstract

In this study, the effect of fire flame on the punching shear strength of steel fiber reinforced concrete flat plates was experimentally investigated using nine half-scale specimens with dimensions of 1500×1500 mm and a total thickness of 100 mm. The main investigated variables comprised the steel fiber volume fraction 0, 1, and 1.5% and the burning steady state temperature 500 and 600 °C. The specimens were divided into three groups, each group consists of three specimens. The specimens in the first group were tested with no fire effect to be the reference specimens, while the others of the second and third groups were tested after being exposed to fire-flame effect. The adopted characteristics of the fire test were; (one hour) burning time duration and 500 and 600 °C steady state temperature with sudden cooling process (water sprinkling directly after burning). The test results proved that exposing to direct fire effect for one hour caused a reduction in the punching shear strength with an increase in the ultimate mid-span deflection. Also, it was noticed that using steel fiber in the concrete mix leads to a significant increase in the punching shear strength for both the unburned and burned specimens. The ultimate punching load increased by about 11 and 16.6% for the unburned specimens with 1.0 and 1.5% steel fiber volume fraction, respectively, and by about 22.4 and 19% for the burned specimens at 500 °C with 1.0 and 1.5% steel fiber volume fraction, respectively. While, it was increased by about 29.2 and 21.5% for the burned specimens at 600 °C with 1.0 and 1.5% steel fiber volume fraction, respectively, as compared with the reference specimen of each group.

Keywords: Punching Shear; Steel Fibers; Flat Plates; Fire.

1. Introduction

A flat plate is a reinforced concrete floor which is usually with or without drops, supported generally without beams or girders [1]. Reinforced concrete flat plates are chosen by architects and engineers because they provide an elegant form of construction. In addition, they simplify and speed up site operation, allow easy and flexible partitioning of space and reduce the overall height of building [2]. One of the main problems in these slabs is the punching shear failure occurred at the connection between column and slab. Punching shear failure takes place when a plug of concrete is pushed out from the slab immediately above the column [3]. At elevated temperatures, concrete and steel undergo a reduction in their properties such as the strength, stiffness and physical properties [4, 5]. Some of these properties cannot recoverable after cooling, therefore, the punching strength of flat slabs subjected to fire is expected to be significantly affected [6]. Recently, new technique by adding steel fiber to modify the cracking control

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and punching shear resistance of the slab-column connection has been confirmed to show good results. Moreover, steel fiber also indicates high performance in the structures that sustained lateral loads i.e. seismic resulted from their ability to absorb the dissipation in energy of the structures [7, 8]. Therefore, the main goal of this study is to investigate experimentally the effect of adding steel fibers on the punching shear strength of the flat plates exposed to fire where, it is expected that the addition of fiber in concrete mix leads to an increase in the compressive and tensile strength and it is also can reduce spalling and enhance concrete resistance at fire.

2. Literature Review

Kamal et al. [9] investigated the effects of different fibers (steel and polypropylene fibers) on the mechanical properties of self-compacting concrete. A total of (90) cubes $100 \times 100 \times 100$ mm were tested to determine the compressive strength. The results showed that the optimum percentage of steel and polypropylene fiber was 0.75 and 1.0% of the cement content, respectively resulted in an increase in the compressive strength of concrete by about 37 to 13%, respectively. Minh et al. [10] studied the behavior of steel fiber reinforced concrete flat slabs in case of punching shear. Results showed that steel fiber improved the punching shear capacity of the tested slabs between 9 to 39.8% as a result to adding 30 to 60 kg/m^3 of steel fiber where this increase was proportional to the fiber volume fraction. Also, the average crack width in the slabs was reduced by about 70.8%. An experimental study about the effect of fire on some mechanical properties of concrete was carried out by Umran [11]. The compressive strength of concrete was measured by cubes of 150 mm whereas the flexural strength of concrete was measured by prisms of $100 \times 100 \times 400$ mm dimensions. The specimens were fired at three burning temperatures 400, 500, and 700 °C with duration of 0.5, 1.0, 1.5, and 2.0 hours. Results showed that the reduction in the compressive strength was between 15-30% at 400 °C, 22-41% at 500 °C and 38-57% at 700 °C. While, the reduction in the flexural strength was between 22-33% at 400 °C, 33-60% at 500 °C and 55-80% at 700 °C.

