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Thermal-Mechanical Coupling Response of Modular Steel Structure under Fire

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ABSTRACT

Modules of steel-structure modular buildings are usually connected semi-rigidly via welding or bolting, this connection method is between complete rigid connection and ideal hinge joint, therefore it's called semi-rigid connection. To accuracy simulate and analyze the fire resistance of steel structure under fire, it's necessary to study the connection node with self-locking and unlocking functions, model its bending moment-rotation angle-temperature relations, and analyze the thermal coupling response. Existing studies haven't considered the difference between damaged and non-damaged nodes in terms of fire resistance duration and bearing capacity, or explored into the mechanical performance and deformation of connection node during the temperature drop stage in the later period of fire, and the analysis on the overall robustness of node during fire is not specific enough. To fill in these research blanks, this paper aims to give a thermal coupling response analysis on modular steel-structure under fire. At first, this paper performed finite element analysis on self-locking/unlocking connection node, analyzed the stress distribution, bearing capacity mechanism, and failure mode of the node under tensile force based on stress cloud map, figured out the effect of different parameters on the tensile-force bearing capacity and stress state of the node, and discussed the effect on the robustness of self-locking/unlocking connection node under fire. Then, this paper set a corner piece rotary connection node and a self-locking/unlocking connection node and performed static tensile simulation tests on them, then load-placement curves were attained and compared, and the bending moment-rotation angle relation of self-locking/unlocking connection node under fire was derived. At last, experimental results of thermal coupling response of modular steel-structure under fire were given.

1. INTRODUCTION

Steel-structure modular buildings have become a hot spot in both academic research and engineering practice since their properties accord with China's policy of promoting the construction of green buildings [1-6]. For steel-structure buildings, the design of fire prevention is a building design problem, through which we can simulate the load distribution of the steel structure, the restraints at ends of structural components, and the temperature stress, so that the structure could meet the fire resistance duration requirement stipulated by the fire prevention specifications of buildings [7-10]. However, for steel-structure modular buildings, most modules are generally welded or bolted and a small part of them are pre-stressed, these joint methods are semi-rigid connection between complete rigid connection and ideal hinge joint [11-19]. To accurately simulate and analyze the fire resistance of steel structure under fire, it's necessary to study the connection node with self-locking and unlocking functions, model its bending moment-rotation angle-temperature relations, and analyze the thermal coupling response.

Hou et al. [20] attained a regression model for high temperature performance of steel strands based on existing test data of high temperature mechanical properties of 1860 grade steel strands, which could be used for theoretical analysis and numerical calculation. Then, based on the non-stationary temperature field model in the fire of tall and large space buildings, authors adopted a non-linear finite element numerical analysis method with time integral effect taken into consideration and built a fire resistance numerical model for large-span pre-stressed steel structures. After that, the paper used a fire resistance calculation example of beam string structure to discuss the effect of fire source position on the fire resistance performance of pre-stressed steel structures. Scholar Wang [21] analyzed the deficiencies of structural fire protection design in existing normative and performance-based design methods in his paper, and proposed an improved Gaussian transformation model which was then applied to the overall fire performance analysis of complex space steel structure, the model could be used for theoretical research and practical application based on simulation and analysis of the overall fire protection performance of complex space buildings. Dellepiani et al. [22] studied the thermo-mechanical response of Steel-Timber Composite (STC) structures in fire and proposed three different STC floor structural configurations with similar pre-fire performance for evaluating their response when subjected to a given fire scenario. In their study, a representative room of residential building was defined to simulate an accidental fire scenario to which the STC floor structures were exposed, and the results indicate that STC structures with closed cross sections of steel beams have a better fire performance than those included open cross sections such as I-shaped ones. Pinho-da-Cruz et al. [23] pointed out in their study that for behaviour of structures in case of fire, the validation of numerical models is very important for formulating precise and safe design rules for members at high temperature and applying advanced calculation methods on part or complete building structures under fire. The authors proposed a new constitutive law model for stainless steel at high temperature based on a two-stage Ramberg-Osgood formula and implemented it in the SAFIR finite element program to better figure out the fire behaviour of stainless steel structures and the effect of new constitutive law. In their work, after verifying the implementation scheme according to chosen benchmark tests, different numerical and experimental fire tests drawn from reference papers were numerically simulated with axially compressed columns, beams, and eccentrically loaded columns taken into consideration.

