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Seismic Behavior of Zipper Braced Frames; A Review

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ABSTRACT

Inverted-V-braced frames are one type of ordinary concentrically braced frame. The behavior of this system is controlled by the buckling of the first story braces in compression, resulting in localization of failure and loss of lateral resistance. The unexpected failure of steel structures during past strong seismic excitation led to full fill adequate strength for modern structures in seismic areas. Concentrically Braced Frames (CBF) shows a concentration of damage within a single floor and tendency of strong mechanism formation. The undesired effect of the unbalanced force can be reduced by adding zipper struts which is labeled zipper frames. As a consequence, the results showed that zipper struts can improve the seismic performance of CBF system.
KEYWORDS: Concentrically braced frame, Seismic behavior, Unbalanced Force, Zipper struts.

1. INTRODUCTION

Frequent damage was found in CBF buildings during Northridge earthquake on 1994, and Kobe earthquake [1, 2]. Concentrically Braced Frames (CBF) is an economical system for resisting lateral loads when lateral forces applied, brace elements initially provide both tensile and compressive resistance to balance lateral effect. In general for a brace element, the tensile capacity is greater than the compression capacity, when reaching its compressive capacity, the brace members buckle and a plastic hinge is developed at its mid length. As a result a big displacement occurred under strong seismic excitations; braces in compression have buckled, and in consequence lose their buckling resisting strength. After buckling of braces occurred, beams were deflected downward as a result of the combined action of the gravity loading and the unbalanced force developed at the braces to beam intersection point due to difference between tensile and post-buckling capacity of brace members. So, strong floor beams are required to stabilize the system when the unbalance vertical load transferred from braces to beams has increased due to the attaining the post-buckling strength in the compressive braces. Thus, because of this characteristic, CBF system has a limited efficiency in terms of distributing the lateral loads over the building height.

In spite of this limitation, several studies have shown that the system is still prone to soft strong mechanism under seismic ground motions. Khatib et al. [3] proposed to link all beam-to-brace intersection points of adjacent floor and to transfer the unbalanced load to the vertical element called zipper struts [1, 2].

As a result, all compressive braces will be forced to buckle almost simultaneously while only a few tensile braces will yield. When ground motion reversed, braces that acted previously in tension buckle in compression, while the zipper strut transfers the unbalanced vertical load upwards, and downwards depending on ground motion signature.

Previous studies on zipper frame:

Khatib et al. [3] proposed zipper braced frames. Sabelli [4] suggested design method for concentrically brace frame with weak zipper strut. In this case, zipper struts are allowed to buckle and to yield, while braces behave in inelastic range. Tremblay and Trica [5] developed design method for CBF system with strong zipper strut, in this design method, zipper struts were designed to behave in elastic range [2, 6, 7, 8].

Leon and Yang [2003] and Yang et al. [2008] proposed to add a truss system at the top floor while top floor braces were designed to respond inelastic range, labeled CBF with suspended zipper strut. Chen [1] and Tirca and Tremblay [10] developed and found method, called CBF system with elastic zipper strut. The research conducted in the field of zipper braced frame is focused on low and mid-rise building. Along with the increase in building height, adverse effect, such as large lateral deformation due to the activation of higher modes could drive the building near collapse [1, 2].

Zipper braced frame

Typically, in the CBF system, large story drifts is concentrated within a few stories and large ductility demand is required. Khatib et al. [3] developed a modified CBF system called zipper braced frame. Zipper strut is a vertical element added to a CBF system, to link together all brace-to-beam intersecting points. In this case, the zipper strut can behave either in tension or in compression. The vertical unbalanced force transferred to

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zipper strut pushes the zipper intension if the first buckled brace is located at the first floor and buckling of braces progress upward or pushes the zipper strut in compression, if brace of the roof floor buckles and buckling is propagated downward [`1, 2, 5, 9, 13].

Therefore, after brace buckled and the unbalance force is transferred to the zipper strut, this element is able to redistribute the transferred force to the braces located on the verge of buckling either at the floors above or below depending on the direction of brace buckling propagation. In this way, the damage concentrated at one floor is spread along the structure height. This configuration results in a better hysteric response and more uniform energy dissipation over the height of the building. Khatib et al. [3] investigated CBF systems with a variety of bracing configuration including v, x, inverted v and split-x configuration [13]. For zipper braced frames, it was anticipated that the response would not be sensitive to ground motion signatures and it has a more uniform distribution of damage along the building height. Also, the story shear force-displacement curve is trilinear.

