Role of macro fibers (steel and hybrid-synthetic) in the residual response of RC beams exposed to high temperatures

A. Khalighi¹ · R. A. Izadifard¹ · A. Zarifian¹

Received: 20 June 2020 / Accepted: 29 October 2020 / Published online: 11 November 2020
© Springer Nature Switzerland AG 2020

Abstract

Inclusion of fibers can mostly enhance the mechanical properties of concrete; however, the role of those in reinforced concrete beams wherein the interaction between concrete, steel reinforcement, and fibers is crucial can be different. This paper provides an experimental study to evaluate the residual behavior of macro fiber-RC beams exposed to high temperatures. Thirty-six scaled reinforced concrete beams were designed and fabricated according to the ACI 318 criteria and requirements, subjected to high temperatures up to 800 °C. In this investigation, mechanical and deformation properties of heated RC beams, failure patterns, and confinement role of fibers were examined, discussed, and compared with non-heated specimens. This investigation indicated, adding steel fibers noticeably improved the residual bearing capacity and bond interaction between steel bars with concrete at high temperatures. Hence, this value for RC beams reinforced with steel and hybrid-synthetic fibers at 800 °C was 65% and 48% of their initial capacity, respectively; however, for plain concrete was about 40%. Moreover, the transformation of failure patterns depended on the type of used fibers and experienced temperatures.

Keywords Fibrous RC beam · Residual bearing capacity · Bond interaction · High temperatures · Experiment

1 Introduction

Widely used in the building, industrial ground, and airport, concrete as a structural material has a good resistance under fire conditions due to high thermal capacity, low thermal conductivity, and slow deterioration of mechanical properties [1]. In recent decades employing fibers in the concrete mixture has been also growing in popularity. Besides proven, desired effects of steel fibers on concrete through numerous studies, the recent research has confirmed that the application of macro-synthetic fibers not only can enhance ductility and load capacity but can fulfill the required shear strength [2]. That is why it is considered as an alternative way to reinforcing, when pre-stressed elements, hollow-core slab, and tunnel segments

are concerned [3, 4]. However, their performance at a high temperature can be a moot question.

Generally, high temperatures impose physical and chemical changes on concrete structures, and in turn, a degradation in strength, elasticity model, and durability [5, 6]. This reduction of mechanical properties depends on the maximum temperature, heating scenario, exposure time, material properties, and level of stress [6, 7]. Regarding post-fire behavior, additional factors such as cooling method, recovery properties, and level of applied load can be influential as well [6, 7]. Since, adding fibers is able to address some of those issues and improve the mechanical properties of concrete, using fibrous concrete has grown in popularity during recent decades. In the case of concrete, a considerable number of studies have been conducted about the effect of steel and polymer fibers at high

✉ A. Khalighi, A.khalighi@edu.ikiu.ac.ir; R. A. Izadifard, izadifard@eng.ikiu.ac.ir; A. Zarifian, A.zarifian@edu.ikiu.ac.ir | ¹Department of Civil Engineering, Imam Khomeini International University, Qazvin, Iran.

temperatures, most of which indicated the presence of fibers can enhance the fire properties of the concrete's element [8–12]. Regarding steel fibers, the addition of those leads to an improvement in the mechanical properties of heated concrete such as tensile, compression and flexural strength [10, 12, 13], and it also slows down the loss of residual mechanical properties at high temperatures [12, 14]. However, some researchers claimed that adding fibers, especially steel ones, may have no significant effect on concrete behavior [15]. As for polymer fibers, although the advantages of using those in case of fire, spalling in particular, are undeniable [16–18], the effects on the mechanical properties are still a source of conflict. While some studies have indicated the presence of polypropylene fibers can enhance the mechanical properties of concrete at the elevated temperature [19–21], others showed, it has indiscernible or even adverse effects on the mechanical properties, whether in the ambient or high temperatures [16, 22, 23]. Pilya et al. [24] showed, after 600 °C, PP fibers have no significant effect on the residual mechanical properties. Also, Rudnik and drzymala [25] used monofilament and fibrillated in concrete at different sizes and indicated the kind and the amount of PP fibers on the thermal stability are not significant. Notwithstanding comprehensive study around PP fibers, far fewer investigations have been conducted on the effect of hybrid macro-synthetic fibers on concrete at high temperatures while a certain dose can improve the residual mechanical properties of concrete, together with minimizing the proportion of spalling [26, 27]. Therefore, it benefits ductility under compression and energy absorption capacity under tension [27].

When it comes to the structural concrete members like Beams, as opposed to concrete elements, Scant information about the effect of fibers, especially macro ones, can be found at the high temperature. In general, concrete strength, and its residual strength after fire exposure do not have a significant influence on the residual bearing capacity of RC beams; however, the residual strength of steel reinforcements, depending on the temperature experienced by rebars during the fire exposure, has the crucial role [28, 29]. Moreover, residual bearing capacity of the RC beams at high temperatures will decline by increasing the steel reinforcement ratio [30]. Concerning the steel-fiber reinforced beam, fibers can prevent cracks propagation, modifying the nonlinear behavior, increasing ductility, and delaying the time of spalling [10–13, 31, 32]. Furthermore, Liu Jin et al. [30] conducted an investigation which showed by increasing the dosage of steel fibers, shear failure in RC beam turn into flexural one, and steel fibers content had not a significant effect on the mechanical properties of the RC beam at high temperatures.

Scant information about the effect of macro fibers on RC beams on the one hand, and the dearth of tabulated

data in current standards on another hand illustrate a bewildering picture of the role of the fibers in the case of reinforced concrete members. In addition, the behavior of the RC members, due to the presence of steel bars and their interaction between fibers and concrete, are more complicated than mere concrete and fibers. That is why, this study tries to depict a more realistic and clear view of the impact of different types of macro fibers on the residual behavior of reinforced concrete beams, together with the role of bond interaction between steel bars and Macro fibers in the flexure and failure mode. Hence, three different types of RC beams (plain, macro-steel fibers, and hybrid macro-synthetic fibers) were fabricated. After high-temperature exposure (25, 400, 600, 800 °C), 4 points loading test was performed to examine the residual capacity of specimens. At the first stage, in addition to measuring degraded mechanical properties of concrete and steel reinforcements, deteriorated mechanical properties of RC beams, including load-bearing capacity, deflection, flexural stiffness, and energy absorption, were studied. Then, by developing a numerical model together with experimental results, the role of fibers in bond interaction between concrete and steel reinforcements were studied in different types of beams. The precision of ACI terms concerning fibrous concrete at high temperatures was discussed as well.

