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Study on Fire Resistance of Buckling Restrained Braces with Different Forms of Restraint Elements

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Abstract: This paper compares and analyzes the differences in fire performance between concrete-based Buckling-Restrained Braces (BRBs) and all-steel BRBs. Concrete-based BRBs achieve thermal insulation through the low thermal conductivity and high specific heat capacity of the concrete shell, with a fire resistance duration of over 2 hours. However, there is a risk of steel core exposure due to concrete spalling. All-steel BRBs are vulnerable to high temperatures due to the high thermal conductivity of steel, with a fire resistance duration of less than 1 hour without protection, requiring reliance on external protective measures such as fire-resistant coatings, but they offer better repairability and adaptability. The study indicates that concrete-based BRBs are suitable for scenarios with high fire protection requirements, while all-steel BRBs have advantages in seismic-prone areas and scenarios requiring rapid installation. In the future, it is necessary to further optimize the fire-resistant coating technology for all-steel BRBs.

Keywords: Buckling-restrained Braces, Fire Performance, Concrete-based, All-steel, Fire Resistance Duration, Heat Conduction.

1. Introduction

As a sudden strong natural disaster with great destructive power, earthquakes often cause a large number of casualties and property losses in the short term. Under the action of earthquake load, a large number of building structures have been destroyed or even collapsed, which seriously endangers people 's life and property safety. It is inevitable to carry out seismic design and reinforcement of buildings. As the key research object of traditional seismic fortification, the seismic resistance of engineering structure can realize the ability of structure to resist earthquake disaster through reasonable design of overall structure and component level and relatively perfect structural measures. The traditional engineering seismic system is based on ductility design to improve the seismic performance of the structure itself, mainly to increase the section size of the component, delay the emergence of plastic hinge, develop high-performance structural system, develop high-performance structural materials, develop high-performance structural system, and set concentric support frame for seismic design[1]. Compared with the traditional seismic design scheme, the emergence of energy dissipation and isolation technology makes the reinforcement requirements of important buildings can be fully met. Buckling-Restrained Braces (BRBs) are widely considered as effective energy dissipation devices because of their excellent bearing and energy dissipation capacity. And because of its stable hysteresis performance and excellent low cycle fatigue performance, it has been widely used in architectural design[2].

At the same time, as a key component to resist extreme loads such as earthquakes and fires in modern structural engineering, the performance of buckling restrained braces directly affects the safety and reliability of building structures. In the context of frequent fires, the fire performance of BRBs has become the focus of academic and engineering circles. Some scholars[3] according to the constraint unit according to the different forms of composition is divided into two forms : one is the mortar or concrete filling, external connection steel casing concrete buckling restrained brace ; the other is all-steel buckling restrained brace, which has the advantage of convenient assembly. Concrete-filled steel tubular BRBs and all-steel BRBs are two main types of systems. There are significant differences in material composition, thermal conductivity and mechanical response mechanism between them, resulting in completely different fire performance.

Through the composite effect of steel core and concrete shell, concrete filled steel tube type BRBs form a natural thermal barrier by using the low thermal conductivity and high specific heat capacity of concrete, delaying the heating rate of steel core, thus improving the fire resistance. However, the concrete layer may spall or crack at high temperatures, exposing the steel core and causing degradation of mechanical properties. Due to the high thermal conductivity of steel, all-steel BRBs face the challenge of rapid heating and strength attenuation in fire, and need to rely on external fire-retardant coatings or insulation materials to make up for the defects. However, its high strength, high ductility and easy repairability still make it irreplaceable in specific scenarios.

At present, the comparative study on the fire resistance of the two types of BRBs is not systematic, especially the material failure mechanism, quantitative analysis of fire resistance time and engineering application suitability still need to be further discussed. By integrating the existing research results, this paper comprehensively analyzes the fire performance differences between concrete-filled steel tubular BRBs and all-steel BRBs from the dimensions of heat conduction mechanism, mechanical property evolution, fire resistance time comparison and practical application scenarios, in order to provide theoretical basis for the selection of BRBs, optimization of fire prevention measures and fire risk assessment in structural design.

