Post-Cyclic Fire Response of Buckling-Restrained Braced Frames

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ABSTRACT

In this study, after validating the numerical simulation procedures, a three-dimensional model of a regular steel moment-resisting frame equipped with buckling-restrained braces (BRBs) was developed using Abaqus. A coupled displacement-thermal analysis was conducted on the frame under fire exposure following cyclic lateral loading. The effects of fire temperature, loading amplitude, and BRB geometric parameters on the frame's behavior were investigated. Results showed that increasing the fire temperature applied to the bottom-story columns and braces (from 777°C to 1067°C) raised the lateral force, bending moment, and rotation of the frame during fire exposure after cyclic loading. This increase highlights the sensitivity of steel moment frames (including those with BRBs) to fire temperature, especially at higher temperatures. Furthermore, under various fire temperatures, raising the cyclic lateral loading amplitude from 30 mm to 60 mm led to significant increases in lateral force (60%), bending moment (60%), and rotation (116%) during fire exposure. This demonstrates the high sensitivity of frame behavior to fire temperature at large loading amplitudes. Finally, reducing the BRB core thickness from 6 mm to 2 mm (particularly from 6 mm to 4 mm) under different fire temperatures decreased lateral force (67%), bending moment (67%), and rotation (56%) during fire exposure. This reduction indicates the strong sensitivity of BRB behavior, and consequently of the braced steel moment frame, to fire temperature and BRB geometric parameters, especially core thickness.

Keywords: Steel frame; Buckling-restrained brace; Cyclic loading; fire heat; Finite element method

1. Introduction

In structural design, particularly for structures exposed to risks such as earthquakes and fires, adequate consideration of the resilience of structures following such sudden events can significantly reduce casualties and economic losses[1]. One approach to enhancing the resilience of structures after such incidents is to mitigate structural and non-structural risks. To reduce structural risks (to prevent the rapid collapse of the entire structure during critical conditions), stress concentration in specific areas of the structure can be minimized[2].

When a fire occurs, the ambient temperature rises sharply, affecting various elements exposed to this high temperature. For instance, steel is a material that undergoes significant changes during a fire. At elevated temperatures, it experiences a reduction in stiffness and thermal expansion, which can alter its shape and dimensions if exposed to high ambient temperatures for an extended period [3-4].

Bracing systems, such as buckling-restrained bracing (BRB) systems, transfer loads from buckled columns to other structural members and unbuckled columns during seismic conditions. This action prevents minor damage from escalating into the total collapse of a steel structure. Furthermore, since steel enters a nonlinear stage at high temperatures, bracing systems can also play a crucial role in the stability and resilience of steel structures during fire conditions [5-6].

Buckling-restrained braces (BRBs) not only address the critical weaknesses of other bracing systems but are also introduced as suitable alternatives to various bracing systems and shear walls. They provide stiffness and strength while offering high energy dissipation capacity and ductility. Additionally, BRB systems are considered an effective solution for enhancing structural resistance against fire and earthquakes and for preventing the progression of minor damage to total structural failure. Their symmetrical cyclic behavior also ensures the necessary energy dissipation capacity in structures [7- 10].

Despite extensive research on the thermomechanical behavior of certain structures, comprehensive studies on the thermomechanical behavior of braced steel structures (particularly with BRBs) remain limited, especially after various types of dynamic loading. There are uncertainties regarding the sensitivity of these structures to fire-induced heat (particularly at high fire temperatures following seismic events) and complexities in the influence of load amplitude and the safe and optimal geometric parameters of BRBs on such behavior.

In this study, using data from a thermal (fire-induced) experiment conducted by Rubert and Schaumann [11-12] on a small-scale steel moment frame, the accuracy of three-dimensional numerical simulations performed using the finite element software Abaqus was validated. Subsequently, a three-dimensional numerical model of a regular steel moment frame braced with BRBs was developed in Abaqus. Coupled displacement-thermal analysis was carried out under fire conditions following cyclic lateral loading. During the application of three different levels of ISO 834 standard fire temperatures [13] to the columns and braces of the lower story, the following objectives were pursued:

Investigating the effect of fire temperature on the behavior of steel moment frames braced with BRBs after cyclic lateral loading.

Evaluating the role of cyclic lateral loading amplitude in influencing the effect of fire temperature on the behavior of steel moment frames braced with BRBs after cyclic lateral loading.

Studying the effect of BRB core thickness on the influence of fire temperature on the behavior of steel moment frames braced with BRBs after cyclic lateral loading.

Examining the role of BRB casing thickness in influencing the effect of fire temperature on the behavior of steel moment frames braced with BRBs after cyclic lateral loading.

The study begins with a detailed explanation and validation of the simulation methods, followed by presenting the results of these simulations.

2. Numerical Simulation Method

Abaqus, one of the most powerful finite element software programs, allows for explicit and implicit formulations and provides extensive capabilities for simulating steel, concrete, and other structures through two-dimensional and three-dimensional modeling [14]. Thus, it can model braced steel frames and analyze their thermomechanical behavior under fire conditions.

For this study, three-dimensional numerical simulations were performed using Abaqus. The numerical model specifications were adopted from the studies by Mirzaei and Garami [12]. Following cyclic lateral loading (via nonlinear dynamic analysis, based on a cyclic loading protocol shown in Fig. 1 [15] and with varying loading amplitudes), the behavior of a five-story steel moment frame braced with BRBs (with different core and casing thicknesses) was evaluated. During the application of three levels of ISO 834 standard fire temperatures (shown in Fig 2 [13]) to the columns and braces of the lower story, the frame's behavior—including lateral force, bending moment, and frame rotation—was assessed.

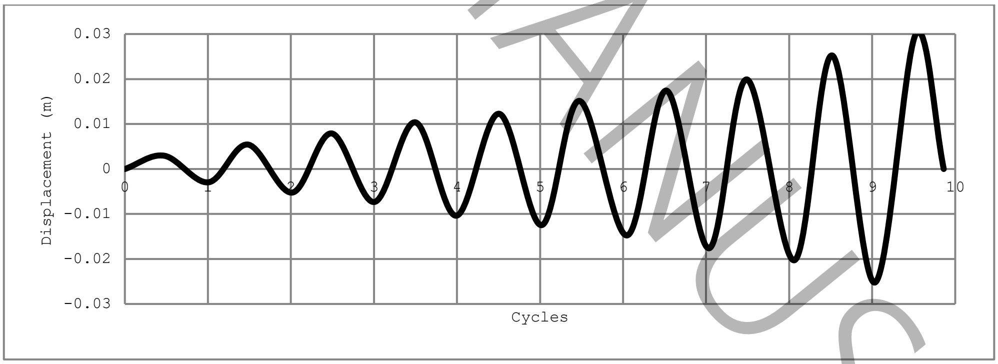

Fig. 1. Lateral Displacement Curve of the Applied Cycles at the Top of the Frame in the Studied Models [15]

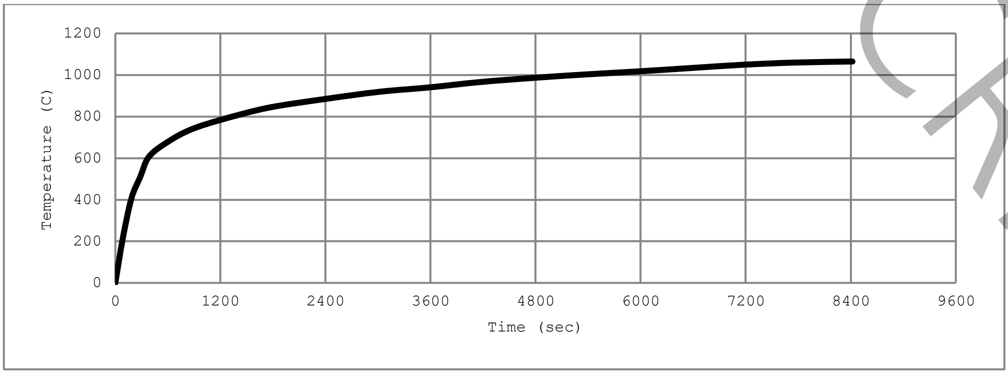

Fig. 2. Standard ISO 834 Fire Time-Temperature Curve [13]

The aforementioned large-scale numerical models consist of a five-story, three-bay steel moment frame (with a story height and bay width of 3.5 meters and 5 meters, respectively). The frame includes IPE beams and HEB columns, designed as specified in Table 1. These steel members are rigidly connected to form an integrated structure, with welds used to ensure full fixity between the members. The geometry and dimensions of the plan and elevation of the frame are shown in Fig 3 [12].

Table 1. Design of Beams and Columns of the Steel Frame Studied [12]

Sample frame	Story	Corner columns	Middle columns	Beams
5-story frame	1-3	HEB 240	HEB 300	IPE 300
	4	HEB 240	HEB 280	IPE 270
	5	HEB 240	HEB 280	IPE 240

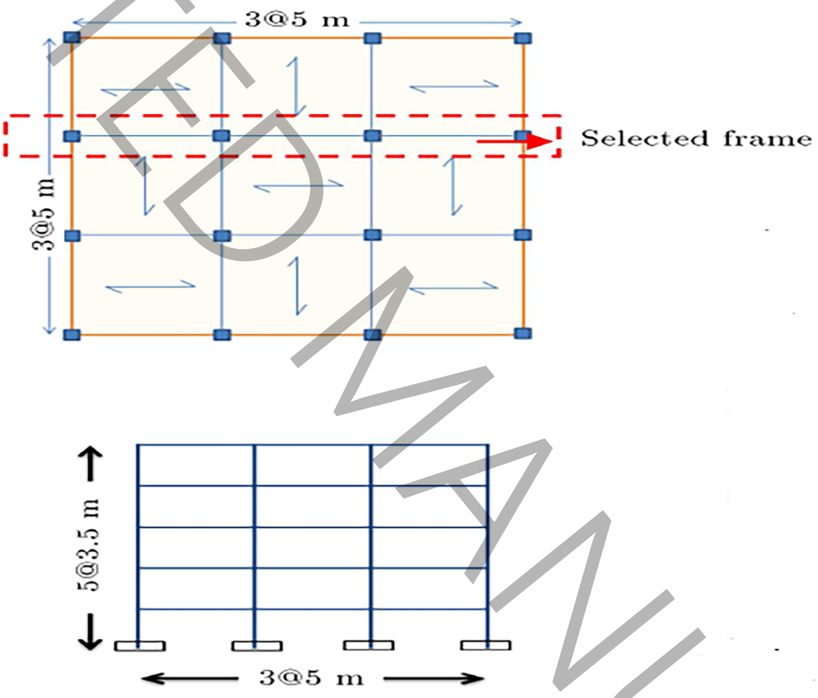

Fig. 3. Geometry and Dimensions of the Plan and Elevation of the Studied Steel Frame [12]

In these simulations, to perform coupled displacement-thermal analysis of the frame under fire conditions, after applying gravity loads to the beams and subsequently applying cyclic lateral loads to the frame (via nonlinear dynamic analysis following a cyclic loading protocol shown in Fig 1 [15]), the ISO 834 standard fire temperature (as shown in Figure 2 [13]) was applied to the columns and braces of the lower story of the frame. Additionally, to ensure structural stability during the analysis, the base of the columns and braces in the lower story was constrained against translational and rotational displacements.

