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The Effects of Heat on the Cyclic Behavior of Retrofitted Concrete Columns (by Steel Plates and CFRP)

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Abstract

In this research, in addition to ensuring the accuracy of the numerical simulations, a 3D reinforced concrete column is numerically modeled in three conditions, including a non-retrofitted state, as well as two states retrofitted with steel plates and CFRP. The coupled temperature-displacement analysis of these columns is conducted under cyclic lateral loading in various heat levels, and the effects of both the retrofits and heat on the cyclic lateral behavior of the columns are studied and compared. According to the results of the study, with temperature rise, both lateral forces and energies increase in the non-retrofitted column, the column retrofitted with steel plates, and the column retrofitted with FRP. This is even more significant at 500°C, particularly in retrofitted columns with steel plates. Besides, retrofitting the columns with steel plates (compared to FRP plates) causes a more substantial increase in the heat sensitivity of the column during cyclic lateral loading.

Keywords

reinforced concrete column, FRP plates, steel plates, heat, cyclic loading, finite element method

1 Introduction

Columns play a substantial role in ensuring the overall stability of a structure. Any malfunctions and damages to these members can result in local and progressive deterioration and even complete structural collapse. On the other hand, concrete is a material with a well-earned reputation for its durability, widely used in fortress and nuclear facilities due to its excellent tolerance against high temperatures and fire, as well as its rigidity and high energy absorption. However, concrete material suffers from low flexibility and weak performance in tension, especially when subjected to dynamic loads and their associated local stresses. Accordingly, it is vital to pay special attention to the seismic behavior of concrete members, including concrete columns, and to strengthen these members against seismic loads, which are among the causes of progressive damage and even complete collapse. That said, the ability of concrete to tolerate high temperatures and fire does not mean that these conditions do not affect concrete at all. Instead, at high temperatures, there is a likelihood of changes in appearance (such as color and shape) and physical changes (such as a decrease in compressive strength and the elasticity modulus), which are the most damaging factors for concrete materials. Therefore, it is crucial to consider the seismic behavior of concrete columns at high temperatures and seismically strengthen them for such conditions. One of the most common methods for seismically retrofitting concrete columns is using fiber-reinforced plastic plates (FRP) or steel shafts on the lateral surfaces of these columns.

FRP plates have been widely used in recent years as a successful method to enhance the seismic behavior of structures. Unlike traditional retrofitting methods that may involve using shotcrete or other materials, FRP plates cause no overweight or change in the dynamic properties of the existing system due to their excellent resistance to corrosion and high strength-to-weight ratio. Previous studies have mainly focused on concrete slabs and beams retrofitted with FRP outer covers. However, limited attention has been paid to the effects of FRP plates on the strength of other structural members such as concrete columns under lateral loads, especially at high temperatures.

Depending on the type of project, there are various retrofitting methods available, including FRP jacketing, crack injection, steel jacketing, steel bracing, and RC jacketing, as well as the utilization of dampers and base isolators.

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However, the effectiveness of each of these methods depends on the project type, and each may have its advantages and disadvantages. For instance, the use of base isolators and dampers may require a larger construction cost and specialized workforce compared to other methods. Additionally, the injection of cracks may not have a significant impact on the overall performance of the structure and may not be efficient when improving the global behavior of the structure. On the other hand, FRP and RC jacketing techniques can be more cost-effective and may not have the aforementioned drawbacks of the other methods, which makes them effective for retrofitting purposes.

In 2014, Adelzadeh et al. [1] investigated the fire resistance of concrete slabs by numerically simulating several 2D reinforced concrete slabs with FRP under uniform thermal loading. In their study, the slippage of FRP bars in the concrete was neglected.

Nowadays, the clever combination of steel and concrete makes an effective composite system that is more efficient than the individual functions of these materials. This system is successfully used in columns, beams, slabs with medium to large bays in buildings, as well as the pillars and beams of bridges. The use of composite columns is increasing worldwide due to the good and dual cooperation of steel and concrete. Composite columns not only bring about numerous advantages in the construction phase (especially in terms of speed and cost), but they also significantly improve the dynamic properties of structures compared to steel and concrete elements. The use of steel-concrete composite columns started to grow gradually from 1950, with their applications in high-rise buildings markedly increasing due to their several advantages. Steel-concrete composite columns are fabricated with a variety of sections. Based on the position of concrete and steel, these columns are categorized into two main types, including composite columns buried in concrete (SRC) and composite columns filled with concrete or concrete columns with steel shafts (CFT). This highlights the importance of studying the performance of steel shafts in the seismic retrofitting of concrete columns, especially at high temperatures. Yermak et al. [2], in 2018, conducted a numerical study on the behavior of a steel column filled with concrete in connection with a steel beam. In 2014, Han and Gillie [3] used 2D numerical simulation to evaluate the time-temperature curve at various points of a steel pipe cross-section filled with concrete under large uniform thermal loading. Besides comparing the numerical and experimental results, they also provided a simplified 2D numerical model (instead of a 3D model) to measure the temperature at various points of the steel pipe cross-section filled with concrete exposed to fire. Rodrigues and Júnior Moreno [4], presented a simplified numerical approach in 2017 to predict the temperature of steel-concrete composite columns exposed to fire using the 3D numerical simulation of a steel pipe filled with concrete under high uniform thermal loading and the thermal analysis of the mentioned column.

Rad et al. [5] presented a novel computational optimization model to control the plastic behavior of reinforced concrete haunched beams using the complementary strain energy of residual forces formed inside the steel reinforcing bars. A limit value was used to control plastic deformation within the steel bars during loading progress. By avoiding plastic deformation in the steel bars, the overall behavior of the haunched reinforced concrete beams could be improved.

In 2023, Khaleel Ibrahim and Rad [6] conducted research on the reliability limitation index for simulated strengthened haunched beams. They considered randomness in concrete and CFRP properties, as well as the complementary strain energy value, which acts as a plastic behavior controller that indicates the damage amount within the reinforcement steel bars. In their study, the effects of randomness were evaluated on the behaviors of the presented models with different numbers of CFRP strips. The reliability index served as a limitation index while taking into account concrete characteristics and complementary strain energy as random variables. In another study by Habashneh and Rad [7] in 2023, a computational technique was developed for applying reliability-based design to thermoelastic structural topology optimization. Their study involved optimizing the topology of thermoelastic structures based on reliability-based design through geometrical nonlinearity analysis to study a 2D L-shaped beam problem.