2 Experimental program

2.1 Scope of program

In this study, the effect of the macro fibers on the mechanical and deflection behavior of RC beams was investigated. Hence, thirty-five scaled RC beams (Fig. 1), made with plain and fibrous concrete (steel and hybrid synthetic), were fabricated to expose four target temperatures (25, 400, 600, and 800 °C) (Table 1). Moreover, the influence of

Fig. 1 RC beams specimens

Table 1 Nomenclature and testing scope of RC beams

Name of RC beams	Used fibers	Curing (days)		Target temperatures (°C)			
		water	Room temperature	25	400	600	800
Number of specimens							
P	–	28	47	3	3	3	3
MS	Hybrid-macro-synthetic	28	47	2	3	3	3
S	Macro-steel	28	47	3	3	3	3

fibers on the bond interaction between concrete and steel reinforcement, together with its influence on the failure mode, has been examined.

2.2 Test specimens and parameters

An experimental program was conducted to study the behavior of RC beams after exposure to high temperatures. For this purpose, 35 scaled RC beams (including plain and fiber reinforced concrete beams), according to the American concrete institute (ACI 318) [33], were fabricated by using ordinary portland cement. The beams were made from the normal strength concrete, cured 28 days into the water, and 47 days at room temperature to avoid the effect of excessive moisture. Also, the average compressive cylinder strengths of the concrete, measured at 28, were 25 MPa (as a conventional strength), and the aggregates were siliceous gravel with maximum size 12 mm, which met the ASTM requirements [34]. More detail of concrete mix designs and cement properties are shown in Tables 2 and 3. Regarding RC beams specimens, dimensions were dictated according to several items such as the available equipment (furnace and hydraulic jack), the proper scale of real RC beams, and design codes for the flexural test. For instance, according to the German standards for fiber-reinforced concrete, the dimension of the beams for the four-point bending test is 150*150*800 mm. Because of that, we tried to keep the specimens' dimension with a scale of 1:4, closing to the DAfStb standard [35]. The longitudinal ribbed steel bars and the stirrups were S400 steel; therefore, the yield strength of the steel bars with a diameter of

8 mm was about 450 MPa, and the ultimate strength was 650 MPa (Table 3). Each beam was 800 mm long, and of rectangular cross-Sect. (100*150 mm) that Four Ø8 mm bars were used in the beams two bars as the compressive reinforcement and the others as tensile reinforcement with a longitudinal ratio ($\frac{A_s}{b \times h}$) of 0.013. The shear reinforcement of the beams comprised Ø 2.5 mm stirrups at a spacing of 100 mm over the length of the specimens, and ties were bent at 135°, at the transverse ratio ($\frac{A_{sv}}{s}$) of 0.098. Also, the thickness of cover from the bottom and top was 10 mm and 20 mm, respectively. More details on the specifics of the beams are given in Fig. 2.

2.3 Fibers' properties

Two kinds of macro fibers, hybrid-synthetic and steel, were used in the concrete mixture (Fig. 3). Using macro synthetic fibers were confined to the 0.27% of concrete's volume, which is equivalent to 2.4 kg/m³, and also the corresponding value for steel fibers (according to their specific gravity) was 20 kg/m³. According to recent studies adding 1% steel fiber by volume of concrete can help to improve fire properties, while more than 1.5% fiber content may be an adverse effect on the mechanical properties [1, 13]. Moreover, this figure for polypropylene fibers is at the range of 0.5–3 kg/m³ [12]. Also, polymer fibers in this project were color-blended macro synthetic fiber made of 100% virgin copolymer/polypropylene. Its twisted-bundle monofilament and fibrillated fibers yield a high-performance concrete reinforcement.

Table 2 Mix proportions per cubic meter of concrete

Type of concrete beam	Cement (kg/m ³)	Coarse aggregate (kg/m ³)	Fine aggregate (kg/m ³)	w/c	Maximum aggregate size (mm)	Silica fume (kg/m ³)	Macro synthetic fibers (kg/m ³)	Steel fibers (kg/m ³)
P-RC beam	400	900	800	0.45	12	8	–	–
MS-RC beam	400	900	800	0.45	12	8	2.4	–
S-RC beam	400	900	800	0.45	12	8	–	20

Table 3 Characteristics of cement, steel bars, and concrete

Chemical properties of cement (%)													
SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Cl	SO ₃	Lo.I	I.R	Free CaO	Total alkalis	C ₃ A		
21.10	4.90	4.00	64.20	2.20	0.025	2.20	1.00	0.35	1.30	0.75	6.00		
Mechanical properties of concrete (Kg/cm ²)													
2 day		7 day		28 day									
180		410		550									
Mechanical properties of steel bars													
Fy (MPa)	Fu (MPa)			E		ε _{max}							
458	644.7			1211.4		0.25

Fig. 2 Detail of elevation and cross-section of RC beams

Fig. 3 Macro fibers: **a** Steel; **b** Hybrid-synthetic

Table 4 Properties of fibers

	Steel fiber	Macro-synthetic fiber
Length (cm)	5	5.4
Thickness (mm)	0.55	–
Length/diameter	65	–
Tensile Strength (MPa)	1100–1200	570–660
Specific Gravity	7.8	0.91
melting point (°C)	1516	160
Absorption	Nil	Nil
Materials	low carbon steel	Virgin Copolymer/Polypropylene
Form	solid	Monofilament/Fibrillated
Compliance	ASTM 510 M	A.S.T.M. C-1116, D-7508 and SDI C-2011 Standard 13.a.3

to the fibers test at high temperatures, by the increase in temperature, the steel fibers became fragile, and its color turned into the black, While the macro-synthetic fibers melted at 400 °C and completely evaporated at

the temperature of 600 °C (Fig. 6). However, regarding the RC beams, this trend is slightly different. Thus, the synthetic fibers were sparsely presence at the 400 °C, and hardly ever at 600 °C into the RC beams, which could be

Fig. 4 Detail of heating and cooling process

Fig. 5 Electrical-element furnace

related to the high ambient pressure into the RC beams and solidifying after decay phase.