2.1. Modeling the Steel Members of the Moment Frame

For the numerical modeling of beams and columns (geometry, dimensions, and design as per Fig 3 and 4 and Table 1 [12]) in the five-story steel moment frame, homogeneous and isotropic shell structural elements were used. The behavior of these members was defined using a perfectly elastoplastic material model, where the steel exhibits elastic behavior up to the yield stress. The specific weight, Young's modulus, Poisson's ratio, yield strength, ultimate strength, specific heat capacity, thermal conductivity, and thermal expansion coefficient were set to 78.5 kN/m³, 210 GPa, 0.3, 240 MPa, 370 MPa, 667 J/(kg·K), 27.2 W/(m·K), and 0.0000178 /°C, respectively [12]. Naturally, when a steel structure is exposed to fire, both the modulus of elasticity and the yield stress decrease so these effects were considered in Abaqus software equations[14].

It is worth mentioning that to model the weld connections between the steel members (assuming full fixity provided by the welds), the Tie constraint was employed.

It should be noted that, in order to increase the accuracy of the thermo-mechanical analyses, the mechanical properties of the steel used (such as elastic modulus and yield strength) in modeling the moment frame members have been defined as temperature-dependent functions. For this purpose, using the ISO 834 standard fire time-temperature curve (Figure 2 [13]), temperature-dependent reduction factors for the aforementioned mechanical properties of the steel have been incorporated to account for the loss of strength and stiffness of the steel in the moment frame members during the stepwise application of the ISO 834 standard fire to the model. These factors are defined in the Abaqus software in such a way that as the temperature of the steel frame members increases at different times of the fire, the mechanical properties of the steel in these members automatically decrease (Table 3).

2.2. Modeling the Steel Members of Buckling-Restrained Braces (BRBs)

To model the steel core of the buckling-restrained braces located at the mid-height of the stories in the moment frame, homogeneous and isotropic shell structural elements were used. These cores had a length of 4.1 meters and a variable cross-sectional height (two heights of 100 mm and 50 mm) with a constant thickness along their length, as shown in Fig 4. The behavior of these members was defined using a perfectly elastoplastic material model, where the steel exhibits elastic behavior up to the yield stress, with mechanical properties as specified in Table 2 [16]. The specific heat capacity, thermal conductivity, and thermal expansion coefficient were set to 667 J/(kg·K), 27.2 W/(m·K), and 0.0000178 /°C, respectively [12].

For the steel casing (tube) of the buckling-restrained braces located at the mid-height of the frame, homogeneous and isotropic shell structural elements were also used. These tubes had a length of 3 meters and a rectangular cross-section with dimensions of 100 mm and a specified thickness for all stories, as shown in Fig 4. The behavior of these members was also defined using a perfectly elastoplastic material model, with mechanical properties as specified in Table 2 [16]. Similarly, the specific heat capacity, thermal conductivity, and thermal expansion coefficient were set to 667 J/(kg·K), 27.2 W/(m·K), and 0.0000178 /°C, respectively [12].

As previously mentioned, in order to increase the accuracy of the thermo-mechanical analyses of the models and also considering the sensitivity of the behavior of buckling-restrained braces to heat, the effect of temperature on the mechanical properties of the steel used (such as the elastic modulus and yield strength of the steel) has been taken into account for the steel core and the casing of these braces. Therefore, similar to Section 2-1, the mechanical properties of the steel used (e.g., elastic modulus and yield strength) in the modeling of the buckling-restrained brace members have been defined as temperature-dependent functions. For this purpose, using the ISO 834 standard fire time-temperature curve (Figure 2 [13]), temperature-dependent reduction factors for the aforementioned mechanical properties of the steel have been incorporated to account for the loss of strength and stiffness of the steel in the buckling-restrained brace members during the stepwise application of the ISO 834 standard fire to the model. This ensures that the load-bearing capacity of the buckling-restrained braces and the nonlinear behavior of the core and casing of these braces during the fire exposure are accurately simulated, considering the loss of strength and stiffness due to temperature rise, and that the thermo-mechanical interaction between the core and casing is correctly accounted for in the numerical model. Furthermore, these factors are defined in the Abaqus software in such a way that as the temperature of the steel members of the braces increases at different times of the fire, the mechanical properties of the steel in these members automatically decrease (Table 3).

Table 2. Mechanical Properties of the Steel Used in the Buckling Restrained Braces [16]

Parameter **Type**	$\gamma\ (\mathrm{kN/m^3})$	**E (Mpa)**	ν	f_y (Mpa)	f_u (Mpa)
Core	78.5	21000	0.3	280	480
Tube	78.5	21000	0.3	351	510

Table 3. Temperature-dependent reduction factors for mechanical properties of steel used in moment frame members and buckling-restrained braces[13]

Temperature (C)	**Reduction Factors**
20	1
100	1
200	1
300	0.97
400	0.9
500	0.78
600	0.61
700	0.37
800	0.17
900	0.06
1067	0

2.3. Meshing of Steel Members

For the meshing of steel members in the numerical models, four-node thermal shell structural elements with reduced integration (referred to as **S4RT** in the Abaqus software [12]) were utilized (Fig 5).

Fig. 4. Geometric Model of the Steel Frame with Buckling Restrained Braces

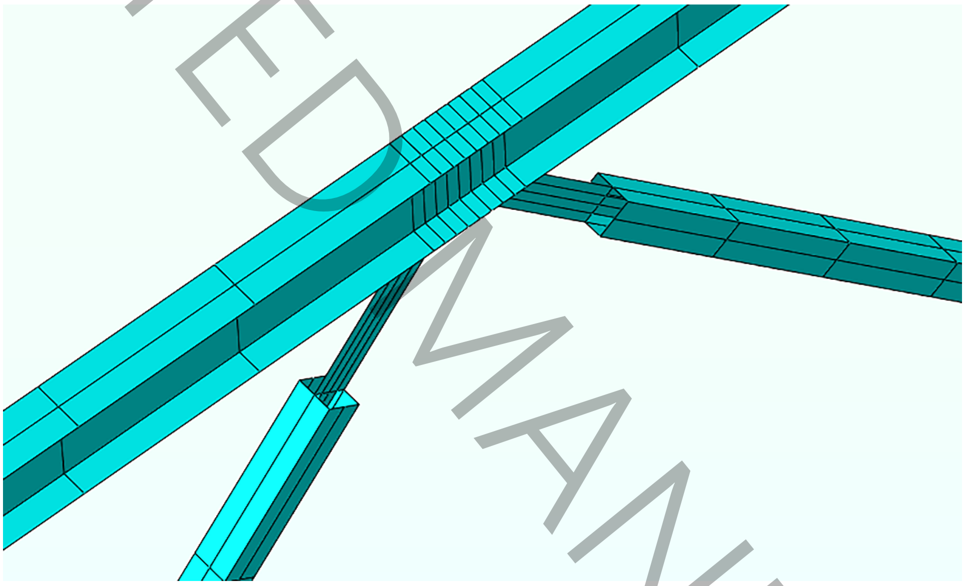

Fig. 5. Meshing of Steel Moment Frame Braced with Buckling-Restrained Braces (BRBs)

2.4. Boundary Conditions

To ensure the stability of the numerical models during the analysis, all translational and

rotational displacements at the column bases and the braces of the bottom story of the frame are restrained (Figure 6).

2.5. Gravity Loading

For gravity loading due to dead and live loads of the numerical models, the dead and live loads of the bays perpendicular to the frame in each story (with a width of 5 meters) are applied linearly to the frame beams [12].

It is worth mentioning that, based on Standard 2800 (likely a local building code), the dead and live loads of the floor slabs are considered to be 500 and 200 kg/m², respectively. These loads, according to the direction of the floor joists (Figure 3 [12]), are applied linearly to the frame beams.

2.6. Coupled Displacement-Thermal Analysis of the Models

To achieve the behavior of the steel moment frame braced with buckling-restrained braces (BRBs) during the application of the ISO 834 standard fire (as shown in Fig 2 [13]) to the columns and braces of the bottom story of the frame that is, to obtain the heat-lateral force, heat-bending moment, and heat-rotation curves of the steel moment frame braced with BRBs after applying the gravity load to the frame beams and subsequently the cyclic lateral loading of the frame (using a nonlinear dynamic method according to a cyclic loading protocol as shown in Fig 1 [15] and within the desired loading range), the numerical models, at the desired temperature, have undergone coupled displacement-thermal analysis (Fig 6).

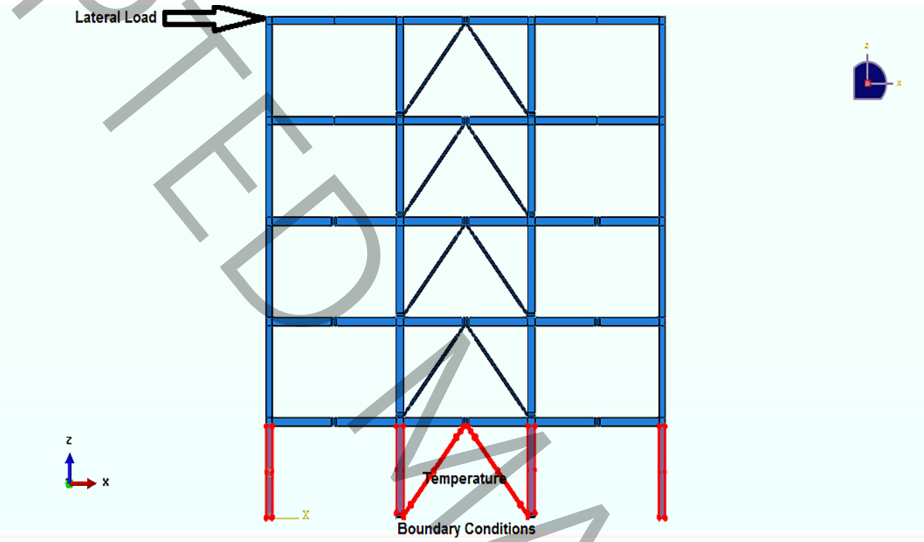

Fig. 6. Loading and Boundary Conditions of Steel Moment Frame Braced with Buckling-Restrained Braces (BRBs)

The bottom story was selected because it typically sustains the highest gravity and seismic shear loads. Furthermore, in real-world scenarios, fires in ground floors (often used for commercial purposes or housing utilities) pose a critical risk of progressive collapse for the entire structure.

To validate the method of three-dimensional numerical simulations using the Abaqus finite element software in this research with regard to the proportional reduction of the modulus of elasticity and the yield stress, by three-dimensional numerical modeling of the thermal (fire-induced) experiment performed (by Rubert and Schaumann [11-12]) on a steel moment frame under vertical and lateral loads (as shown in Fig 7), the lateral displacement of the top surface of the side column of this frame during the coupled thermal-displacement analysis was evaluated by the mentioned software and compared with this displacement measured from the laboratory specimen in the fire test, as shown in Fig 8.

2.6.1. Experimental Setup

The mentioned small-scale laboratory specimen was a one-story, two-bay steel moment frame (with a story height and bay width of 1.18 and 1.2 meters, respectively) composed of IPE80 beams and columns.

