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Research Progress on Fire Resistance Performance of Buckling Restrained Braces

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Abstract

Starting from the key influencing factors such as core material, size effect, thickness of fireproof coating, filler and filling gap, the research progress of Buckling-restrained Brace (BRB) fire resistance is systematically reviewed, and it is pointed out that optimizing the thermal expansion matching between the restraining member and the core material and using the coating with low thermal conductivity can significantly improve its high-temperature bearing capacity. Secondly, the failure mechanism of three types of BRB under fire is analyzed, and the applicability of the existing fire resistance limit calculation methods is compared and evaluated. Then, starting from the fire prevention measures, the advantages and disadvantages of intumescent fire retardant coatings, cladding composite fire retardants, aerogel composite coatings and other protection schemes were analyzed, and it was proposed that multi-functional composite coatings with both lightweight, high efficiency and durability were an important development direction for BRB fire protection in the future.

Keywords

Buckling Constraint Support; Fire and High Temperature; Seismic Performance; Fireproof Coating; Thermo-mechanical Coupling.

1. Introduction

Fire, as a highly destructive disaster, severely threatens the safety of building structures. According to statistics, in 2022 alone, the national fire and rescue teams received and handled 2.092 million alarms of various types, dispatching 22.472 million fire and rescue personnel and 4.013 million fire engines, rescuing 168,000 trapped individuals, and evacuating 267,000 people in distress. A total of 825,000 fires were reported, resulting in 2,053 deaths, 2,122 injuries, and direct property losses of 7.16 billion yuan [1].

As a new type of energy dissipation component, the Buckling-Restrained Brace (BRB) effectively avoids the traditional brace compression buckling problem through passive control technology [2,3]. It exhibits excellent energy dissipation capacity and stable hysteretic performance under earthquake action, and is widely used in seismic retrofitting of various building structures and new construction projects. Under high-temperature fire environments, the mechanical properties of BRB will significantly deteriorate, thereby affecting the overall fire safety performance of the structure. Therefore, conducting in-depth research on the fire resistance performance of BRB has important practical engineering significance for ensuring the safety and integrity of building structures in fires.

2. Inffuencing Factors of BRB Fire Resistance Performance

2.1. Core Material

It is generally considered that the higher the strength grade of the steel, the more significant the attenuation of its yield strength at high temperatures, and the stronger the sensitivity of the

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thermal conductivity to temperature changes, leading to an increased internal temperature gradient of the structure, which results in a higher risk of deformation failure or buckling damage in a fire [4-5].

Commonly used core materials include low-yield-point steels (such as Q235, LY160, etc.) and special alloy steels [6]. He Wenfu [7] et al. found that the hysteretic curve of the LYP160 buckling-restrained brace degraded under fire. Through elastic-plastic dynamic time-history analysis of a multi-story steel frame energy dissipation structure under fire, it was found that the inter-story drift angle of the BRB structure significantly decreased under fire; Hu et al. [8] found that the yield strength of LYP160 steel decreased by about 20.6% and the tensile strength increased by 25% at 226°C, but the ductility significantly decreased, and through simulating the ISO834 standard fire for 1 hour, analyzed the internal temperature field distribution and hysteretic performance degradation of the BRB.

Existing studies have shown [9-11] that as the temperature rises, both the yield strength and elastic modulus of steel exhibit a downward trend, leading to a decrease in the bearing capacity of the core material; the softening phenomenon of low-yield-point steel at high temperatures is more obvious, and its high-temperature mechanical property degradation rate is faster compared to ordinary steel.

2.2. Size Effect

Section size is one of the main factors affecting the fire resistance of BRB. Due to the thermal inertia of concrete, the larger the cross-sectional size of the BRB, the lower the core material temperature will be. Talebi [12] et al. found that the cylindrical section has better fire resistance than the rectangular section due to uniform stress distribution, and found that increasing the gap size can improve the temperature distribution and delay the heating of the core material. Yang [13] et al. found that stress concentration at high temperatures is prone to occur in the corner areas of rectangular sections, leading to early cracking of the concrete filled layer. Mao [14] et al. studied the fire resistance of 8 steel reinforced concrete columns, finding that the cross-shaped steel section provides a good restraint effect on the core concrete and can inhibit crack development. Zhu Meichun [15-16] et al. studied the temperature field test of 8 composite column short specimens and the fire resistance of 10 composite column long specimens, finding that the temperature of the I-shaped steel section varies depending on the distance from the fire-exposed surface, but it has little effect on the overall temperature field. Yang Hua [17] analyzed the cross-sectional temperature field of rectangular concrete-filled steel tubular columns exposed to fire on one side and compared the working conditions of single-side and four-side fire exposure, pointing out that when the aspect ratio of the rectangular section is too large, fire exposure on the narrow side will exacerbate the asymmetry of the temperature distribution and significantly reduce the fire resistance limit.