Regarding Mass loss, in this study, all specimens were weighed before and after the heating process. Mass loss in heated-concrete, as a result of evaporation of moisture, occurs by increasing temperatures and depends on some factors, such as kind of aggregate and the fire scenario, in which, the type of aggregate plays a more important role [6]. Also, it can be accompanied by mass reduction caused by spalling after fire exposure. Since siliceous aggregates were used in the specimens' mixture, the loss of mass at all temperatures was minimum for all concrete types. The reduction of the MS-RC beams was higher compared with two others until 400 °C; however, by the increase in temperature, they got the same trend and at the 800 °C, and experienced about a 10% decrease of their original mass.

2.6 Testing procedure

The four-point loading test was performed to examine the residual strength of RC beams. The RC beams were tested under the simply-supported condition that had a span of 700 mm. The load was applied through a load cell, and two LVDTs measured deflections during the loading test in the mid-span of specimens, as well. The load was applied until failure moment, and mid-span deflection monitored simultaneously (Fig. 7). Generally, the benefit of the four-point bending test arrangement is the constant value of the bending moment, with no shear force in the middle third of the specimen, and consequently the elimination of the effect of shear force.

3 Results and discussion

3.1 Mechanical degradation of rebar and concrete caused by temperature

The strength of steel reinforcements, likewise concrete, was declined by the increase in temperature. Since the residual capacity of the RC beam is significantly influenced by the residual strength of reinforcement [28], having reduction values of steel bars caused by temperatures play a key role in a better understanding of the heated-RC beams' behavior. Thus, not only the effect of the target temperatures (25, 400, 600 and 800 °C) were investigated on their strength (Fig. 8), but also the influence of recovery days (after cooling down, 7-day and 28-day) were studied in this case (Table 5). Moreover, the color induced by temperature on the steel reinforcement is shown in Fig. 9.

Yield and ultimate tensile strength of heated-steel reinforcement indicated the strength degradation of steel bars caused by high temperatures, was relatively small, and the effect of recovery days was not noticeably tangible. However, after 28 days, the steel bars experienced slightly improved on their strength. Thus, the residual yield strength of steel bars, which was about 83% of their initial strength at 400 °C and 600 °C, improved merely 2% after 7 and 28 days of recovery. But a relative improvement occurred at the 800 °C, where the yield strength for 7 days of recovery was about 76% of their initial strength, and after 28 days, it reached 84%. Regarding the ultimate strength, 8% increase in residual strength was observed at 28-day, as well (Figs. 10 and 11). By and large, the temperatures and recovery time had no significant effect on the residual tensile strength of reinforcement in this research. Also, this practice has been seen in the maximum strain of steel bars, most of which recorded almost a similar maximum strain (Table 5). It

Fig. 6 Changes in fibers by increasing temperature: **a** Steel fibers; **b** Hybrid-synthetic

Fig. 7 Test setup

should be pointed out; all the specimens were cooled down gradually with air.

Moreover, the ratio of ultimate stress to yield stress, which was 1.4 at the room temperature, increased after exposure to high temperatures and, eventually, reached 1.5 at 800 °C for all types of beams (based on the average). This means that the strain-hardening will be unchanged after decay phase, even after exposure to high temperatures. To calculate the flexural strength of RC beams two factors of concrete's compressive and bar's tensile strength are taken into consideration. Hence, to estimate the strength, those were chosen from the experimental values of residual strength opted from tensile test result and cylindrical compressive strength of concrete (Fig. 12).

The normalized values are presented in Fig. 13. Also, the shaded area represents reported data for residual compressive strength of fibrous concrete done by other researchers [13, 14, 19, 27, 38–40] (Fig. 13).

3.2 Residual load-bearing capacity

The ultimate bearing capacity of RC beams was reduced by an increase in the temperatures. Generally, three main factors including the hydration of the C-S-H, thermal incompatibility between the cement paste and aggregate, and pore pressure contribute to the strength degradation of concrete at high temperatures [13]. Concerning reinforced concrete beams, the

Fig. 8 Tensile test of heated-steel reinforcement

Fig. 9 Color change in steel reinforcement by temperature

mechanical degradation of tensile reinforcement, and bond strength between them with concrete will also affect the RC beams' behavior [41]. According to the following figures, plain RC beams, compared to the fibrous one, generally demonstrated lower residual capacity at all temperatures and lower ultimate deflection at range of 25–600 °C. Moreover, as a result of the increase in temperature, the linear stage of the load–deflection curves becomes gentle and eventually completely disappears at 800 °C (Fig. 14). But, the addition of fibers caused an improvement in the bearing capacity in all temperatures. Generally, the presence of micro-fibers in the concrete's mixture can enhance the strength and stiffness respond before carking while employing macro ones can curb the formation of wide cracks. In other words, macro fibers capable of effecting cracks' mechanism and delay the propagation, which increases the concrete strength [32]. Also, adding steel fibers to the concrete mixture led to a considerable increase in bearing capacity that remained almost constant until 600 °C (Fig. 14). The slope of the linear stage in the load–deflection curves has been unchanged even at 600 °C, as well. On the other hand, although MS-RC beams showed fine performance at room temperature, with the increase in temperature and

Fig. 10 The Normalized value of yield strength according to the temperature and days of recovery

as a result of melting fibers, they experienced a drop in their strength. In the absence of fibers at the high temperatures, a series of channels (which evacuated the water's vapor) released pore pressure. The first result of such a mechanism is reducing temperature, and in turn,

Table 5 Residual strength of steel reinforcement according to the temperature and days of recovery

	1-day			7-day			28-day		
	Fy (MPa)	Fu (MPa)	$\Delta L/L_1$	Fy (MPa)	Fu (MPa)	$\Delta L/L_1$	Fy (MPa)	Fu (MPa)	$\Delta L/L_1$
25 °C	458	644.72	0.25	458	644.72	0.25	458	671.59	0.25
400 °C	400.7	599.3	0.23	409.4	613.4	0.23	410.36	607.2	0.22
600 °C	412.9	606.1	0.25	408.1	595.4	0.24	411.87	609.94	0.22
800 °C	370.3	562.2	0.25	362.6	556.8	0.24	403.1	602.98	0.25

Fig. 11 The Normalized value of ultimate strength according to the temperature and days of recovery

Fig. 12 Compressive test Specimens

decreasing the crack at the decay phase [11]. Table 6 and Fig. 14 demonstrate the residual load-bearing capacity of beams and corresponding load–deflection curves. It should be pointed out that all values correspond to the failure moment.