Venkatesh, [12] indicated different levels of decrease in the compressive strength of the concrete subjected to fire. The compressive strength of the concrete decreased slightly up to 400 °C and decreased rapidly at about 600 °C. This decrease began to diminish continuously as the temperature increased and approximately disappeared at 1000 °C. Rawaa et al. [13] investigated the effect of fire on the compressive strength of reactive powder concrete. Different burning temperatures 300, 400 and 500 °C with three steel fiber volume fraction 0, 1 and 1.5% were investigated in this study. Two cooling methods were adopted, sudden and gradual. Results showed that steel fibers ratio 1% presented the optimum response. Moreover, the sudden cooling method was improved to be the critical cooling method. Moss et al. [14] studied experimentally the behavior of two way reinforced concrete slab affected by fire. Moss noticed that the concrete and steel reinforcement in the lower face of the slab were heated well prior those in the upper face of the slab. When the temperature reached to 300°C in the steel reinforcement, the steel yield strength began to decrease causing a decrease in the bending moment and membrane strength. Hamed et al. [15] investigated experimentally the effect of fire on punching strength of flat slabs. Fourteen specimens were fired on their tension and then cooled gradually or suddenly by spraying water. Results showed that there was a reduction in the initial crack loads and ultimate punching loads by about 18.3 and 43%, respectively resulted from exposure of slabs to fire. Sudden cooling was found to reduce punching strength by 25% compared to specimens gradually cooled.

3. Experimental Program

The experimental program of this study consists of nine half-scale flat plates specimens of $1500 \times 1500 \times 100$ mm dimensions designed according to the ACI-318M-2019 [16] requirements as a simply supported along the four edges as shown in Figure 1. These nine specimens were divided into three groups where each group consists of three specimens of identical properties to those in the second and third groups as illustrated in Table 1.

Table 1. Details of the experimental specimens

Group No.	Specimen Designation	Steel fiber content %	Steady State Temperature (o C)
Group 1	NFC-NF	0	No fire effect
	SF1-NF	1	No fire effect
	SF1.5-NF	1.5	No fire effect
Group 2	NFC-F500	0	500
	SF1- F500	1	500
	SF1.5- F500	1.5	500
Group 3	NFC-F600	0	600
	SF1- F600	1	600
	SF1.5- F600	1.5	600

The test methodology is described in Figure 2 where the specimens of the first group (unburned group) were tested in punching directly. While specimens of the second and third groups were tested after being exposed to fire flame effect of 500 and 600°C steady state temperature for one hour simultaneously with an application of a uniformly constant equivalent dead load 8 kN/m² that represented 40% from the service load. Sudden cooling process by water sprinkling application was adopted to reduce the temperature of the burned specimens as shown in Figure 3.