These steel members are all rigidly connected, for which welding was used to establish fixity between these members. In Fig 7, the geometry and dimensions of the view of the mentioned laboratory specimen are shown [11-12].

2.6.2. Test Procedure

In this experiment, following the vertical loading of the columns (at 74 kN) and also the lateral loading (at 28.5 kN) of the top surface of the specimen, the ISO 834 standard fire (as shown in Fig 2 [13]) was applied to the columns and beam in one bay of the specimen. Also, in the meantime, to ensure the stability of the specimen during the experiment, the base (bottom) of the specimen's columns was restrained against translational displacements using pinned supports [11-12].

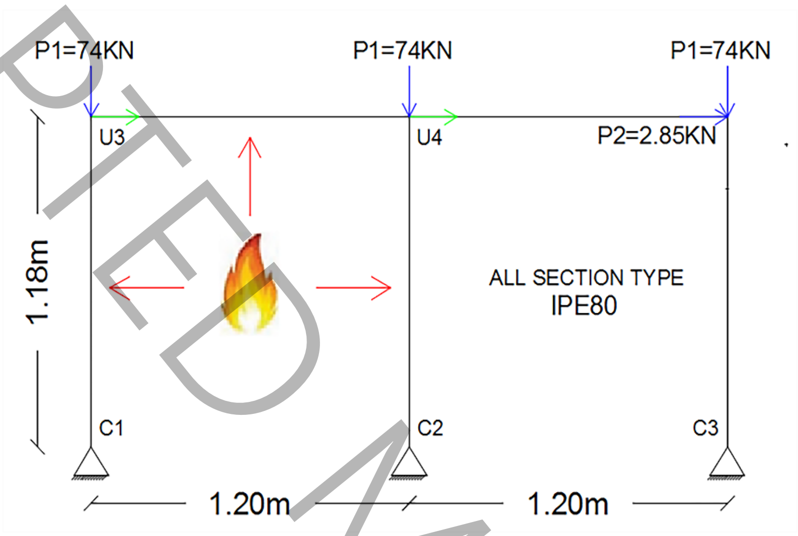

Fig. 7. Geometric Model of the Laboratory Specimen [11 and 12]

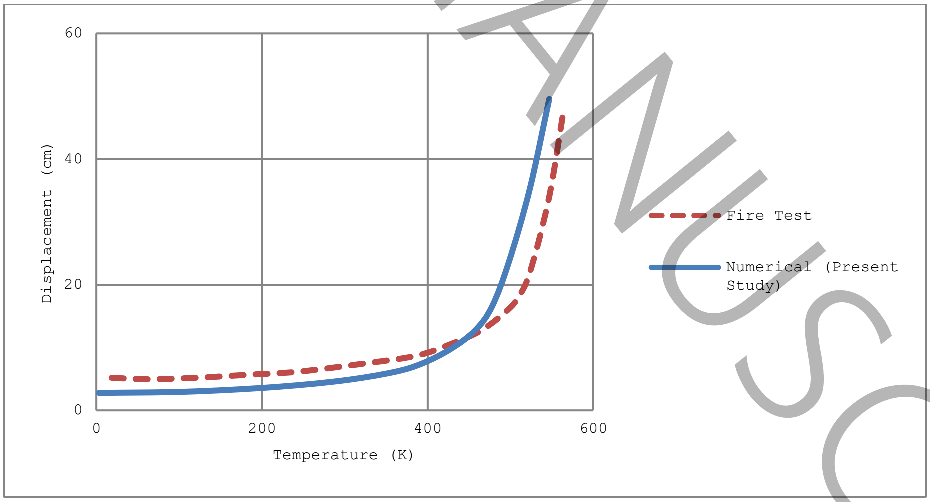

Fig. 8. Comparison of Temperature-Lateral Displacement Curves of the Top Surface of the Side Column of the Steel Frame During Numerical Analysis and Fire Test [11- 12]

Fig 8 shows the good agreement between the magnitude and trend of the lateral displacement of the top surface of the side column of the steel moment frame during the coupled thermal-displacement analysis and this displacement measured from the laboratory specimen in the fire test. This demonstrates confidence in the accuracy of the three-dimensional numerical simulations performed using the Abaqus finite element software in this research.

2.7. Evaluation and Analysis of Numerical Simulation Results

To analyze the results of the numerical simulations described in the previous sections, at three fire temperatures T (777, 997, and 1067 °C), by varying the core thickness of the buckling-restrained braces (BRBs) (from 2 to 6 mm) and also the range of cyclic lateral loading U (from 30 to 90 mm), the heat-lateral force, heat-bending moment, and heat-rotation curves of the steel moment frame braced with BRBs during the application of fire after cyclic lateral loading, and finally the maximum values of these responses (from the mentioned curves) were evaluated (Fig 9 to 29).

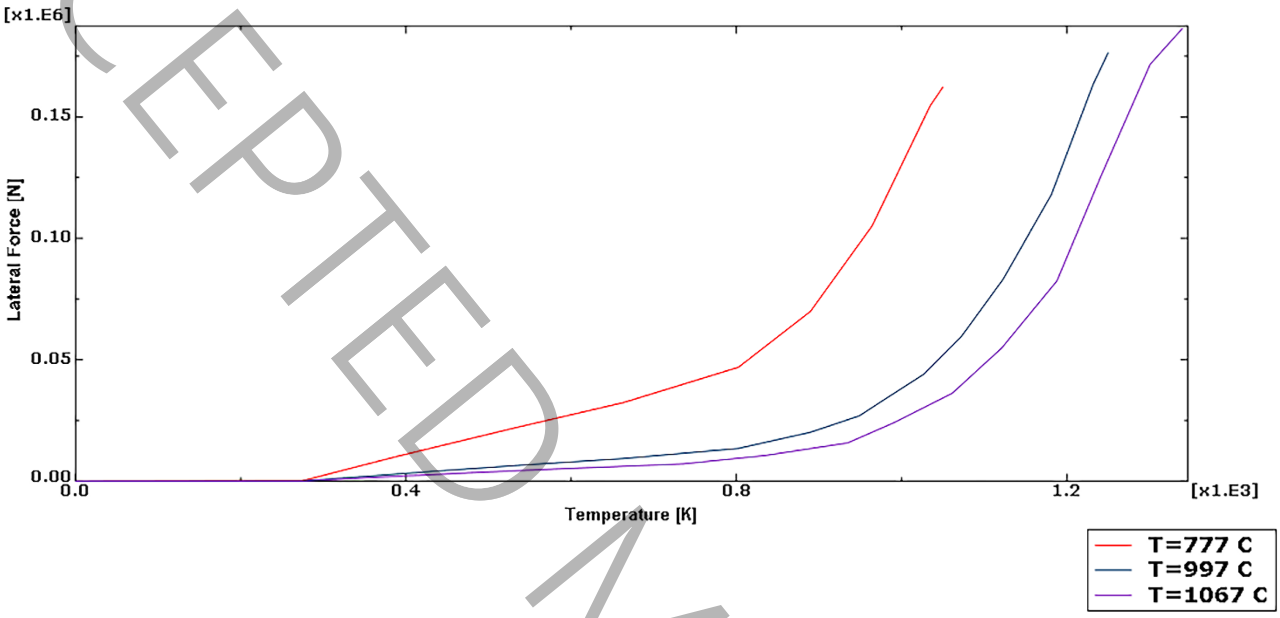

Fig. 9. Effect of Fire Temperature on the Temperature-Lateral Force Curve of the Steel Moment Frame Braced with Buckling-Restrained Braces (BRBs) During Fire Application After Cyclic Lateral Loading(t_t=4 mm & t_c=4 mm ,D=30 mm)

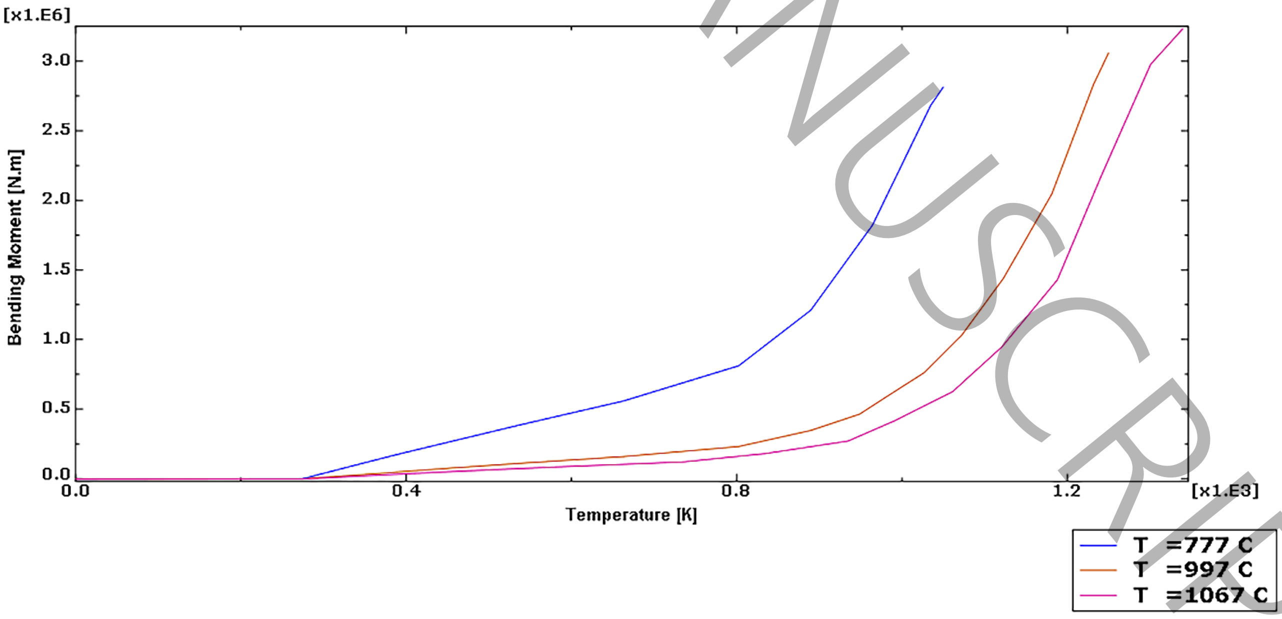

Fig. 10. Effect of Fire Temperature on the Temperature-Bending Moment Curve of the Steel Moment Frame Braced with Buckling-Restrained Braces (BRBs) During Fire Application After Cyclic Lateral Loading(t_t=4 mm & t_c=4 mm ,D=30 mm)

