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The behavior of reinforced concrete frames exposed to high temperature under cyclic load effect

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ABSTRACT

Continued use of the structure through minor renovations and repairs without a complete and accurate determination of the extent of damage to the structure and its elements exposed to high temperature effects due to fire, etc. will cause more loss of life and property in the event of an earthquake that may occur later. The aim of this study is to determine the losses on the lateral load and energy damping capacities and stiffness of reinforced concrete frames exposed to 200, 400, 600 and 800 °C high temperatures for 60, 120 and 180 min. For this purpose, 13 reinforced concrete frame test elements with the same concrete and steel material properties and dimensions were produced. All reinforced concrete frame test members were brought to the specified target temperature within one hour and exposed to high temperature effects for 60, 120 and 180 min at these target temperatures. The test members then allowed cooling down on their own and when they reached room temperature, they removed from the oven and subjected to cyclic lateral loading tests. The data obtained from the cyclic lateral loading tests processed to obtain lateral load - horizontal displacement, stiffness - horizontal displacement, cumulative energy consumption - horizontal displacement and strength envelope curves for each test element. According to the results of the cyclic lateral loading tests, it was determined that the lateral load carrying capacities of the test members exposed to high temperature for 60, 120 and 180 min decreased by 24 %, 33.33 % and 36 % in push, and by 25.76 %, 37.6 % and 38.72 % in pull, respectively. In addition, the energy consumption of the test elements exposed to high temperature for 60, 120 and 180 min decreased by 30.98 %, 42.41 % and 39.62 %, respectively, compared to the reference test element. The initial stiffness of all test elements exposed to the high temperature effect decreased compared to the initial stiffness of the reference test element not exposed to the high temperature effect. According to these results, the effect of high temperature causes losses in many parameters that are of vital importance in the building elements, but also highly affects the earthquake behavior of the building.

1. Introduction

The temperature factor plays a crucial role in many physical and chemical events occurring on Earth's surface. Additionally, it directly or indirectly affects all engineering structures. The temperature effect is also a result of uncontrolled combustion of substances on Earth, known as fire, which adversely affects the behavior of structures.

The high temperature generated by fires reduces the strength of concrete and steel materials, subsequently negatively affecting the load-carrying capacity of reinforced concrete structures. The fire resistance of concrete is influenced by factors such as the type of aggregate and cement used in its composition, the temperature and duration of the fire, the dimensions of structural elements, and the moisture content of the concrete [1,2]. Aggregates generally exhibit high fire resistance. However, non-uniform heating of aggregates or quenching of heated aggregates with water spray can generate internal pressure, leading to aggregate disintegration. Part of the deformation in concrete arises from the expansion of the cement in its composition. Hydrated Portland cement contains a significant amount of free calcium hydroxide and decomposes into calcium oxide at 400–450 °C due to the loss of water. If this calcium oxide is moistened or kept in a humid environment after be cooled, it transforms back into calcium hydroxide. These volume

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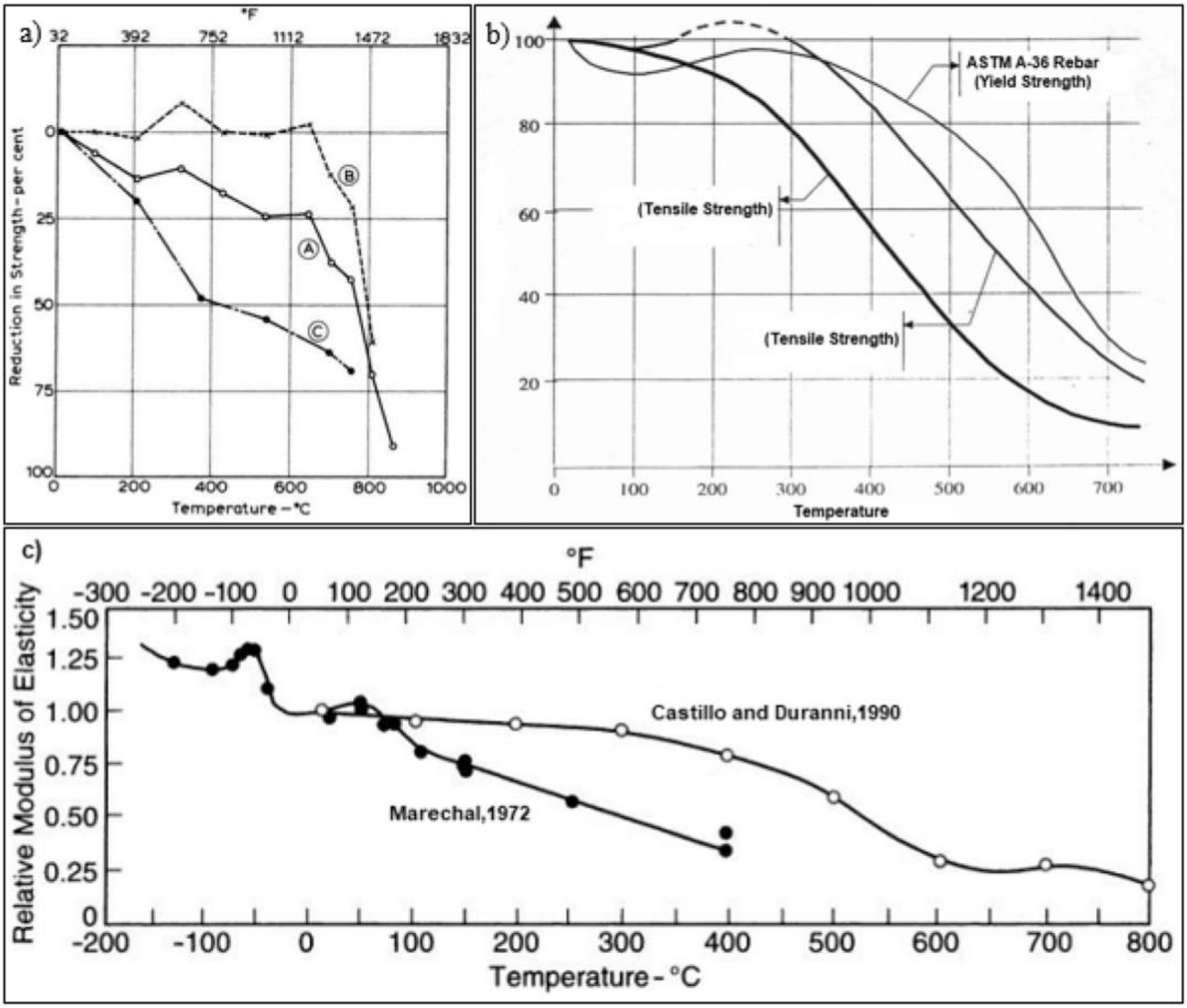

Fig. 1. Variation of mechanical properties of concrete and steel materials with temperature.

changes can cause concrete to disintegrate [3–6].

Reinforced concrete structures sometimes exposed to the effects of fire. While there are various methods to extinguish fires, dousing with water commonly employed. However, this can lead to different stresses in reinforced concrete elements at high temperatures, potentially causing a reduction in their load-carrying capacity [7]. Neville (2000) [8] conducted a study investigating changes in concrete compressive strength based on loading conditions. He found that both specimens heated without any loading and specimens heated and kept at 21 °C for 7 days exhibited reduced compressive strength (Fig. 1a). According to CEB (1991) [9], significant decreases in tensile strength occur in concrete starting from 100 °C, with a 70 % loss in tensile strength as temperatures reach 600 °C. Similarly, the elastic modulus of concrete affected by high temperatures, decreasing as temperatures reach 121 °C [8,10, and 11] (Fig. 1c). In reinforced steel exposed to high temperatures, an increase in tensile strength observed at 200 °C, followed by decreases in both tensile and yield strength from 300 °C onwards. Consequently, it known that plastic deformation occurs between 600 °C and 1200 °C [12]. The variation in yield and tensile strength of different types of structural steel at high temperatures shown in Fig. 1b. The elastic modulus of reinforced steel decreases by around 15 % at 400 °C and about 40 % at 600 °C. This reduction leads to excessive elongation of the steel due to the initiation of plastic deformation.

Literature studies indicate that concrete subjected to high-temperature effects due to fire experiences a decrease in compressive and flexural strengths [13]. It has been determined in the studies that the high-temperature effect, depending on the concrete strength class, alters the seismic behavior of structural elements [14]. However, these studies are limited in their focus on the influence of high temperatures on structural behavior solely based on strength parameters.