In this paper, the numerical models and the utilized software (ABAQUS) are first verified using measured data from the loading test conducted by Haji et al. in [8] on a reinforced concrete (RC) column. Afterwards, the 3D numerical model of this experimental reinforced concrete is implemented in the mentioned software under the three following conditions:

- Non-retrofitted state, hereinafter called the RC model, Retrofitted with steel plates, hereinafter called the RC-steel model,
- Retrofitted with carbon fiber-reinforced plates (CFRP), hereinafter called the RC-CFRP model.

The coupled temperature-displacement analysis of these models is conducted during cyclic lateral loading using the cyclic non-linear dynamic method at different temperatures (due to fire according to the ISO 834 standard [9]). Based on these analyses, the effects of temperature are studied on the cyclic lateral behavior of non-retrofitted reinforced concrete columns, as well as those retrofitted with steel and CFRP plates. Additionally, the role of these retrofits is assessed and compared. In the following, the simulation process is first described and verified, then the obtained results from the mentioned simulations are presented.

In 2021, Bhatt et al. [10] studied the behavior of flexural concrete members (T-shaped beams and slabs) retrofitted with insulating CFRP in the case of a fire. In their study, the strengthened members were protected with insulators and tested under a combination of structural and thermal loadings. The considered variables in their tests included the loading level, strength, and thickness of the thermal insulation applied to the studied structures. The results obtained from fire tests and numerical studies showed that beams and slabs retrofitted with insulating CFRPs could respectively withstand three and four hours of fire exposure under service loading. The insulating layer prevented temperature increase in the member; therefore, the combined effect of CFRP-concrete remained active for a longer time, keeping the temperature of the steel rebar under 400°C, which, in turn, increased the capacities of both beams and slabs.

In another study carried out by Hussain et al. [11], regression models and finite element analyses were used to predict the deformation-load behaviors of retrofitted columns that were damaged due to exposure to temperatures of 300°C, 500°C, and 900°C using innovative materials confined by carbon fibers. Their study found that regression equations and numerical models were better substitutes for experimental methods. In addition, the predicted responses of the numerical model had a negligible difference of less than 10% from the practical response. As a result, they concluded that the numerical models and predictions were in agreement with the experimental results and could be used as an alternative to predict loads and deformations.

In 2018, Kodur and Bhatt [12] studied a numerical approach to model the responses of concrete slabs retrofitted with fiber polymers exposed to fire. Their model considered parameters such as the thermal characteristics of concrete, steel, FRP, and thermal insulation, as well as the debonding temperature at the FRP-concrete interface. The results of the analyses indicated that an FRP-retrofitted concrete slab with no insulation would show a lower fire resistance compared to a non-retrofitted concrete slab. Moreover, they concluded that heat-induced debonding had a considerable impact on the fire resistance of FRP-retrofitted concrete slabs, and neglecting this factor could lead to a non-conservative estimation of resistance to fire.

Jafarzadeh and Nematzadeh [13] studied experimental and numerical results of post-fire flexural behaviors of steel fiber-retrofitted concrete beams. Their research aimed to investigate the flexural behavior of high-strength concrete (HSC) beams retrofitted with glass and steel FRPs exposed to high temperatures. Their considered variables included the applied temperature (200°, 250°, 400°, and 600°C), the volume ratio of the steel fibers (0% and 1%), and the reinforcement ratio (0.314% and 0.872%). Various parameters, including load-carrying capacity, load-deflection ratio, crack pattern in terms of crack width under service and ultimate loading, as well as the flexibility of the beams, were studied and analyzed. The study found that exposing the beams to 250°C heat significantly decreased their load-carrying capacity, while exposure to 400° heat increased their residual load-carrying capacity. However, being exposed to 600°C heat considerably reduced their flexural capacity. Apart from this, steel fibers had no significant impact on the behavior of beams with low reinforcement ratios. However, with an increase in the reinforcement ratio and the applied thermal load, steel fibers effectively improved the load-carrying capacity and decreased service load-induced deflections.

So far, according to the widespread use of concrete structures and the importance of an optimal column design in such systems, numerous studies have been dedicated to thermal and seismic analyses of different types of columns. That said, there is a lack of comprehensive studies on the seismic behavior of concrete columns retrofitted with FRP and steel plates in high temperatures. Moreover, there are ambiguities in the performance of columns with different retrofits, particularly regarding the effects of heat on the seismic behavior of concrete columns. Therefore, considering the high temperature inside concrete columns, achieving safe and optimal parameters to optimally use such methods is complicated. Accordingly, further studies are needed in this regard. This paper addresses this issue using 3D numerical finite element simulations and coupled temperature-displacement analysis of reinforced concrete columns in three conditions: non-retrofitted, steel plate-retrofitted, and CFRP-retrofitted states. To onduct these analyses, the displacements of the columns are investigated under uniform and cyclic lateral loadings under different heat levels. The mentioned thermal analysis is conducted to study the effects of heat on the plastic strain of concrete columns under thermal loading, which is crucial in retrofitting concrete structures against fire.

According to the reviewed background, the novelties of this study are as follows: 1-Investigating the effect of high temperatures on the seismic behavior of reinforced concrete columns, including non-retrofitted columns, as well as those retrofitted with steel plates and CFRP plates. 2-Studying different retrofitting methods for reinforced concrete columns subjected to cyclic lateral loading, including non-retrofitted columns, columns retrofitted with steel plates, and those retrofitted with CFRP plates.

2 Numerical modeling procedure

ABAQUS is a powerful software based on the finite element method that offers both explicit and implicit formulations. It also provides several options for simulating structural members, including concrete, steel, and more, using continuous 3D and 2D meshing techniques [14]. This makes the software capable of modeling steel-concrete composite columns and columns retrofitted with polymer plates, allowing for non-linear coupled temperature-displacement analyses of these structural members based on different dynamic loads, including cyclic loads. In this study, 3D numerical simulations have been made through ABAQUS based on the test sample features presented by Haji et al. [8]. The test sample used in this study was a reinforced concrete column of 600 mm in length and 200 mm in diameter. The column was subjected to a pre-determined uniform vertical displacement of 20.07 mm on the top surface, followed by applying a pre-determined uniform lateral displacement of 57.75 mm on the same surface. The bottom surface of the sample was fixed against transitional and rotational displacements during these loadings to ensure stability [8].