The results of the four-point loading test and the residual flexural capacity of specimens are presented in Figs. 15 and 16. As can be seen, the addition of fibers, either steel or macro-synthetic, had the same effect on the strength of the non-heated beams and increased it about 40% in compared with the plain RC beams (Fig. 16). This fact indicates the performance of hybrid macro-synthetic fibers is close to steel ones at the room temperatures.

When the temperature increased to 400 °C, the reduction values of bearing capacity for S-RC beams and P-RC

Fig. 13 Reduction value of concrete and steel reinforcement by temperature

beams were 4 and 6%, respectively; however, the MS-RC beams experienced a relatively severe reduction of about 20% caused by the melting of fibers (Fig. 15). After the decay phase, the melted polymer fibers could be observed into the beam section at 400 °C; however, they had not enough strength against tensile stress because their integrity and mechanical properties have been influenced by the melting process.

At the temperatures above 600 °C that degradation of strength reduced at a higher rate, S-RC beams showed a proper performance and experienced just about 4% reduction (Fig. 15). This could be related to the crack-bridging effect of fibers, which prevented the propagation and expansion of cracks. This mechanism certainly led to an improvement in the nonlinear behavior, ductility, and an increase in the bearing capacity of the RC beam [11, 31]. The plain RC beams compared with S-RC ones experienced a more intensive reduction in their strength. At 600 °C, the residual bearing capacity in specimens reinforced with steel fibers was about 65% more than plain ones. Also, the variations of residual strength for the MS-RC beam at the range of 400–600 °C were almost unchanged. Interestingly, Although the MS-RC beams lost the fibers completely at the 600 °C, they still had about 40% more capacity than plain ones, and this practice even occurred at the 800 °C (Fig. 16). The probable reason for such higher capacity could be related to the release of pore pressure at the lower temperature due to the melted fibers. As cited, pore pressure is one of those factors which can have a detrimental effect on the mechanical degradation of concrete. Since this pressure can cause internal stress and trigger the concrete deterioration, controlling it can partly preserve concrete strength. Furthermore, the chemical effects of

Fig. 14 Load–deflection curves of plain and fibrous RC beams at the target temperatures

Table 6 Results of four-point loading test of RC beam

T(°C)	Plain RC beam				MS-RC beam				S-RC beam			
	Capacity (kN)	AVG	St.Dev	C.o.V	Capacity (kN)	AVG	St.Dev	C.o.V	Capacity (kN)	AVG	St.Dev	C.o.V
25	39.47	39.83	1.81	0.04	56.66	56.14	0.72	0.01	50.27	54.87	4.64	0.08
	38.22				55.63				54.79			
	41.80				–				59.55			
400	37.40	37.79	2.40	0.06	47.19	44.6	2.87	0.06	51.72	52.97	3.11	0.05
	35.60				41.50				50.69			
	40.36				45.11				56.52			
600	33.09	31.70	1.47	0.04	45.84	47.47	2.78	0.05	50.69	52.37	2.29	0.043
	31.87				45.89				54.98			
	30.15				50.69				51.44			
800	11.69	15.38	3.51	0.22	23.73	23.90	1.61	0.06	37.96	35.76	3.06	0.08
	15.75				22.38				37.07			
	18.68				25.60				32.27			

melted fibers on the cement paste may be another possible reason that must be scrutinized.

At the 800 °C, the mechanical degradation of the RC beams reached the lowest point, and the residual strength of beams reinforced with steel and macro-synthetic fibers was about 132% and 55% higher than plain ones (Fig. 16).

This fact is an indication of the beneficial effect of fibers on the post-heated RC beam, even at the severe temperatures. Also, reduction values of bearing capacity for steel, syntactic and plain RC beams at 800 °C, with a similar rate, were 34.7, 57.42, and 61.38%, consecutively (Fig. 16).

Fig. 15 Variation of residual bearing capacity by the temperature of plain and fibrous RC beams

Fig. 16 Normalized residual capacity of RC beams at target temperatures

3.3 Flexural stiffness

By examining the slope of the tangent line to load–deflection curves- which is defined as flexural stiffness -can be found that these values are similar for all types of beams at 25 °C. With increasing in temperature and occurrence cracks at the tensile zone, a deviation from those appeared. Fibrous beams, generally, had a slower reduction rate in their stiffness than plain ones, which can be attributed to the different crack mechanism and better non-linear behavior of those. Moreover, due to the crack-bridging effect of steel fibers, these kinds of beams had better performance in terms of stiffness (Fig. 17).

3.4 Energy absorption

The area under load–deflection curves, which can be calculated up to the different deflection ($L/50$, $L/100$, $L/75$ or L_{MOR}), can be a descriptor of energy absorption [31]. In this research, the energy absorption was calculated up to deflection at the modulus of rupture (MOR).

$$E = \int_0^{L_{MOR}} F(s)ds$$

Normalized energy absorption values for different kinds of RC beams are presented in Fig. 18. The absorbed energy for plain concert beams was almost constant until 600 °C, and then experience a 20% reduction at 800 °C, while this value dramatically was higher for fibrous beams. Adding fibers into the concrete's mixture (either steel or macro synthetic) increased the ultimate bearing capacity, leading to an increase in the area under the load–deflection beams had a bit increase in their energy absorption at 600 °C. Since the ultimate bearing capacity for those was constant at the range of 400–600 °C, this increase can be related to the higher deflection at 600 °C. Eventually, all the beams experienced a significant reduction in energy abrogation as a result of server deterioration of concrete and reinforcement at 800 °C (Fig. 18).