Most of the studies in the literature have focused on the seismic performance of concrete and steel materials and reinforced concrete elements after high temperature effects such as fire, rather than the behavior of reinforced concrete structures. In this direction, many studies been carried out to investigate the change in the mechanical properties of concrete and reinforcing steel after exposure to high temperature and the adherence slippage between concrete and steel. Because of these studies, it was determined that high temperature effect significantly affects the compressive strength and modulus of elasticity of concrete [15,16], deformability, yield and ultimate strength of reinforcing steel [17,18], and bond strength between concrete and reinforcement [19,20]. Similarly, as a result of studies on the mechanical

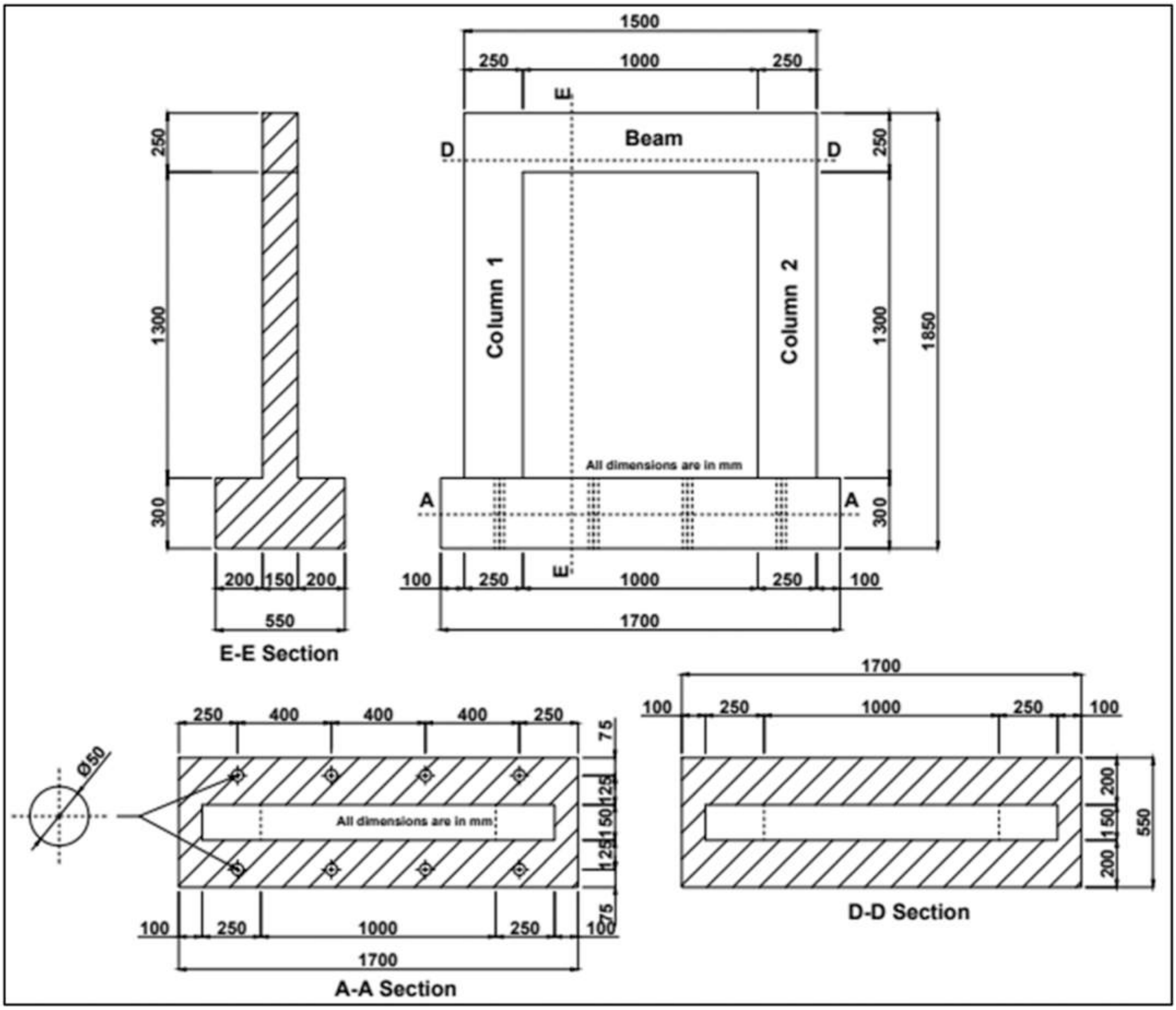

Fig. 2. Formwork layout of the reinforced concrete frame test specimens.

performance of reinforced concrete elements such as beams, columns and slabs after exposure to high temperatures, it was determined that the effect of high temperatures decreases the bearing capacity of reinforced concrete elements and this decrease increases with the prolongation of high temperature exposure time [20–26].

Although there are many research findings on the mechanical properties of reinforced concrete columns, beams and slabs subjected to high temperature effects, the structural behavior of a statically indeterminate reinforced concrete frame structure after high temperature effects is different and much more complex than columns, beams and slabs. The high temperature caused by fire, etc. not evenly distributed among the reinforced concrete frame components, which leads to an increase in the inconsistency of thermal stress distributions. Therefore, the earthquake performance of reinforced concrete frames after high temperature cannot understood from the research results of structural elements [27]. Vechio and Sato [28] conducted tests under a combination of thermal and mechanical loads and found that thermal loads cause damage to be concentrated in localized areas of the reinforced concrete frame member. On the other hand, studies also been conducted on the residual load carrying capacity of reinforced concrete frames after exposure to high temperatures due to fire etc. Raouffard and Nishiyama [29] investigated the behavior of a two-storey reinforced concrete frame during and after high temperature affect and found that the mid-span deflection can be significantly improved due to the recovery of steel reinforcement strength and reduction of bearing capacity. It has also been determined that the damage caused by high temperature is up to 30 %. Zhang et al. [31] investigated nine reinforced concrete frames subjected to high temperature under static load effects and determined that the effect of high temperature on the mechanical properties of the reinforced concrete frame was greater than the fire load. However, it was determined that if the high temperature exceeds 1000 °C, the bearing capacity decreases by 57.3 %. Some studies have investigated the behavioral changes in structural elements due to post-earthquake fire incidents [32]. Sharma et al. [33] conducted a series of thrust and cyclic loading tests to evaluate the residual seismic capacity of seismically damaged reinforced concrete frames subjected to high temperature effects. As a result, it was determined that the level of seismic damage affects the temperature rise in the reinforced concrete frame. Xiao et al. [30] tested four single-span and single-story reinforced concrete frames subjected to high temperature under low-frequency cyclic loading and

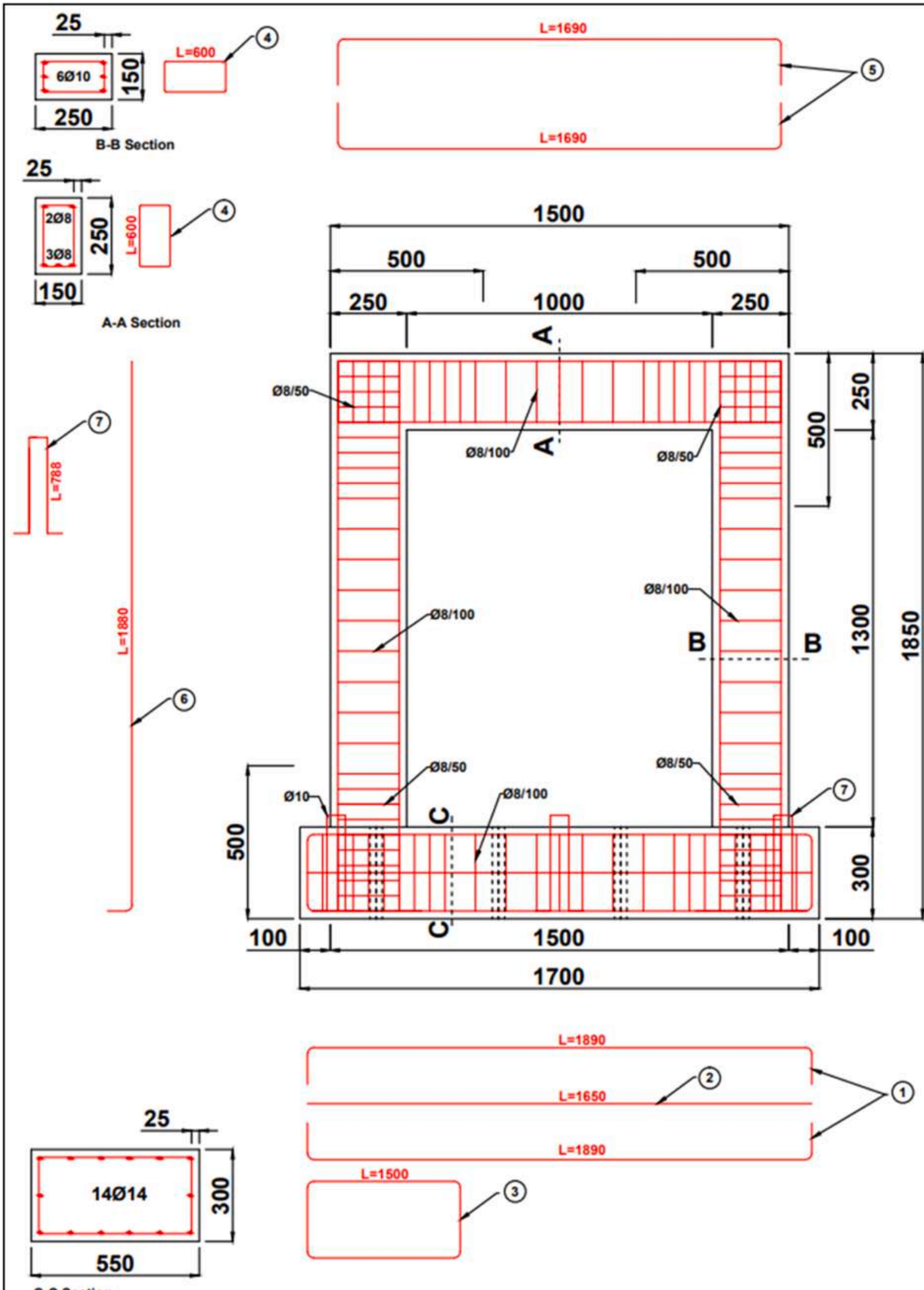

Fig. 3. Reinforcement layout of the reinforced concrete frame test specimens.

Fig. 4. Production of the reinforced concrete frame test specimens.

Table 1
Application of high temperature effect.

Group No	Sample name	Exposure duration (minute)	Temperature level (°C)
1	RCF-1	60	200
	RCF-4		400
	RCF-7		600
	RCF-10		800
2	RCF-2	120	200
	RCF-5		400
	RCF-8		600
	RCF-11		800
3	RCF-3	180	200
	RCF-6		400
	RCF-9		600
	RCF-12		800
4	RCF-13	-	-

found that the difference in stiffness of beams and columns in the reinforced concrete frame can change the seismic collapse mode from strong column - weak beam collapse to strong beam - weak column collapse.

