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# Comparative study on the behaviour of Buckling Restrained Braced frames at fire

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ABSTRACT

In this paper, the use of Buckling Restrained Brace systems (BRBs) in preventing the progressive collapse of the structural frame against fire is investigated using the stiffness reduction technique. Four-storey steel structures fitted with different bracing configurations were modelled using the Vulcan programme. For comparative purpose, the efficiency of BRBs in preventing the progressive collapse of the structure is compared with the Ordinary Concentrically Brace systems (OCBs) in the presence of edge and central bay fire exposures. In order to consider the effect of bracing member stiffness on the collapse prevention of the frame and to provide a comprehensive scheme of progressive collapse mechanism under fire condition, several cross sections of BRBs under different fire scenarios are considered. The results indicate that BRBs provide a higher global collapse temperature for the frame, owing to a greater stiffness and more symmetrical performance offered as compared to OCBs, and thus providing better progressive collapse resistance. Moreover, it is observed that BRBs are stiff enough to redistribute the sustained load by heated columns to adjacent members without any buckling occurrence in the bracing member, maintaining the stability of the whole frame through both heating and cooling phases of fire.



## 1. Introduction

The global collapse of a building is commonly initiated by the spreading of local failures of the structural load bearing elements. Hence, in order to avoid the global collapse of the whole structure, this phenomenon should be prevented. In fire conditions, the overall instability is governed by the spreading of local failure from the heated frame. In this case, if the structure has sufficient load redistribution ability to extend load path and force transfer from the heated elements to other stiffer members, the progressive collapse could be prevented. As a result, this retards the global failure of the whole structural frame.

Vertical bracing systems are widely used in framing structures to resist horizontal forces induced by natural events such as wind and earthquakes. Due to additional strength, these bracing systems not only enhance the horizontal restraint of the frame, but can also be efficient in preventing the progressive collapse [1]. Hence, these resisting systems can be useful in enhancing the stability of the structural frame against fire incidents. In extreme loading conditions such as fire or earthquakes, the structural collapse is initiated by the buckling failure of one or more structural load bearing elements. In this case, if the load previously carried by these buckled elements can be transferred to the stiffer neighbouring structural elements, the collapse of the frame can be prevented [2]. Previous studies have shown that vertical bracing systems can play an important role in redistributing the loads from the buckled elements to other un-buckled structural members. The behaviour of structure at elevated temperature is however somewhat complicated than at room temperature. Changes in material properties and thermal movements at high temperatures can cause high nonlinearities in the structural element's behaviour. As a result, they initiate the formation of plastic hinges in load bearing elements, which then advances to the collapse of the whole structure.

In the last decade, several research studies have focused on the behaviour of different structural resisting systems in preventing the spreading of local collapse to the whole building. Sun et al. [1,3] evaluated the collapse behaviour of moment-resisting steel frames and various ordinary bracing systems under different fire scenarios. They found that bracing systems can remarkably enhance the strength and stiffness of the structural frame against collapse due to fire loading although ordinary bracing members may not be as effective as expected because of the occurrence of local buckling in the bracing members. Agarwal and Varma [4] studied numerically the influence of gravity columns on the progressive collapse of structural steel frames due to fire loadings. Two configurations were considered: moment-resisting frame at perimeter and interior shear walls for lateral resistance. They found that the overall stability of the structural frame is governed by the strength of gravity columns

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against fire. Couto et al. [5] evaluated the buckling length of columns and the elastic range of loads in braced and unbraced structural frames exposed to fire using analytical solution. They demonstrated that when the temperature of a compressive element increases, its buckling length decreases resulting in the reduction of frame's elastic load. In closing, they proposed buckling lengths of 0.5 $L$ and 0.7 $L$ for the intermediate and last storey of a heated braced frame, respectively. Agarwal [6] proposed a simplified relation for computing the effective slenderness of heated column, considering the existence of cooler columns at its top and bottom. The author showed that the axial load capacity of such a column is much higher than that of isolated one. Moreover, the effective length of the heated column was found to be remarkably related to its temperature and slenderness ratio. The progressive collapse responses of eight types of bracing arrangements were modelled by Kim et al. [7] and contrasted with those of special moment-resisting frames in earthquake. All braced structural frames remained in stable condition despite the sudden failure of the column. Also, it was demonstrated that the deflections of the braced frames are less than those of the moment resisting frames. Khandelwal et al. [8] investigated the behaviour of conventional concentric and eccentric bracing systems in regard to the progressive collapse mechanisms of steel structures under seismic events, and concluded that the latter is less vulnerable to the progressive collapse. The outcomes of two fire tests (Cardington and Ostrava) carried out for computing the axial forces developed in the connections during fire, were compared by Wald et al. [9]. They revealed that the horizontal forces generated at connections during fire tests, do not represent the total behaviour of the whole steel structures. In addition, they proposed transformation factors of 1.15 and 1.2 for beam–column connections for the Cardington and Ostrava tests, respectively. Izzuddin et al. [10] and Vlassis et al. [11] proposed an assessment method for the progressive collapse of multi-storey buildings due to column's failure, the frame work of which includes the evaluation of the nonlinear static response, dynamic estimation, and ductility determination. It was found that the local failure of vertical support elements and increase in the span of beam elements in composite structures, enhance the potential of progressive collapse of the entire building.