3.5 Deflection

According to the following figures, the mid-span time-history deflection, at the higher temperatures, increased at a higher rate, and in turn, got the steeper slope. Hence, the time duration of failure at 800 °C, for both types, were about 50% lower than reference specimens (Fig. 19). As

Fig. 17 The Normalized value of flexural stiffness by temperature

Fig. 18 The Normalized value of energy absorption by temperature

could be observed, the ultimate mid-span deflections of the S-RC beams had an upward trend in all temperatures except 800 °C, in which a reduction in the deflection values, as a result of severe material degradation, occurred. Regarding MS-RC beams, the figure decrease as a result of the increase in temperature. Reference specimens of MS-RC beams (25 °C) had more deflection and strength under the loading test. By increasing temperature, and melting of fibers, these specimens behaved the same as plain beams (against the steel-fiber which were present in all temperatures) and rapidly lost their strength.

4 Comparison between numerical and experimental flexural capacity

Generally, the behavior of RC beams in reality due to the bond interaction between reinforcement and concrete can be more complicated [41]. Moreover, when they experience high temperatures, in addition to mechanical degradation of concrete and reinforcement, a weakness in their bond strength and redistribution of stresses within members can culminate in more damage in the heated members [28]. At the room temperature, ACI 318 [33] terms are able to provide an estimate of flexural capacity of RC beams, also ACI 544 [42] provides another term to estimate the nominal moment capacity of singly reinforced fibrous concrete beams, in which, addition to equivalent stress's block at the compression zone, another block that represents tensile strength caused by the addition fibers, is assumed to calculate the beam capacity (Fig. 20).

According to the ACI 544 model, tensile stress stemmed from adding fibers is equivalent to a tensile block in which σ_t can be calculated by Eq. (1). In the following term l and d_f are the fiber's length and diameter, ρ_f is percent by volume of steel fibers and F_{be} is bond efficiency of the fiber [42].

$$\sigma_t = 0.00772 \left(\frac{l}{d_f} \right) \rho_f F_{be} \quad (1)$$

Also, e noted as distance from extreme compression fiber to top of tensile stress block of fibrous concrete (Eq. 2)

$$e = [\varepsilon_s (\text{fibers}) + 0.003] \left(\frac{c}{0.003} \right) \quad (2)$$

In which ε_s is tensile strain and c is distance from extreme compression fiber to the neutral axis.

Fig. 19 Time-history deflection: **a** MS-RC beams **b** S-RC beams

Fig. 20 Stress-strain model of ACI for steel fiber RC beams [41]

According to the mentioned equations, the nominal moment capacity for plain (M_{np}) and fibrous (M_{nf}) RC beam are (Eq. 3 and 4):

$$M_{nf} = A_s f_y \left(d - \frac{a}{2} \right) + A'_s f'_y \left(\frac{a}{2} - d' \right) + \sigma_t b (h - e) \left(\frac{h}{2} + \frac{e}{2} - \frac{a}{2} \right) \quad (3)$$

$$M_{np} = A_s f_y \left(d - \frac{a}{2} \right) + A'_s f'_y \left(\frac{a}{2} - d' \right) \quad (4)$$

On the one hand, the difference between M_{nf} and M_{np} can be considered as the theoretical effect of steel fibers on the moment capacity. On the other hand, the difference between experimental moment of plain and S-RC beam gives the experimental ones. Hence the correction factor of R can be defined as Eq. (5):

$$R = \frac{(M_{nf} - M_{np})_{exp}}{(M_{nf} - M_{np})_{ACI}} \quad (5)$$

Hence, by implementing R on the ACI term, the Eq. (1) is transformed into Eq. (6):

$$\sigma_{tm} = R \sigma_t = 0.03 \left(\frac{l}{d_f} \right) \rho_f F_{be} \quad (6)$$

Since the different conditions of the experiment attribute to the result of moment capacity, the coefficient of 0.00772 has been several modified by researchers, among which imam et al. [43] reached 0.02 as the modified coefficient. Moreover, the nominal moment capacity estimated by ACI 318 was about 10% lower than experimental ones for plain RC beams that this can be due to the reduction coefficients and conservative approach.

As mentioned, the strength of concrete and steel reinforcement are directly used to calculate the moment capacity of RC beams. If the variations in the tensile

strength of steel fibers are assumed unchanged, with having the residual strength of concrete and steel reinforcement and the modified ACI model, the estimation of ACI terms for the heated fibrous and plain concrete RC beams can be validated by experimental results (Fig. 21).

Generally, the behavior of the RC beams due to the bond strength between concrete and steel reinforcement can be more complicated. When tensile cracks occur, the undamaged concrete is responsible for providing tensile stresses and stiffness. This phenomenon, known as tension stiffness, is influenced by local tensile stress, which transfers from steel reinforcement to concrete by the interfacial bond between them [41]. Thus, changes in this bond can play an essential role in the RC beams' capacity. Whenever the RC beams are exposed to the high temperatures, in addition to mechanical deterioration of concrete and reinforcement, this bond will be affected and significantly reduce at the higher temperatures. This reduction can hinder stress transferring, and in turn, influence load-bearing capacity, crack propagation and beam integrity [41]. Moreover, according to the previous studies, the residual load-bearing capacity is significantly influenced by the maximum temperature experienced by the tensile steel reinforcement [28].

Comparison between the experimental moment of plain RC beam and predicted ones demonstrated employing the ACI terms for high temperatures had good agreement with the experimental result (about 9% lower) until 400 °C. But with the increase in temperature to 600 °C, although this difference became smaller, predicted moment capacity gained higher values than test results (about 5%), and this practice continued until 800 °C, in which it was 27% more than experimental values (Fig. 21). The probable reason for this phenomenon is:

As mentioned, the steel bars significantly influence on the residual-bearing capacity of the heated RC beams [41].