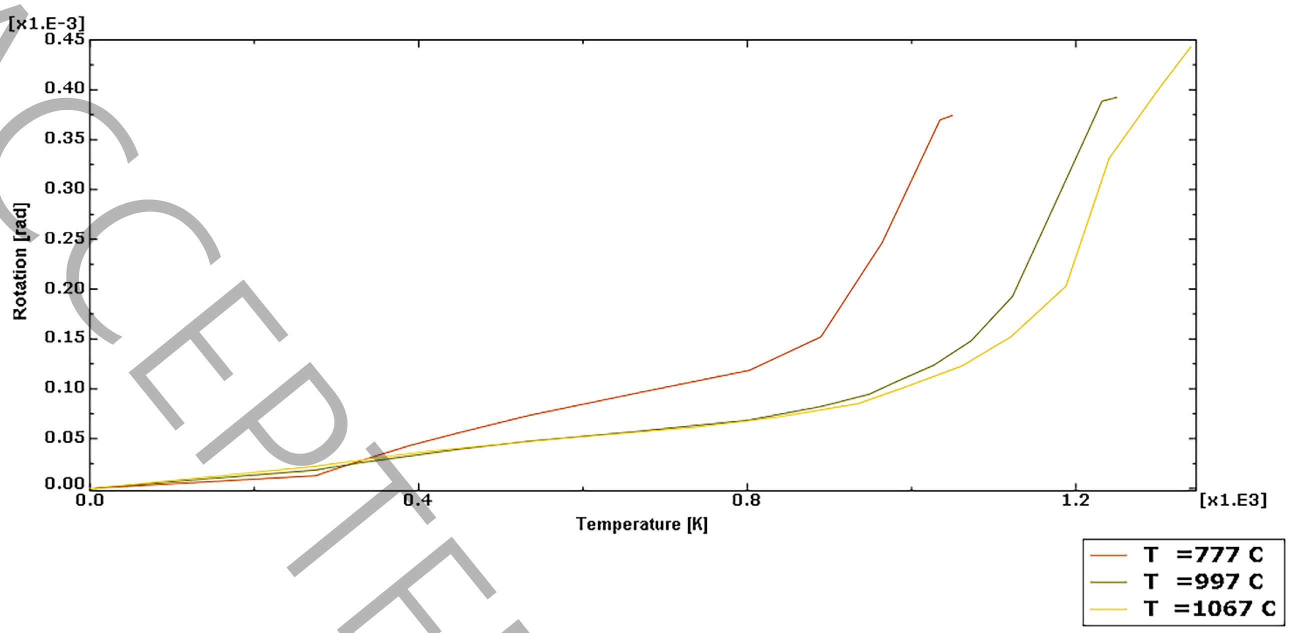

Fig. 11. Effect of Fire Temperature on the Temperature-Rotation Curve of the Steel Moment Frame Braced with Buckling-Restrained Braces (BRBs) During Fire Application After Cyclic Lateral Loading(t_t=4 mm & t_c=4 mm ,D=30 mm)

From Fig 9 to 11, it is observed that as the fire temperature increases (from 777 to 1067 °C) in the columns and braces of the bottom story of the steel moment frame braced with buckling-restrained braces (BRBs), the magnitude of the frame's responses (lateral force, bending moment, and frame rotation) during fire application after cyclic lateral loading increases. This increase in responses indicates the sensitivity of the behavior of steel moment frames (including those braced with BRBs) to fire temperature (especially at high fire temperatures). This is because the occurrence and widespread distribution of large volumetric strains due to fire temperature (especially at high fire temperatures) in the steel columns and braces of the bottom story of the frame (due to the high thermal expansion and conductivity coefficients of steel) lead to an increased distribution and intensity of plastic strains (and an increased probability of failure) in these columns and braces, and consequently in the entire frame, ultimately causing additional displacements and forces in the steel moment frame braced with BRBs after cyclic lateral loading.

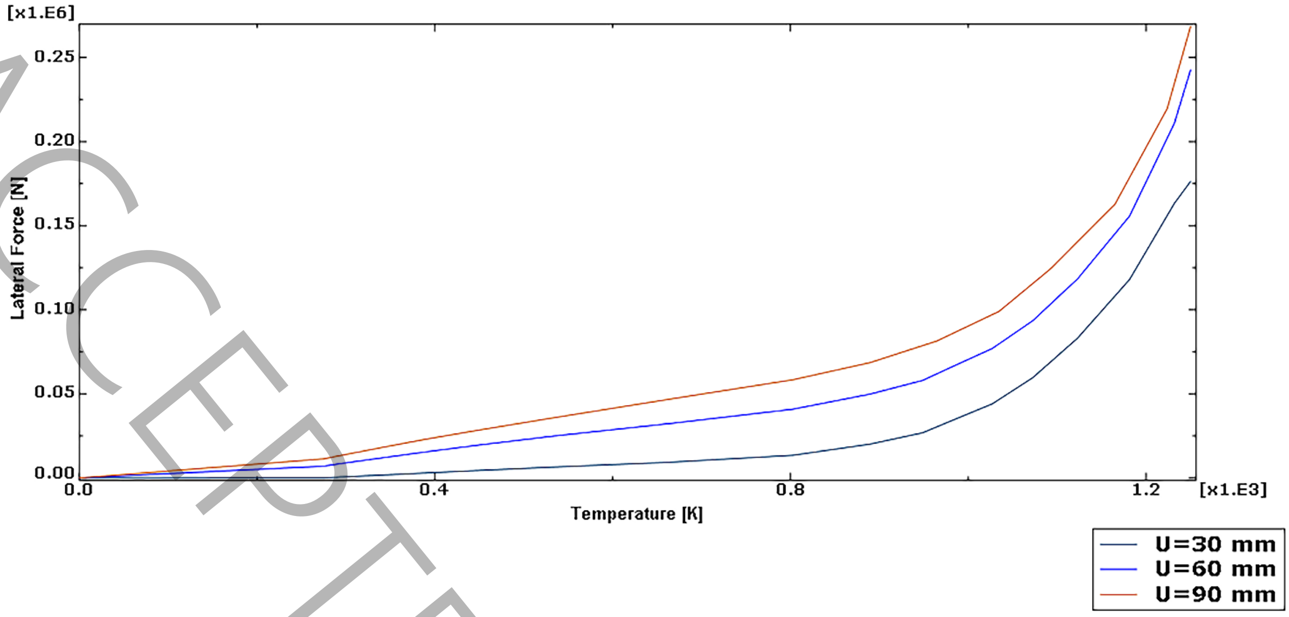

Fig. 12. Effect of Cyclic Lateral Loading Amplitude on the Temperature-Lateral Force Curve of the Steel Moment Frame Braced with Buckling-Restrained Braces (BRBs) During Fire Application (997 °C) After Cyclic Lateral Loading (t_t=4 mm & t_c=4 mm)

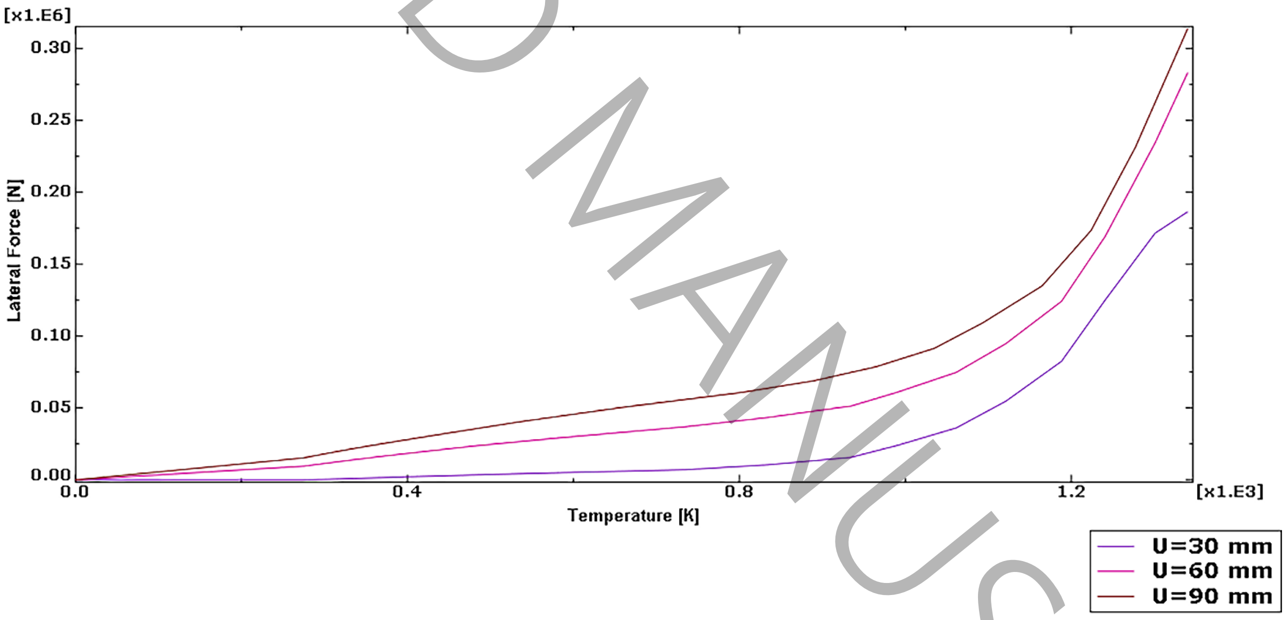

Fig. 13. Effect of Cyclic Lateral Loading Amplitude on the Temperature-Lateral Force Curve of the Steel Moment Frame Braced with Buckling-Restrained Braces (BRBs) During Fire Application (1067 °C) After Cyclic Lateral(t_t=4 mm & t_c=4 mm)

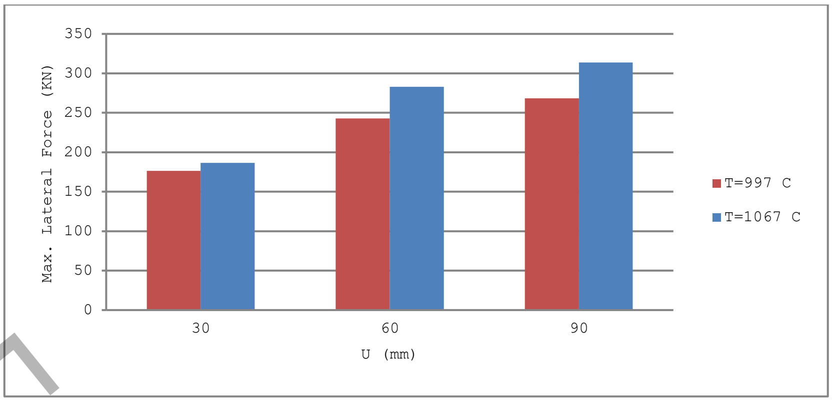

Fig. 14. Interaction Effect of Fire Temperature and Cyclic Lateral Loading Amplitude on the Maximum Lateral Force of the Steel Moment Frame Braced with Buckling-Restrained Braces(BRBs) During Fire Application After Cyclic Lateral Loading(t_t=4 mm & t_c=4 mm)