2. Concrete-filled Steel Tube Buckling Restrained Brace

Concrete-filled steel tubular buckling-restrained braces (BRBs) are an integral part of modern structural engineering, especially in seismic design. These systems are constructed by wrapping the steel core in a concrete shell[4]. The main function of concrete is to provide heat insulation for the steel core, which helps to maintain its structural integrity during fire events[5]. The thermal conductivity of concrete is relatively low, which plays an important role in enhancing the fire resistance of concrete-filled steel tube BRBs by delaying the heat transfer from the external fire environment to the steel core[6]. see Fig. 1.

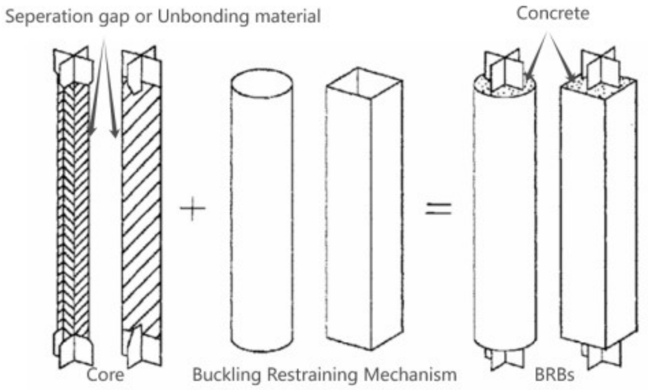

Fig. 1 Composition diagram of concrete buckling restrained brace members[1]

The strength and ductility of steel, combined with the thermal insulation properties of concrete, provide a hybrid solution for structural support. Steel alone is extremely susceptible to heat and loses strength quickly when exposed to fire, but the presence of concrete can significantly mitigate these effects by acting as a thermal barrier. The high specific heat capacity of concrete further delays the rate of temperature rise, thereby improving the fire resistance of BRBs[7]. The concrete shell reduces the direct exposure of the steel core to heat, which helps to maintain the mechanical properties of the steel during fire events, thereby maintaining the integrity of the support and ensuring continuous resistance to lateral forces[8].

Several studies have shown that the concrete shell can extend the fire resistance of BRBs by up to two hours, depending on the thickness of the concrete and the type of steel used[9]. This duration is crucial to maintain the structural stability of the building during the fire. However, the fire resistance of concrete-filled steel tubular BRBs is not infinite, and may be damaged by factors such as insufficient concrete thickness or poor distribution of steel bars. The cracking or spalling of the concrete layer may expose the steel core and reduce the fire resistance of the system. This kind of failure may be caused by excessive internal pressure caused by the expansion of water retention in concrete, which may eventually lead to the shedding of protective concrete layer.

One of the key mechanisms for concrete-filled steel tube BRBs to provide fire resistance is the thermal insulation provided by the concrete protective layer. In fire incidents, concrete acts as a thermal buffer to absorb heat and slow its transfer to the steel core. With the development of the fire, the temperature of the concrete rises, but the steel core is still in the state of heat insulation and protection. The chemical composition of concrete, especially its low thermal conductivity, further stabilizes the steel, preventing a rapid increase in temperature and maintaining its strength at high temperatures[10].

However, although concrete-filled steel tubular BRBs provide excellent fire protection, they are not undamaged. The spalling of concrete is a potential problem because it exposes the steel core to fire. When the concrete heats up too fast, spalling will occur, resulting in internal water expansion and cracking of the concrete, and then the concrete will flake off[11]. Once the concrete peels off, the steel core is more susceptible to direct heat, thereby reducing the overall fire resistance of the system. In addition, the thermal expansion of the steel core during the fire will aggravate the cracking of the concrete and further reduce the fire resistance of the BRB. Therefore, effective design and reinforcement are essential to ensure that the concrete cover remains intact and continues to provide the necessary thermal insulation[12].