After reviewing related literatures, we found that the studies of domestic scholars on fire resistance of steel structure buildings are generally based on complete nodes that are connected ideally, they haven't considered the difference between damaged and non-damaged nodes in fire resistance duration and bearing capacity, or explored into the mechanical performance and deformation of connection node during the temperature drop stage in the later period of fire, and the analysis on the overall robustness of node during fire is not specific enough. To fill in these research blanks, this paper aims to give a thermal coupling response analysis on modular steel-structure under fire. In the second chapter, this paper performed finite element analysis on self-locking/unlocking connection node, analyzed the stress distribution, bearing capacity mechanism, and failure mode of the node under tensile force based on stress cloud map, figured out the effect of different parameters on the tensile-force bearing capacity and stress state of the node, and discussed the effect on the robustness of self-locking/unlocking connection node under fire. In the third chapter, this paper set a corner piece rotary connection node and a self-locking/unlocking connection node and performed static tensile simulation tests on them, then load-placement curves were attained and compared, and the bending moment-rotation angle relation of self-locking/unlocking connection node under fire was derived. In the fourth chapter, experimental results of thermal coupling response of modular steel-structure under fire were given.

2. ROBUSTNESS OF SELF-LOCKING/UNLOCKING CONNECTION NODE IN FIRE

However, now there are not many connection nodes with self-locking/unlocking functions in existing steel structure, which is not conducive to exerting the advantage of modular buildings in re-utilization, and most studies focus on the semi-structured modular unit systems. In case of fire, structural damage mainly occurs at positions of beam edge or column end section, so this paper proposed a new-type self-locking/unlocking connection node to solve the connection problem at edges, middle parts, and corners of structures with load-bearing columns, especially the inconvenient operation in the middle parts. This node has the features of self-locking, fast unlocking, full assembled, and high fault tolerance, and it has a series of merits such as no welding is required on site, no need to set operation holes in advance, and can be removed, re-used, and replaced easily and rapidly later. Figure 1 gives a diagram showing the self-locking/unlocking connection node, and its self-locking flow is given in Figure 2.