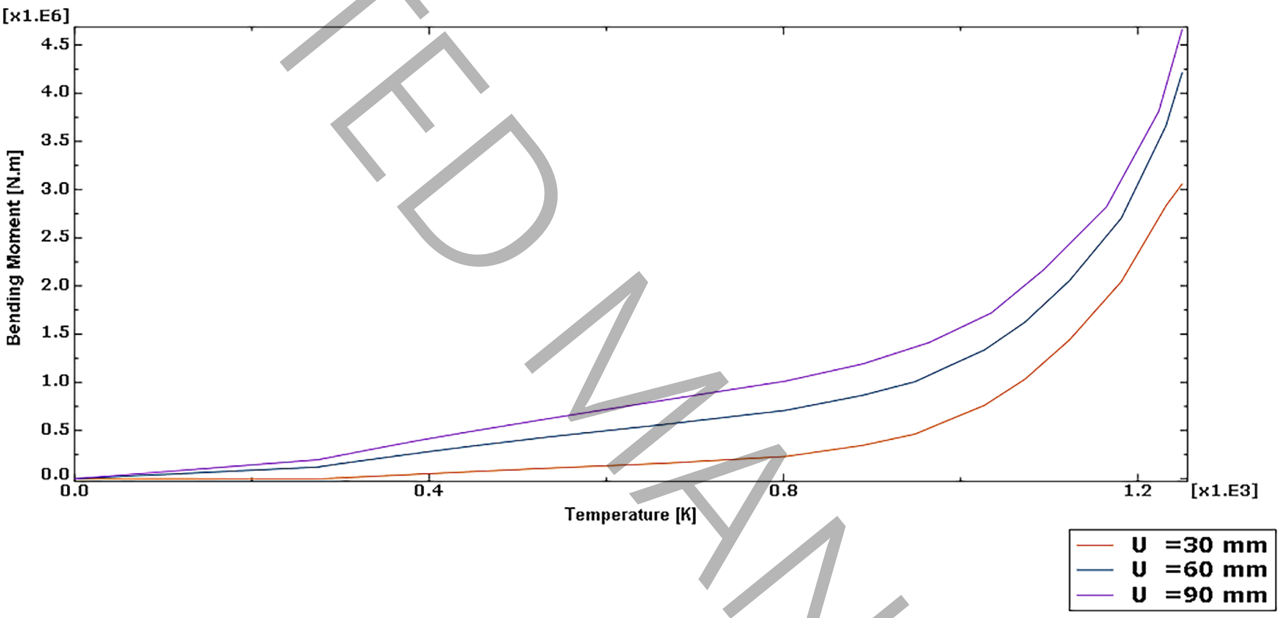

Fig. 15. Effect of Cyclic Lateral Loading Amplitude on the Temperature-Bending Moment Curve of the Steel Moment Frame Braced with Buckling-Restrained Braces (BRBs) During Fire Application (997 °C) After Cyclic Lateral Loading(t_t=4 mm & t_c=4 mm)

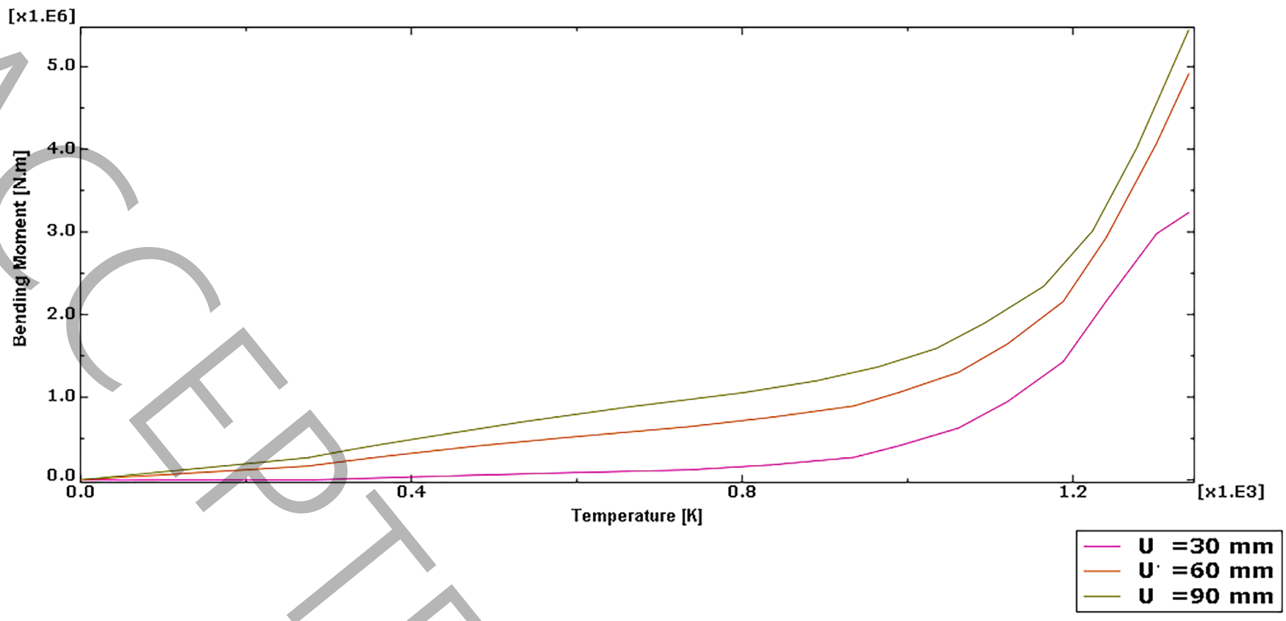

Fig. 16. Effect of Cyclic Lateral Loading Amplitude on the Temperature- Bending Moment Curve of the Steel Moment Frame Braced with Buckling-Restrained Braces (BRBs) During Fire Application (1067 °C) After Cyclic Lateral Loading(t_t=4 mm & t_c=4 mm)

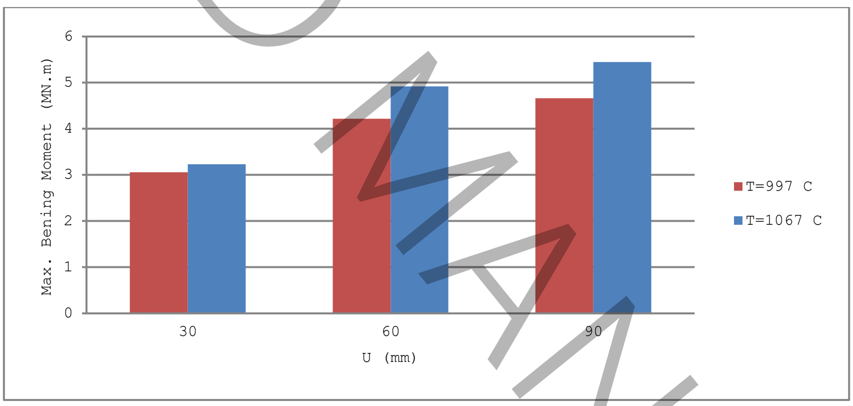

Fig. 17. Interaction Effect of Fire Temperature and Cyclic Lateral Loading Amplitude on the Maximum Bending Moment of the Steel Moment Frame Braced with Buckling-Restrained Braces (BRBs) During Fire Application After Cyclic Lateral Loading(t_t=4 mm & t_c=4 mm)

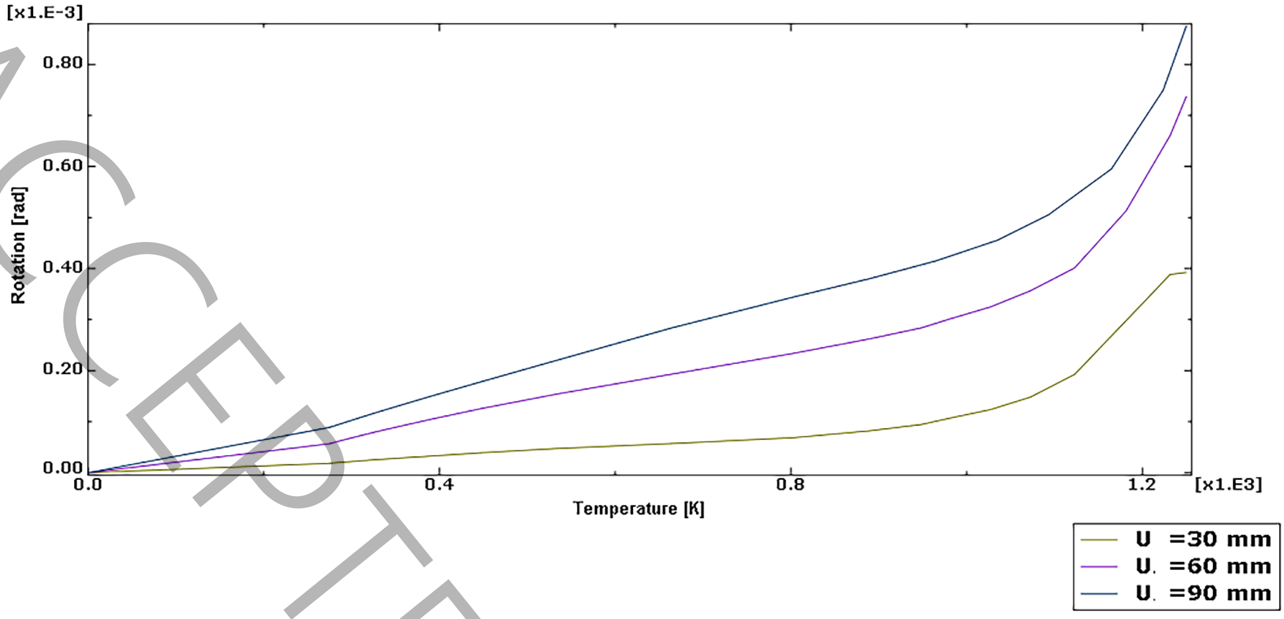

Fig. 18. Effect of Cyclic Lateral Loading Amplitude on the Temperature-Rotation Curve of the Steel Moment Frame Braced with Buckling-Restrained Braces (BRBs) During Fire Application (997 °C) After Cyclic Lateral Loading(t_t=4 mm & t_c=4 mm)

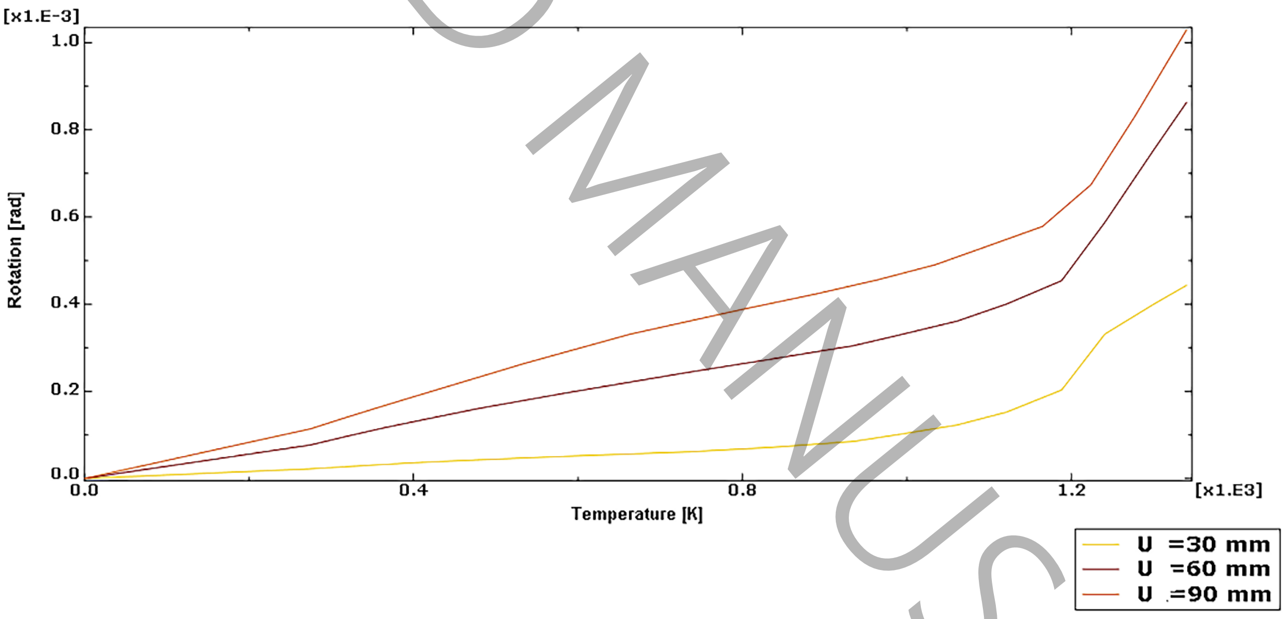

Fig. 19. Effect of Cyclic Lateral Loading Amplitude on the Temperature-Rotation Curve of the Steel Moment Frame Braced with Buckling-Restrained Braces (BRBs) During Fire Application (1067 °C) After Cyclic Lateral Loading(t_t=4 mm & t_c=4 mm)