2.3. Thickness of Fireproof Coating

Fireproof coating is one of the important measures to improve the fire resistance of BRB. Loik [18] et al. analyzed the protection efficiency of fireproof coatings on metal plates through experiments, finding that when the thickness increased from 0.8mm to 2.0mm, the time to reach the critical temperature was extended from 38 minutes to 52 minutes; the coating expanded at high temperatures to form a porous structure, and the optimal thickness was 0.8mm. Mao [19] studied the fire resistance of 8 SRCFST columns and found that a 12mm fireproof coating improved the fire resistance of SRCFST columns by 3.32 times. Yoshifumi Sakumoto [20] et al. found through tests on H-shaped steel members that when the thickness of the intumescent coating exceeded 2.5mm, the volume expansion of the high-temperature foaming layer was excessively large, resulting in a surge in interfacial stress between the coating and the substrate. Mercedes Gómez-Mares [21] et al. found that if the fireproof coating is too thick, the difference in thermal expansion coefficients between the substrate and the

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coating leads to the interfacial shear stress exceeding the limit. An excessively thick fireproof coating can cause high-temperature collapse inside the BRB. Therefore, it is necessary to comprehensively consider factors such as component fire resistance requirements, economic costs, and construction feasibility to reasonably determine the thickness of the fireproof coating.

2.4. Filler and Filling Gap

SAITOH [22] et al. used steel mortar planks to cover the BRB. When the mortar thickness increased from 10mm to 25mm, the fire resistance time improved from 45 minutes to 90 minutes. Talebi [12, 23, 24] et al. (2014, 2015, 2016) compared the effects of metal and concrete filling gaps on the fire resistance of BRB through three-dimensional thermo-mechanical coupling models and fire tests. It was found that after changing the gap filler from metal to concrete, the time to reach the critical temperature was extended by 52%, and the fire resistance of the cylindrical section BRB was superior to that of the rectangular section. However, they did not quantify the impact of the concrete mix ratio on the insulation efficiency, nor did they consider the risk of filler spalling after the fire. They systematically studied the effect of gap size (0.5–3mm) on the fire resistance limit of BRB, finding that when the gap was increased to 2mm, the fire resistance time improved by 40%, but the benefit disappeared when it was >2.5mm. Ostovar [25] et al. used ultra-high-performance fiber-reinforced concrete (UHPFRC) to replace traditional concrete in filling BRB. Finite element simulations showed that its compressive strength increased by 40% and local buckling deformation decreased by 37%.

3. Failure Mechanism of BRB under Fire

3.1. Strength Degradation Caused by High-temperature Softening of Core Materia

The mechanical properties of steel are extremely sensitive to temperature. When BRB is subjected to fire, the temperature of the core material rises rapidly. Generally, around 300°C, the yield strength of steel begins to decrease significantly. As the temperature further increases to 600°C-700°C, the yield strength is only 20%-30% of that at normal temperature [26]. Due to high-temperature softening, the core material not only fails to withstand the design load but also triggers local buckling. This is one of the main reasons for the failure of BRB under fire.

3.2. Interface Failure Caused by Uncoordinated Thermal Deformation of the Restraint System

The peripheral restraint members and the filled concrete have different thermal expansion coefficients under high fire temperatures [27], which will produce uncoordinated thermal deformation [28]. The expansion deformation of the steel casing restraint member at high temperatures is greater than that of the core material, while the core material's ability to resist deformation weakens after heating and softening. Excessive shear stress is easily generated at the interface between the two, leading to interface debonding and cracking. This interface failure destroys the synergistic working mechanism between the restraint system and the core material, making the restraint system unable to effectively provide lateral restraint for the core material [29], and accelerating the failure process of the BRB.

3.3. Deterioration of Overall Stability Performance

Under high fire temperatures, the overall stability performance of BRB significantly decreases. On the one hand, the fire causes dynamic changes in the connection conditions at the ends of the brace, affecting the overall frame behavior. At high temperatures, bolt slip will occur [30], weakening the fixed constraints at the ends of the BRB; on the other hand, internal force redistribution in the frame changes the load status borne by the BRB [24]. Under the combined

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action of axial pressure and additional bending moment, BRB is prone to overall flexural buckling or flexural-torsional buckling failure. In addition, the increased overall deformation of the structure during a fire will also have an adverse effect on the stability of the BRB, further exacerbating the deterioration of the overall stability performance.