To perform the studies mentioned above, the test sample was retrofitted with steel and CFRP plates. For simulating the retrofitting of the column with FRP plates, the lateral area of the column was fully covered up to a thickness of 5 mm with CFRP plates. Similarly, to retrofit the column with steel plates, the lateral area of this column was entirely covered with a 5 mm thick steel shaft. To conduct the coupled temperature-displacement analysis of the models, the lateral area of the column was subjected to a standard fire temperature (as shown in Fig. 1 [9]). For the

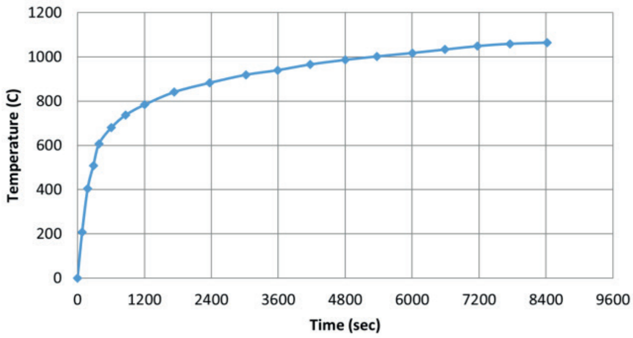

Fig. 1 The standard fire temperature-time curve

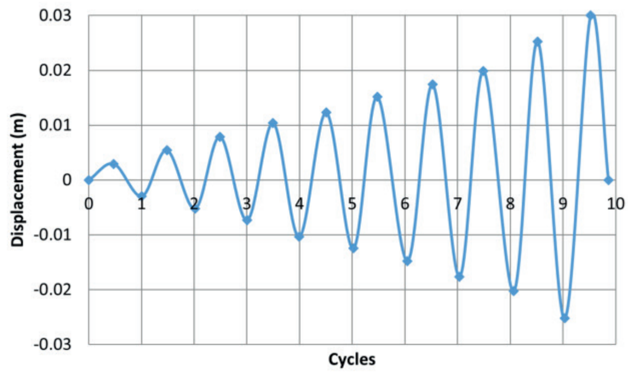

Fig. 2 The applied cyclic lateral displacement curve to the top surface of the column in the models [15]

cyclic lateral loading of the models, a pre-determined cyclic lateral displacement (as per Fig. 2 [15]) was applied to the top surface of the column using the nonlinear cyclic dynamic method.

2.1 Concrete mass modeling

A homogenous isotropic concrete mass with a length of 600 mm and a diameter of 200 mm is used according to Figs. 3–5 [8]. The concrete mass exhibits elastoplastic behavior, and a combined plastic-damage model is employed to define the plastic behavior. The specific weight, compressive strength, and Poisson's ratio of the concrete mass are 23.5 KN/m^3, 30.61 MPa, and 0.15, respectively [8]. The elasticity modulus of the concrete mass (E_c) in the simulations was calculated using the following equation according to its specific weight and compressive strength (ACI 318 code) [16]:

$$E_c = 15000\sqrt{f_c'} \, , \tag{1}$$

where f_c' is the particular strength of concrete in kg/cm^2. On the other hand, the specific heat capacity, thermal conductivity, and thermal expansion coefficient for the concrete mass are 970 j/kg°k, 1.14 W/m°k, and 0.0000117 1/°C, respectively [3, 17].

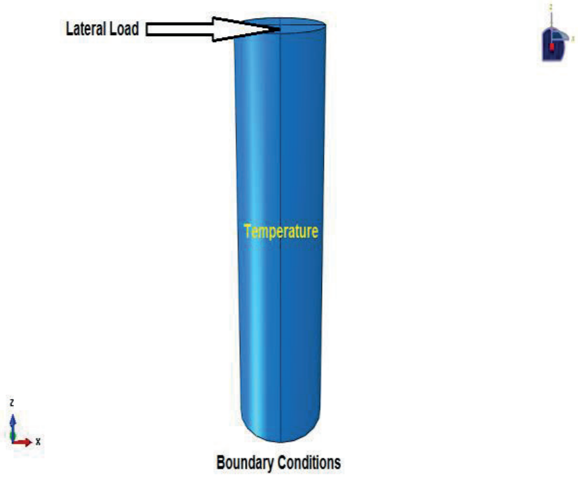

Fig. 3 Geometry of the RC model

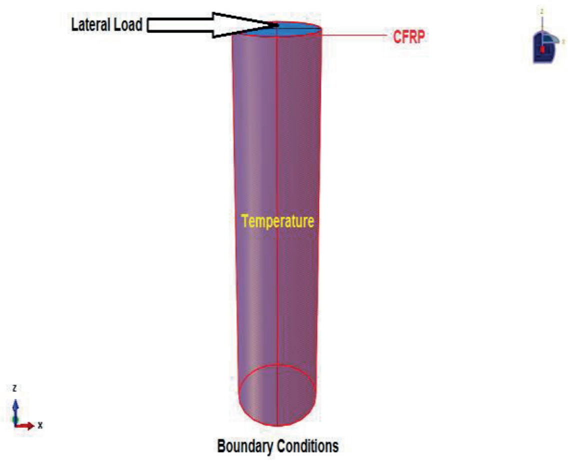

Fig. 4 Geometry of the RC-CFRP model

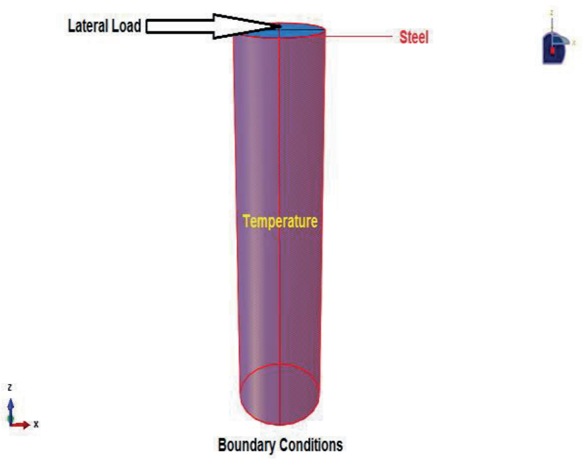

Fig. 5 Geometry of the RC-Steel model

Once the physical, thermal, and elastic properties of the concrete mass are defined in these simulations, the plastic behavior and properties must also be defined. To accomplish this, a combined plastic-damage model is used, which is a continuous plastic model that considers the damage criteria of the concrete through two primary failure mechanisms associated with it: tensile cracking and compressive crushing [18, 19]. To relate the compressive strain and stress of the concrete, the following equation is utilized (Kent and Park equation in 1971) [20]:

$$\sigma_c = f_c^{'}\left[2\left(\frac{\varepsilon_c}{\varepsilon_c^{'}}\right)-\left(\frac{\varepsilon_c}{\varepsilon_c^{'}}\right)^2\right], \quad (2)$$

where σ_c and ε_c are compressive stress and strain, respectively, while f_c' and ε_c' are, respectively, compressive strength and its corresponding strain, which, according to Park and Paulay's report in 1975, are considered 30.61 MPa and 0.002 in these simulations [21]. The mentioned equation creates a curve in which the behavior of concrete becomes linear after reaching its compressive strength. This behavior continues until reaching 20% of this strength, which is due to the fact that concrete retains about 20% of its compressive strength in large compressive strains [20]. Therefore, considering the mentioned curve and equation, the compressive plastic strain is calculated for compressive yield stresses in these simulations, which is then used to define the compressive plastic behavior of the concrete mass. To establish a relationship between tensile stress and strain of the concrete, the compressive strength must be expressed as a percentage of the tensile strength (f_t') (about 7 to 10 percent). Additionally, the behavior of the concrete must be considered elastic and linear until it reaches the tensile strength [20]. Accordingly, the tensile strength of concrete is considered 10% of its compressive strength in this model.

2.2 Longitudinal and transverse reinforcements in the concrete mass

Truss structural members with diameters of 16 mm and 8 mm are used for the numerical modeling of longitudinal and transverse reinforcements in the concrete mass, respectively. The physical and mechanical properties of these members are listed in Table 1 [8], and their behavior is assumed completely elastoplastic (steel shows an elastic behavior before reaching yielding stress). On the other hand, the specific heat capacity, thermal conductivity, and thermal expansion coefficient for these buried reinforcements are 460 j/kg°k, 45 W/m°k, and 0.0000117 1/°C, respectively [3, 17].

In Table 1, γ, E, υ, f_y, and f_u are the specific weight, elasticity modulus, Poison's ratio, yielding strength, and the ultimate power of the transverse and longitudinal reinforcements, respectively.

Table 1 Specifications of steel used in reinforcements [8]

Parameters / Diameter(mm)	γ(KN/m^3)	E (Mpa)	v	f_y(MPa)	f_{cu}(MPa)
8	78.5	201959.18	0.3	494.8	628.82
16	78.5	207779.17	0.3	498.67	658.48

Table 2 Properties of the CFRP plates in the reinforced experimental sample [8]

γ(KN/m^3)	v	E (Mpa)	σ_t (MPa)
3900	0.22	230000	17.90

2.3 Modeling of CFRP plates on the lateral surface of the reinforced concrete mass

To model the CFRP plates on the lateral surface of the reinforced concrete mass, a homogenous non-isotropic shell element is utilized with a thickness of 5 mm. This member is modeled using a combined elastic-damage model, with physical and mechanical properties as listed in Table 2 [8]. The CFRP plate is restrained to the lateral surface of the reinforced concrete mass, as shown in Fig. 4. The specific heat capacity, thermal conductivity, and thermal expansion coefficient for CFRP plates on the lateral surface of the reinforced concrete mass are 1500 j/kg°k, 0.577 W/m°k, and 0.0000144 1/°C [22], respectively.

In Table 2, E, σ_t, γ, and ϑ are Elasticity modulus, tensile strength, specific weight, and Poisson's ratio of the CFRP plates, respectively.

2.4 Modeling of the steel plates on the lateral surface of the reinforced concrete mass

To model the steel plate on the lateral surface of the reinforced concrete mass, a homogenous non-isotropic shell element with a thickness of 5 mm is employed. The behavioral model used for this member is elastoplastic (the behavior of steel material is elastic until reaching the yielding stress). The specific weight, young modulus, Poisson's ratio, yielding strength, ultimate strength, specific heat capacity, thermal conductivity, and thermal expansion coefficient for steel plates are 78.5 KN/m^3, 208 GPa, 0.3, 498.67 MPa, 658.48 Mpa, 460 j/kg°k, 45 W/m°k, and 0.0000117 1/°C [3,17], respectively. This member is restrained to the lateral surface of the reinforced concrete mass, as shown in Fig. 5.

2.5 Modeling of the boundary conditions

All rotational and transitional displacements are restrained at the bottom of the column (as shown in Figs. 3–5). The bottom surface of the reinforced concrete mass has a rigid boundary condition, with fixed displacement on this surface. Under cyclic loads, a displacement of 100 cm occurs only along the x-axis on the upper surface of the reinforced concrete mass. The boundary condition for CFRP plates of the reinforced concrete mass under coupled temperature-displacement analysis is 1273° Kelvin, and the boundary condition for longitudinal and transverse reinforcements of the reinforced concrete mass under coupled temperature-displacement analysis is 273° Kelvin.

2.6 Modeling of the coupled cyclic-thermal loading

The considered temperature (T) according to standard fire is applied to the lateral surface of the column (as shown in Fig. 1 [9]). In addition, the pre-determined cyclic displacements are applied to the top surface of the column (as shown in Fig. 2 [15]). This is done to simulate the lateral loading and energy of the numerical models during the coupled thermal-cyclic loading (during the analysis of the coupled temperature-displacement models via the cyclic nonlinear dynamic method) (Figs. 3–5).

2.7 Meshing of the models

The concrete mass is meshed using the 8-node continuous 3D thermal solid element with a length of 60 mm and a diameter of 30 mm, which is known as C3D8T in ABAQUS [14]. To model the longitudinal and transverse reinforcements, the T3D2T in ABAQUS is applied, which is a 2-node 3D thermal truss element with a length of 60 mm [14]. In contrast, the 4-node thermal shell element named S4T in ABAQUS with a length of 60 mm and a diameter of 30 mm is employed to mesh the steel and CFRP plates in the simulations. This element is subjected to the coupled temperature-displacement analysis (Figs. 6–9).