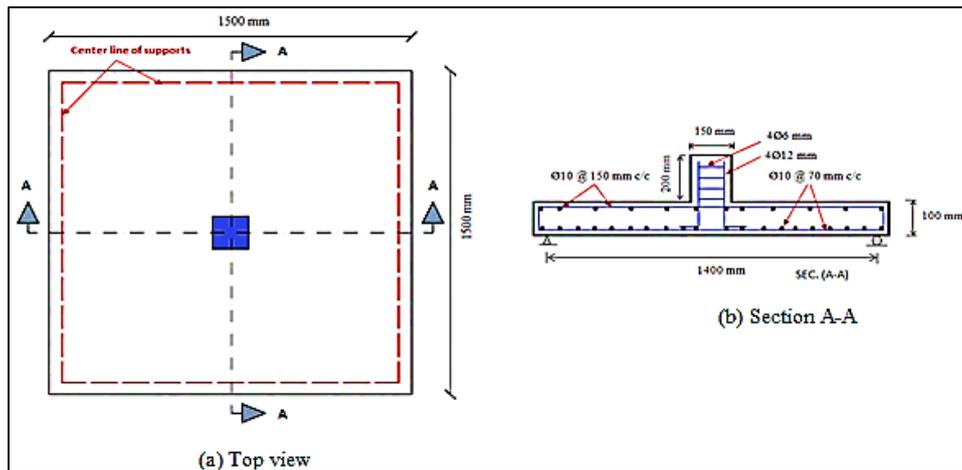


Figure 1. Details of the specimens

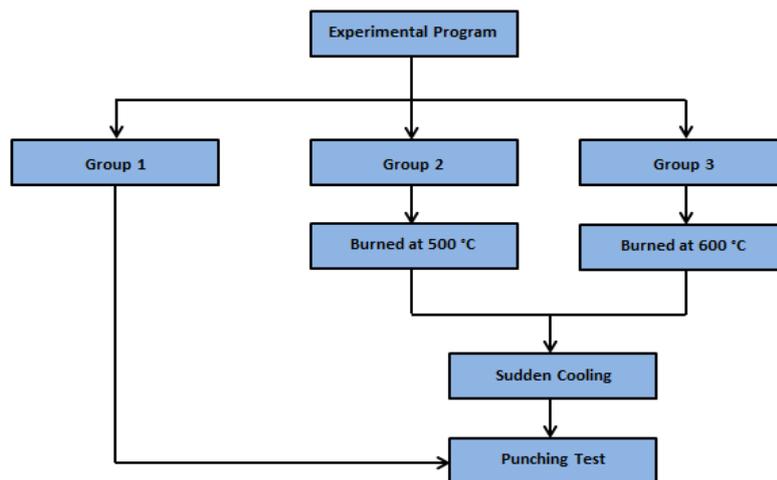


Figure 2. The test methodology

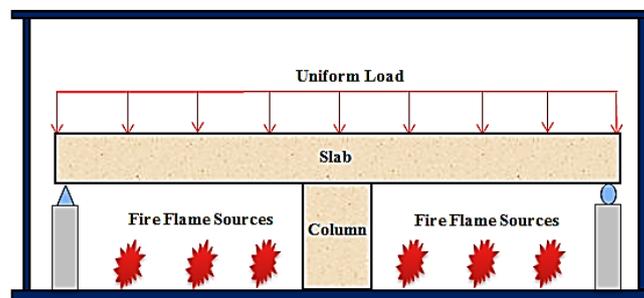


Figure 3. Burning setup

4. Materials

The concrete mixes adopted in this study were prepared using ordinary Portland cement tested according to the Iraqi Specification No. 5/2019 [17], coarse aggregate of 12 mm maximum size and natural sand (Zone 2) tested according to the Iraqi Specification No. 45/1993 [18]. Figure 4 presents the sieve analysis results for coarse and fine aggregate.

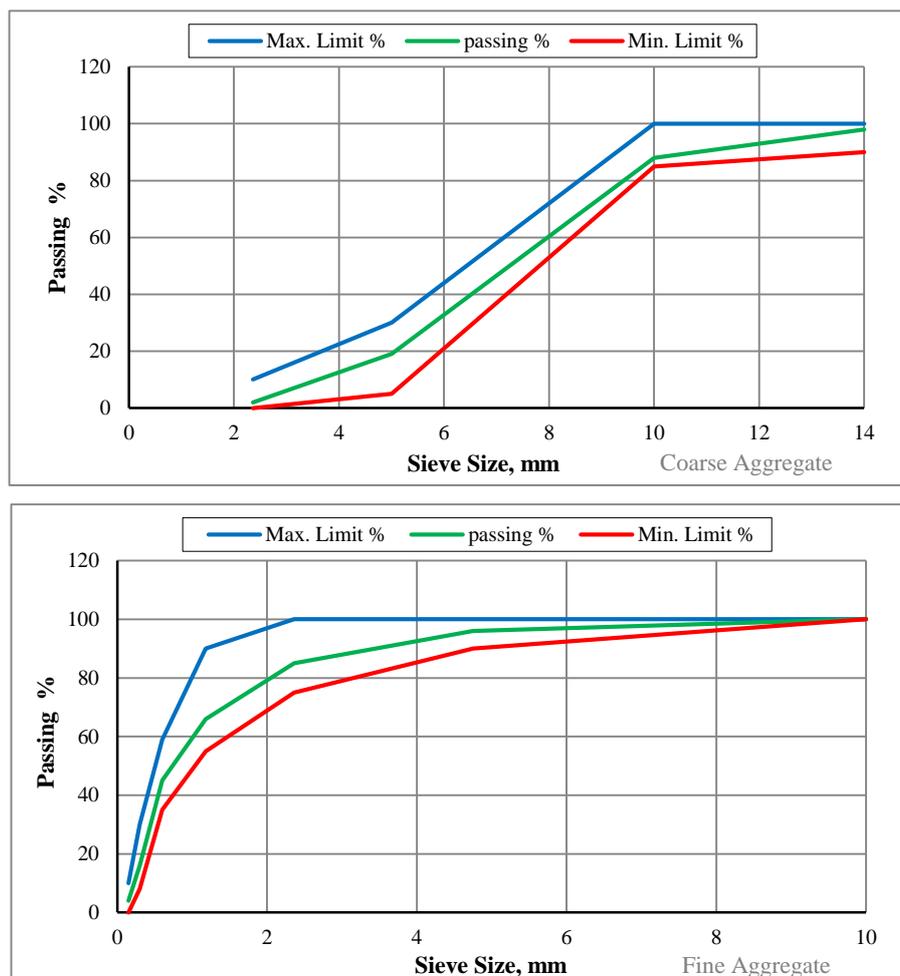


Figure 4. Sieve analysis results for coarse and fine aggregate

Hooked steel fiber was used with an average length and a diameter of 30 and 0.375 mm, respectively. While the ultimate tensile strength and the modulus of elasticity of this fiber were 1700 MPa and 200 GPa, respectively. All the specimens were reinforced by deformed steel bars of 10mm diameter and yield strength of 470 MPa, the considered space was (70 mm) c/c for both directions in the tension zone and (150 mm) c/c for both directions in the compression zone. Table 2 shows the proportion details of the concrete mixes used in this study.

