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Catenary action in steel framed buildings with buckling restrained braces

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ABSTRACT

Progressive collapse is disproportionate failure of the structure due to the failure of a relatively small part of it. Catenary action is a load mechanism that is developed to resist the additional loads as a result of sudden column loss and prevent disproportionate collapse. Buckling restrained braces (BRBs) have been widely adopted as a dependable lateral load mechanism since the early 1990s. The impact of BRBs on the performance of steel frames subjected to lateral seismic forces suggests that BRBs might be beneficial to steel frames that are subjected to progressive collapse loads as well. The objective of this research is to conduct a detailed study on the impact of BRBs on the catenary action demands in steel framed structures. Push-down analysis of three, five and eight story steel frames with and without BRBs was carried out. The results showed that buckling restrained braced frames had a higher load carrying capacity compared to the bare steel frames. Different BRB placement scenarios and building heights were considered for this study. The BRB placement scenarios had more impact on the catenary action demands of the steel frame compared to the different building heights. Different loading types were studied and results showed that the loading of the model has significant impact on developed catenary forces. Finally, the results of the study highlight the importance of incorporating BRBs in future guidelines addressing the progressive collapse resistance of steel structures.

1. Introduction

The local damage of structural elements from extreme events that results in global collapse of the structure is called progressive collapse. Progressive collapse of buildings can be addressed either through direct or indirect design methods. The U.S. General Services Administration, GSA, (2003) [1] proposed the Alternate Path Method (APM), which is a direct design method. APM is commonly referred to as the “missing column scenario”. After the column is removed, the double span beam above it resists the resulting additional loads. This causes the beam to transition from flexural action to catenary action in order to sustain the additional loads. In this research, APM was adopted to investigate the progressive collapse and development of catenary action in braced steel frames. Previous research had shown that BRBs can have a significant impact on the performance of steel structures subjected to lateral loads [2,3]. The buckling restrained braced steel frame is a structural system in which a steel frame is braced with buckling restrained braces. Buckling restrained braces (BRBs) are passive control devices that have superior ductility and energy dissipative behavior compared to other bracing systems. BRBs are composed of a steel core supported by mortar-filled steel casing to eliminate buckling under axial loading. Three building heights, four BRB placement scenarios and three loading types were studied. The impact of BRBs on the generated forces in the adjacent frames to the double span beam suffering from column removal was highlighted. A comparison between the developed catenary action in the steel frames with and without the BRBs was conducted. Finally, the implications of the different building heights, BRB placement scenarios and loading types are discussed.

2. Previous research

Several studies have focused on the impact of different types of braces on the seismic behavior of steel frames. Many researchers have shown that the braces play a significant role in resisting earthquake loads. Similarly, catastrophic disproportionate failures of structures around the world have triggered research to develop a better understanding of progressive collapse. Catenary action was studied as a load carrying mechanism that can be a potential solution to arrest progressive collapse of steel structures. The literature review in this article will be divided into two categories. The first category covers the relationship between braced frames and seismic behavior and catenary action that reflects the potential role that BRBs can play in improving the load carrying capacity of the structure, while the second category covers the research on progressive collapse.

In regard to the braced frames and its impact on seismic behavior of structures, Sabelli (2001) [2] analyzed a series of three and six story braced framed buildings that were designed for a site in metropolitan