3 Verification of the numerical modeling procedures

To validate the numerical simulations, a 3D numerical model of the sample tested by Haji et al. was utilized. To accomplish this verification, a uniform lateral displacement is applied step by step to the top surface of the model (nonlinear static analysis). The results are then compared with the experimental measurements to verify the accuracy of numerical modeling, as shown in Figs. 10 and 11.

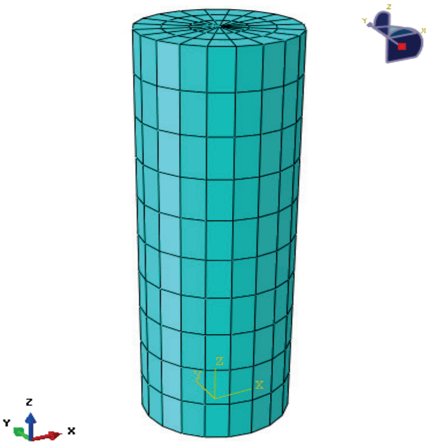

Fig. 6 Concrete mass meshing

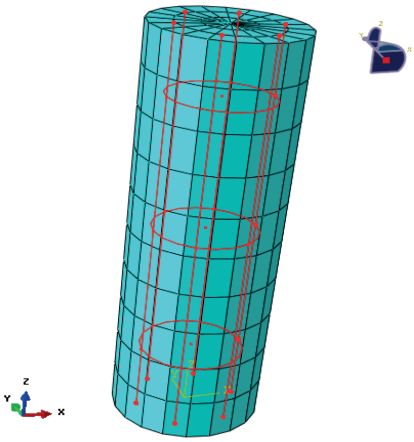

Fig. 7 Meshing of longitudinal and transverse reinforcements in the concrete mass

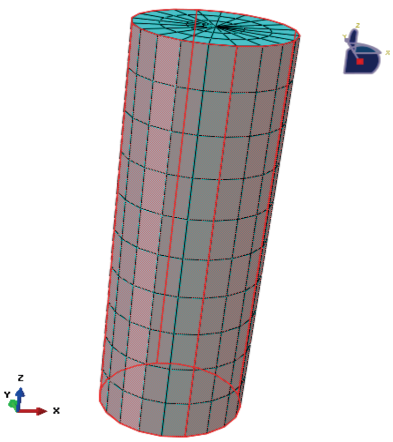

Fig. 8 Meshing of CFRP plates on the lateral surface of the reinforced concrete mass

Figs. 10 and 11 show a strong agreement between the numerical pushover curve of the lateral to vertical displacement ratio-lateral loading of the sample and the corresponding experimental pushover curve of the same parameters. The maximum error observed between the

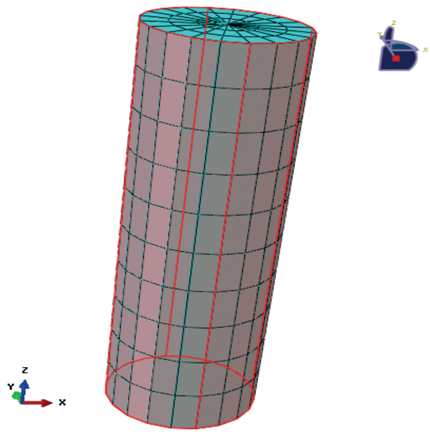

Fig. 9 Steel plate meshing on the lateral surface of the reinforced concrete mass

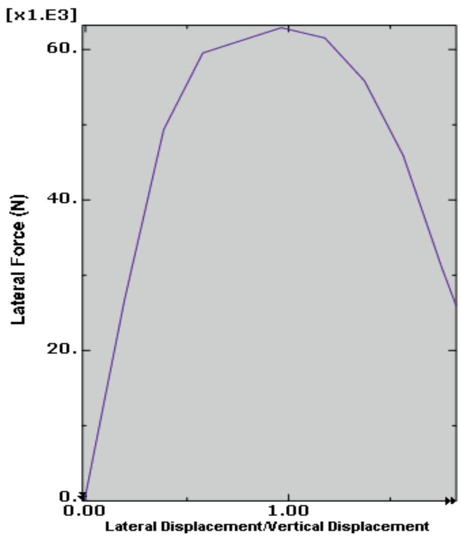

Fig. 10 The numerical curves of the sample behavior (lateral to vertical displacement ratio-lateral loading of the sample in meters)

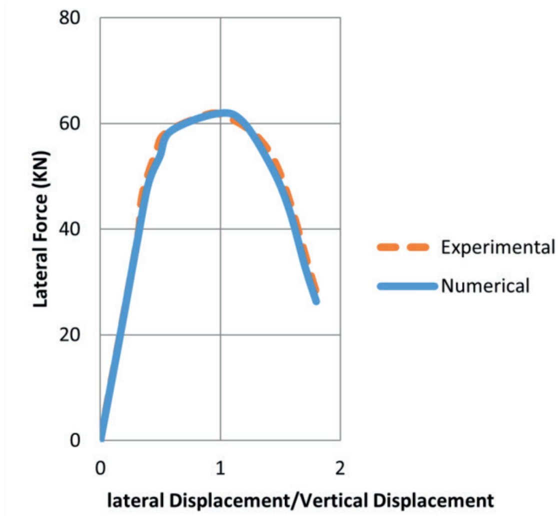

Fig. 11 The comparison between the numerical (present research) and experimental curves [8] of the sample behavior (lateral to vertical displacement ratio- lateral loading of the sample in meters)

two curves is 1.85%, which shows the high reliability of both the numerical modeling and the ABAQUS software in this research.