Table 2. Proportion details of the concrete mixes

Mix Type	Cement (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)	Water (L/m ³)	Super plasticizer (L/m ³)	Steel fiber (%)
NFC	420	490	1042	189	3	---
MSF(1)	420	490	1042	189	3	1
MSF(1.5)	420	490	1042	189	3	1.5

5. Test Specimens and Instrumentation

All specimens were simply supported along the four edges and tested in punching mode with a single-point load applied by a testing machine of 100 ton capacity as shown in Figure 5. To evaluate the concrete compressive strength for each specimen, three standard concrete cylinders with 150×300 mm dimensions were tested according to ASTM C39-01 [19]. Also, the concrete tensile strength for each specimen was evaluated using three standard concrete cylinders with 150×300 mm dimensions were tested according to ASTM C 496-04 [20]. The vertical deflections were measured using a mechanical dial gauges of 0.01mm sensitivity and maximum capacity of 30 mm placed at the center and at the quarter span in each direction. The strains in concrete were measured using two electrical strain gauges 60 mm length with a nominal resistance of (120 Ω) and a nominal gauge factor of 2.13 were manufactured by Tokyo Sokki Kenkyujo Company (TML) in Japan. These strain gauges were installed at distance (d/2) from the face of the column in each direction. Figure 6 shows the details and the locations of all the considered instrumentation. The specimens of the second and third groups were burned before punching test using a furnace of 3500×2000×900 mm

dimensions. The temperature was monitored with time by a digital thermometer reader of ATP DT-612 model manufactured in UK, as shown in Figure 7.



Figure 5. Punching test setup

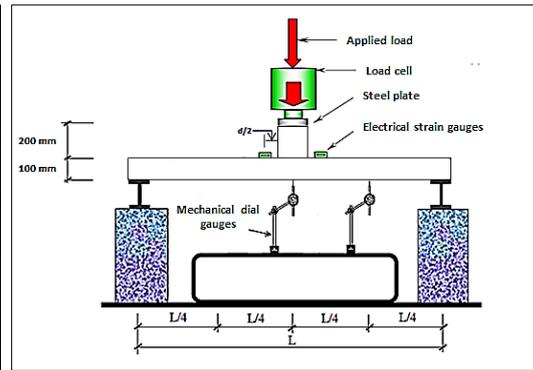


Figure 6. Details of the test setup



Figure 7. Burning procedure and setup

6. Results and Discussion

6.1. Compressive and Tensile Strengths of Concrete

Table 3 shows the compressive and tensile strengths for the concrete mixes before burning 25 °C and after burning at temperature 500 and 600 °C.

Table 3. Compressive and tensile strengths for all concrete mixes

Mix Type	Burning temperature (°C)	f'_c (MPa)	Residual compressive strength %	f_t (MPa)	Residual tensile strength %
NFC	---	35.52	---	3.8	---
	500	21.81	61.4	1.78	46.8
	600	18.36	51.7	1.45	38.2
MSF(1)	---	38.75	---	4.9	---
	500	27.1	70	3.3	67.3
	600	23.87	61.6	2.82	57.5
MSF(1.5)	---	40.32	---	5.15	---
	500	26.37	65	3.16	61.3
	600°	21.83	54.14	2.63	51

Regarding the results of the burned control specimens, a reduction in the compressive and tensile strengths was observed at the adopted burning temperatures 500 and 600 °C. Also, it can be noticed that, using steel fibers resulted in a positive effect on the compressive and the tensile strengths of unburned control specimens and the residual strengths after burning. Steel fiber ratio 1.5% by volume fraction presented the optimum enhancement in both compressive and tensile strengths for unburned state. While, the steel fiber ratio 1% by volume fraction was more sufficient than the ratio 1.5% in both burning temperatures 500 and 600°C since the ratio 1.5% resulted in a great reduction in the compressive and tensile strengths of concrete than that in the ratio 1% due to the effect of the expansion damage for the steel fiber which was greater in amount in the ratio 1.5% than that's in the ratio 1%.