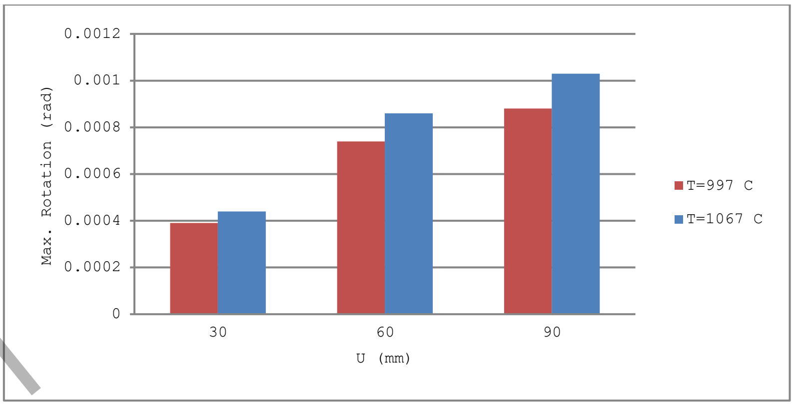

Fig. 20. Interaction Effect of Fire Temperature and Cyclic Lateral Loading Amplitude on the Maximum Rotation of the Steel Moment Frame Braced with Buckling-Restrained Braces(BRBs) During Fire Application After Cyclic Lateral Loading(t_t=4 mm & t_c=4 mm)

From Fig 12 to 20, it is also observed that with the increase in fire temperature in the columns and braces of the bottom story of the steel moment frame braced with buckling-restrained braces (BRBs), the magnitude of the frame's responses (lateral force, bending moment, and frame rotation) during fire application after cyclic lateral loading increases. Furthermore, it is seen from these figures that at different fire temperatures applied to the columns and braces of the bottom story of the steel moment frame braced with BRBs, by increasing the cyclic lateral loading amplitude (from 30 to 90 mm) applied to the frame, the magnitude of the frame's responses (lateral force, bending moment, and frame rotation) during fire application after cyclic lateral loading increases significantly. This significant increase in responses indicates the high sensitivity of the behavior of steel moment frames (including those braced with BRBs) to fire temperature at high cyclic lateral loading amplitudes. This is because increasing the cyclic loading amplitude of the frame leads to an increase in the distribution and intensity of plastic strains in the frame, and consequently increases the frame's fatigue, which in turn leads to the intensification of the occurrence and distribution of large volumetric strains due to fire temperature in the steel columns and braces of the bottom story of the frame, and consequently intensifies the displacements and additional forces in the steel moment frame braced with BRBs after cyclic lateral loading.

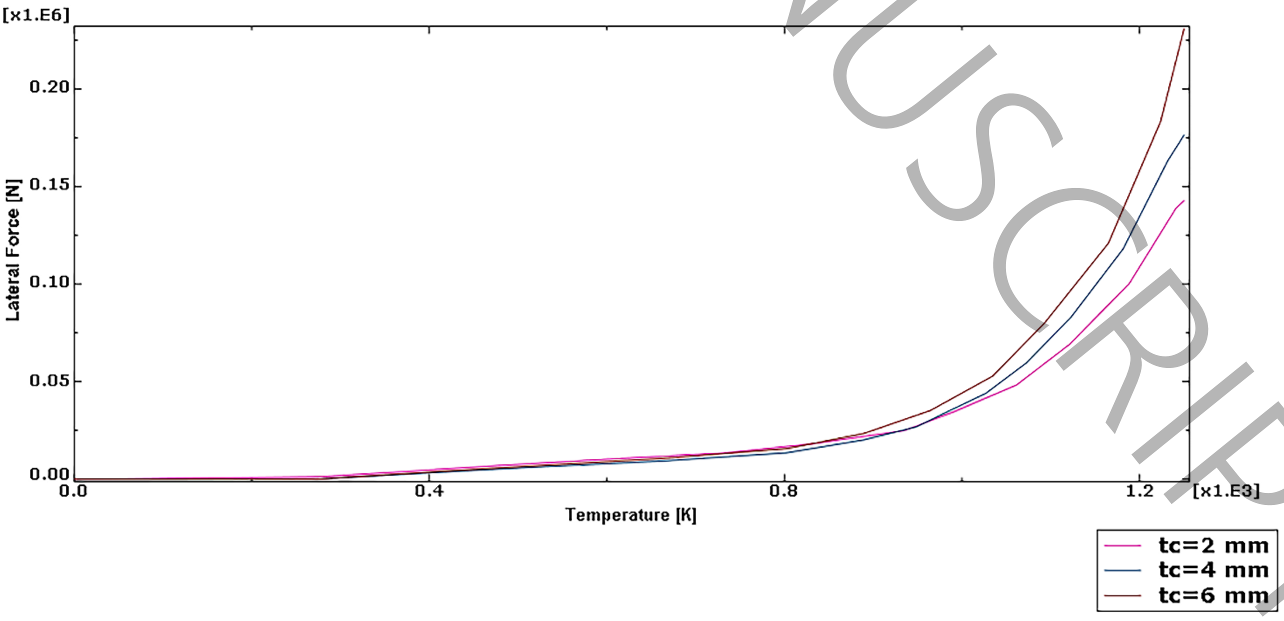

Fig. 21. Effect of Buckling-Restrained Brace (BRB) Core Thickness on the Temperature-Lateral Force Curve of the Steel Moment Frame Braced with BRBs During Fire Application (997 °C) After Cyclic Lateral Loading(t_t=4 mm & D=30 mm)

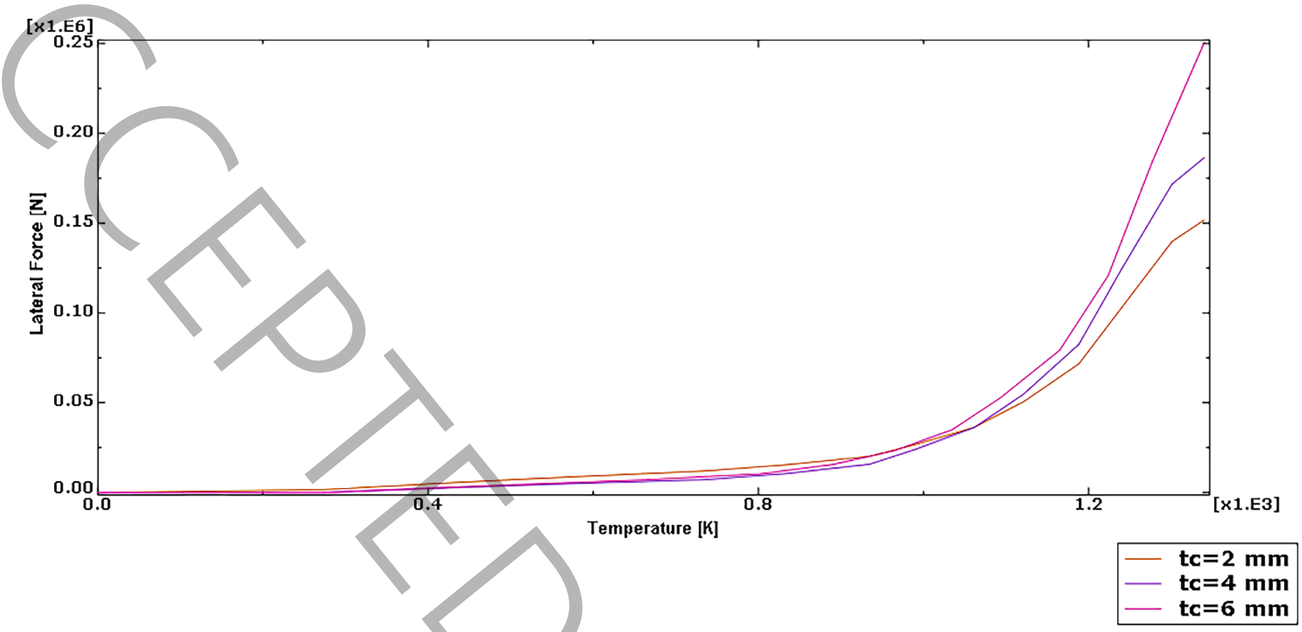

Fig. 22. Effect of Buckling-Restrained Brace (BRB) Core Thickness on the Temperature-Lateral Force Curve of the Steel Moment Frame Braced with BRBs During Fire Application (1067 °C) After Cyclic Lateral Loading(t_t=4 mm & D=30 mm)

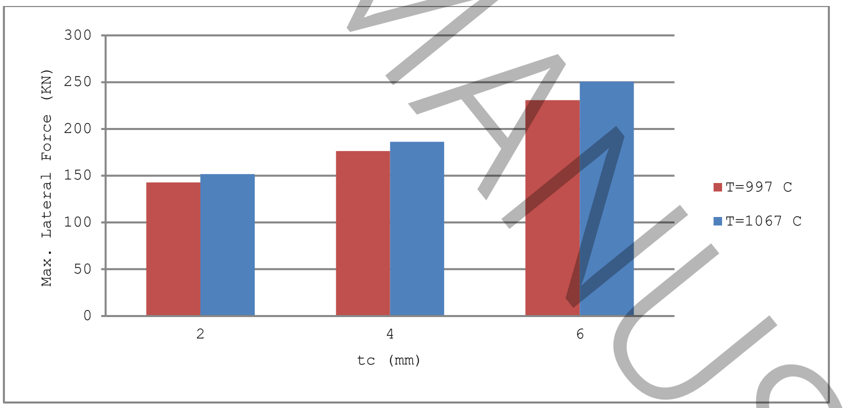

Fig. 23. Interaction Effect of Fire Temperature and Buckling-Restrained Brace (BRB) Core Thickness on the Maximum Lateral Force of the Steel Moment Frame Braced with BRBs During Fire Application After Cyclic Lateral Loading(t_t=4 mm & D=30 mm)