Concrete-filled steel tubular buckling-restrained braces (BRBs) exhibit significantly different mechanical properties before and after exposure to fire. Before the fire, the concrete shell provides good protection for the steel core, so that it has high strength and ductility under normal working conditions. However, after a fire, concrete may crack or peel off, exposing the steel core to a high temperature environment, thereby significantly reducing its mechanical properties.

According to the study[13], the yield strength and ultimate strength of concrete-filled steel tube BRBs are about 400 MPa and 600 MPa before fire, respectively. However, after exposure to fire, the yield strength and ultimate strength decreased to about 200 MPa and 300 MPa, respectively, due to the spalling of concrete and the increase of steel core temperature. This change indicates that fire has a significant negative impact on the mechanical properties of concrete-filled steel tubular BRBs. see Table 1.

Table 1. Performance comparison of concrete-filled steel tube BRB before and after fire[13]

performance index	Before the fire	after fire
yield strength(MPa)	400	200
ultimate strength(MPa)	600	300
ductility factor	0.25	0.15
fire endurance(h)	>2	<1(When seriously peeled off)

Fire has a significant effect on the mechanical properties of concrete-filled steel tube BRBs, which is mainly manifested in the significant reduction of yield strength and ultimate strength, as well as the decrease of ductility coefficient. Although concrete provides good thermal insulation, the spalling of concrete during fire can cause the steel core to be exposed, thus weakening its mechanical properties. Therefore, in the design of concrete-filled steel tubular BRBs, special attention should be paid to the thickness of concrete and fire prevention measures to ensure their performance in fire.

3. All-steel Buckling Restrained Brace

All-steel buckling-restrained braces (BRBs) are commonly used in seismic applications due to their superior strength and energy dissipation characteristics. As shown in Fig.2, the all-steel buckling constraint structure diagram. These supports are entirely made of steel, making them very effective in resisting lateral forces. However, unlike concrete-filled steel tube BRBs, the all-steel system does not have the thermal insulation advantage provided by concrete[14]. The steel is known for its high thermal conductivity, which means that it absorbs and conducts heat very quickly. This characteristic makes all-steel BRBs particularly vulnerable to rapid temperature rise in fire, which may lead to deterioration of their mechanical properties.

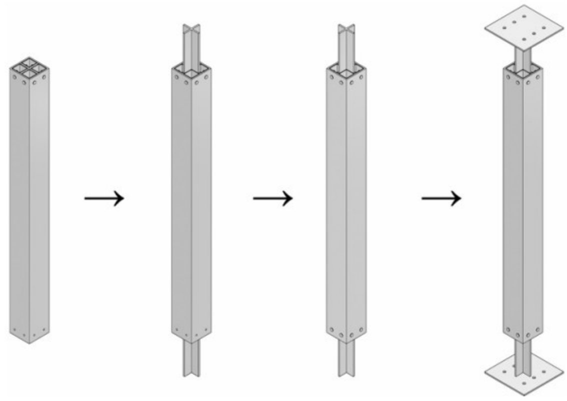

Fig. 2 All-steel buckling-restrained brace component composition diagram[15]

When the steel is exposed to fire, its strength will decrease significantly with the increase of temperature. At temperatures above 300 ° C, the yield strength of the steel begins to decrease, and at temperatures around 600 °C, it may lose up to 50 % of its original strength. The high thermal conductivity of steel accelerates this process because it promotes the rapid transfer of heat throughout the steel structure. Therefore, all-steel BRBs are prone to deformation, buckling and even complete failure if exposed to intense fire conditions for a long time[16].

All-steel buckling-restrained braces (BRBs) also exhibit significantly different mechanical properties before and after exposure to fire. Before the fire, the all-steel support has high strength and good ductility, which can effectively resist the lateral force. However, during fire, due to the high thermal conductivity of the steel, its temperature rises rapidly, resulting in a significant decrease in strength.

According to the study[16], the yield strength and ultimate strength of all-steel BRBs are about 350 MPa and 550 MPa before fire, respectively. After exposure to fire, the yield strength and ultimate strength of the steel decreased to about 150 MPa and 250 MPa, respectively, due to the rapid increase of temperature. This change indicates that fire has a serious negative impact on the mechanical properties of all-steel BRBs. see Table 2.