6.2. Ultimate Load Capacity (P_u)

Table 4 shows the ultimate load with its corresponding deflection for all the tested groups. The outcomes indicated that adding steel fiber to concrete mix resulted in a significant enhancing in the ultimate load for both unburned and burned specimens as compared with no fiber reinforced corresponding specimens. Specimens (SF1-F600) characterized the optimum modification that's reached to 29.2%. This behavior belongs to the fiber contribution to bridge cracks that formed in the concrete and transfer the tensile stresses between the two opposite sides of cracks until these fiber are completely broken or pulled-out. For this reason, the tensile region in the specimen still resist the applied load until the stage of wide formation and distribution of cracks. This leads to an increasing in the tensile strength of the concrete and indirectly causes a case of optimum punching shear capacity. Regarding group 1, it was concluded that the specimen of 1.5 % steel fiber volume fraction showed the highest improvement in the ultimate load reached to 16.6% as compared with the reference specimen (NFC-NF). While in group 2 and 3, the specimens with (1) % steel fiber volume fraction presented the better improvement for the ultimate load by about 22.4 and 29.2%, respectively as compared with the reference specimen of each group. This can be interpreted by the reduction percentage in the mechanical properties of each specimen that caused by the exposing to elevated temperatures where the expansion damage was greater in the amount in specimen of 1.5% than that's in specimen of 1% resulted in a greater reduction in both compressive and tensile strengths of concrete.

Table 4. Ultimate load and ultimate deflection for specimens

Group	Specimens	f_c (MPa)	P_u (kN)	Increment in P_u %	Ultimate deflection (mm)
1	NFC-NF	35.52	180	---	15.5
	SF1-NF	38.75	200	11	16.7
	SF1.5-NF	40.32	210	16.6	17.22
2	NFC-F500	21.81	147	---	16.76
	SF1-F500	27.1	180	22.4	18.97
	SF1.5-F500	26.37	175	19	18.81
3	NFC-F600	18.36	130	---	17.42
	SF1-F600	23.87	168	29.2	19.89
	SF1.5-F600	21.83	158	21.5	19.65

6.3. Load-Deflection Relationship

Figure 8 shows the load-central deflection curves for the tested specimens in each group. It can be noted that the behavior of unburned specimens was similar and approximately linear at the elastic stage, before cracking generation. After cracking stage, the increasing rate in the deflection was escalating as the applied load increased where the cracks increased in number and width resulted in a decrease in the specimen stiffness. This leads to a change in the trend of the deflection curves. This behavior was changed in the burned specimens at 500°C where the linear stage reduced. Moreover, in case of burning steady state temperature 600°C, the behavior was completely nonlinear due to the increasing of specimen fire damaged. For the burned references specimens, strain hardening was achieved. This can be interpreted by the highly concrete damaged that causes an increase in the steel reinforcement stresses while this case was avoided in the fiber reinforced specimens since the steel fiber contributes to bridge concrete parts and softening the tensile strength behaviour of them. In general, at the same level of loading, the deflection of fiber reinforced specimens was less than that of no fiber contain (references) in each group. This indicated that, adding steel fiber to the concrete mix modified the specimen stiffness which can be more observed beyond the cracking stage since steel fiber contributes to reduce the damage in concrete below the neutral axis of the specimen's cross section through its bridging influence. While, before cracking, steel fiber produced low modification for the specimen stiffness as a result to the slightly increase in the modulus of elasticity. However, at the same level of loading, the specimen of 1.5% steel fiber volume fraction showed the less deflection in group 1. While in group 2 and 3, the specimens with 1% steel fiber volume fraction presented the less deflection in these groups. Comparing the results of the burned specimens with those of the corresponding unburned specimens showed that there is a reduction in the punching shear resistance for

all the burned specimens with an increase in the ultimate deflection at failure since the burning resulted in a specimen's damage which leads to a reduction in the stiffness that is directly proportion with the deformability of the burned specimens.