The fact that the studies on the seismic performance of reinforced concrete frames after high temperature are still quite limited, that most of the studies only consider the changes in the concrete strength parameter due to high temperature effect, and that the behavior on element basis is investigated based on the changes caused by the high temperature effect on the mechanical properties of concrete and steel materials reveal the need for a wider research on this subject.

In this direction, in the present article, the effect of the change in two different parameters such as the degree of high temperature and the duration of impact will be reported on the seismic performance of the reinforced concrete frame, and this effect will be evaluated through the horizontal load carrying capacity, energy absorption capacity and stiffness of the frame obtained by cyclic loading tests to be performed after high temperature.

2. Materials and methods

In this study, the behavior of reinforced concrete frames exposed to the effects of high temperature under repeated Lateral loading been investigated. For this purpose, 13 reinforced concrete frame test specimens fabricated. In all test specimens, the concrete strength class was determined as C25/30, and the steel strength class designated as B420C. The dimensions and cross-sectional properties of all test specimens are similar. The formwork layout of the reinforced concrete frame test specimens shown in Fig. 2, and the reinforcement layout illustrated in Fig. 3.

Basic dimensions of the test specimens were determined as 550 × 1700 × 300 mm (width x length x height), with a total height of 1850 mm. To ensure secure anchoring to the ground during the application of repeated lateral loads, eight voids with a diameter of 50 mm left within the foundation at 400 mm intervals (Fig. 2).

In the column regions of the reinforced concrete frame test

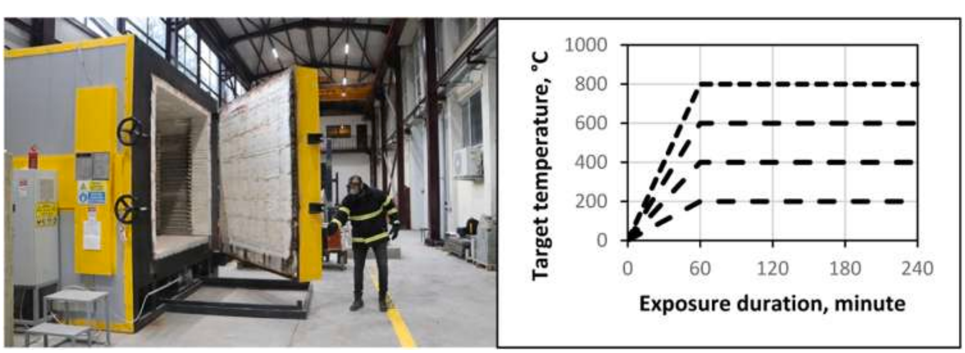

Fig. 5. Test furnace and application of high-temperature effect.

Fig. 6. Test specimens exposed to the high-temperature effect and concrete sample examples.

Fig. 7. Blistering and spalling on the concrete surface.

specimens, a minimum reinforcement ratio (p = 0.01) of six longitudinal 10 mm rebars was selected. In the beam regions, to ensure ductile behavior, three longitudinal 8 mm rebars were chosen, maintaining a reinforcement ratio between the minimum (p_{min}= 0.0026) and maximum (p_{max}= 0.017) values. Across all specimens, transverse reinforcement placed at intervals of 50 mm within the confinement zone and 100 mm outside it (Fig. 3).

The production of the reinforced concrete frame test specimens carried out in accordance with the formwork and reinforcement details shown in Figs. 2 and 3, and illustrated in Fig. 4. After casting the concrete, the test specimens demolded and cured under a continuously wet cover for 28 days. The exposure of the test specimens to high temperature conducted approximately 60 days after the production of the test specimen where the change in concrete strength had stabilized. During the production of the test specimens, decisions made based on the compressive strength of 150 mm × 150 mm cube samples taken at intervals of 7 days after the 28th day.

2.1. Application of high temperature effect to test specimens

After the production process was completed, the reinforced concrete frame test specimens were subjected to high-temperature effects of 200 ℃, 400 ℃, 600 ℃, and 800 ℃ for durations of 60, 120, and 180 min each (Table 1).

An automotive-based test furnace used for the application of the high-temperature effect (Fig. 5). The furnace has dimensions of 2000 mm in width, 1500 mm in length, and 2000 mm in height. It features two K-type thermocouples, with a maximum operating temperature of 1100 °C, placed inside. One thermocouple used to measure the temperature within the furnace, while the other positioned to prevent the internal temperature from reaching an undesired level. With the assistance of an existing thermostat in the test furnace, temperature-time curves can be input (Fig. 5).

Fig. 5 shows the temperature - time curves of the fire test furnace. According to these curves, the reinforced concrete frame test members were brought to the target temperatures (200, 400, 600 and 800 °C) within the first 60 min and then kept at these target temperatures for 60, 120 and 180 min in accordance with the test matrix specified in Table 1.

The investigation of high temperature effect in concrete and reinforced concrete test elements generally applied by heating the target temperatures until they completely pass through the cross-section of the test element or by exposing the test elements to the temperatures specified in ISO 834 [35] for varying periods. In this study, it aimed to determine the performance of reinforced concrete elements subjected to different temperature effects for different durations under cyclic lateral load. In this context, in the present study, the experimental elements subjected to four different temperatures for three different periods and their performance under cyclic lateral load investigated. Since the parameters such as horizontal displacements, energy consumption and stiffness reductions of the experimental elements examined among themselves and in comparison with the reference specimen depending on temperature and time, no vertical load applied to any specimen.

The reinforced concrete frame test specimens exposed to the high-temperature effect allowed to cool naturally and removed from the test furnace when room temperature reached (Fig. 6). Changes in color and the formation of cracks observed on the concrete surfaces of the test specimens subjected to the high-temperature effect. In particular, blistering and spalling were observed on the surface of RCF-10, RCF-11 and RCF-12, which were exposed to 800 °C high temperature for 60, 120 and 180 min, a few days after cooling. Leaving these test elements to cool on their own means that the concrete surface is exposed to the atmospheric environment. CaO, which reacts with CO_2 in the air, turns into $CaCO_3$ and causes volume expansion in hardened concrete. Therefore, it observed that the cracked concrete surface poured due to the high temperature effect (Fig. 7).

The images of the test specimens before entering the test furnace and after the application of the high-temperature effect for durations of 60 min, 120 min, and 180 min provided in Fig. 8, respectively.

Thermocouples were placed in the column and beam body sections in order to determine and monitor the temperature distribution inside the frames during the application of the high temperature effect on the experimental elements. In line with the information obtained from the thermocouples, the temperature distributions shown in Fig. 9 were drawn.

2.2. Cyclic lateral loading test setup and loading protocol

For applying cyclic lateral loads to the reinforced concrete frame test

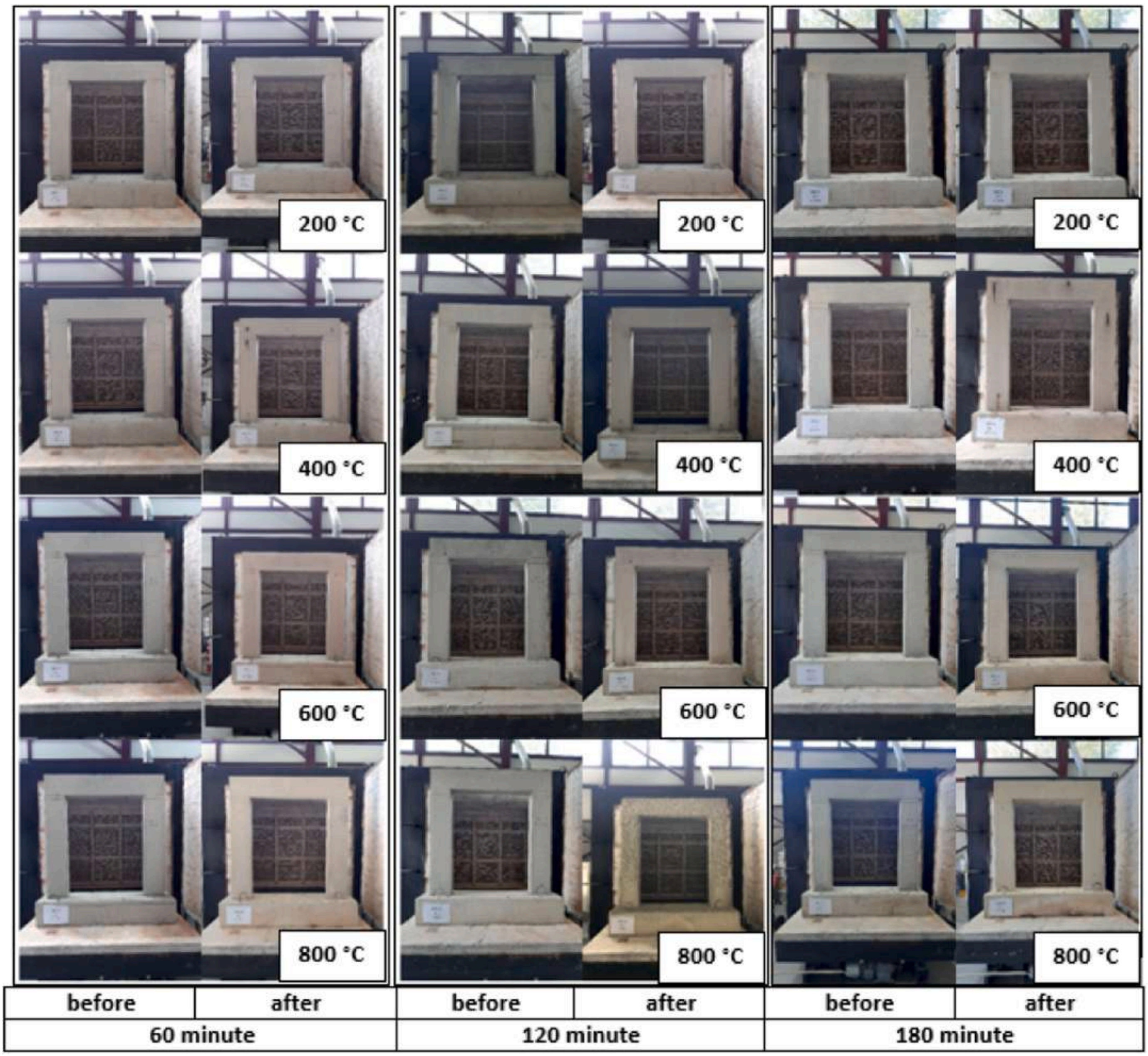

Fig. 8. Before and after images of the test specimens exposed to the high-temperature effect.