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Los Angeles. The buckling restrained braces were designed and modeled as unbonded yielding steel core inside a mortar filled steel tube. The models were selected to represent a range of earthquake events that might occur at the building location over a long period of time. The results indicated that the buckling restrained braces perform better than the special concentric braces. The BRBs provided significant benefits compared to the conventional braced frames and moment-resisting frames. Kim & Choi (2004) [3] investigated the energy dissipation capacity and earthquake response of steel structures with buckling restrained braces. They also presented a simple design procedure to meet a given target displacement. The authors analyzed five and ten story steel frames to study the seismic response of structures with BRBs. They concluded that as the stiffness of BRB increases, the equivalent damping ratios of BRB braced SDOF structures generally increase. Another finding was that the use of low strength steel for BRB reduces structural damage. The reason is that the low strength steel undergoes large plastic deformation and dissipates more energy than the high strength steel. Mahin et al. (2004) [4] performed large-scale tests on buckling restrained braced frame subassemblies to assess their seismic performance. They investigated the behavior of a one story, beam-column frame with Unbonded Braces with three different buckling restrained brace designs. The authors concluded that the three buckling-restrained braced frame subassemblies performed well as a seismic lateral system. The hysteretic and elongation behavior of the braces appeared not to be influenced by the combined axial and flexural loading of the subassemblies. Sabelli et al. (2003) [5] investigated the seismic demands on steel braced frame buildings with buckling-restrained braces. The authors analyzed three and six story concentrically braced frames utilizing buckling-restrained braces. The results showed that the buckling-restrained braces can potentially solve many problems associated with special concentric braced frames. The authors also found out that the response appears to be sensitive to structural proportioning which suggests that further improvements in response may be obtained by better estimation of a structure's dynamic properties. Mashhadiali and Kheyroddin (2013) [6] assessed the progressive collapse-resisting capacity of new hexagrid structural system for tall buildings. The hexagrid structure is an innovative tube-type system. The authors studied 28-story and 48-story frames using nonlinear static and dynamic analysis methods. The results showed that the hexagrid has enough potential of force redistribution to resist progressive collapse using its special configuration. The results also showed that the structural system performance against progressive collapse improved when buckling was constrained. Khandelwal et al. (2009) [7] investigated the progressive collapse resistance of seismically designed steel braced frames. The authors considered special concentrically braced frames and eccentrically braced frames. A two-dimensional ten-story steel prototype building was analyzed using the alternate path method. The results showed that the eccentrically braced frame designed for high seismic risk is less vulnerable to gravity-induced progressive collapse than the special concentrically braced frame designed for moderate seismic risk. Additionally, the results highlighted the limited strength of the shear-tab connections in resisting the progressive collapse once a gravity column is lost. Hayes et al. (2005) [8] investigated the possible relationship between seismic detailing and blast and progressive collapse resistance. The authors analyzed three possible strengthening schemes for the Alfred P. Murrah Federal building if it were located in a seismically active region. The three schemes are a pier-spandrel system, a new special concrete moment frame and a set of internal shear walls. Additionally, the original moment frame was redetailed to comply with the current building code provisions. The results showed that the pier-spandrel system, special moment frame, and the re-detailed original system provided higher earthquake resistance and subsequent blast and progressive collapse resistance. However, the internal shear walls were not as effective in reducing the blast and progressive collapse resistance. Khandelwal and El-Tawil (2011) [9] studied pushdown resistance as a possible measure of robustness in progressive collapse analysis. The authors proposed three nonlinear analysis techniques. A uniform pushdown, bay pushdown and incremental dynamic pushdown of 10-story steel moment frames designed for moderate and high levels of seismic risk were performed. The results showed that the incremental dynamic pushdown gives the most realistic estimate of residual capacity and collapse modes. Additionally, tensile catenary action forces were developed in some components of the damaged frame, which means that there are compressive forces developed in other parts of the system. The authors suggest that these force patterns are a result of frame action within the structural system. Kim et al. (2011) [10] examined a combined system of rotational friction dampers connected to high strength tendons to enhance both seismic and progressive collapse resisting capacity of existing structures. The authors designed the friction dampers using the capacity spectrum method to satisfy given performance objectives against seismic load. The nonlinear static and dynamics analysis results showed that the non-seismic-designed model collapsed when a column was suddenly removed. On the other hand, the model with the frictional dampers remained stable after the column was suddenly removed. Guneyisi (2012) [11] investigated the seismic reliability of the application of BRBs for seismic retrofitting of steel moment resisting framed buildings. The author performed fragility analysis on three and eight story steel moment resisting frames. The results showed that the BRBs improved the structural seismic behavior of the building by increasing the median values of the fragility curves.

In regard to the research on progressive collapse, Byfield and Paramasivam (2007) [12] studied the catenary action demands in steel-framed structures. The authors investigated the tying force method as a viable way for a load redistribution mechanism when a perimeter column is removed from a steel building. Their findings indicated that the provision of emergency bracing (stiff masonry panel walling) is the most effective means of redistributing loads away from damaged columns. The bracing proved to be a more reliable method to redistribute loads following localized damage rather than relying only on catenary action to ensure robustness. Tan and Astaneh-Asl (2003) [13] investigated the use of steel cables to prevent progressive collapse of existing buildings. The authors carried out experimental testing on existing buildings (one story steel structure with steel deck and concrete slab). The results showed that the slab provided significant tensile capacity in resisting progressive collapse. Additionally, the high strength steel cables provided additional strength, stiffness and toughness to resist the progressive collapse. The authors also recommended that the weld on shear tabs be designed to sustain loads equivalent to the capacity of the shear tabs. Khandelwal et al. (2008) [14] investigated the progressive collapse resistance of seismically designed steel moment frames using macromodel-based simulation. The authors calibrated the models using detailed finite-element models of beam-column subassemblages. They designed two ten story steel moment frames located in moderate and high seismic risk regions. The results suggested that the ductility demands associated with column loss in the moment resisting bays of both types of frames are relatively small. Also, they noticed that even though the shear tab connections have the necessary ductility to develop catenary action, the connections do not have the strength to resist progressive collapse. Khandelwal and El-Tawil (2007) [15] tried to validate the perception that seismic detailing has a positive impact on the progressive collapse resistance of the steel buildings. The authors used computational structural simulation to investigate different design variables that can influence formation of catenary action in steel special moment resisting frame subassemblages. The results established that out-of-plane pulling action resulting from transverse beams has no adverse effect on system behavior. However, the ductility and strength were adversely affected by the increase in beam depth and yield to ultimate strength ratio. Izzuddin and Nethercot (2009) [16] evaluated two different design-oriented approaches for progressive collapse assessment. The two approaches are the load-factor and the ductility-centered methods. The authors considered