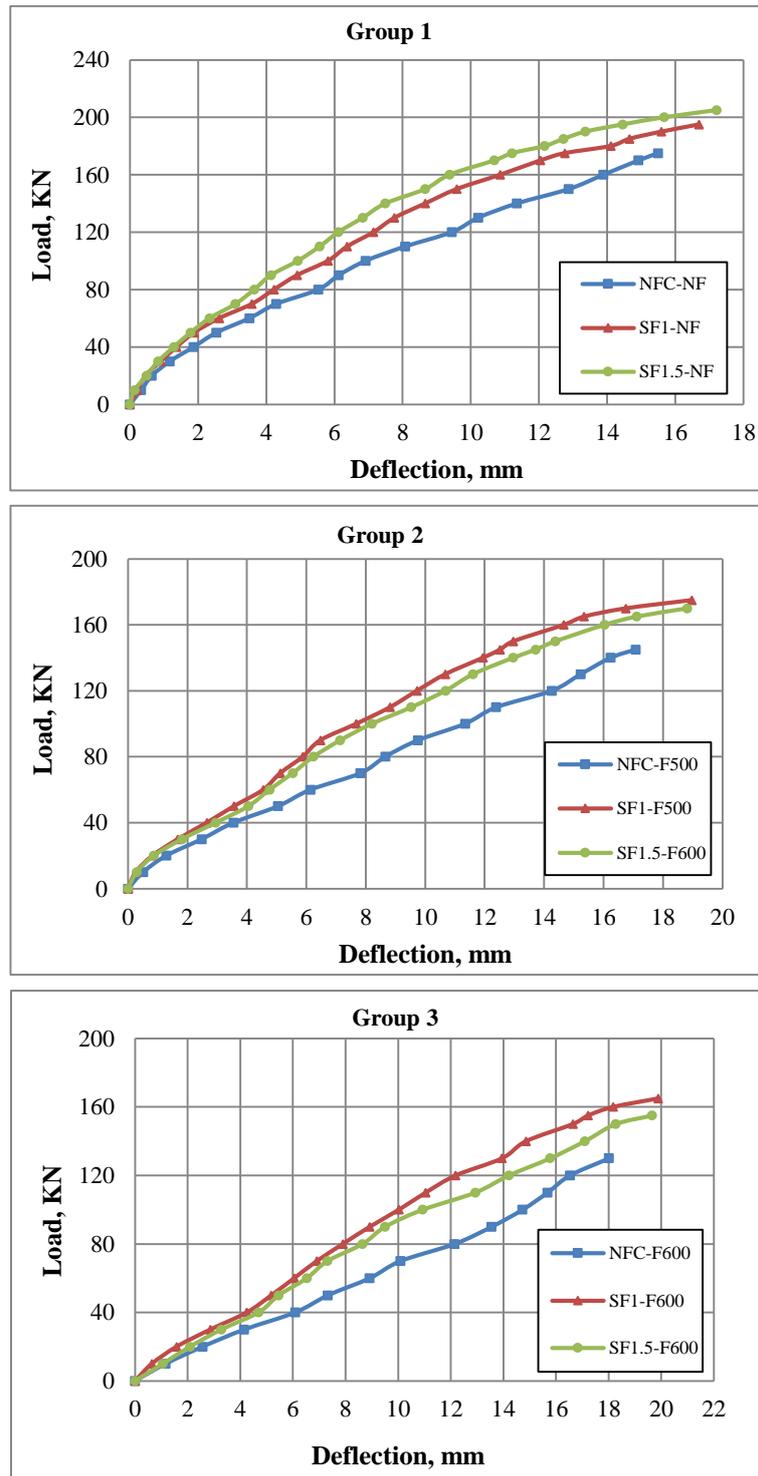


Figure 8. Load-central deflection curve

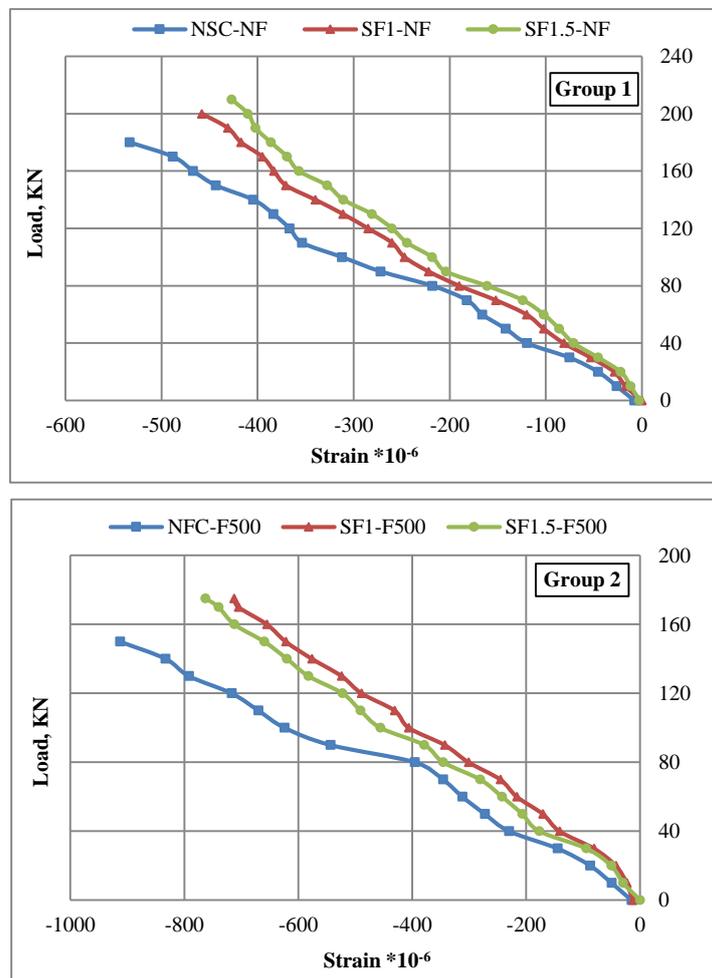
Table 5 symmetrized the outcomes of the tested specimens including the ultimate punching loads and their corresponding ultimate deflections in a new category. The specimens were grouped according to the fiber's kind (no fiber, steel fiber). In general, there is a significant reduction in the punching shear resistance with an increase in the peak deflection for the burned specimens compared with the corresponding unburned specimens as shown in Table 5. The main reasons beyond this behavior are the fire flame damage that caused a reduction in the stiffness of the burned slabs. The maximum drop in the punching load was detected at burning temperature 600°C by the specimen (NFC-F600) to be 27.78%, this was improved in case of steel fiber where the optimum modification was presented by the specimen (SF1-F600) in which the reduction percentage was 16 %.