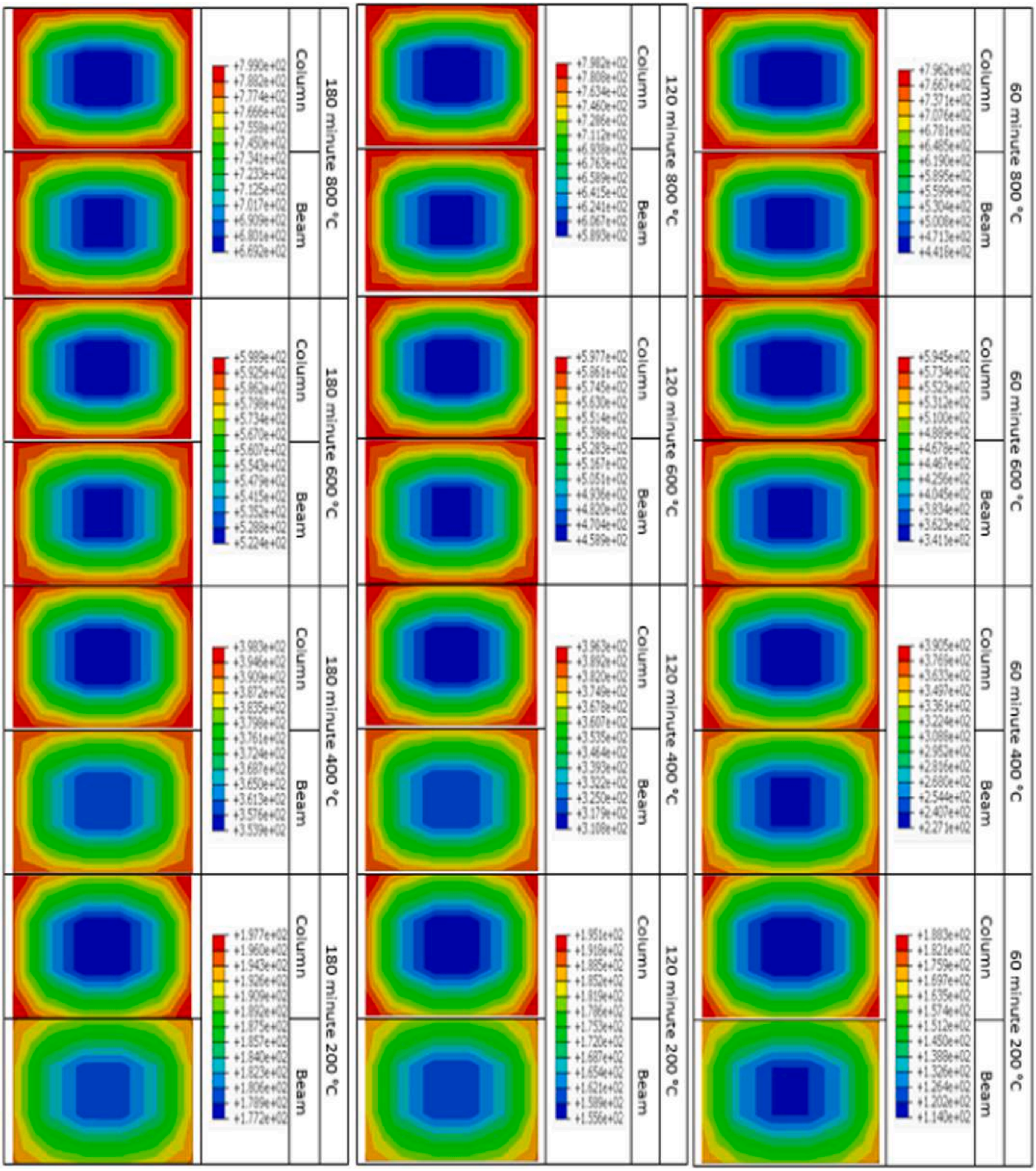

Fig. 9. Temperature distribution in a reinforced concrete frame.

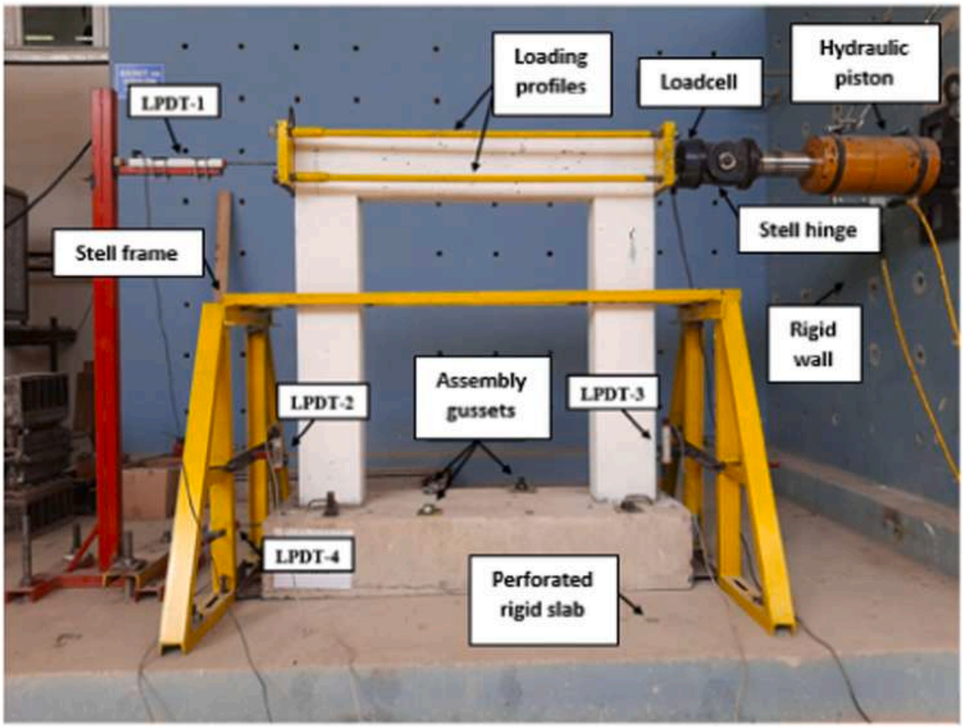

Fig. 10. Cyclic lateral loading test setup and measurement systems.

Fig. 11. Measurement systems and support details.

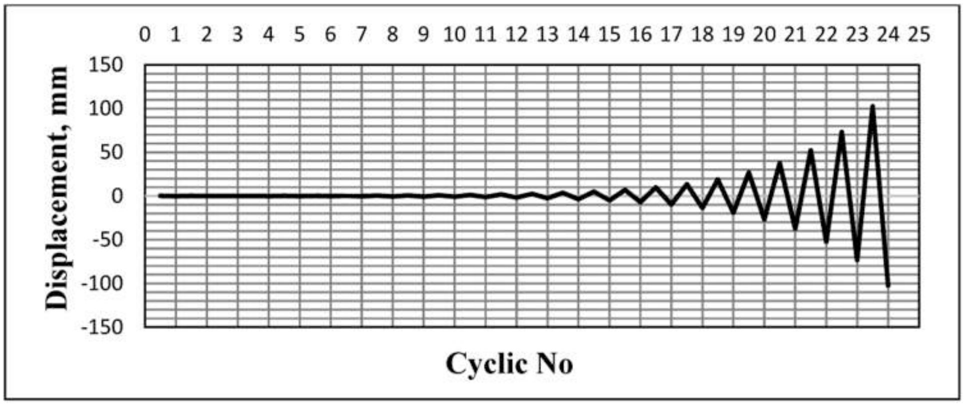

Fig. 12. Cyclic lateral loading protocol.

specimens exposed to the high-temperature effect, the experimental setup indicated in Fig. 10 was prepared.

The application of lateral loads utilized a computer-controlled hydraulic piston with a capacity of 1000 kN, capable of applying both 150 mm of compression and tension. The hydraulic piston affixed to a 100 cm-thick reinforced rigid loading wall using two high-strength bolts with a diameter of 42 mm. To prevent lateral movement of the test specimens, eight voids with a diameter of 50 mm created at the foundation, and the specimens' wanchored to a rigid reinforced concrete floor using high-strength bolts with a diameter of 38 mm. To prevent out-of-plane behavior of the reinforced concrete frame during cyclic lateral loading, two frame systems constructed from UPN100 profiles utilized. These frame systems connected to the rigid floor using four high-strength bolts with a diameter of 38 mm. For the measurement of the applied lateral load during cyclic lateral loading tests, a load cell capable of measuring 1000 kN of compression and tension was attached to the end of the computer-controlled hydraulic piston. Linear Potentiometric Displacement Transducers (LPDT) employed to measure horizontal and vertical displacements in the test specimen during lateral loading (Fig. 11).