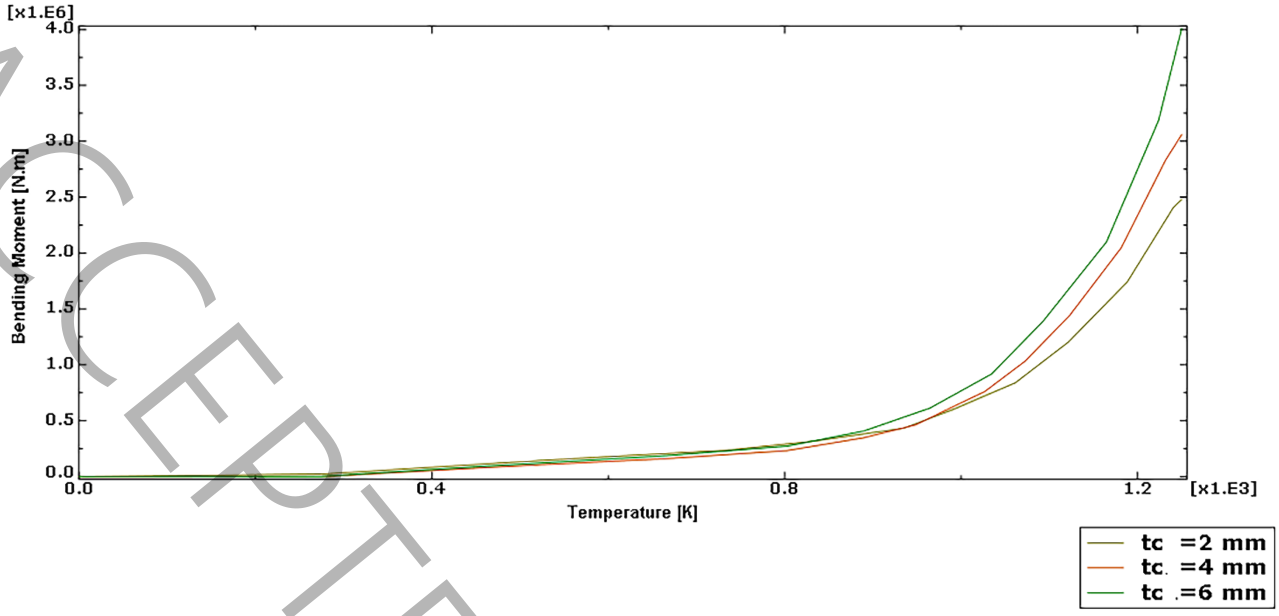

Fig 24. Effect of Buckling-Restrained Brace (BRB) Core Thickness on the Temperature-Bending Moment Curve of the Steel Moment Frame Braced with BRBs During Fire Application (997 °C) After Cyclic Lateral Loading(t_t=4 mm & D=30 mm)

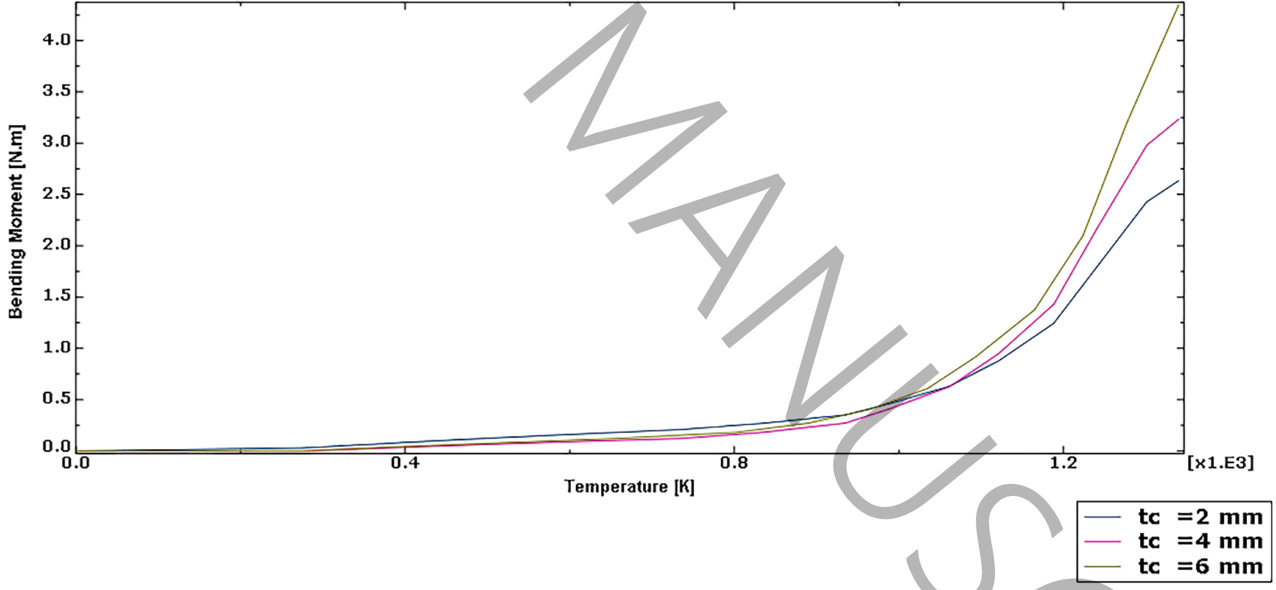

Fig. 25. Effect of Buckling-Restrained Brace (BRB) Core Thickness on the Temperature-Bending Moment Curve of the Steel Moment Frame Braced with BRBs During Fire Application(1067 °C) After Cyclic Lateral Loading(t_t=4 mm & D=30 mm)

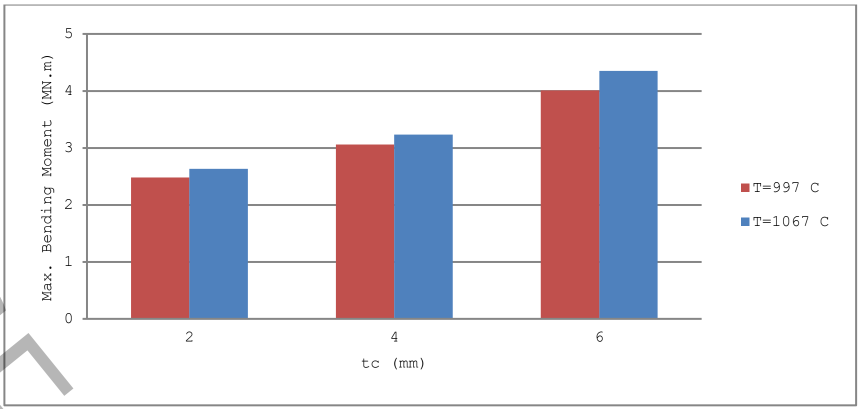

Fig. 26. Interaction Effect of Fire Temperature and Buckling-Restrained Brace (BRB) Core Thickness on the Maximum Bending Moment of the Steel Moment Frame Braced with BRBs During Fire Application After Cyclic Lateral Loading(t_t=4 mm & D=30 mm)

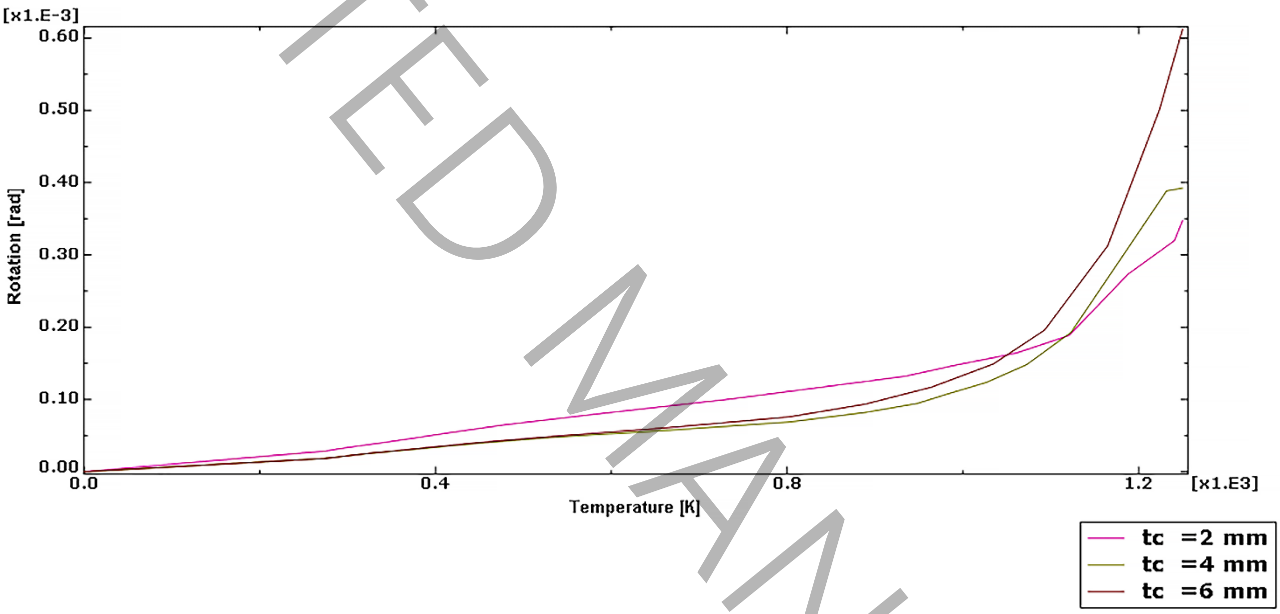

Fig. 27. Effect of Buckling-Restrained Brace (BRB) Core Thickness on the Temperature-Rotation Curve of the Steel Moment Frame Braced with BRBs During Fire Application (997 °C) After Cyclic Lateral Loading(t_t=4 mm & D=30 mm)

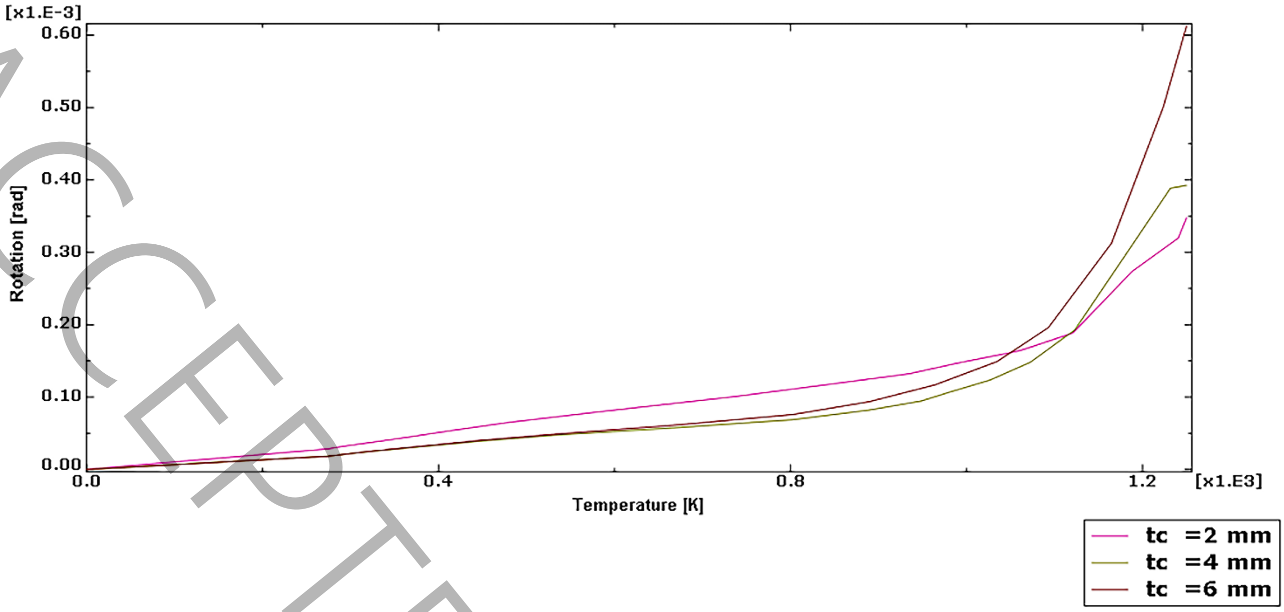

Fig. 28. Effect of Buckling-Restrained Brace (BRB) Core Thickness on the Temperature-Rotation Curve of the Steel Moment Frame Braced with BRBs During Fire Application (1067 °C) After Cyclic Lateral Loading (t_t=4 mm & D=30 mm)