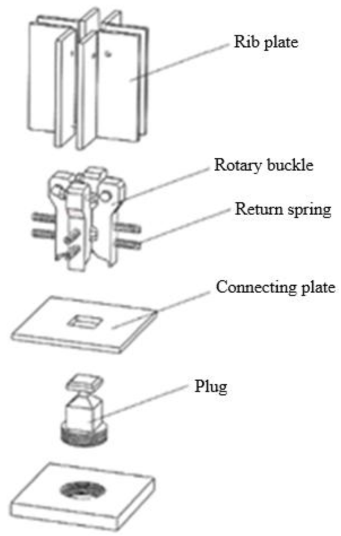


Figure 1. Structure of the new-type self-locking/unlocking connection node

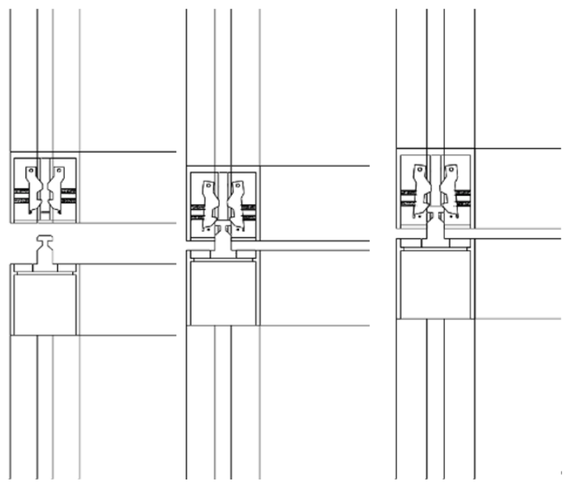


Figure 2. Self-locking flow of the new-type connection node

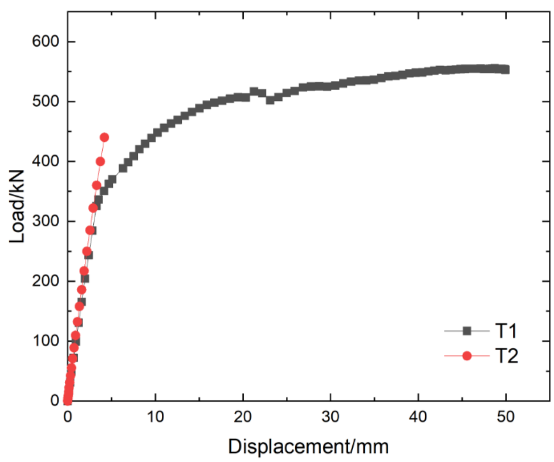


Figure 3. Static tensile stress at connection node of the rotary module units of corner piece

The robustness of modular steel structure under fire refers to the ability of the structure to maintain its bearing capacity without changes or serious damages in its core part. To ensure the reliability and stability of modular steel structures that use this new-type self-locking/unlocking connection node, design variables should be set reasonably so that the disturbance resistance ability of the modular steel structure could be enhanced under the action of various uncertain factors. The current robustness analysis of nodes is usually limited to qualitative analysis, and there isn't a universal method of quantitative calculation yet. This paper made comparisons of node robustness by analyzing and adjusting main parameters of the new-type self-locking/unlocking connection node, specifically, the parameters include plug neck width, neck width of rotary buckle, and diameter of the rotating shaft.

At first, this paper built a finite element model for connection node of rotary module units of corner piece, and analyzed its static tensile stress, as shown in Figure 3.

In finite element analysis software *ABAQUS*, 10 finite element models were built for the static tensile stress test of this new-type self-locking/unlocking connection node, numbered as T1-T10, respectively. The models adopted 8-node reduced integral C3D8R solid units for simulation analysis, to ensure the accuracy of the results, for connecting plates and other components that have openings, the opening part was meshed into two layers and the welding part adopted binding contact. For core areas such as corner piece, plug, rotating shaft, and rotary buckle, the meshes were denser; while for areas such as module column and connecting plate, the meshes were of normal density, the meshing, boundary conditions, and load-applying situations are given in Figure 4.

Importance of the rotary module units of corner piece is mainly reflected in the degree of influence of the failure of node area module units on the bearing capacity and fire resistance limit of the modular steel structure in case of a fire. Figure 5 shows the actual fire conditions of the node. According to the definition of importance coefficient of existing steel structure module units, it's known that this coefficient can measure the overall influence range of modular steel structure node after local failure of rotary module units happens under the action of external load in case of a fire.

Assuming: L and $L+\Delta L$ respectively represent the overall stiffness of the modular steel structure before and after fire damage; the load vector S remains unchanged; s represents the displacement vector of connection node before damage; $s+\Delta s$ represents the displacement vector of connection node after damage, then balance equations of the connection node before and after damage can be constructed as:

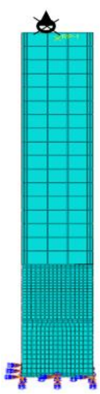


Figure 4. Meshing, boundary conditions, and load-applying situations

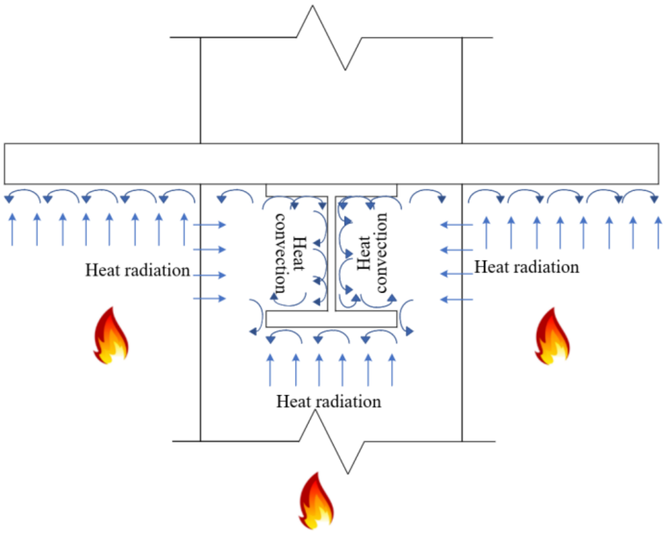


Figure 5. Actual fire conditions of the node

$$Ls = S \tag{1}$$

$$(L+\Delta L)(s+\Delta s) = S \tag{2}$$

The total strain energy O of modular steel structure before damage can be calculated by the following formula:

$$O = \frac{1}{2} s^T Ls \tag{3}$$

If the i-th rotary module unit of the corner piece fails, then the total strain energy O_p' of the modular steel structure under fire can be calculated by the following formula:

$$\begin{aligned} O_i' &= \frac{1}{2}(s+\Delta s)^T (L+\Delta L)(s+\Delta s) \\ &= \frac{1}{2}(s+\Delta s)^T L(s+\Delta s) + \frac{1}{2}(s+\Delta s)^T \Delta L(s+\Delta s) \end{aligned} \tag{4}$$

After sorting out above formula, we can get the formula for calculating the total strain energy change ΔO_p of modular steel structure caused by the failure of the i-th rotary module unit of the corner piece during fire:

$$\Delta O_i = O_i' - O_p = \frac{1}{2}(s+\Delta s)^T Ls - \frac{1}{2} s^T Ls = \frac{1}{2}\Delta s^T Ls \tag{5}$$

Assuming: l_i represents the element stiffness matrix of the i-th rotary module unit of corner piece, s_i represents the node displacement vector of the i-th rotary module unit of corner piece before damage, and s'_i represents the node displacement vector of the i-th rotary module unit of corner piece after damage, for matrix transition introducing displacement vectors, there is:

$$\Delta O_i = \frac{1}{2}(s')^T l_i s_i \tag{6}$$

The contribution value β_i of the i-th rotary module unit of corner piece can be defined by the following formula:

$$\beta_i = \Delta O_i \tag{7}$$

According to above formula, β_i represents the role of the i-th rotary module unit of corner piece in the total energy distribution of nodes in the modular steel structure, the larger the value of β_i, the greater the contribution of the i-th rotary module unit of corner piece, namely the higher the importance in the robustness of the connection node of modular steel structure.

Assuming: R_i represents the damage degree of the rotary module unit of corner piece, after analyzing the node bearing capacity contribution of each module unit and the failure range of the rotary module units of corner piece after the node is subjected to the action of continuous high-temperature during fire, this paper defined an importance coefficient ZY_i for rotary module units of corner piece to describe the importance degree of module unit, as shown in Formula 8:

$$ZY_i = \frac{\beta_i}{\max\{\beta_i\}} \bullet \frac{R_i}{\max\{R_i\}} \tag{8}$$

Because under the condition that the rotary module unit of corner piece does not break or crack, the performance of the material of the modular steel structure plays a dominant role in the robustness of modular steel structure nodes, and the effect of continuous load on the fire resistance ability of connection node when the modular steel structure deforms and damages during fire could be ignored, this paper takes the number of damaged units as the indicator for evaluating the vulnerability coefficient of the rotary module units of corner piece, assuming: ψ represents the vulnerability coefficient of the i-th rotary module unit of corner piece, K_p represents the number of damaged units at time moment p, K represents the total number of damaged units when the rotary module unit of corner piece reaches the damage limit, then there is:

$$\psi_i = K_t / K \tag{9}$$

The value range of Ψ_i is [0,1]. If ψ_i is equal to 0, it indicates that there is no damaged unit, namely there's no damage inside and outside the material of the modular steel structure; when ψ_i is equal to 1, it indicates that the rotary module unit of corner piece has serious damage and reaches the failure limit. The damage process of the rotary module unit of corner piece can be considered as the increase process of ψ_i.