In the cyclic loading tests, a semi-static loading protocol employed as specified in FEMA 461 [34]. The loading protocol commenced with a horizontal displacement of 0.24 mm and continued for the first six cycles following the guidelines of FEMA 461 [34]. Subsequent cycles increased this value by 40 % each cycle (Fig. 12).

3. Results and discussion

After the reinforced concrete frame test specimens were allowed to cool naturally following exposure to the high-temperature effect, data obtained from cyclic lateral loading tests were processed to establish the lateral load - horizontal displacement relationship, stiffness - horizontal displacement relationship, cumulative energy consumption - horizontal displacement relationship, and strength envelope curves.

3.1. Lateral load - Horizontal displacement relationship

In Fig. 13, individual lateral load - horizontal displacement curves obtained from the cyclic loading tests for each test specimen presented separately.

The lateral load capacities in compression and tension of the test specimens subjected to high-temperature effects at 200 °C, 400 °C, 600 °C, and 800 °C for durations of 60, 120, and 180 min, along with the RCF-13 reference test specimen not exposed to high-temperature effects, are presented in Table 2.

Fig. 14 illustrates the strength envelope curves obtained from the cyclic lateral loading tests for the reinforced concrete frame test specimens exposed to high-temperature effects at 200 °C, 400 °C, 600 °C, and 800 °C for durations of 60, 120, and 180 min. The lateral load - horizontal displacement curves for all test specimens compared in Fig. 14. The reduction in lateral load-carrying capacity presented in Fig. 15. Accordingly, it has been determined that the lateral load-carrying capacities of the test specimens subjected to high-temperature effects for 60, 120, and 180 min decreased by approximately 25.2 %, 33.33 %, and 36 % in compression, and by approximately 25.76 %, 37.6 %, and 38.72 % in tension, respectively.

The greatest reduction in lateral load-carrying capacity occurred in tension with a decrease of 38.72 % and in compression with a decrease of 36 % in the RCF_12 test specimen exposed to 800 °C for 180 min. For the test specimens exposed to high temperatures for 60 min, RCF_1, RCF_4, RCF_7, and RCF_10, it was determined that the lateral load-carrying capacity decreased by 17.39 % in compression and 12.26% in tension when the high-temperature effect was increased from 200 °C to 800 °C. Similarly, for the test specimens exposed to high temperatures for 120 min, RCF_2, RCF_5, RCF_8, and RCF_11, the lateral load-carrying capacity decreased by 28.57 % in compression and 29.09 % in tension with the increase of high-temperature effect from 200 °C to 800 °C. Lastly, for the test specimens exposed to high temperatures for 180 min, RCF_3, RCF_6, RCF_9, and RCF_12, the lateral load-carrying capacity decreased by 30.94 % in compression and 31.61 % in tension when the high-temperature effect was increased from 200 °C to 800 °C.

Table 3 summarizes the variations with temperature of the reduction in the maximum lateral load carrying capacity of all specimens tested in this study compared to the RCF_13 reference element.

It is extremely important to restore the lateral load carrying performance of structural elements exposed to high temperature effects such as fire and to regain the service capability of the structures. In general, the reduced capacity of reinforced concrete structural elements poses threats to structural safety at various levels, which requires performance improvement through repair measures. The C-S-H gel of concrete decomposes when its temperature reaches 550 °C. When the maximum temperature of the fire environment is below 600 °C, Poon et al. [36] suggested that the original strength can be restored without the need for repair if appropriate curing conditions are applied. Scanning electron microscopy (SEM) investigations have shown that the healing is due to a series of rehydration processes that regenerate calcium-silicate-hydrate (C-S-H) [36].

In this study, the variation of the compressive strength of concrete with temperature shown in Table 4 (Fig. 16) by taking concrete core samples from the reinforced concrete frame test members that were subjected to repeated loading tests after high temperature. According to Table 4, the compressive strength of concrete decreases as the degree and duration of temperature increases. The decrease in the compressive strength of concrete supports the decrease in the horizontal load carrying capacity of the frame.

According to Table 3, it seen that there is a decrease of more than

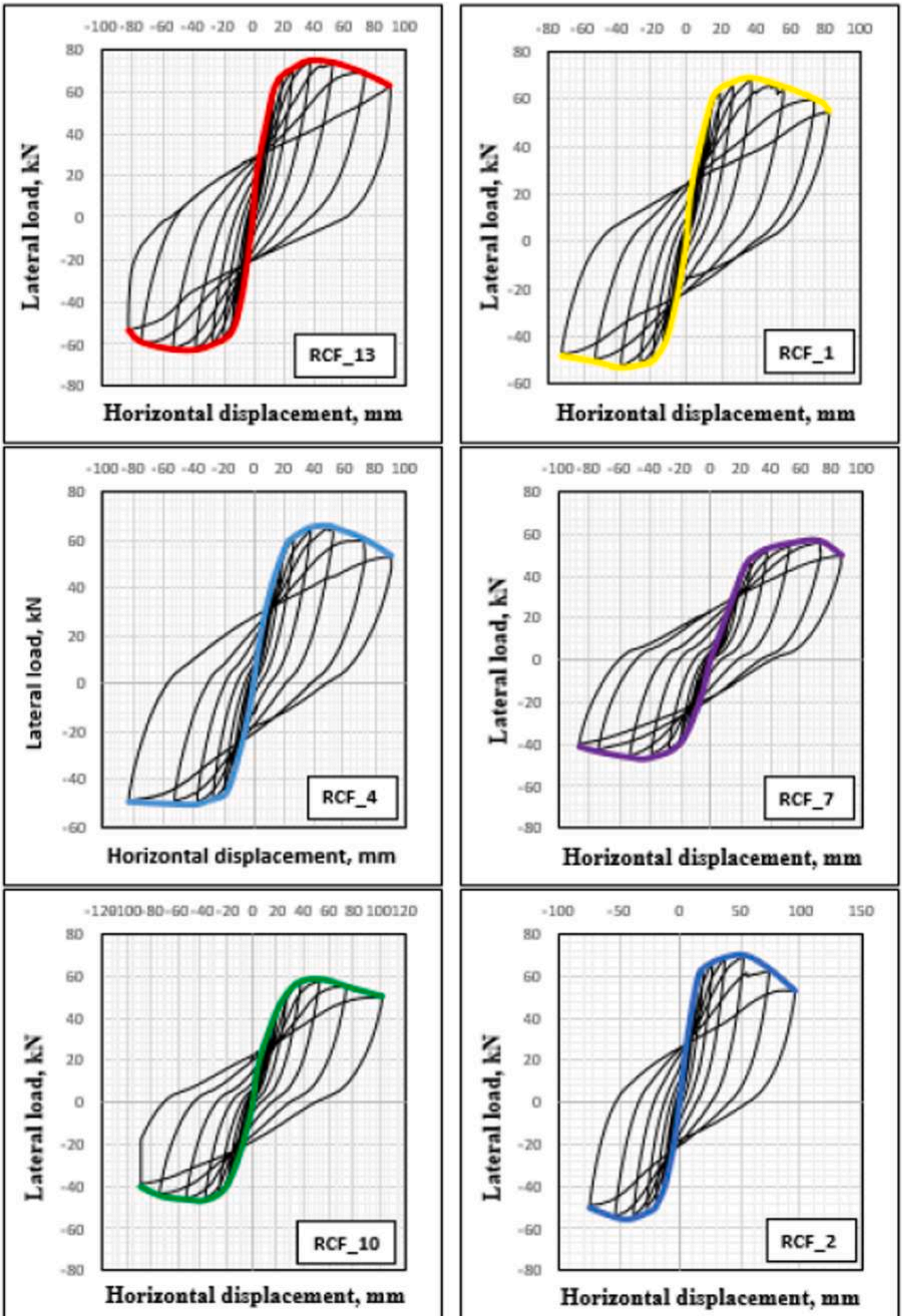

Fig. 13. Cyclic lateral load - horizontal displacement curves for all test specimens.