Table 2. Performance comparison of all-steel BRB before and after fire[16]

performance index	Before the fire	after fire
yield strength(MPa)	350	150
ultimate strength(MPa)	550	250
ductility factor	0.2	0.1
fire endurance(h)	<1(No fire-resistant coating)	<0.5(No fire-resistant coating)

Fire has a significant effect on the mechanical properties of all-steel BRBs, which is mainly reflected in the significant decrease of yield strength and ultimate strength, as well as the decrease of ductility coefficient. Although all-steel supports have high strength under normal operating conditions, their performance declines rapidly during fire. Therefore, it is necessary to use fire-resistant coatings or insulating materials to improve the fire resistance of all-steel supports.

In order to reduce the impact of fire on all-steel BRBs, fire retardant coatings or insulation materials are usually applied to steel. These coatings delay the temperature rise by providing an additional protective layer. For example, the intumescent coating expands when heated, forming a thick insulating layer that enhances the fire resistance of the steel core[17]. The effectiveness of these coatings depends on the type of material used and the thickness of the coating. In some cases, these coatings can extend the fire resistance time of all-steel BRBs to up to 90 minutes, which is crucial for maintaining their structural integrity in the case of fire[18].

Despite these protective coatings, all-steel BRBs are generally more vulnerable to fire damage than concrete-filled steel tubular systems. If there is not enough fire protection, the steel support will fail more quickly under fire exposure. Experimental studies have shown that all-steel BRBs without fireproof coatings fail within a few minutes of exposure to high temperatures[19]. This highlights the importance of adopting effective fire prevention measures when using steel BRBs in fire-prone environments. The vulnerability of steel to high temperatures makes external fire protection, such as fire retardant coatings or insulation, indispensable for ensuring the fire resistance of all-steel BRBs [20].

A potential advantage of all-steel BRBs is their rapid response to temperature changes. The low thermal mass of steel means that it heats up and dissolves faster than concrete[21]. This feature may be useful in applications that require rapid response to temperature changes, such as in architectural designs that require rapid structural adjustment to fluctuating fire conditions. In addition, compared with concrete-filled steel tubular BRBs, all-steel BRBs are easier to repair and replace after fire exposure, and concrete-filled steel tubular BRBs may suffer severe concrete damage that is difficult to repair[22].

4. Fire Performance Comparison

Concrete provides effective thermal insulation and significantly delays heat transfer to the steel core. The duration of fire resistance depends on the thickness of concrete and the quality of steel bar. The spalling and cracking of concrete will affect the overall fire resistance of concrete-filled steel tube BRBs.

The steel has high thermal conductivity, resulting in rapid heat absorption and strength loss. Fire-resistant coatings and insulation are essential to improve fire resistance. The performance of all-steel BRBs is highly dependent on the external fire protection system.

The comparison between concrete-filled steel tubular BRBs and all-steel BRBs reveals significant differences in fire resistance. Concrete-filled steel tubular BRBs have excellent fire resistance due to the insulating properties of concrete, which helps to prevent the rapid increase of steel core temperature[23]. As a natural barrier, the concrete shell slows down the transfer of heat from the external environment to the steel, thereby maintaining the mechanical properties of the steel at high temperatures. Therefore, concrete-filled steel tubular BRBs can maintain their structural integrity for a longer period of time, and usually withstand fire conditions for more than two hours.

In contrast, all-steel BRBs are more susceptible to rapid temperature rise because they lack the insulating properties of concrete. The high thermal conductivity of steel allows heat to spread rapidly throughout the support, resulting in the steel core losing strength at a faster rate. The performance of all-steel BRBs under fire conditions depends largely on the use of fire-resistant coatings or insulation, which can extend the fire resistance time to a certain extent. However, in the absence of these protective measures, the failure rate of all-steel BRBs is much faster, usually within 60 to 90 minutes[13].