Table 5. Variation in the ultimate load and deflection at different burning temperatures

Specimens	Temperature (°C)	P_u (kN)	Reduction in P_u (%)	Ultimate deflection Δ_u (mm)	Increasing in Δ_u (%)
NFC-NF	25	180	----	15.50	----
NFC-F500	500	147	18.33	16.76	8.13
NFC-F600	600	130	27.78	17.42	12.39
SF1-NF	25	200	----	16.7	----
SF1-F500	500	180	10	18.97	13.6
SF1-F600	600	168	16	19.89	19.1
SF1.5-NF	25	210	----	17.22	----
SF1.5-F500	500	175	16.67	18.86	9.52
SF1.5-F600	600	158	24.76	19.65	14.11

6.4. Load-Concrete Compressive Strain Relationship

Figure 9 shows the load-concrete strain curves for the tested specimens of each group at distance (d/2) from the face of the column, only in one direction. It can be noted that, the magnitude of the compressive strain in concrete was decreased by about 14 and 19.9% for the unburned specimens with 1 and 1.5% steel fiber volume fraction, respectively and by about 19.5 and 16.4% for the burned specimens at 500 °C with 1 and 1.5% steel fiber volume fraction, respectively. While, it was decreased by about 20.4 and 16.3% for the burned specimens at 600°C with (1 and 1.5% steel fiber volume fraction, respectively, compared with the reference slab of each group. This can be interpreted by the steel fiber influence upon the concrete compressive strength improving and this modified the performance of the specimen by allowing higher forces to be transferred across the slab-column connection. By comparison between the three groups, the specimen with 1.5% steel fiber volume fraction showed the highest decrease in the concrete compressive strain as compared with the reference specimen (NFC-NF). While in group 2 and 3, the specimens with 1% steel fiber volume fraction showed the highest decrease in the concrete compressive strain as compared with the reference specimen without fibers of each group. This can be interpreted by the percentage of reduction in the compressive strength of concrete for the specimens of each group.



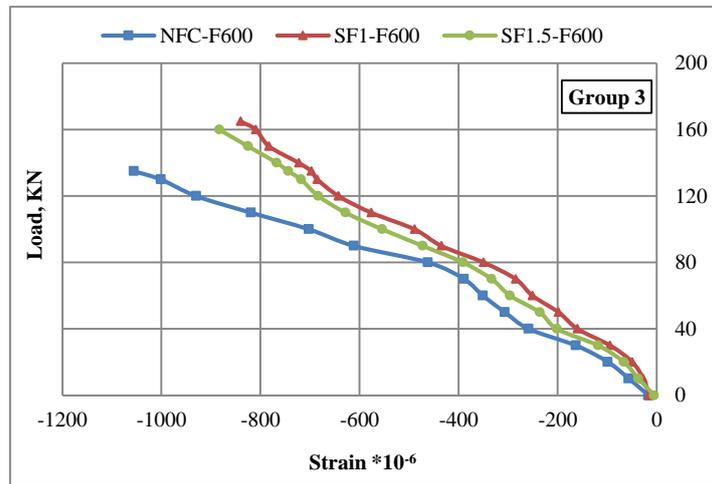


Figure 9. Load-concrete compressive strain relationships

6.5. Crack Patterns

After burning, hair cracks were appeared randomly on the concrete surface that subjected to fire effect. The hair cracks in the specimens of group 3 were more in number than those observed in the specimens of group 2 as shown in Figure 10.