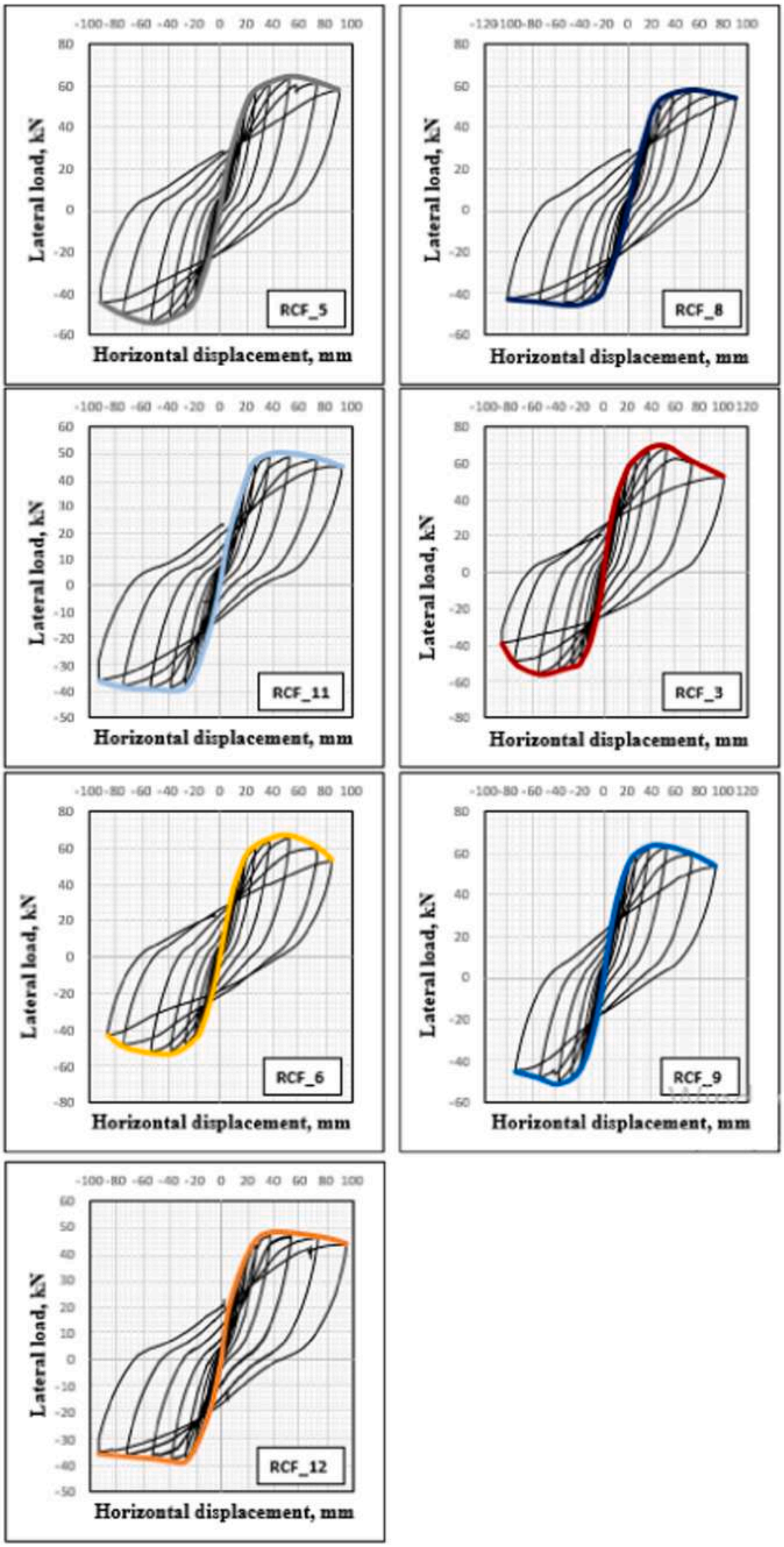

Fig. 13. (*continued*).

Table 2
Lateral load capacities of test specimens subjected to high temperatures.

High temperature level (°C)	Lateral load (kN)					
	60 min		120 min		180 min	
	Push (+)	Pull (-)	Push (+)	Pull (-)	Push (+)	Pull (-)
200	69	53	70	55	68.5	56
400	66	50.6	64.5	54	63.5	53
600	57	46.5	56	45.5	54.2	51
800	56.1	46.4	50	39	48	38.3
RCF_13	Push (+) 75			Pull (-) 62.5		

15% in the lateral load carrying capacity of reinforced concrete frames at temperatures of 600 °C and above. Considering that the reduction of the bearing capacity of the frame elements to 85 % of the lateral load carrying capacity will cause collapse, it can said that temperatures above 550 °C are critical for reinforced concrete frames.

3.2. Cumulative energy consumption – Horizontal displacement relationship

The energy consumed by the test specimens during the cyclic lateral loading tests, exposed to high-temperature effects of 200 °C, 400 °C, 600 °C, and 800 °C for durations of 60, 120, and 180 min, along with the reference specimen RCF_13 not subjected to high-temperature effects, is presented in Table 5. During each cycle of the cyclic lateral loading, the area under the lateral load – horizontal displacement curve was calculated, and the calculated areas cumulatively summed to determine the amount of energy dissipated by the test specimen during the experiment.

Fig. 17 illustrates the relationship between cumulative energy consumption and horizontal displacement obtained from the cyclic lateral load tests for concrete frame specimens exposed to high-temperature effects at durations of 60 min, 120 min, and 180 min under temperatures of 200 °C, 400 °C, 600 °C, and 800 °C. The cumulative energy consumption – horizontal displacement curves of all test specimens compared in Fig. 17.

According to Fig. 18, the decrease in energy consumption capacity is illustrated. Accordingly, the energy consumption capacities of the test specimens exposed to high-temperature effects for 60, 120, and 180 min

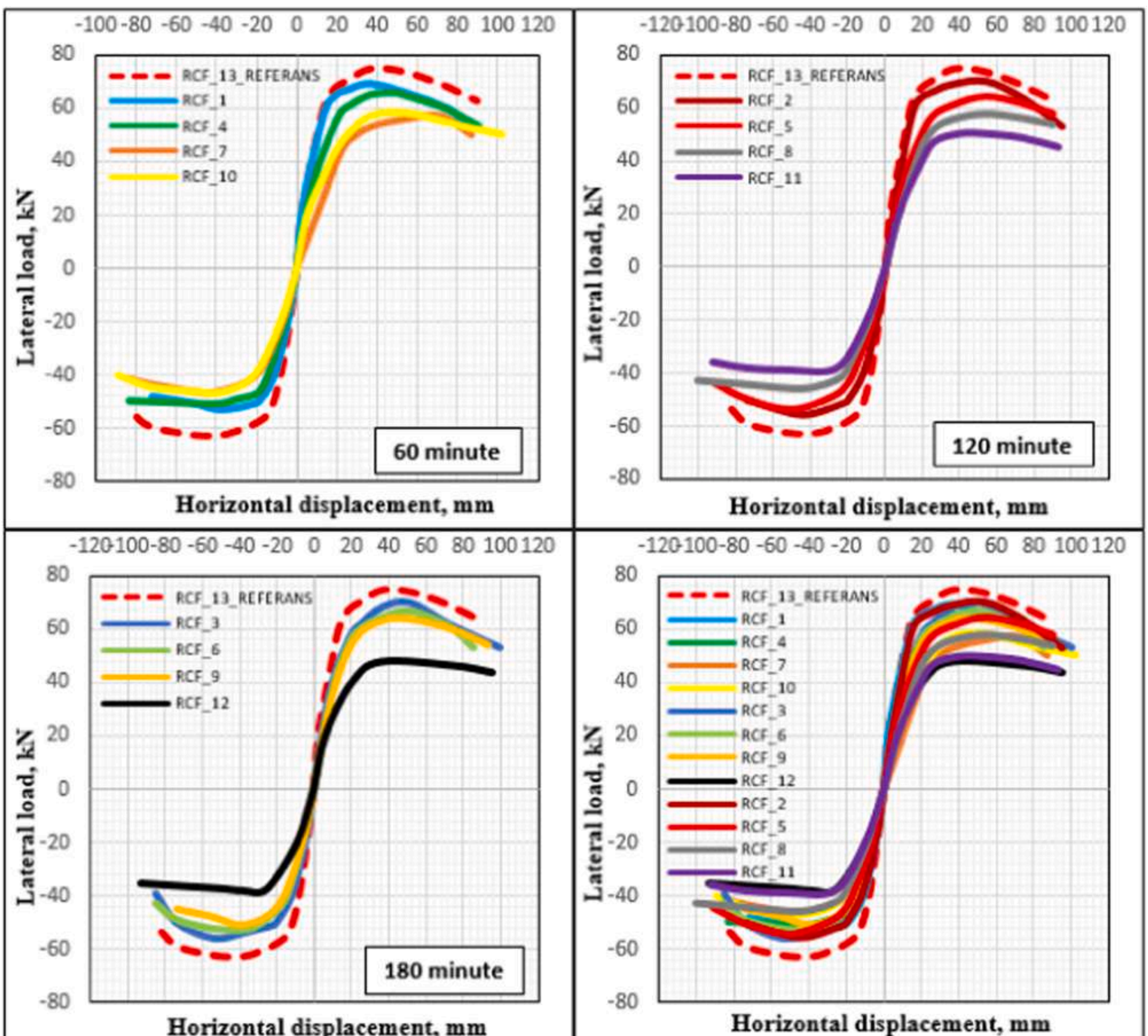

Fig. 14. Lateral load - horizontal displacement relationship (Strength envelope curves).

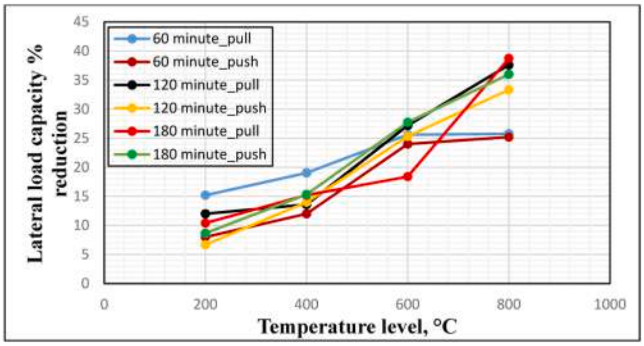

Fig. 15. Variation of reduction in Lateral load-carrying capacity with temperature.

Table 3
. Variation of the decrease in lateral load carrying capacity with temperature (%).

Temperature level	60 min		120 min		180 min	
	Push	Pull	Push	Pull	Push	Pull
200	8	15.20	6.67	12	8.67	10.40
400	12	19.04	14	13.60	15.33	15.20
600	24	25.60	25.33	27.20	27,73	18.40
800	25.2	25.76	33.33	37.60	36	38.72

Table 4
Variation of concrete compressive strength with temperature (MPa).

Temperature level	60 min	120 min	180 min
20	19.86		
200	13.05	12.93	9.77
400	13.02	12.10	7.45
600	11.44	9.26	7.37
800	10.62	6.82	-

Fig. 16. Core sampling process from test elements.

Table 5
Variation of duration – Cumulative energy consumption (kJ) relationship with temperature.