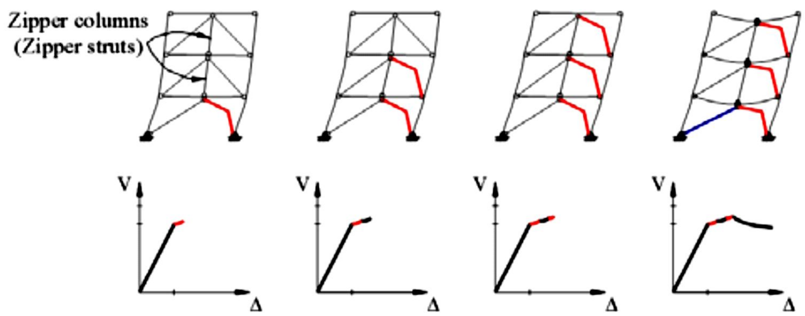

Figure 1. Expected behavior and performance of zipper frame [7]

CBF system with weak zipper struts

Sabelli [4] suggested weak zipper method in order to prevent the formation of weak strong mechanism and pursuit a uniform drift distribution along the building height. In this method, the design of brace elements should follow the same code requirements as provided for CBF s' Braces. He proposed that the compressive and tensile capacity of zipper struts must reach the strength of braces located at the level below. Also, the inelastic demand in both cases when zipper columns act in tension and compression should be considered in design. Sabelli [4] concluded that by adding zipper struts, the inter story drift demand is more uniformly distributed than that in CBF system with strong beams. Sabelli [4] studied a 3-and-6-story zipper braced frames and concluded that the 3-story zipper braced frame shows better seismic performance than the 6-story frame. Also, for the 6-story frame, several discrepancies have been observed. The deformed shape of the 6-story frame approximated the shape of the second mode of vibration instead of deflecting on the first mode [4]. Figure 2 shows the behavior of CBF system with weak zipper struts.

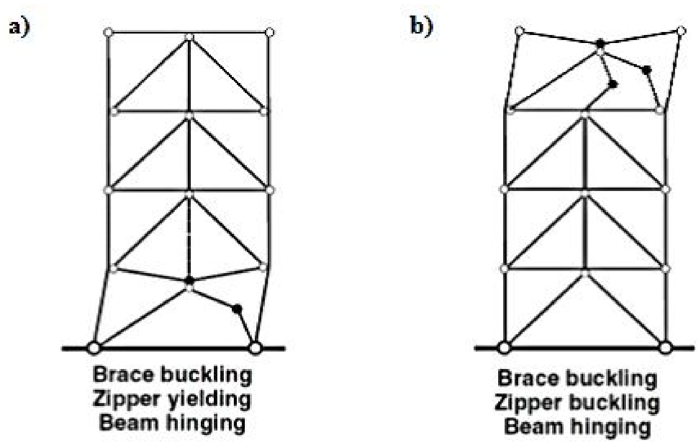

Figure 2. a) Zipper yields in tension; b) Zipper buckles in compression

CBF system with strong zipper

Tremblay and Tirca [5] studied another design method labeled strong zipper strut method. The aim of this method is maintaining the zipper struts to behave elastically under strong ground excitation. Based on this method, a 4-8- and 12- story zipper braced frames have been designed and studied. The results have shown that the zipper mechanism can be developed either in tension or in compression. In the first case zipper struts act in tension and the brace buckling starts at the bottom story and propagates upward in the frame. So, zipper struts are subjected to tensile force. On the other hand, for the case of zipper acting in compression, the first brace buckles at the top floor and then propagates downward. In this case, the unbalanced vertical force transferred to zipper columns as compression forces. These two cases are shown in Figure 3 [1, 2, 4].

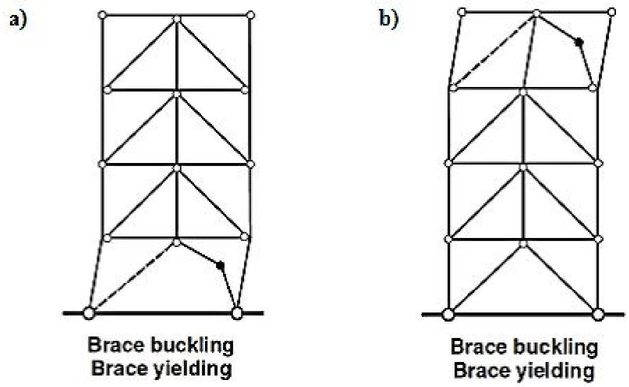

Figure 3. Behavior of zipper braced frame system with strong zipper columns [10]: a) brace buckling initiated at the base; b) brace buckling initiated at the roof.

CBC with suspended zipper strut

Roberto Lean and Young [8], from Georgia institute of technology, suggested a modified zipper braced frame called suspended zipper frame. This system consists of a zipper frame system with a hat truss located at the top floor level. In This case, the top floor braces behave in elastic range and prevent the formation of a full-height zipper mechanism. So, the failure is defined when the partial-height zipper mechanism is formed. In this method, the top level braces remain in elastic range while all other compression braces in other stories have buckled. In this frame, the top floor bracing members are designed to be bigger than the lower floor ones so as to suspend the zipper struts from the roof of the structure. Accordingly, the suspended zipper struts undergo the unbalanced vertical forces induced by lower floor bracing members in combination with gravity loads collected from the beams when the structures enter the nonlinear range. Since the primary function of the suspended zipper struts is to sustain only tension forces, and the suspended zipper struts support the beams at the middle span, the beam can be designed to be flexible. This results in significant savings in the amount of steel (up to 40%) and a clear force path that considerably simplifies design (Figure 4) [1, 2, 6, 8].