3. DERIVATION OF BENDING MOMENT-ROTATION ANGLE RELATION OF SELF-LOCKING/UNLOCKING CONNECTION NODE IN FIRE

Scholars in the research field have conducted a lot of research on the performance of steel structures under normal temperature condition to understand the bearing capacity and initial elastic stiffness of modular steel structure connection module units, the majority of these studies are experiments, and some of them are theoretical research or the optimization of calculation methods.

This paper built a corner piece rotary connection node and a self-locking/unlocking connection node and performed simulated static tensile tests on them, the attained load-displacement curves are shown in Figure 6. The yield load value was respectively calculated by the geometrograph method, the equal-energy method, and the Park method and then averaged, the calculation results are given in Table 1. According to the table, the limit load and yield load of the corner piece rotary connection node are both less than those of the self-locking/unlocking connection node, and the limit load of the self-locking/unlocking connection node is 63% higher than that of the corner-piece rotary connection node. The tensile force bearing capacity of the self-locking/unlocking connection node is better than that of the corner piece rotary connection node.

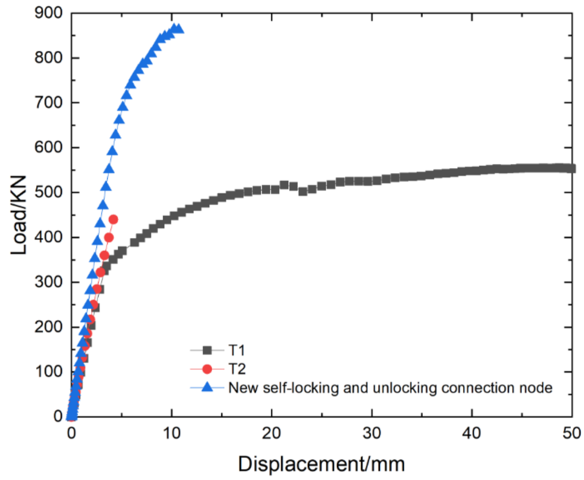


Figure 6. Load-displacement curves of self-locking/unlocking connection node and corner piece rotary connection node

Table 1. Comparison of yield load and limit load

Model Name	Yield Load/KN	Limit Load/KN
*T*1	445.774	555.511
*T*2	422.082	440.099
The new-type self-locking/unlocking connection node	764.804	863.752

Based on the above experimental results, we can fully understand the whole-process stress response of the corner piece rotary connection node and the self-locking/unlocking connection node. Moreover, this paper analyzed the influencing factors of the whole-process stress response and modeled the bending moment-rotation angle relation on this basis to realize overall analysis of the stress-strain features of modular steel structure under high temperature during fire.

Based on the results calculated by mathematical software *Mathematic*, the bending moment-rotation angle curve of corner piece rotary connection under the condition of a rotation angle less than 0.0755*rad* can be attained by the piece-wise functions shown as follows:

$$N = R_{dp}\Psi; \Psi \le \Psi_o \tag{10}$$

$$N = \frac{19}{35}N_t + \frac{R_{dp}}{11}\Psi; \Psi_o \le \Psi \le \Psi_b \tag{11}$$

$$N = \frac{128}{155}N_t + \frac{R_{dp}}{48}\Psi; \Psi_b \le \Psi \le \Psi_0 \tag{12}$$

Assuming: N_t represents the plastic bending moment bearing capacity of the connection; N_o represents the elastic bending resistance bearing capacity of the connection; Ψ_0 represents the rotation angle caused by the plastic deformation of end plate; the R_{dp} can be obtained by the component method: $N_t=3/2N_o$, $\Psi_o=N_o/L_i$, $\Psi_b=(13/3L_i)N_t$, $N_0=\Psi_0R_{dp}/50+137/150N_t$, $O_f/O=0.003$ and $\Psi_0=0.07655rad$. Similarly, the bending moment-rotation angle curve of corner piece rotary connection under the condition of a rotation angle greater than $0.0755rad$ can be attained by the piece-wise functions shown as follows:

$$N = N_0 + R'_{dp}\left(\Psi - \Psi_0\right); \Psi_0 \le \Psi \le \Psi'_o \tag{13}$$

$$N = N'_o + \frac{R'_{dp}}{11}\left(\Psi - \Psi'_o\right); \Psi'_o \le \Psi \le \Psi'_b \tag{14}$$

$$N = N'_b + \frac{R'_{dp}}{50}\left(\Psi - \Psi'_b\right); \Psi \ge \Psi'_b \tag{15}$$