High temperature level (°C)	Exposure duration		
	60 min	120 min	180 min
200	18.68	19.70	22.70
400	18.15	20.33	20.53
600	17.04	18.93	15.23
800	17.47	14.22	14.08
RCF_13	24.69		

have decreased by approximately 30.98 %, 42.41 %, and 42.97 %, respectively, compared to the reference test specimen. The most significant reduction in energy consumption capacity occurred in the RCF_12 test specimen exposed to 800 °C high temperature for 180 min.

When compared to the RCF_13 reference test specimen, the RCF_1 test specimen consumed approximately 24.34 % less energy, RCF_4 consumed around 26.49 % less energy, RCF_7 consumed about 30.98 % less energy, RCF_10 consumed around 29.28 % less energy, RCF_2 consumed approximately 20.21 % less energy, RCF_5 consumed around 17.66 % less energy, RCF_8 consumed about 23.33 % less energy, RCF_11 consumed approximately 42.41% less energy, RCF_3 consumed around 8.06 % less energy, RCF_6 consumed about 16.85 % less energy, and RCF_9 consumed around 38.32 % less energy.

3.3. *Stiffness – Horizontal displacement relationship*

The degradation of stiffness mainly related to the degradation caused by high temperature and phase change of materials [37]. Furthermore, high temperatures cause microcracks in concrete and soften steel. In general, after high temperatures, reinforced concrete frames have lower stiffness than unheated ones [37]. In this context, in this part of the study, the stiffnesses of the reinforced concrete frame test members exposed to high temperature were determined in two different conditions: after cooling and after cyclic loading tests. The stiffnesses of the test samples exposed to high temperature effects of 200, 400, 600 and 800 °C for 60, 120 and 180 min, after cooling down are presented in Table 6.

The change in the stiffness of the reinforced concrete frame test members exposed to high temperature after cooling (stiffness before repeated horizontal load tests) shown in Fig. 19. Accordingly, it was determined that the stiffness of reinforced concrete frames exposed to 200 °C for 60, 120 and 180 min decreased by 30 %, 50.67 % and 50.38 %, respectively. The stiffness of reinforced concrete frames exposed to 400 °C for 60, 120 and 180 min decreased by 51.9 %, 54.5 % and 49.94 %, respectively, and the stiffness of reinforced concrete frames exposed to 600 °C decreased by 69.29 %, 50.24 % and 31.33 %, respectively. The stiffness of reinforced concrete frames exposed to 800 °C for 60, 120 and 180 min decreased by 3 %, 50.38 % and 25.23 % respectively.

According to Fig. 19, it was determined that the initial stiffness of the reinforced concrete frame test members exposed to 400 and 600 °C for 60 min increased by 13.72 % and 6.94 % in tension, respectively. The initial stiffness of the reinforced concrete frame test members exposed to 200 °C for 120 and 180 min increased by 11.9 % and 5.75 % in tension, respectively. According to Fig. 19, the stiffness of reinforced concrete frame test members exposed to high temperature decreased compared to unheated frames. However, this reduction varies depending on the degree of temperature to which the reinforced concrete frame is exposed and the duration of the effect.

The change in stiffness in cyclic loading tests after exposure of reinforced concrete frame members to high temperature considered as an important parameter in evaluating the lateral load carrying capacity of the frame [36]. Reinforced concrete frames expected to have sufficient stiffness to avoid excessive deformation.

Fig. 20 illustrates the stiffness – horizontal displacement relationship obtained from the cyclic lateral load tests for concrete frame test specimens exposed to high-temperature effects at 200 °C, 400 °C, 600 °C, and 800 °C for durations of 60, 120, and 180 min. The stiffness – horizontal displacement curves of all test specimens compared in Fig. 20. Accordingly, the stiffness of the frame members decreased as the number of cycles increased due to the increase in temperature (Fig. 20).

Fig. 21 shows the superposition of hysteresis cycles of reinforced concrete frames exposed to different temperatures for different durations.

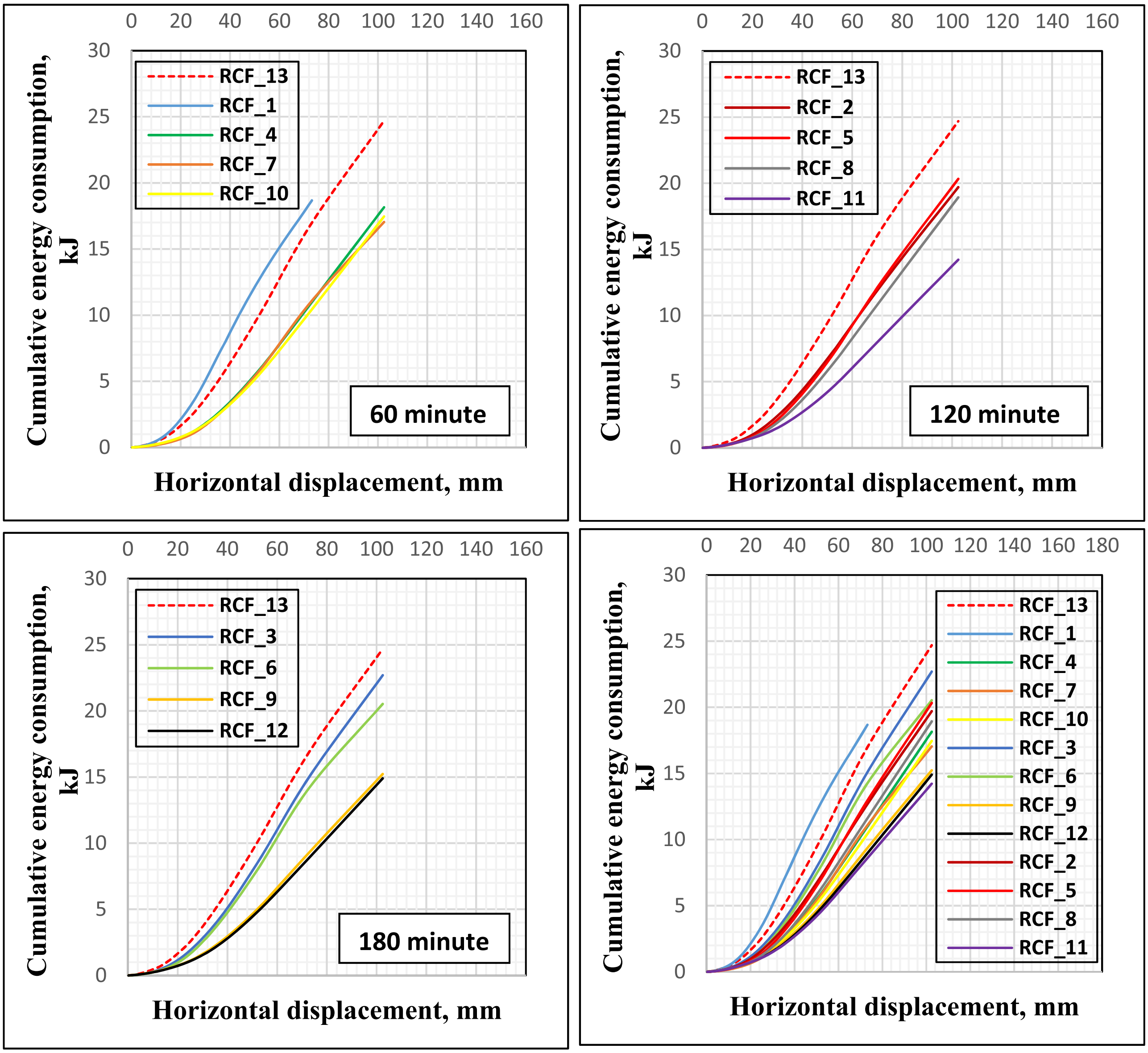

Fig. 17. Cumulative Energy Consumption – Horizontal Displacement Relationship.

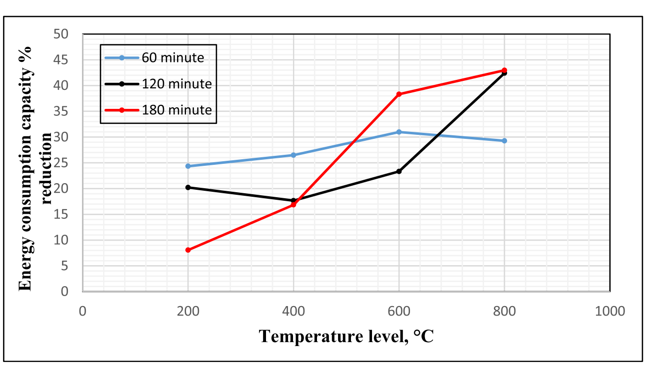

Fig. 18. Variation of energy consumption capacity reduction with temperature.

Table 6
Variation of initial stiffness with exposure duration.