Fig. 21 Comparison between numerical and experimental values of plain and fibrous RC beams

Also, according to the tensile test, they showed a proper residual strength against high temperatures, even at 800 °C. RC beams degradation induced by temperatures was low until 400 °C. With the increase in the temperature, the characteristics of the beam and concrete in particular gradually deteriorated, and in turn, weakness in the concrete led to the reduction of bond strength between concrete and bars. At this time, predicted values of moment capacity exceeded experimental ones. In other words, although the steel reinforcements had proper residual strength after experiencing temperatures above 600 °C, due to loss of the bond interaction with concrete, they were not able to perform against tensile stresses. Whereas this reduction was not taken into consideration in the extended ACI model, at the high temperatures where this reduction predominated, the estimated values for moment capacity went beyond the experimental ones.

According to the recent studies, the addition of fibers in the concrete mixture can increase the crack-resistance effect, which leads to preventing crack propagation, enhancing nonlinear behavior [11, 31], and eventually, an increase in the moment capacity of the RC beams [32]. Also, the bridge-effecting caused by steel fibers capable of influencing the cracking mechanism at the range of 400–800 °C, although it will decrease as a result of the softening effect in the fibers at the severe temperatures [31].

As could be observed, the results of predicted values for S-RC beams according to the extended terms of ACI and modified coefficient, were higher than plain ones with an almost similar trend. But the main point was about the different behavior of S-RC beam compared to the plain ones. Generally, the experimental result of

S-RC beam should have had the same residual capacity to plain ones plus an additional capacity caused by steel fibers. In contrast to the plain RC beam, which experienced a decrease in their moment capacity at 400 °C, the S-RC beam had a good residual bearing capacity until 600 °C (Fig. 21). Since all the characteristics of the RC beams were similar, this distinctive results can be attributed to the presence of fibers. But this improvement cannot be entirely related to the increased tensile strength of concrete by steel fibers. What kept the moment capacity of S-RC beam unchanged until 600 °C, was the effect of steel fibers on the bond strength of steel bars and concrete. Because the residual capacity of the RC beams is influenced by the residual strength of tensile reinforcement (which had a good performance after exposure to the high temperatures), when the bond strength degradation can be reduced, RC beams may present better residual strength. To clarify, steel fibers provide a confinement effect between steel bars and concrete (Fig. 22). This confinement causes an improvement in the tensile stresses transferring in the surrounding concrete and steel bars and leads to the increase in the residual moment capacity of S-RC beam compared with the plain one. Since this effect is not considered in the calculation, the experimental values are higher than predicted ones for all temperatures.

Furthermore, by comparison between the reported effects of steel fibers on the tensile and flexural strength of fibrous concrete (without steel reinforcement) and current results from this study, the greatest improvements can be observed in the RC beams' results. This discrepancy can be mainly related to the beneficial effect of

Fig. 22 Expected mechanism about confinement effect **a** without fibers **b** with steel fibers

steel fiber in reinforced concrete and confinement effect; however, improving the tensile strength of concrete and preventing crack propagation have also positive effects.

5 Failure mode

Experienced temperature and type of fiber was two factors which affected crack propagation and failure mode. In addition, another factor that can be influential is the ratio of shear-span to the depth (a/d), by which, the RC beams fall under three categories, namely normal or long beam ($2.5 < \frac{a}{d}$), short beam ($1 < \frac{a}{d} < 2.5$), and deep beam ($\frac{a}{d} < 1$) [44]. Since in this study, the RC beams are close to both short and normal beams, the crack patterning at room temperature may be expected to correspond to Fig. 23, or likewise the normal beam, which has a completely flexural failure. Generally, shear strength of short-RC beams is higher than the diagonal tensile strength, while in the normal ones those are equivalent. Because of that, with the increase in loading, the first cracks will form due to the flexural tension, then by penetrating into the compression zone, tensile cracking may spread into the region of the lesser moment as a secondary crack and make flexural shear cracks [44, 45] (Fig. 23). When the loading goes increased, shear and diagonal tensile stresses will also go up. Whenever those exceed the tensile strength of concrete, a sort of cracks will appear on the beam's web known as diagonal cracks. If in a certain region both of the flexural moment and shear force are high, firstly tensile cracks will form in the compressive zone, and when tensile diagonal stresses exceed tensile strength at the end of one of those, the diagonal flexural cracks will develop

which are named as flexural-shear cracks [45] (Fig. 23). Furthermore, the shear strength of the RC beam is provided by a combination of shear strength of undamaged concrete, the interaction between aggregate, longitudinal bars and stirrups [45]. Before occurrence cracks, providing shear capacity rest with concrete, while with the increase in loading, and in turn, crack propagation, stirrups take responsibility for providing shear strength and controlling extending of cracks.

Figure 24 represents the pattern of the cracks at the failure moment. Regarding plain RC beams, flexural failure only occurred in reference specimens (25 °C), which means shear and diagonal tensile stresses were also lower than the tensile strength. With the increase at the temperature, a weakness at those parts that provides shear strength appeared, and in turn, led to the reduction in shear capacity. Because of that, diagonal tensile stresses reached the tensile strength of concrete and flexural -shear cracks developed at 400 °C. This reduction, which continued at 600 °C and 800 °C, led to appearing shear-cracks before the flexural and flexural -shear cracks (Fig. 25).

When fibers, especially macro-steel ones, were added to the mixture of RC beams, the crack mechanism completely was changed, so, until 600 °C, only the flexural cracks developed. As mentioned, the shear strength is provided by undamaged concrete, the interaction between aggregate, longitudinal bars before crack propagation, and after that, stirrups are mainly responsible for it [45]. Preventing crack propagation due to the crack-bridging effect, steel fibers increase the shear strength. In other words, steel fibers helped resistant factors and acted as excess stirrups. This increase in the tensile and shear strength did not allow stresses, including shear and diagonal, to exceed;

Fig. 23 Typical shear failure in short beam [43]

Fig. 24 Failure mode of RC beams according to the experience temperature and type of fibers

Fig. 25 The schematic pattern of failure's cracks according to the kinds of the beam and experienced temperature

therefore, just flexural cracks could be seen on the steel fiber RC beams. When the temperature rose by 800 °C different parts of the RC beam, which were responsible for providing shear strength, experienced severe degradation and in turn, shear capacity of the RC beam noticeably reduced. Because of that, just shear cracks were developed at this temperature (Fig. 24). The macro-synthetic fibers slightly improved failure patterns, as well. Thus, at the reference beams, just flexural cracks could be observed, and at the higher temperature, the flexural- shear and shear cracks were developed. All types of RC beams experienced just shear failure at 800 °C (Fig. 24).