In above formula, $N'_b=80kN\cdot m$, $N'_o=2/3N'_b$, R_{dp} can be obtained by the component method: $\Psi'_o=\Psi_0+N'_o-N_0/R'_{dp}$, $\Psi'_b=\Psi'_o+11/R'_{dp}(N'_o-N_0)$.

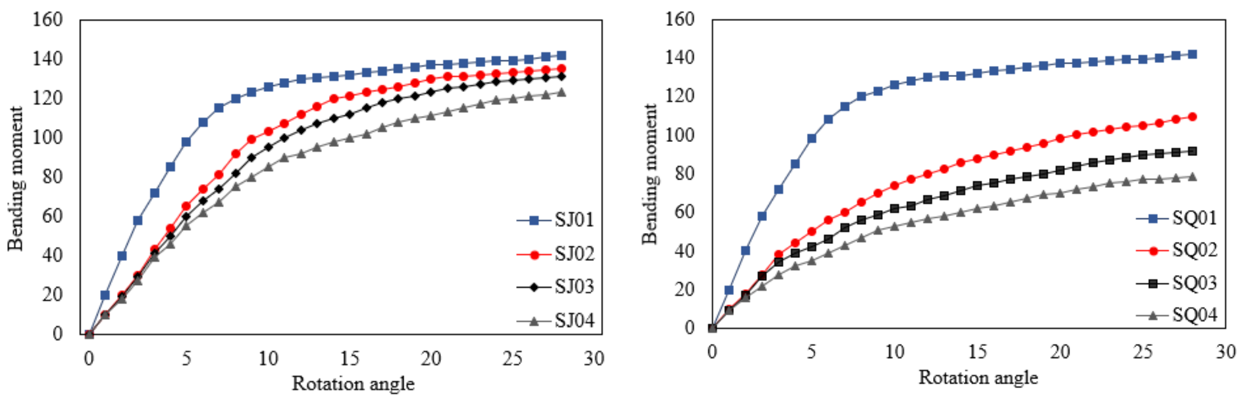
4. EXPERIMENTAL RESULTS AND ANALYSIS

According to the stress features of self-locking/unlocking connection under fire, the effect of plug neck width, rotary buckle neck width, and rotating shaft diameter on the robustness of modular steel structure nodes was analyzed respectively. Table 2 gives the calculation results of the number of damaged units in node area, the importance coefficient, and the vulnerability coefficient of different steel structure nodes after subjected to the action of continuous high temperature. For node area in which the reciprocating displacement has acted for 1-3 times, no corner piece rotary module unit is broken or damaged, after the action of the high temperature of fire, only module units with a 1-time action of reciprocating displacement are not damaged. However, based on the action of reciprocating displacement, for module unit with 5-6 times action of reciprocating displacement, the probability of damage increases largely, and the number of damaged units is far more than the number of damaged units caused by the action of high temperature during fire. At the same time, with the increase of displacement, the vulnerability coefficient of module units increases. According to the table, the vulnerability of rotating shaft diameter is greater than that of plug neck width and rotary buckle neck width, indicating that during the process of reciprocating displacement, rotating shaft will be damaged easily and its structure needs to be strengthened.

The actual fire conditions have a large impact on the semi-rigid performance of self-locking/unlocking connection under fire. In this paper, two kinds of actual fire conditions were selected to compare the performance of nodes in case of a fire. To simulate all surface fire conditions of modular steel structure with a fire starts from the inside, the condition 1 designed in this paper is that all surfaces of beams of the modular steel structure are on fire, and all surfaces of columns (except the outermost flange) are on fire.