It is worthwhile to state that although several researches had discussed the progressive collapse mechanisms of structures under various accidental loadings, none of them has considered the effects of applying new types of braced systems such as BRBs, in preventing the progressive collapse of structural frames in presence of fire conditions.

The use of BRBs has been extensive in recent decades owing to their supreme structural behaviour in terms of enhancement of lateral resistance of the structural frames against earthquakes. The efficiency of using this system under static and seismic loadings at ambient temperature had been well studied and documented [12–14]. However, only limited literature [15,16] had explored its performance in fire situation. So, there is a lack of understanding on the elevated temperature behaviour of such braces in preventing progressive collapse of the structural frame. The principal strong features of BRBs are high energy dissipation capability, high ductility and almost symmetrical hysteretic responses both in tension and compression [12]. BRBs are composed of a yielding steel core, non-yielding and buckling-restrained transition parts, non-yielding and unrestrained end regions as shown in Fig. 1. Fig. 2 shows the steel core, which is encased in a concrete-filled steel hollow casing, to prevent its buckling. About 60%–70% of the entire length of the core is restrained by the casing [14]. In these bracing systems, compression stresses are mainly sustained by the restrained portion of the core. On the other hand, the yield strength of the steel core is much lower than that of the steel tube casing. Because of this, the core yields identically in tension and compression, prior to the failure of casing, such that it considerably enhances the energy dissipation capabilities in comparison to the ordinary bracing system. Due to the Poisson's effect of the steel core, it expands when it is in compression. To prevent the axial

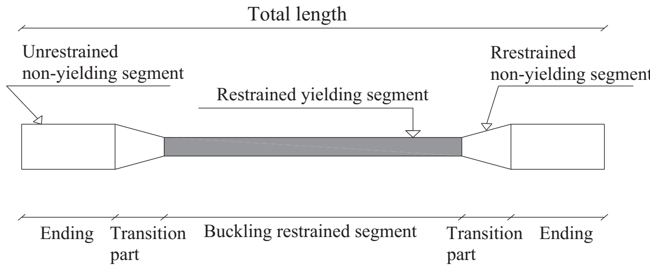


**Fig. 1.** Buckling Restrained Brace systems (BRBs).

stress transition from the core to the restrainer that results in friction between them, a certain amount of clearance between the core and concrete is provided. In addition, a debonding agent is applied to the surface of the core to neutralize any unwanted friction between these two main segments (Fig. 2).

Having stated the advantages of BRBs, the aim of this paper is to investigate its influence in preventing the progressive collapse of a structural frame under fire conditions. The efficiency of BRBs in the redistribution of loads from (heated) buckled columns to the adjacent load bearing elements is compared with the work carried out by Sun et al. [1] on the collapse behaviour of ordinary braced frames in presence of fire in terms of the process of global failure. To perform our analysis, a two-dimensional nonlinear plane frame finite element model is developed using Vulcan programme [17], which has been developed in the last decade by researchers at the University of Sheffield [18–23]. In our models, the main temperature-dependent characteristics of materials, such as thermal expansion and degradation of stress–strain curve at high temperatures, are taken into account. Also, geometric and material nonlinearities are considered. The details of our modelling settings are offered next.

## 2. Fire scenarios and frame details

### *2.1. Problem description*

In this work, the influence of BRBs on a steel moment frame is investigated for two bracing configurations, namely “hat truss” and “vertical” systems, as shown in Fig. 3.

As shown in Fig. 3, the frame has 4 storeys, each level of which is 3.6 metre high. There are 5 bays with 6.0 metre span each. The structure is assumed to be a typical office building with the design loads of 3.5 kN/m$^2$ and 5.0 kN/m$^2$ for dead and live loadings, respectively. Thus, a total line load of 40 kN/m is assumed to be uniformly distributed along the length of girders under the influence of fire, considering a one-way behaviour for floor slabs. For the frame, the bracing system should be designed to withstand probable horizontal forces from wind and earthquake. The frame restrained with BRB system is designed seismically in accordance with the AISC Seismic Provisions for Structural Steel Buildings [24], using a response modification factor of 7. Besides, to have a conforming comparison with the previous model proposed

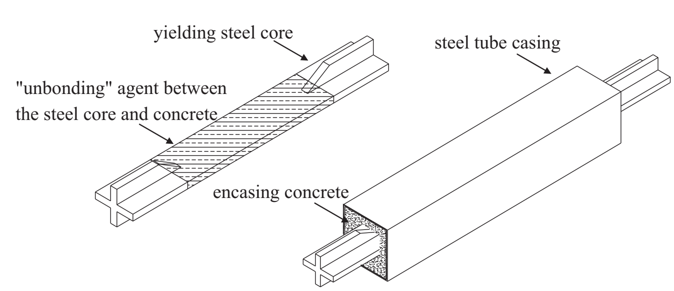


**Fig. 2.** Buckling Restrained Brace components.