Figure 25 provides a comparison of cracks patterns in different temperatures based on the type of beams. Red,

Black, and gray lines represent cracks in plain, synthetic, and steel fibers beams, respectively. As can be seen in the reference specimens (25 °C), all of those experienced flexural failure. As a result of an increase in temperature, the flexural failure in the P-RC beam turned into a shear failure, while flexural-shear failure and flexural failure was observed in MS-RC beams and S-RC beams at 400 °C, consecutively. This figure was unchanged in 600 °C; however, the cracks developed to a greater extent. Finally, at 800 °C, the shear failure was the predominant in all types of beams. In summary, when flexural strength is higher than shear strength, the shear crack will appear before flexural ones. This is similar to the behavior of cross-section with a high ratio of reinforcement in which failure is brittle. With

the increase in the temperatures, the deteriorating rate will increase in the concrete and cement paste, despite the proper residual strength of steel reinforcements. In other words, the shear strength of the RC beams has experienced a higher reduction rate compared with flexural strength, and this made the RC beams act like high ratio reinforcement beams. That is why the shear cracks appeared on the beams at higher temperatures.

6 Conclusion

In this study, the influence of the macro fibers (steel and hybrid synthetic) on the mechanical properties of RC beams was investigated at high temperatures. In addition to residual-load bearing capacity, the influence of fibers on the load–deflection curves, bond interaction, and failure mode were discussed as well. Eventually, a sort of numerical calculations-based on the ACI 318 and ACI 544 -were developed for high temperatures, and its accuracy was examined with experimental results.

Generally, employing macro steel fibers had beneficial effects on the load-bearing capacity of RC beams, enhancing the residual bearing capacities by reducing strength deterioration. Thus, the reduction value for RC-beam reinforced by steel fibers was a mere 4% until 600 °C (about 40% improvement compared with plain RC beams). In other words, steel fibers by providing confinement effect the surrounding steel reinforcement, curbed the bond degradation, helped to better transfer of local tensile stress at high temperatures, which in turn, increased the residual load-bearing capacity (as opposed to plain RC beam which experienced severe degradation in temperatures above 600 °C). In contrast, specimens that were reinforced by hybrid-synthetic fibers experienced a considerable reduction as a result of melted fibers; however, they had still relatively higher residual strength than plain ones.

Concerning deflection properties, Macro fibers, especially steel ones, influenced the load-deflection curves and improved the nonlinear behavior of RC beams, leading to an increase in energy absorption and flexural stiffness values at high temperatures. It is worth mentioning that the failure mode of RC beams was also significantly influenced by temperature and type of fiber. As a result of an increase in temperature, the strength of concrete was degraded at a higher rate than steel reinforcement, and the flexural cracks turn into flexural-shear and shear ones. Since using steel fibers partly controlled this reduction, just flexural failure could be observed until 600 °C in the S-RC beam.

Further study should be carried out developing an analytical model to predict the residual bearing capacity of RC beams according to the type of adopted fibers and experienced temperature. Moreover, the investigation in the

different dosages of fibers and its effects on the mechanical properties can be another subject as well.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Compliance with ethical Standards

Conflict of interest The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

References

1. Dügenci O, Haktanir T, Altun F (2015) Experimental research for the effect of high temperature on the mechanical properties of steel fiber-reinforced concrete. *Constr Build Mater* 75:82–88
2. Navas FO, Navarro-Gregori J, Herdocia GL, Serna P, Cuenca E (2018) An experimental study on the shear behaviour of reinforced concrete beams with macro-synthetic fibres. *Constr Build Mater* 169:888–899
3. Conforti A, Ortiz-Navas F, Piemonti A, Plizzari GA (2020) Enhancing the shear strength of hollow-core slabs by using polypropylene fibres. *Eng Struct* 207:110172
4. Conforti A, Trabucchi I, Tiberti G, Plizzari GA, Caratelli A, Meda A (2019) Precast tunnel segments for metro tunnel lining: A hybrid reinforcement solution using macro-synthetic fibers. *Eng Struct* 199:109628
5. Arioiz O (2007) Effects of elevated temperatures on properties of concrete. *Fire Saf J* 42(8):516–522
6. Kodur V (2014) Properties of concrete at elevated temperatures. *ISRN CivEng* 2014:1–15
7. Crook D, Murray M (1970) Regain of strength after firing of concrete. *Mag Concr Res* 22(72):149–154
8. Khitab A, Arshad MT, Hussain N, Tariq K, Ali SA, Kazmi S et al (2013) Concrete reinforced with 0.1 vol% of different synthetic fibers. *Life Sci J* 10:934–939
9. Morita T, Beppu M, Suzuki M (2017) An experimental study on the temperature and structural behavior of a concrete wall exposed to fire after a high-velocity impact by a hard projectile. *Fire Saf J* 91:506–516
10. Saidani M, Sarairoh D, Gerges M (2016) Behaviour of different types of fibre reinforced concrete without admixture. *Eng Struct* 113:328–334
11. Serrano R, Cobo A, Prieto MI, de las Nieves González M (2016) Analysis of fire resistance of concrete with polypropylene or steel fibers. *Constr Build Mater* 122:302–309
12. Yermak N, Pliya P, Beaucour A-L, Simon A, Noumowé A (2017) Influence of steel and/or polypropylene fibres on the behaviour of concrete at high temperature: spalling, transfer and mechanical properties. *Constr Build Mater* 132:240–250
13. Lau A, Anson M (2006) Effect of high temperatures on high performance steel fibre reinforced concrete. *Cem Concr Res* 36(9):1698–1707
14. Varona FB, Baeza FJ, Bru D, Ivorra S (2018) Influence of high temperature on the mechanical properties of hybrid fibre reinforced normal and high strength concrete. *Constr Build Mater* 159:73–82
15. Ding Y, Azevedo C, Aguiar J, Jalali S (2012) Study on residual behaviour and flexural toughness of fibre cocktail reinforced