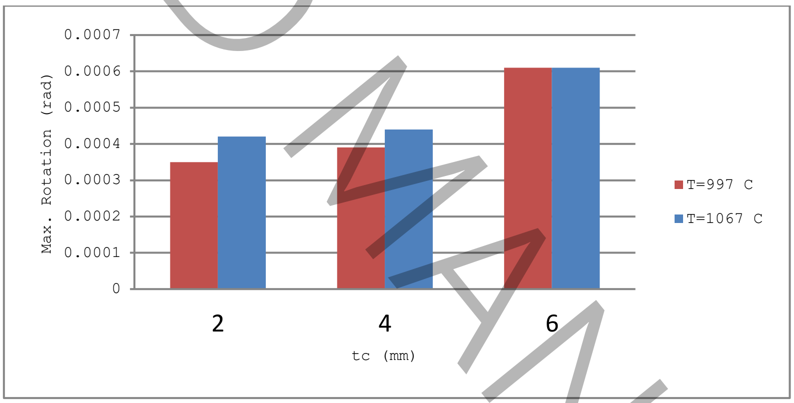

Fig. 29. Interaction Effect of Fire Temperature and Buckling-Restrained Brace (BRB) Core Thickness on the Maximum Rotation of the Steel Moment Frame Braced with BRBs During Fire Application After Cyclic Lateral Loading(t_t=4 mm & D=30 mm)

From Fig 21 to 29, it is also observed that with the increase in fire temperature in the columns and braces of the bottom story of the steel moment frame braced with buckling-restrained braces (BRBs), the magnitude of the frame's responses (lateral force, bending moment, and frame rotation) during fire application after cyclic lateral loading increases. Furthermore, it is seen from these figures that at different fire temperatures applied to the columns and braces of the bottom story of the steel moment frame braced with BRBs, by decreasing the BRB core thickness (from 6 to 2 mm, and especially down to 4 mm), the magnitude of the frame's responses (lateral force, bending moment, and frame rotation) during fire application after cyclic lateral loading decreases. This decrease in responses indicates the high sensitivity of the behavior of BRBs and, consequently, the steel moment frames braced with these braces to fire temperature and the geometric parameters of the mentioned braces (especially the core thickness).

It is worth mentioning that the steel members of the BRBs (i.e., the core and the steel casing), in combination, create buckling-restrained conditions (despite high energy absorption), so that with the yielding of the BRB core during loading and the resulting high plastic strains and strain energy in the core during loading, the casing also prevents the buckling of the braces. With this explanation, increasing the BRB core thickness (especially from 4 mm) leads to the non-yielding of the core during loading and the resulting low plastic strains and strain energy in the core, but a high distribution and intensity of plastic strains in other steel members of the frame and consequently increases the frame's fatigue. This leads to the intensification of the occurrence and distribution of large volumetric strains due to fire temperature in the columns of the bottom story of the frame and consequently intensifies the displacements and additional forces in the steel moment frame braced with BRBs after cyclic lateral loading. Therefore, it can be said that thickening the BRB core (especially from 4 mm) reduces the proper performance of these braces in improving the thermo-mechanical behavior of steel moment frames braced with BRBs after cyclic lateral loading.

3. Conclusions:

In this research, while ensuring the accuracy of the numerical simulations, by evaluating the lateral force, bending moment, and rotation of a steel moment frame braced with BRBs during fire application after cyclic lateral loading, and by changing the cyclic lateral loading amplitude and BRB core thickness (at different fire temperatures), the following results were obtained:

- Increasing the fire temperature (from 777 to 1067 °C) in the columns and braces of the bottom story of the steel moment frame braced with BRBs increases the magnitude of the frame's responses (lateral force, bending moment, and frame rotation) during fire application after cyclic lateral loading, which indicates the sensitivity of the behavior of steel moment frames (including those braced with BRBs) to fire temperature (especially at high fire temperatures).
- The occurrence and extensive distribution of large volumetric strains due to fire temperature (especially at high fire temperatures) in the steel columns and braces of the bottom story of the frame (due to the high thermal expansion and conductivity coefficients of steel) leads to an increase in the distribution and intensity of plastic strains (and an increased probability of failure) in these columns and braces and consequently the entire frame, and finally creates displacements and additional forces in the steel moment frame braced with BRBs after cyclic lateral loading.
- At different fire temperatures applied to the columns and braces of the bottom story of the steel moment frame braced with BRBs, by increasing the cyclic lateral loading amplitude (from 30 to 60 mm), the magnitude of the frame's responses (lateral force, bending moment, and frame rotation) during fire application after cyclic lateral loading increases significantly, which indicates the high sensitivity of the behavior of steel moment frames (including those braced with BRBs) to fire temperature at high cyclic lateral loading amplitudes.
- Increasing the cyclic loading amplitude of the frame leads to an increase in the distribution and intensity of plastic strains in the frame, and consequently increases the frame's fatigue, which in turn leads to the intensification of the occurrence and distribution of large volumetric strains due to fire temperature in the steel columns and braces of the bottom story of the frame, and consequently intensifies the displacements and additional forces in the steel moment frame braced with BRBs after cyclic lateral loading.
- At different fire temperatures applied to the columns and braces of the bottom story of the steel moment frame braced with BRBs, by decreasing the BRB core thickness (from 6 to 2 mm, and especially down to 4 mm), the magnitude of the frame's responses (lateral force, bending moment, and frame rotation) during fire application after cyclic lateral loading

decreases. This decrease in responses indicates the high sensitivity of the behavior of BRBs and, consequently, the steel moment frames braced with these braces to fire temperature and the geometric parameters of the mentioned braces (especially the core thickness).

- The steel members of the BRBs (i.e., the core and the steel casing), in combination, create buckling-restrained conditions (despite high energy absorption), so that with the yielding of the BRB core during loading and the resulting high plastic strains and strain energy in the core during loading, the casing also prevents the buckling of the braces.
- Increasing the BRB core thickness (especially from 4 mm) leads to the non-yielding of the core during loading and the resulting low plastic strains and strain energy in the core, but a high distribution and intensity of plastic strains in other steel members of the frame and consequently increases the frame's fatigue. This leads to the intensification of the occurrence and distribution of large volumetric strains due to fire temperature in the columns of the bottom story of the frame and consequently intensifies the displacements and additional forces in the steel moment frame braced with BRBs after cyclic lateral loading.
- Thickening the BRB core (especially from 4 mm) reduces the proper performance of these braces in improving the thermo-mechanical behavior of steel moment frames braced with BRBs after cyclic lateral loading.

References

[1] Xiaohui Y, Kuangyu D, Yushi L, Bing L. Seismic resilience assessment of corroded reinforced concrete structures designed to the Chinese codes. Earthq Eng Eng Vib 2021;20:303–16. https://doi.org/10.1007/s11803-021-2021-z.

[2] Castiglioni CA, Kanyilmaz A, Calado L. Experimental analysis of seismic resistant composite steel frames with dissipative devices. J Constr Steel Res 2012;76:1–12. https://doi.org/10.1016/j.jcsr.2012.03.027.

[3] T. Silva, M. Carić, C. Couto, P. Vila Real, N. Lopes, and D. Skejic. Buckling Analysis of Steel Frames Exposed to Natural Fire Scenarios, *Structures*, vol. 10, pp. 76–88, 2017, doi: 10.1016/j.istruc.2017.02.003.

[4] T. C. H. Liu, M. K. Fahad, and J. M. Davies. Experimental investigation of behaviour of axially restrained steel beams in fire. *J. Constr. Steel Res.*, vol. 58, no. 9, pp. 1211–1230, 2002, doi: 10.1016/S0143-974X(01)00062-1.

[5] Sun R, Huang Z, Burgess IW. The collapse behaviour of braced steel frames exposed to fire. J Constr Steel Res 2012;72:130–142. https://doi.org/10.1016/j.jcsr.2011.10.006.

[6] Lamont S, Lane B, Usmani A. The behaviour of multi-storey composite steel frame structures in response to compartment fires. Fire Saf Sci 2005;8:177–188. https://doi.org/10.3801/IAFSS.FSS.8-177.

[7] Rahmanian F, Ismail I. Fire after earthquake. University of Canterbury; 1992. Canterbury, New Zealand.

[8] Rahnavard R, Thomas RJ. Numerical evaluation of the effects of fire on steel connections; Part 1: Simulation techniques. Case Stud Therm Eng 2018;12:445–453. https://doi.org/10.1016/j.csite.2018.03.010.

[9] Guerrero H, Terán-Gilmore A, Ji T, Escobar JA. Evaluation of the economic benefits of using Buckling-Restrained Braces in hospital structures located in very soft soils. Eng Struct 2017;136:406–419. https://doi.org/10.1016/j.engstruct.2017.01.008.

[10] Zhou Y, Shao H, Cao Y, Lui EM. Application of buckling-restrained braces to earthquake-resistant design of buildings: A review. Eng Struct 2021;246:112991. https://doi.org/10.1016/j.engstruct.2021.112991.

[11] Rubert A, Schaumann P. Structural steel and plane frame assemblies under reaction. Fire Saf J 1986;10(3):173–184. https://doi.org/10.1016/0379-7112(86)90007-0.

[12] Mirzaei P, Gerami M. Collapse assessment of protected steel moment frame under post-earthquake fire. Scientia Iranica, Transactions A: Civil Engineering 2020;27:2775–2789. https://doi.org/10.24200/sci.2020.54600.4466.

[13] International Organization for Standardization. ISO 834: Fire Resistance Tests-Elements of Building Constructions. Geneva: ISO; 1999.

[14] Dassault Systèmes. Abaqus User's Manual, Version 6.11-1. Providence, RI: Dassault Systèmes; 2011.

[15] Tsai KC, Lin CH, Qu B, Bruneau M. Sub-Structural Pseudo-Dynamic Performance of Two Full-Scale Two-Story Steel Plate Shear Walls. J Constr Steel Res 2010;66:1467–1482. https://doi.org/10.1016/j.jcsr.2010.05.008.

[16] Takeuchi T, Hajjar JF, Matsui R, Nishimoto K, Aiken ID. Effect of local buckling core plate restraint in buckling restrained braces. Eng Struct 2012;44:304–311. https://doi.org/10.1016/j.engstruct.2012.05.002.