High temperature level (°C)	Exposure duration					
	60 min		120 min		180 min	
	Push (+)	Pull (-)	Push (+)	Pull (-)	Push (+)	Pull (-)
200	11.5238	7,6154	8.16	9.875	8.2083	9.2308
400	7.9565	10.0833	7.5263	5.72	8.28	5.8261
600	5.07937	9.30435	8.2307	5.92	11.36	7.26
800	16.0455	3.7083	8.2083	5.875	12.3684	6.75
RCF_13	Push (+)			Pull (-)		
	16.5417			8.7		

4. Conclusions

In this study, cyclic loading tests were conducted to investigate the seismic performance of reinforced concrete frames subjected to 200, 400, 600 and 800 °C high temperature for 60, 120 and 180 min. In this context, the main purpose of this study is to investigate the stiffness,

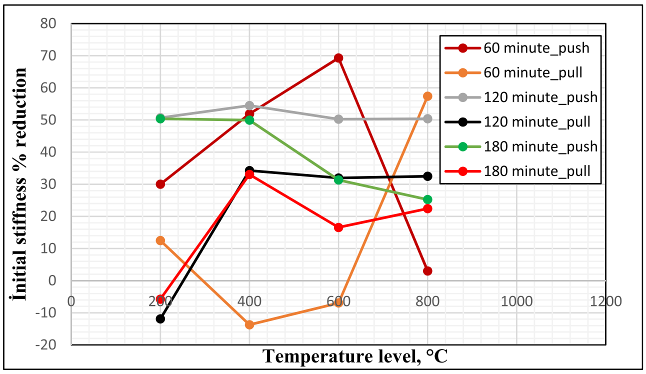

Fig. 19. Variation of initial stiffness reduction with temperature.

energy absorption and horizontal load carrying capacity losses of frames exposed to different ambient temperatures for different periods after repeated horizontal load effects and to provide useful information to the reader on whether the frames can used without strengthening. The main results can summarized as follows:

- All reinforced concrete frame test members exposed to high temperatures of 200, 400, 600 and 800 °C for 60, 120 and 180 min showed deterioration of the concrete surfaces. This deterioration was more intense in RCF-11 and RCF-12 where the high temperature was 800 °C and the exposure time was 120 and 180 min.
- In RCF-11 and RCF-12, which left to cool down on their own after be exposed to high temperature effect, spalling occurred in the concrete cover thickness due to the effect of atmospheric environment. This blistering and spalling only occurred in the test elements where the high temperature was 800 °C and the duration of action was 120 to 180 min.
- The horizontal load carrying capacity of the reinforced concrete frame obtained as a result of the cyclic lateral load tests performed after high temperature decreased with increasing high temperature in all groups where the impact time was 60, 120 and 180 min.
- The hysteretic loops shown in the lateral load - horizontal displacement curves of the reinforced concrete frames subjected to high temperature effects are in a more compressed state compared to the RCF-13 reference test member not subjected to high temperature effects. This result shows that the seismic performance of the test elements exposed to high temperature decreases.
- The energy consumption capacity of the reinforced concrete frame obtained as a result of cyclic lateral load tests after high temperature decreased with increasing temperature in all groups where the duration of impact was 60, 120 and 180 min. The maximum reduction realized in RCF-12 test member exposed to 800 °C high temperature for 180 min and the minimum reduction realized in RCF-3 test member exposed to 200 °C high temperature for 180 min.
- Reinforced concrete frames exposed to high temperature have a lower stiffness than unheated frames. It thought that the loss in initial stiffness measured after the high temperature effect is due to the opening and closing of cracks.
- The stiffness of the reinforced concrete frames under cyclic loading decreased as the number of cycles increased due to deterioration of concrete caused by high temperature and yielding of steel.
- It is recommended that frames exposed to ambient temperatures of 600 °C and above for 60, 120 and 180 min should not be used without strengthening due to the decomposition of the C-S-H gel in concrete at temperatures above 550 °C and the decrease in concrete strength and the fact that a decrease of more than 15% in the lateral load carrying capacity of reinforced concrete frames may cause collapse.

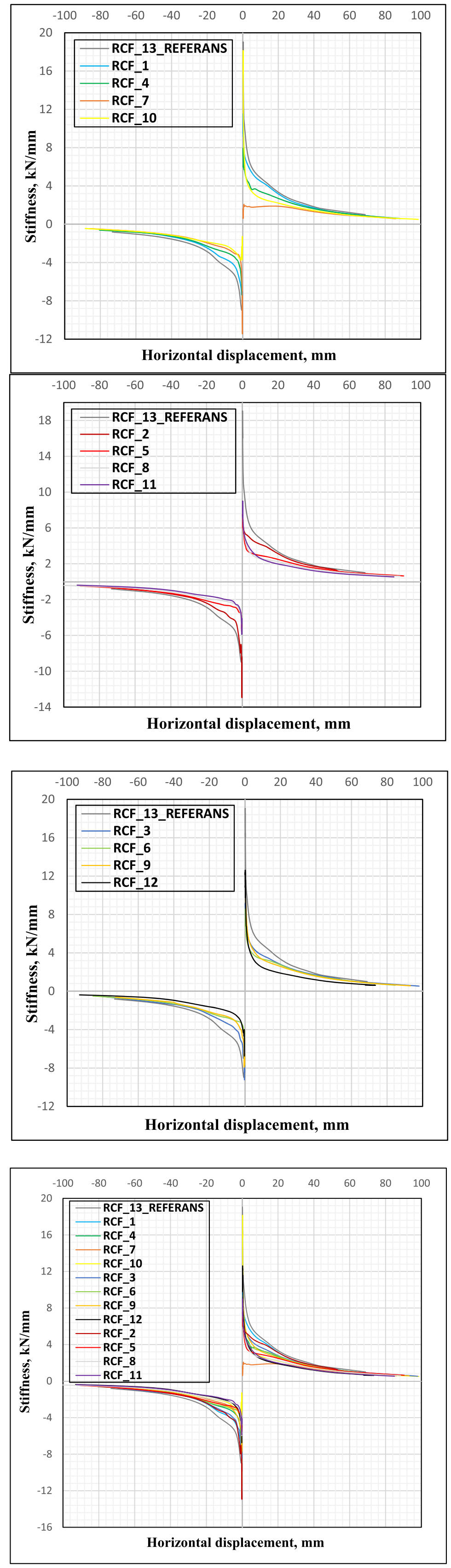

Fig. 20. Stiffness – Horizontal Displacement Relationship.

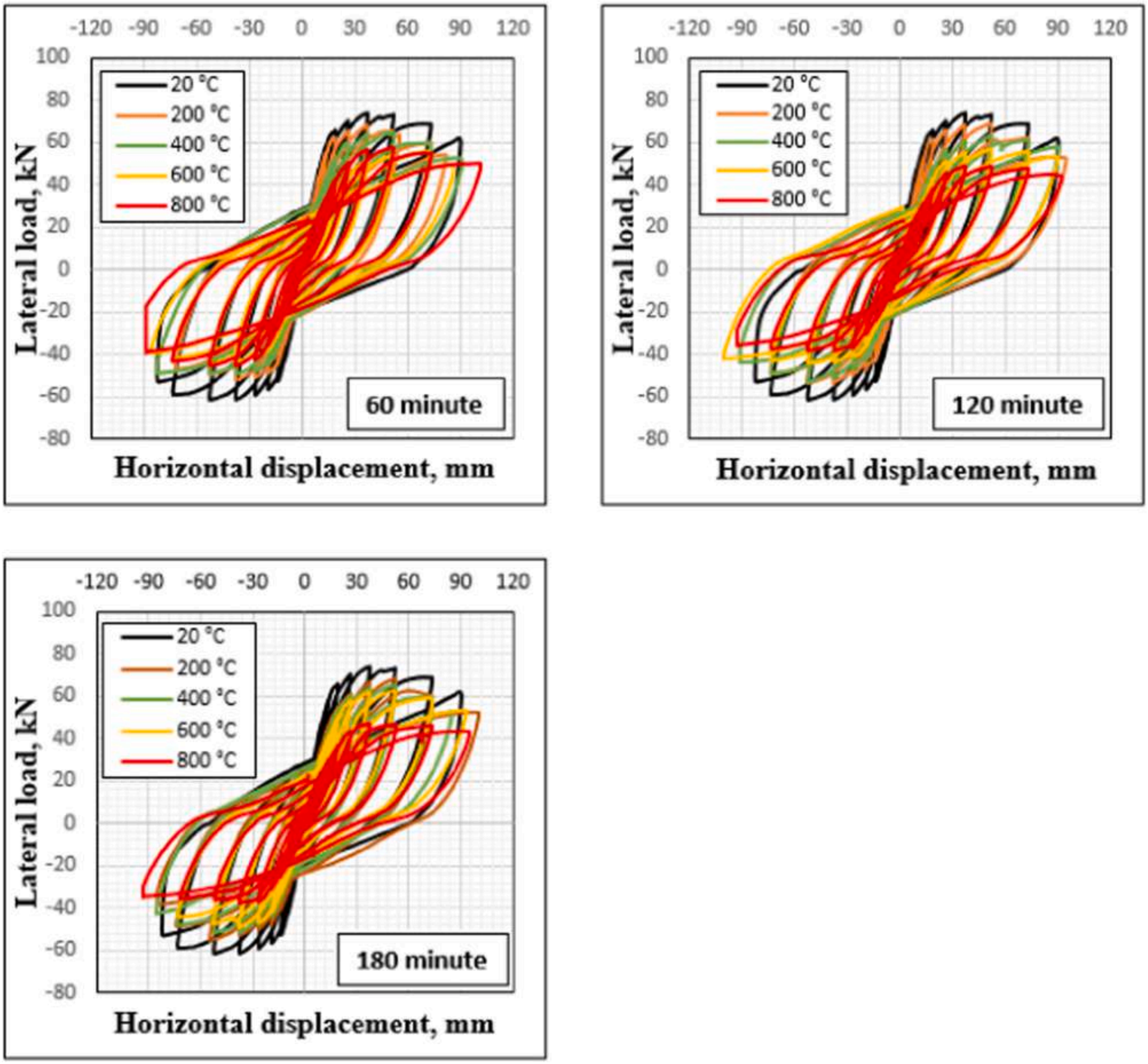

Fig. 21. Comparison of the variation of hysteresis cycles with temperature.

- At temperatures of 400 °C and below, since the C-S-H gel structure can repair itself and the reduction in the horizontal load carrying capacity of reinforced concrete frames is less than 15%, it is considered that reinforced concrete frames exposed to ambient temperatures of 400 °C and below for 60, 120 and 180 min can be used without strengthening.
- It is observed that the lateral load carrying capacity, stiffness and energy consumption capacities of reinforced concrete frame elements after exposure to high temperature effects decreased significantly depending on the temperature and exposure time.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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