In terms of fire resistance duration, concrete-filled steel tube BRBs are significantly better than all-steel BRBs. Due to the thermal barrier formed by the concrete shell, the concrete-filled steel tube system can provide longer protection time. On the other hand, all-steel BRBs require additional external fire protection, such as coatings, to achieve a similar level of performance[24]. Experimental studies have shown that concrete-filled steel tubular BRBs can work normally for more than two hours during fire, while all-steel BRBs usually fail within one hour without sufficient fire protection.

However, all-steel BRBs have certain advantages over concrete-filled steel tube BRBs in terms of repairability and maintenance. After a fire, steel-based systems are easier to inspect, repair, and replace than concrete-filled steel tubular moulding systems that may suffer extensive concrete damage. In addition, the adaptability of all-steel systems allows for a variety of fire prevention strategies, as coatings and insulation materials can be customized to meet specific fire safety requirements[25].

Concrete-filled steel tubular BRBs provide better fire resistance time and insulation performance. All-steel BRBs require external fire protection, such as coatings, to function effectively. The repairability and adaptability of all-steel BRBs make them a more flexible choice in some applications[26].

In summary, the fire resistance of concrete-filled steel tube and all-steel BRBs has different advantages and challenges. According to the research[6,14], concrete-filled steel tube type BRBs and all-steel type BRBs have their own application ranges in practical applications :

Concrete-filled steel tubular BRBs : Due to their good thermal insulation and high fire resistance, they are suitable for long-span structures and buildings with high fire safety requirements, such as high-rise buildings and large bridges.

All-steel BRBs : Due to their high strength and good ductility, they have advantages in earthquake-prone areas and scenarios requiring rapid installation.However, due to its sensitivity to fire, additional fire protection measures, such as fire retardant coatings or insulation materials, are usually required.

Although all-steel BRBs have high strength and flexibility, they are more susceptible to heat-induced damage. Fire-resistant coatings and insulation are critical to improving the fire resistance of these systems, but in most cases, they still cannot provide the same level of protection as concrete-filled steel tube systems. Nevertheless, the ease of maintenance and adaptability of all-steel BRBs makes them a viable option in some cases, especially where there is an effective fire protection system[27].

5. Conclusion

In this paper, by comparing and analyzing the fire resistance performance of concrete-filled BRBs and all-steel BRBs, the core differences and applicable scenarios of the two types of components in fire environment are revealed. The main conclusions are as follows :

With the low thermal conductivity and high specific heat capacity of the concrete shell, concrete-filled BRBs form a natural thermal barrier, which can effectively delay the temperature rise of the steel core. Its fire resistance time can reach more than 2 hours, which is outstanding in high fire protection demand scenarios. However, the concrete layer has the risk of spalling at high temperature, which may lead to the exposure of steel core and the degradation of mechanical properties (the yield strength and ultimate strength after fire are about 50 % lower than those at room temperature). Therefore, the thickness and crack resistance of concrete should be optimized in the design to reduce the risk of spalling.

Due to the high thermal conductivity of steel, the fire resistance time of all-steel BRBs is less than 1 hour without protection, and the yield strength and ultimate strength decrease by more than 57 % after fire, which is strongly dependent on external fire prevention measures. However, its fire resistance time can be extended to 90 minutes by means of protection methods such as fire-resistant coatings, and it has excellent repairability and adaptability, which is more advantageous in scenarios where seismic requirements are prominent or rapid installation is required.

The difference in fire performance between the two types of BRBs determines the differentiation of their application scenarios : concrete-filled steel tube BRBs are suitable for high-rise buildings, large bridges and other structures with strict fire protection requirements ; all-steel BRBs are more suitable for earthquake-prone areas and rapid construction projects, but reliable fireproof coating technology is needed. Future research should focus on the optimization of all-steel BRBs fire retardant coatings (such as improving the high-temperature stability and durability of coatings), and deepen the long-term performance degradation mechanism of the two types of components under complex fire conditions, so as to provide more accurate theoretical support for engineering selection and fire protection design.

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