4 Evaluation and investigation of the results obtained from the numerical modeling

Following the verification of the numerical modeling, this study evaluates the effects of temperature on the cyclic lateral behavior of non-retrofitted reinforced concrete columns as well as those retrofitted with CFRP and steel plates (Figs. 12–19). This is accomplished by investigating the lateral forces and energies of the RC, RC-steel, and RC-CFRP models during cyclic lateral loading under standard fire temperatures of 250°C, 500°C, and 1000°C. Figs. 12 to 14 and 16 to 18 depict the results of this investigation. Furthermore, to evaluate and compare the effectiveness of retrofitting reinforced concrete with steel and CFRP plates, the cyclic lateral behavior of reinforced concrete columns due to elevated temperatures ranging from 250°C to 500°C and from 250° to 1000°C is evaluated. Figs. 15 and 19 illustrate the results of this investigation. The study also analyzes dimensionless parameters of the models, including the percentage increase of lateral load ($\Delta F/F_{(250\ C)}$) and the percentage increase of energy ($\Delta E/E_{(250\ C)}$). Here, $F_{(250\ C)}$ and $E_{(250\ C)}$ are the maximum values of the lateral loading and power exhibited by each model under standard fire conditions (250°C), respectively. ΔF and ΔE represent the differences in lateral loading and the power observed in each model due to temperature increase in the normal fire, specifically from 250°C to 500°C and 1000°C, respectively.

Fig. 12 indicates that with an increase in the temperature of the standard fire in reinforced concrete (from 250°C to 1000°C), the lateral forces of the column during cyclic lateral loading undergo a slight increase (by 3% from 250°C to 500°C, and 1% from 500°C to 1000°C added that this small increase (about 4% due to the increase in temperature from 250 to 1000°C) of the cyclic lateral force of the reinforced concrete column (RC model), is more significant up to 500°C (about 3%). This is attributable to the volume strains caused by the temperature increase, particularly at 500°C, which lead to a slight elevation in stresses (by about 4%) and internal forces of the column during cyclic lateral loading.

Fig. 13 shows that with an increase in the temperature of the standard fire in reinforced concrete columns retrofitted with steel plates (from 250°C to 1000°C), the lateral forces of the column significantly increase during cyclic

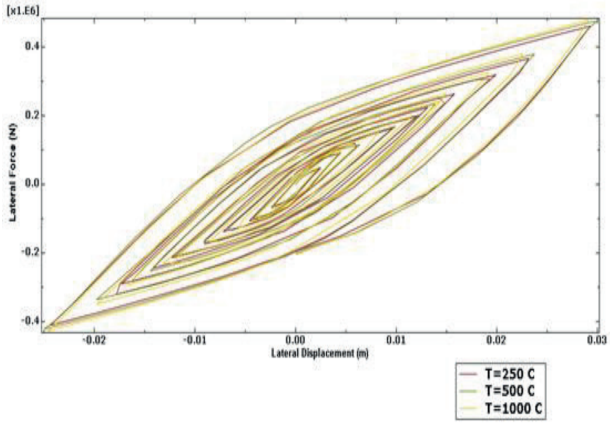

Fig. 12 The influence of temperature on lateral forces of the RC model during cyclic lateral loading

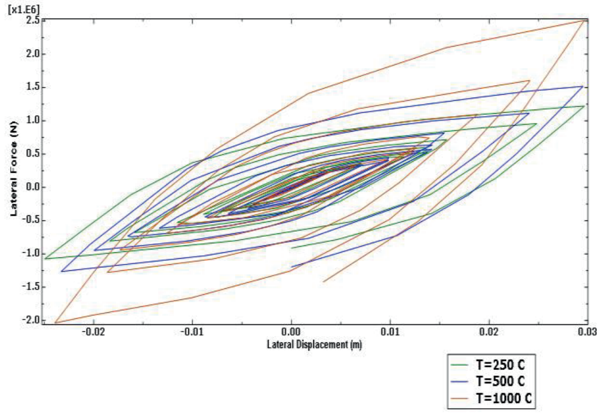

Fig. 13 The influence of temperature on lateral forces of the RC-Steel model during cyclic lateral loading

lateral loading (by 24% from 250°C to 500°C and 81% from 500°C to 1000°C). This increase of 105% from 250°C to 1000°C is even higher in RC-Steel retrofitted reinforced concrete columns (81%), especially at temperatures higher than 500°C. This is due to the wide distribution of volumetric strains caused by the temperature increase (especially after 500°C) in retrofitted columns since steel has a high thermal conductivity of 45 W/m°K, whereas concrete has a conductivity of 1.14 W/m°K. This, in turn, causes a high level of stress (105%), leading to increased forces exerted on the column during cyclic lateral loading.

As shown in Fig. 14, following an increase in the temperature of the standard fire in reinforced concrete columns with FRP (between 250°C to 1000°C), the lateral forces of the column increase during cyclic lateral loading (by 15% from 250°C to 500°C and 38% from 500°C to 1000°C). This rise in cyclic lateral forces observed in RC-CFRP columns (by 53% from 250°C to 1000°C) is more significant after 500°C (38%) due to the volumetric strains caused by the temperature increase, especially from 500°C in the column retrofitted with FRP plates. This effect can be mainly attributed to the high thermal expansion coefficient of FRP (0.0000144 1/C) which is higher than that of concrete (0.0000117 1/C), resulting in a 53% increase in stresses and forces during cyclic lateral loading. However, reducing the thickness of FRP plates might mitigate the temperature effects (particularly at temperatures lower than 500°C) on the lateral forces of reinforced concrete columns retrofitted with FRP plates during cyclic lateral loading.

As Fig. 15 illustrates, with an increase in the temperature of the standard fire in non-retrofitted concrete columns, as well as those retrofitted with steel plates and FRP plates (from 250°C to 1000°C), the lateral forces experienced by these columns increase (by 4% for the RC model, 105% for the RC-steel model, and 53% for the RC-CFRP model). This increase is even more noticeable after 500°C, particularly for retrofitted reinforced concrete columns (especially those retrofitted with steel plates), with an increase of 1% for the RC model, 38% for RC-CFRP, and 81% for RC-steel. This is attributed to volumetric strains resulting from the temperature increase (especially after 500°C), which causes a rise in the stresses and forces