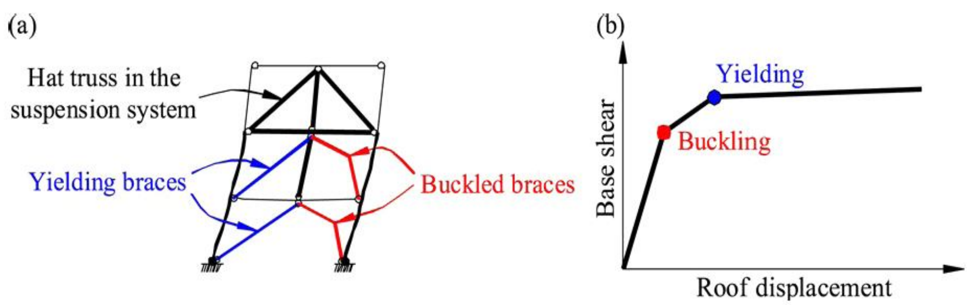

Figure 4. Behavior of ZBF with suspended zipper strut [13]

Also, the zipper braced frame behavior can be significantly improved if additional damping and energy dissipation is built into the braces. For example, by using bracing elements made of shape memory alloys (SMA) [14]. During the process of forming partial-height zipper mechanism, the hat truss helps to redirect the unbalanced forces into the exterior columns which transfer the forces back to base. The loading path of suspended zipper braced frame is well defined. The members of the hat truss are designed to behave elastically and thus, larger sections are required. In addition, along with the increase of the number of stories, the amount of forces carried by the hat truss can be substantially increased. In that case, the cross-sections of hat truss members became unacceptable large, which creates construction challenges and decrease the cost-efficiency of the system. Therefore, the suspended zipper frame structure is limited by the height of the building or in other words, by the number of stories [1].

Experimental research on zipper braced frame:

To solve the problems with CBF system, a new class of bracing system, called zipper frame, was developed and tested. In the experimental part of the research four laboratories (Georgia Tech (GT), U. at Buffalo (UB), U. at California at Berkeley (UCB), and U. of Colorado at Boulder (CU)) conducted studies on the behavior of whole systems subassemblage and individual elements. These experiments were tested under different types of load ranging from shake table tests to quasi-static ones, in order to provide comprehensive data in these experiments, three different 3-story prototypes were designed for a high seismic area. The goal of this study was to show benefits of a zipper frame. Figure 5 shows the response of three prototypes [14].

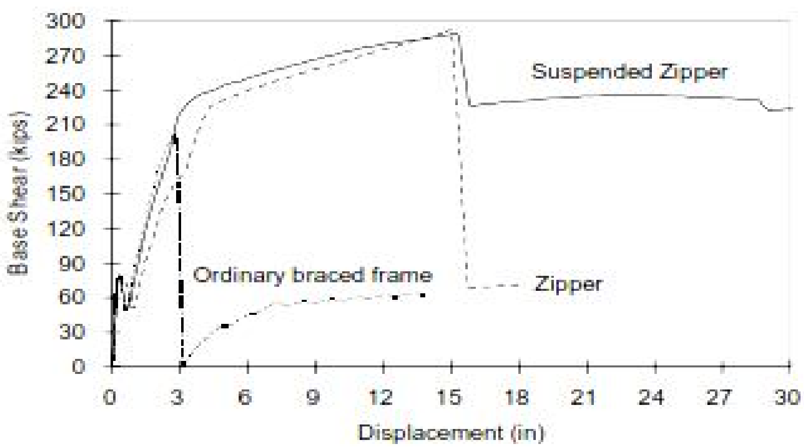

Figure 5. The response of three prototypes

From analytical studies conducted using opensees and using El Centro ground motion, the left bottom brace sustains more tension than the right bottom brace, while the latter sustains more compression. So, the zipper struts are subjected to tension only [14].

At maximum response, the second-floor zipper strut had yielded and the third-floor zipper strut was in an incipient yielding state. When the unbalanced vertical forces form, they are transmitted up to the top floor through the struts, and then sustained by the third floor bracing members. As a result, the analysis shows that those third floor bracing elements are always subjected to compression and remain in the elastic range. The nonlinear static pushover analyses indicate that suspended zipper system has a more ductile behavior than the conventional zipper frame and the capacity of each element can be fully utilized [14, 15, 16].

3. CONCLUSION

Result of experimental researches show that suspended zipper frames have more ductile behavior and higher strength than ordinary zipper frame [15]. The suspended zipper braced system is useful in improving the seismic behavior of inverted-v brace frames. The use of suspended zipper concept to rehabilitation and strengthening of existing structures is economical and practical [7]. In the zipper braced frames all of the braces participated in seismic energy dissipation and better damage distribution was achieved and the frame exhibited more strength and ductility [16]. The effects of higher modes, which become more important as the number of stories increases, appear to account for the increase conservatism of procedure as the number of stories increased [9]. The suspended zipper frames appear to reduce the tendency of chevron-braced frames to form soft stories and to improve seismic performance without having to use overly stiff beams [8].

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