Table 2. Damage index of finite element model

Test Piece No.	Reciprocating Displacement	Number of Damaged Units		Number of Damaged Units After Subjected to High Temperature		Vulnerability Coefficient of the Structure	
		Neck width	Diameter	Neck width	Diameter	Neck width	Diameter
A	1 time	0/41200	0/1720	1/41200	0/1720	--	--
	2 times	0/41200	1/1720	102/41200	19/1720	--	--
	3 times	0/41200	0/1720	102/41200	31/1720	--	--
	4 times	21/41200	23/1720	102/41200	48/1720	0.23	0.39
	5 times	49/41200	76/1720	102/41200	86/1720	0.52	0.82
	6 times	75/41200	80/1720	102/41200	99/1720	0.81	0.83
B	1 time	0/41200	0/1720	1/41200	0/1720	--	--
	2 times	0/41200	1/1720	99/41200	31/1720	--	--
	3 times	0/41200	0/1720	99/41200	41/1720	--	--
	4 times	31/41200	13/1720	99/41200	63/1720	0.29	0.31
	5 times	53/41200	71/1720	99/41200	91/1720	0.53	0.78
	6 times	74/41200	82/1720	99/41200	98/1720	0.80	0.81



(1) (2)

Figure 7. Bending moment-rotation angle curves of nodes at different heating times under fire condition 1

Table 3. Performance of nodes at different heating times under fire condition 1

Test Piece No.	Heating Time	Initial Rotation Stiffness	Effective Bending Moment Bearing Capacity	Ultimate Bending Moment Bearing Capacity
SQ01	0s	26.71	116.55	142.71
SQ02	100s	26.41	115.03	142.22
SQ03	200s	23.35	109.23	141.30
SQ04	300s	20.29	100.61	139.46
SQ05	400s	18.23	93.58	138.02
SQ06	500s	16.88	88.07	136.23
SQ07	600s	14.98	80.92	132.77
SQ08	700s	13.02	72.84	124.35
SQ09	800s	11.03	63.48	108.91
SQ10	900s	10.31	54.78	93.76
SQ11	1000s	8.84	46.61	78.81

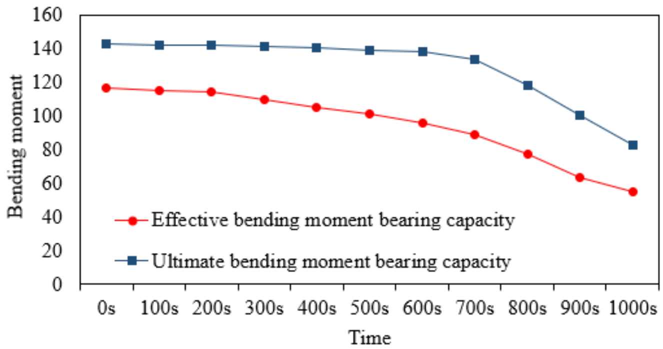
Table 4. Node performance at different heating times under fire condition 2

Test Piece No.	Heating Time	Initial Rotation Stiffness (KN·m/mard)	Effective Bending Moment Bearing Capacity (KN·m)	Ultimate Bending Moment Bearing Capacity (KN·m)
JH01	0s	26.73	116.54	142.73
JH02	100s	26.42	115.09	142.29
JH03	200s	23.77	114.55	142.37
JH04	300s	20.89	109.43	141.49
JH05	400s	19.35	105.32	140.66
JH06	500s	18.85	101.30	139.34
JH07	600s	16.33	95.94	138.37
JH08	700s	15.02	88.74	133.34
JH09	800s	12.93	77.49	117.90
JH10	900s	11.31	63.48	100.46
JH11	1000s	9.82	54.78	82.61

Based on the calculation results of *ABAQUS*, the bending moment-rotation angle curves of nodes at different heating times under fire were plotted, as shown in Figure 7. Table 3 summarizes the changes of performance indexes of nodes at different temperature rise times under fire, including the initial rotation stiffness, effective bending moment bearing capacity, and ultimate bending moment bearing capacity.