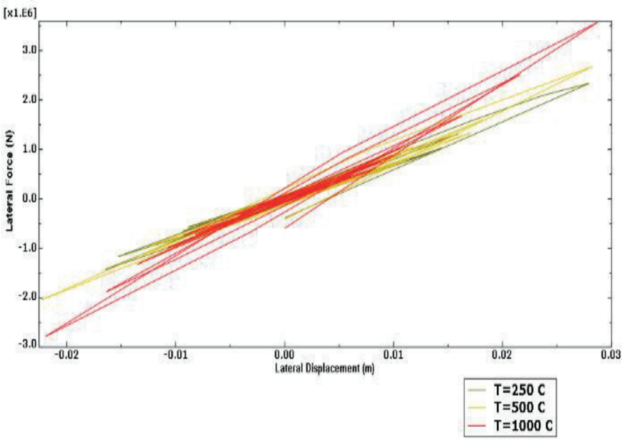

Fig. 14 The influence of temperature on lateral forces of the RC-CFRP model during cyclic lateral loading

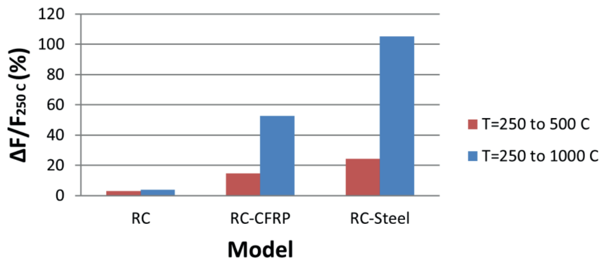

Fig. 15 The comparison between the percentage increases (due to the temperature rise) of the lateral forces of the models during the cyclic lateral loading

experienced by the column during cyclic lateral loading. There is a markedly more significant increase in pressures and cyclic pressures experienced by reinforced concrete columns with steel plates and FRP plates due to the high thermal conductivity of steel (45 W/mK), compared to concrete (1.14 W/mK) and the high thermal expansion coefficient of FRP (0.0000144 1/C), compared to concrete (0.0000117). The increase in pressures is around 38% for RC-CFRP and 81% for RC-steel.

Therefore, it can be said that retrofitting reinforced concrete columns with steel plates and FRP plates, especially the latter, significantly increases the thermal sensitivity of reinforced concrete during cyclic lateral loading (101% for RC-Steel and 49% for RC-CFRP compared to the RC model). This increase due to temperature rise is more considerable after 500°C (38% for RC-CFRP and 81% for the RC-Steel model). Fig. 15 shows that retrofitting reinforced columns with steel plates (rather than FRP plates) escalates the thermal sensitivity of the reinforced concrete column during cyclic lateral loading to a higher level (52%). This is due to the higher thermal conductivity of steel compared to FRP (by 44.423 W/mK), which causes more heat and volumetric strains being transferred from steel to concrete. This phenomenon leads to a more significant rise (52%) in stresses and forces experienced by reinforced concrete columns with steel plates (compared to those with FRP plates) during cyclic lateral loading.

According to Fig. 16, with a rise in the temperature of the standard fire in retrofitted reinforced concrete columns (from 250°C to 1000°C), a slight increase in energy is observed during cyclic lateral loading (by 6% from 250°C to 500°C, and 4% from 500°C to 1000°C). This slight increase in energy (about 10% from 250˚C to

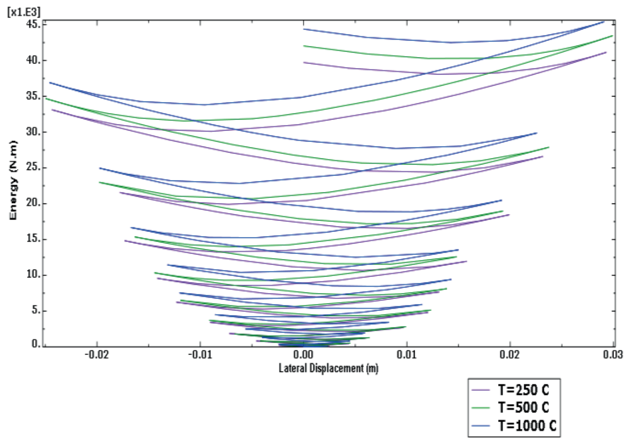

Fig. 16 The impact of temperature on the energy of the RC model during cyclic loading

1000°C) is more significant at 500°C (6%) in the RC-steel model. This is mainly due to volumetric strains, stresses, and forces resulting from the temperature rise (especially up to 500°C) in the reinforced concrete column, leading to a slight increase (10%) in the strain energy of the column during cyclic lateral loading.

Fig. 17 reveals that a rise in the temperature of the standard fire in reinforced concrete columns retrofitted with steel plates (between 250°C to 1000°C) increases the energy of the column during cyclic lateral loading (by 35% from 250°C to 500°C and 137% from 500˚C to 1000°C). This energy increase is even more notable (172% after a temperature rise from 250°C to 1000°C) in RC-Steel reinforced concrete columns at 500°C (which is about 137%). The occurrence and distribution of volumetric strains and stresses due to the temperature rise (especially after 500°C) in the mentioned column lead to a significant increase in the strain energy of this column during cyclic lateral loading (because of the high thermal conductivity of steel i.e., 45 W/mK compared to 1.14 W/mK for concrete).

Fig. 18 shows an energy increase in the reinforced column retrofitted with FRP plates during cyclic lateral loading (by 29% from 250°C to 500°C and 91% from 500°C to 1000°C) caused by the temperature rise (from 250˚C to 1000°C). This escalation in energy (120% due to the temperature rise from 250°C to 1000°C) is even more significant in the RC-CFRP reinforced column at 500°C (which is around 91%). This is due to the volumetric strains, stresses, and forces generated by the temperature rise in the reinforced concrete column with FRP plates due to the high thermal conductivity of FRP, (0.0000144/°C) compared to concrete (0.0000117/°C), ultimately causing an increase in the strain energy by 120% under cyclic lateral loading.

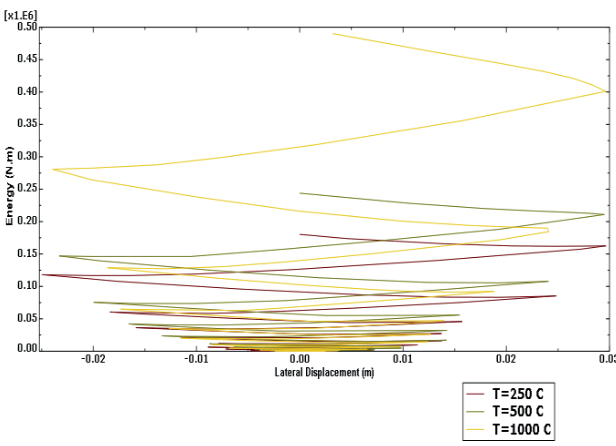

Fig 17 The impact of temperature on the energy of the RC-Steel model during the cyclic loading

However, reducing the thickness of the FRP plate might potentially mitigate the effect of temperature (especially under 500°C) on the energy increase of the reinforced column with FRP plates during cyclic lateral loading.