4. Calculation Methods for BRB Fire Resistance Limit

Currently, the calculation methods for BRB fire resistance limits mainly include the empirical formula method based on experimental data, the simplified theoretical model method, and the finite element numerical simulation method. The empirical formula method establishes an empirical relationship between the fire resistance limit of components and various influencing factors through statistical analysis of a large amount of test data. The calculation process is simple, but its universality and accuracy are greatly affected by the limitations of the test samples. The simplified theoretical model method is based on the basic principles of structural mechanics and heat transfer. It makes simplified assumptions about the force and heat transfer process of BRB under fire, and establishes a theoretical calculation model. It can reflect the mechanisms of the main influencing factors, but its ability to handle complex boundary conditions and nonlinear problems is limited. The finite element numerical simulation method relies on large-scale general finite element software, such as ABAQUS, ANSYS, etc., to conduct fine simulations of the thermo-structural coupling behavior of BRB. It can consider factors such as material nonlinearity, geometric nonlinearity, and complex boundary conditions. The calculation results are relatively accurate, but the calculation process is complex and has high requirements for computational resources.

The empirical formula method is suitable for the quick estimation of BRB fire resistance limits in the preliminary design stage, and has certain reference value for relatively simple working conditions similar to the test conditions. The simplified theoretical model method can to a certain extent reveal the inherent laws of BRB fire resistance performance, and is suitable for qualitative analysis and parameter research of component performance, but its simulation accuracy is insufficient for complex and variable situations in actual fires. The finite element numerical simulation method can relatively realistically simulate the mechanical behavior of BRB under fire, and is suitable for in-depth analysis and evaluation of BRB fire resistance performance under important structures or complex fire scenarios. However, existing finite element models still have some problems when considering the temperature-load-deformation coupling effect, such as the accuracy of material constitutive models at high temperatures needs to be further verified, and contact algorithms have certain errors in simulating the interface failure process, which need to be further improved.

5. Fire Protection Measures

5.1. Intumescent Fire Retardant Coatings

Fireproof coating is a layered material applied with a certain thickness on the surface of a concrete structure. During a fire, it can effectively reduce the speed of fire propagation and improve the fire resistance of the structure by preventing heat transfer [31].

Intumescent coatings can expand to form a porous carbonized layer, thereby reducing the thermal conductivity and delaying the spread of fire [32-34]. They have the advantages of thin coating thickness, convenient construction, and good decoration, and are widely used for BRB fire protection. However, intumescent fire retardant coatings have poor durability. When exposed to the natural environment for a long time, the coating is prone to aging and peeling, affecting the fire protection effect. In addition, their intumescent performance is highly affected by the fire heating rate and peak temperature, and they may not be able to fully exert their fire protection role in some special fire scenarios.

5.2. Cladding Composite Fire Protection

Cladding composite fire protection is a type of fire protection measure formed by the combination of fireproof boards and fireproof cotton felts covering the wall of steel members. Compared with coating fire protection, it has the advantages of dry construction, good durability, and integrated decoration [35]. The wrapped layer has good thermal insulation performance, high strength, and flexibility, which can effectively protect BRB from fire attacks. The construction process of fiber-reinforced fireproof wrapped layers is relatively simple, and customized processing can be performed according to the shape of the component, with good durability. It is suitable for BRBs of various complex shapes. However, its disadvantage is its heavy weight, which will increase the self-weight of the structure and affect the seismic performance of the structure to a certain extent.

5.3. Aerogel Composite Coatings

The latest research results of aerogel composite coatings in high-temperature protection mainly focus on improving their high-temperature resistance, thermal insulation performance, and mechanical properties. For example, alumina aerogels have significantly improved their thermal stability, mechanical strength, and thermal insulation performance by introducing reinforcing phases and doping modifications. Research shows that by introducing SiC nanowires, aerogel materials with ultra-low density (about 5 mg/cm^3), high recoverable compressibility, and excellent high-temperature stability can be prepared, and their thermal conductivity is only $0.026 W \cdot m^{-1} \cdot K^{-1}$.

6. Conclusion

In summary, certain achievements have been made in the study of the fire resistance of buckling-restrained braces, but there are still many problems to be solved in aspects such as influencing factor analysis, failure mechanism revelation, perfection of fire resistance limit calculation methods, and optimization of fire protection schemes. With the development of building structures towards high-rise, large-scale, and complex directions, higher requirements are placed on the safety performance of BRB under extreme disasters such as fires. In the future, it is necessary to strengthen basic theoretical research, carry out multi-disciplinary cross-integration, and deeply and systematically carry out research on the fire resistance of BRB through a combination of experimental research, numerical simulation, and theoretical analysis, to provide solid theoretical support and technical guarantee for the fire safety design of building structures.

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