According to Figure 7 and Table 3, when the heating time is less than 400s, the performance indexes of self-locking/unlocking connection node vary slightly, the differences are controlled within 5%. The main reason is that the duration of high temperature in the early stage of the fire is relatively short, and the yield strength of steel structure below 400°C is basically stable, so the effective bending moment bearing capacity and the ultimate bending moment bearing capacity of the node remain unchanged. However, with the increase of temperature, the initial rotation stiffness of the connection always exhibits a gradual decreasing trend, and the main reason is that the elastic modulus of the modular steel structure is gradually decreasing, and the stiffness of the connection node declines obviously.

The fire condition 2 designed in this paper is that the corner piece rotary connection node is subjected to temperature load only near the node area, and Table 4 gives the node performance at different heating times under fire. According to the table, there is no significant decrease in the initial rotational stiffness of the corner piece rotary connection node, the main reason is that the duration of high temperature in the early stage of the fire is relatively short, the temperature in node area fluctuates around 100°C. Compared with the standard value of the elastic modulus reduction coefficient of steel structure, when the temperature is around 100°C, the elastic modulus of steel structure is basically stable, so the initial rotation stiffness of the node remains unchanged. But as the heating time accumulates, the elastic modulus of steel structure decreases constantly and the initial rotation stiffness of the node decreases with it.



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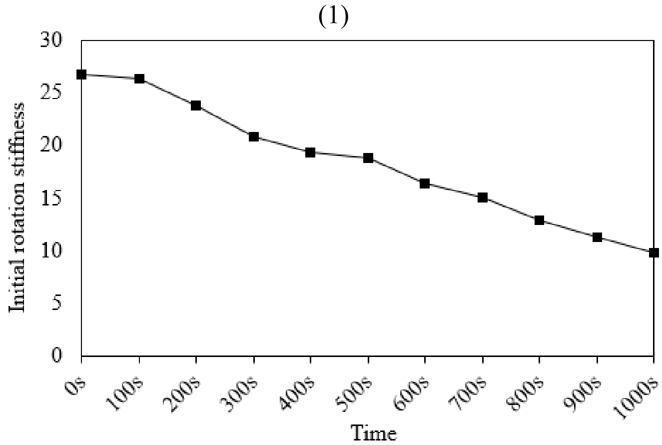

(2)

Figure 8. Node performance curves at different heating times under fire condition 2

Figure 8 shows curves of the bending moment and initial rotational stiffness of the corner piece rotary connection node at different heating times under fire condition 2, as can be seen from the figure, when the heating time is less than 200s, the effective bending moment bearing capacity of the node is basically stable, then with the passing of time, the yield strength of steel structure gradually decreases with the increase of local area temperature, and the effective bending moment bearing capacity of the node declines.

According to the experimental results of the two fire conditions designed in this paper, in case of a same heating time, the three performance indexes of self-locking/unlocking connection node under condition 1 are lower than those of the corner piece rotary connection node under condition 2, the main reason is that the expansion of fire area can cause the temperature in node area of the modular steel structure to rise, and the elastic modulus and yield strength of the modular steel structure would show obvious decrease.

5. CONCLUSION

This paper studied the thermal-mechanical coupling response of modular steel structure under fire. At first, this paper performed finite element analysis on self-locking/unlocking connection node, analyzed the stress distribution, bearing capacity mechanism, and failure mode of the node under tensile force based on stress cloud map, figured out the effect of different parameters on the tensile-force bearing capacity and stress state of the node, and discussed the effect on the robustness of self-locking/unlocking connection node under fire. Then, this paper set a corner piece rotary connection node and a self-locking/unlocking connection node and performed static tensile simulation tests on them, then load-placement curves were attained and compared, and the bending moment-rotation angle relation of self-locking/unlocking connection node under fire was derived. In experiments, this paper gave the calculation results of the number of damaged units in node area, the importance coefficient, and the vulnerability coefficient of different steel structure nodes after subjected to the action of continuous high temperature. At last, two actual fire conditions were selected for the comparison of node performance, and the effect of actual fire conditions on the semi-rigid performance of self-locking/unlocking connection was analyzed.

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