As shown in Fig. 19, following a temperature increase in all tested columns, including the non-retrofitted model, columns retrofitted with steel plates, and those retrofitted with FRP plates (from 250°C to 1000°C), the value of energy during cyclic lateral loading increases in these columns (10% for RC, 172% for RC-Steel, and 120% for RC-CFRP). This escalation (due to the temperature rise) is more significant (by 4% for RC, 137% for RC-Steel, and 91% for RC-CFRP) after 500°C, particularly in retrofitted concrete columns (especially those with steel plates). This is due to the volumetric strains resulting from the temperature rise (especially after 500°C), which results in an increase in stresses, forces, and the strain energy of the column during cyclic lateral loading (10% for RC, 172% for RC-Steel, and 120% for RC-CFRP). This is even more significant (137% for RC-Steel and 91% for RC-CFRP (especially after

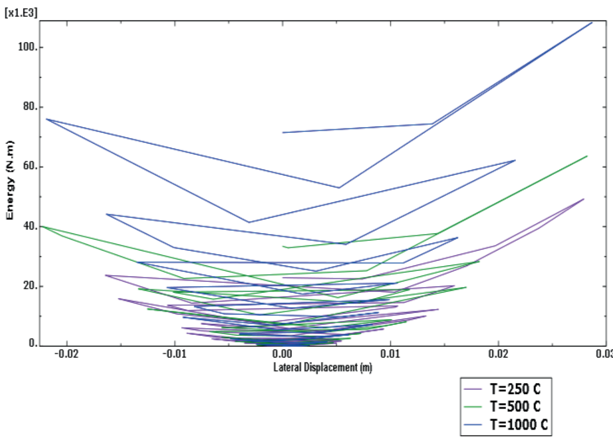

Fig. 18 The impact of temperature on the energy of the RC-CFRP model during cyclic loading

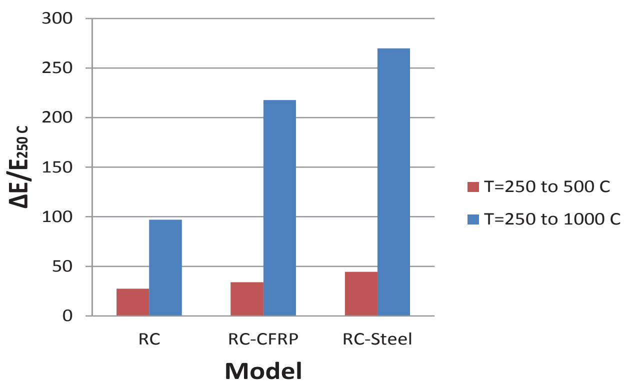

Fig. 19 The comparison between the percentage increase of the energy of the models (due to temperature rise) during the cyclic lateral loading

500°C)) in columns with steel plates (because of the high thermal conductivity of steel, which is 45 W/m°K compared to 1.14 W/m°k for concrete) and also in reinforced concrete columns with FRP plates (due to the high thermal expansion coefficient of FRP (0.0000144 1/°C compared to 0.0000117 1/°C for concrete). Therefore, it can be said that retrofitting reinforced concrete columns with steel and FRP plates (especially with steel plates) leads to a marked increase in the thermal sensitivity of the reinforced columns during cyclic lateral loading (162% for RC-Steel and 110% for RC-CFRP compared to the RC model). This increase in the energy of reinforced concrete columns (due to the temperature rise) is more significant after 500°C (137% for RC-Steel and 91% for RC-CFRP models). In Fig. 19, it is evident that retrofitting reinforced concrete columns with steel plates (rather than FRP plates) increases the thermal sensitivity of the column to a greater extent (by 52%). Given the higher thermal conductivity of steel plates compared to FRP (44.4223 W/m°K greater than FRP plates), a more tremendous amount of heat and volumetric strain is transformed from steel to concrete, which leads to more strain energy in columns with steel plates compared to those with FRP (52% during cyclic lateral loading).

5 Conclusions

In this research, after verifying and validating the numerical models, the following results were obtained from investigating the lateral forces and energies of RC, RC-Steel, and RC-CFRP models during cyclic lateral loading while being exposed to standard fire temperatures of 250°vC, 500°C, and 1000°C:

- After an increase in the temperature of the standard fire in all three models, RC, RC-Steel, and RC-FRP, (from 250° to 1000°C), the value of lateral forces increased. This increase in cyclic responses of the column due to the temperature rise was more significant after 500°C, particularly in retrofitted reinforced concrete columns (especially those retrofitted with steel plates)
- The volumetric strains due to the temperature rise in the column (especially after 500°C) resulted in an increase in stresses, forces, moments, and the strain energy of the column during cyclic lateral loading. In reinforced concrete columns retrofitted with steel plates (with a high thermal conductivity) and reinforced concrete columns with FRP plates (with a high thermal expansion coefficient), a significant percentage rise was observed in stresses, forces, and strain energies of the columns (especially after 500°C). As a result, retrofitting concrete columns with steel and FRP plates (especially with steel plates) could increase the thermal sensitivity of reinforced concrete columns during cyclic lateral loading.
- Retrofitting reinforced concrete columns with steel plates, rather than FRP plates, could cause a more enormous thermal sensitivity in the column during cyclic lateral loading. The more significant thermal conductivity of steel plates compared to FRP could result in a more significant transformation of heat and volumetric strains from concrete to steel and a more significant increase in stresses, forces, and strain energies of reinforced concrete columns with steel plates during cyclic lateral loading.
- Reducing the thickness of the FRP plate could lessen the impact of temperature (especially temperatures lower than 500°C) on the increase in the lateral forces and energies of reinforced concrete columns with FRP plates during cyclic lateral loading.

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