Figure 10. Hair cracks in the burned



Figure 11. Crack patterns for specimens of Group 1



Figure 12. Crack patterns for specimens of Group 2



Figure 13. Crack patterns for specimens of Group 3

At the punching test, when the applied load increased, an initial crack was appeared around the column in the tension side for all the tested specimens. As the load increased, other cracks began to appear at the center of the tension side and extended diagonally towards the edges of tested slab causing the punching failure at the ultimate load. The number and width of these cracks in the burned specimens were more than those formed in the unburned specimens of group 1. The average maximum width of crack in group 1 was 0.65 mm for specimen without fiber and 0.5 mm for steel fiber reinforced specimens. In group 2, it was 0.8 mm for specimen without fiber and 0.65 mm for steel fiber reinforced specimens. While, in group 3, it was 0.95 mm for specimen without fiber and 0.75 mm for steel fiber reinforced specimens. Also, it should be mentioned that, in the specimens without fiber (reference specimens), there was an extensive spalling in the concrete cover of the tension side within the flexural cracks at failure. While in the other specimens which contain steel fiber, the spalling in the concrete cover of the tension side was less than that noticed in the reference specimen. This indicated that, fiber in the concrete mix works as a connector between the damaged concrete parts in the bottom surface of the specimen. Also, it was noticed that, the reference specimen (without fiber) in each group failed in punching with sudden and brittle mode. Whereas in the other specimens which are fiber reinforced, the failure was punching in a gradual way with more ductile mode than that observed in the reference specimen since the steel fiber increase the ductility of the specimen through modifying the deflection at the ultimate load. Figures 11 to 13 shows the crack patterns of the tested specimens.

6.6. Shape and Size of the Failure Zone

The punching failure mode for all the tested specimens was like the pyramid in the shape that making an angle with the lower face of the specimen. The failure angle was measured by the dimensions of the crushed region at the line passing across the loaded area where, the small value of failure angle means wider base for the failure pyramid that was pushed out. Several previous studies confirmed that the steel fiber reinforced concrete slabs tended to have higher failure angle than that in the conventional reinforced concrete slabs [21]. Table 6 shows the perimeter, the area and the failure angle of the punching failure zone for the specimens of each group. It can be noted that, the failure angle of the reference specimen in each group was smaller than that in the other fiber reinforced specimens, therefore, the failure punching perimeter was the largest. This indicates that, adding steel fiber to the concrete mix resulted in a failure punching perimeter reduction as compared with no fiber reinforced specimens. Since steel fiber contributes to prevent the disintegration in the concrete cover at the tension side of the specimen and helps to integrate the whole section. From the comparison between the three groups, it can be noticed that, the specimens of 1.5% steel fiber volume fraction presented the optimum decrease in the punching failure perimeter of group 1 by about 20.8%. While in group 2 and 3, the specimens with 1% steel fiber volume fraction characterized the highest decrease in the punching failure perimeter by about 14.3 and 17.5%, respectively, as compared with the reference specimen of no fiber contain in each group.

Table 6. Perimeter, area and failure angle for specimens

Group	Specimen	Perimeter (mm)	Decrease in Perimeter %	Area (mm ²)	Failure angle (θ°)
1	NSC-NF	3080	---	592900	17.9
	SF1-NF	2680	13	448900	21
	SF1.5-NF	2440	20.8	372100	23.5
2	NSC-F500	3640	---	828100	14.7
	SF1-F500	3120	14.3	608400	17.6
	SF1.5-F500	3160	13.2	624100	17.3
3	NSC-F600	4120	---	1060900	12.8
	SF1-F600	3400	17.5	722500	16
	SF1.5-F600	3560	13.6	792100	15.2

7. Conclusions

The following main conclusions can be drawn:

- Specimen exposing to direct fire for one hour caused a reduction in the ultimate punching load compared to the corresponding unburned specimen. This reduction was improved by adding steel fiber to the specimen;
- The punching failure was suddenly with brittle mode in the reference specimens (without fiber). While, it was more ductile with gradual way in the fiber reinforced specimens;
- Adding steel fiber optimize the behavior regarding the perimeter of failure punching zone, crack width, concrete spalling and concrete compressive strain for both unburned and burned specimens;
- Steel fibers ratio 1.5% by volume fraction was more effect than the ratio 1% for unburned specimens. While, for burned specimens, the ratio 1% was more effect in both burning temperatures 500 and 600°C.

8. Declarations

8.1. Author Contributions

Conceptualization, A.N. and S.D.; methodology, A.N.; software, A.N.; validation, A.N. and S.D; formal analysis, A.N; investigation, A.N; resources, A.N; data curation, A.N; writing—original draft preparation, A.N; writing—review and editing, A.N; visualization, A.N; supervision, S.D.; project administration, A.N; funding acquisition, funding acquisition. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available in article.

8.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

8.4. Conflicts of Interest

The authors declare no conflict of interest.

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