- self compacting high performance concrete after exposure to high temperature. *Constr Build Mater* 26(1):21–31
16. Abdul-Rahman M, Al-Attar AA, Hamada HM, Tayeh B (2020) Microstructure and structural analysis of polypropylene fibre reinforced reactive powder concrete beams exposed to elevated temperature. *J Build Eng* 29:101167
 17. Jang H-S, So H-S, So S (2016) The properties of reactive powder concrete using PP fiber and pozzolanic materials at elevated temperature. *J Build Eng* 8:225–230
 18. Ozawa M, Morimoto H (2014) Effects of various fibres on high-temperature spalling in high-performance concrete. *Constr Build Mater* 71:83–92
 19. Amancio FA, de Carvalho Rafael MF, de Oliveira Dias AR, Cabral AEB (2018) Behavior of concrete reinforced with polypropylene fiber exposed to high temperatures. *ProcediaStructIntegr* 11:91–98
 20. Behnood A, Ghandehari M (2009) Comparison of compressive and splitting tensile strength of high-strength concrete with and without polypropylene fibers heated to high temperatures. *Fire Saf J* 44(8):1015–1022
 21. Eidan J, Rasoolan I, Rezaeian A, Poorveis D (2019) Residual mechanical properties of polypropylene fiber-reinforced concrete after heating. *Constr Build Mater* 198:195–206
 22. Ma Q, Guo R, Zhao Z, Lin Z, He K (2015) Mechanical properties of concrete at high temperature—A review. *Constr Build Mater* 93:371–383
 23. Müller P, Novák J, Holan J (2019) Destructive and non-destructive experimental investigation of polypropylene fibre reinforced concrete subjected to high temperature. *J Build Eng* 26:100906
 24. Pliya P, Beaucour A, Noumowé A (2011) Contribution of cocktail of polypropylene and steel fibres in improving the behaviour of high strength concrete subjected to high temperature. *Constr Build Mater* 25(4):1926–1934
 25. Rudnik E, Drzymała T (2018) Thermal behavior of polypropylene fiber-reinforced concrete at elevated temperatures. *J Therm Anal Calorim* 131(2):1005–1015
 26. de la Fuente A, Escariz RC, de Figueiredo AD, Aguado A (2013) Design of macro-synthetic fibre reinforced concrete pipes. *Constr Build Mater* 43:523–532
 27. Rambo DAS, Blanco A, de Figueiredo AD, dos Santos ERF, Toledo Filho RD, Gomes OdFM (2018) Study of temperature effect on macro-synthetic fiber reinforced concretes by means of Barcelona tests: an approach focused on tunnels assessment. *Constr Build Mater* 158:443–453
 28. Kodur V, Agrawal A (2016) An approach for evaluating residual capacity of reinforced concrete beams exposed to fire. *Eng Struct* 110:293–306
 29. Kodur V, Dwaikat M, Fike R (2010) An approach for evaluating the residual strength of fire-exposed RC beams. *Mag Concrete Res* 62(7):479–488
 30. Jin L, Zhang R, Dou G, Du X (2018) Fire resistance of steel fiber reinforced concrete beams after low-velocity impact loading. *Fire Saf J* 98:24–37
 31. Huang H, Wang R, Gao X (2019) Improvement effect of fiber alignment on resistance to elevated temperature of ultra-high performance concrete. *Compos B Eng* 177:107454
 32. Turker K, Hasgul U, Birol T, Yavas A, Yazici H (2019) Hybrid fiber use on flexural behavior of ultra high performance fiber reinforced concrete beams. *Compos Struct* 229:111400
 33. Committee A, Standardization IOF (2008), editors. Building code requirements for structural concrete (ACI 318–08) and commentary, American Concrete Institute
 34. Materials ASOT (2002) ASTM C33–02: Standard Specification for Concrete Aggregates
 35. Teutsch M, Wiens U, Alfes C (2010) Stahlfaserbeton nach DAf-Stb-Richtlinie “Stahlfaserbeton.” *Beton-und Stahlbetonbau* 105(8):539–551
 36. Rilem T (1995) 129-MHT, ‘Test methods for mechanical properties of concrete at high temperatures’, Part 1: Introduction, Part 2: Stress-strain relation, Part 3: Compressive strength for service and accident conditions. *Mater Struct* 28(181):410–414
 37. Zarifian A, IzadiFard RA, Khalighi A (2020) Experimental study on the behavior of thermally insulated RC beams strengthened with CFRP after their exposure to high temperatures compared to non-insulated ones. *Can J CivEng* 47(7):875–883
 38. Anumala S, Sharma U (2011) Residual mechanical properties of fibre reinforced concrete after exposure to elevated temperature. *J Struct Fire Eng* 2(2):123–137
 39. Goremikins V, Blesak L, Novak J, Wald F (2017) Experimental investigation on SFRC behaviour under elevated temperature. *J Struct Fire Eng* 8(3):287–299
 40. Moghadam MA, Izadifard R (2019) Evaluation of shear strength of plain and steel fibrous concrete at high temperatures. *Constr Build Mater* 215:207–216
 41. Kodur V, Agrawal A (2017) Effect of temperature induced bond degradation on fire response of reinforced concrete beams. *Eng Struct* 142:98–109
 42. (ACI) ACI (2009) Design Consideration for Steel Fiber Reinforced Concrete (ACI 5444R-88)
 43. Imam M, Vandewalle L, Mortelmans F (1995) Shear–moment analysis of reinforced high strength concrete beams containing steel fibres. *Can J Civ Eng* 22(3):462–470
 44. Joint ASCE-ACI (1973) Task Committee 426 on Shear and Diagonal Tension of the Committee on Masonry and Reinforced Concrete of the Structural Division A. The Shear Strength of Reinforced Concrete Members. *J Struct Div* 99(6):1091–187.
 45. AM. K. انالیز و طراحی سازه های بتن آرمه (Analyze and design of reinforced concrete structures). Iran: Isfahan: University of Technology; 1992 (In persian).

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.