STUDY OF SEISMIC BEHAVIOR OF SCBF WITH "BALANCED BRACING"

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ABSTRACT :

Bracing members in concentrically braced frames are specially designed to undergo plastic deformations and dissipate hysteretic energy through successive cycles of inelastic buckling in compression and yielding in tension while force controlled elements, such as beams, columns and connections should remain elastic to ensure the gravity load resistance of the frame. Design of a brace for buckling usually requires bigger sections than tension, while due to tension action of brace, the connections and other members should be designed for tensile strength of brace element. In chevron braced frames, beams in bracing frame should possess adequate strength to resist the unbalanced vertical forces due to unequal axial capacity of braces in tension and compression. This result in very big size beams, much stronger than would be required for other brace configurations. This paper describes an innovative brace member, Balanced Bracings, which intend to decrease the difference between tensile and post-buckling strength of braces. To do so the idea of RBS (Reduced Beam Section) in moment resisting frames is implemented in concentrically braced frames. Decreasing steel area in a limited length and at a specific location will result in a reduction in tensile capacity of the brace while it's buckling load and post buckling behavior is not affected significantly. Location and shapes of reduced area in brace are investigated by analytical studies that take into account the possibility of local buckling. The use of balanced bracing result in smaller unbalanced vertical forces on floor beams in chevron configuration, and also smaller design force for gusset plates.

KEYWORDS: Special Concentric Braced Frame, Buckling, Buckling Restraining System, Finite Element Analysis

1. INTRODUCTION

Currently Special Concentrically Braced Frames (SCBF) are considered as effective structural systems to resist lateral loads due to earthquake. Braces are the main source of energy dissipation in these structural systems. Energy dissipation of a brace is achieved by excessive cycles of inelastic buckling in compression and yielding in tension. Therefore the governing failure modes shall be yielding in tension and global buckling in compression (ductile failure modes) and shall occur prior to brittle limit states such as net section rupture and local buckling of elements. Brace hysteretic behavior exhibits unsymmetrical properties in tension and compression and typically shows significant strength deterioration when loaded into the inelastic range in compression.

All other components of the braced frames, such as columns, beams and their connections are force control elements that are designed to remain elastic while braces go through inelastic cycles of buckling and tensile yielding. Braces are usually designed for compression which results section areas that are more than required by tension, while due to tension action of brace the force controlled elements shall be designed for tensile strength of brace element. The braced bay beam in chevron braced frames is a force controlled element which has significant effect on the overall behavior of the braced frame and shall be designed elastically for maximum credible action in braces. The unbalanced vertical force which usually governs the design of braced bay beam in chevron braced frames is applied when one brace has yielded in tension and the compressive brace has experienced significant loss of capacity due to entering the post buckling range. This unbalanced vertical force cause a great increase in height of this beam.

Many of the potential performance difficulties associated with concentrically braced frames rise from the difference between the tensile and compressive capacity of the brace, extensive research has been devoted to reduce this unbalanced force and develop braces with more ideal inelastic behavior. Buckling Restrained Braced Frames (BFBF) are one of the systems developed to improve the seismic behavior of braced frames. A buckling restrained brace is composed of two main components: a steel core that resists the entire brace axial load and provides the axial stiffness for the lateral force resisting system and a confining or restraining exterior element that prevents the core from buckling in compression and allows it to yield in both tension and compression. For the independent action of the steel core from restraining system an un-bonding material is provided between them. The steel core is designed for the forces obtained from different design load combinations and controlling the allowable drift of the structure. In BRBFs, the unbalanced force is diminished by eliminating buckling of the brace, i.e. increasing the compressive capacity.

Balanced braces, similar to BRBs, are used to reduce the difference between the tensile and compressive capacity of the brace and improve the seismic behavior of concentrically braced frames by reducing the area of the brace and defering the buckling of the brace in the reduced area region. Maximum reduction in brace area can be equal to the area required for resisting the design earthquake. Reducing the area of the steel will make the brace sensitive to local and global buckling, therefore a good detailing or a restraining system shall be provided around the reduced area. In this paper, the tensile, compressive (buckling) and cyclic behavior of balanced braces with different configurations is studied by finite element methods.

2. TENSILE BEHAVIOR OF BALANCED BRACES

Reduction in brace area will reduce the tensile yielding capacity of the brace, and the amount of reduction is directly related to the reduced area, but the post yield behavior is also related to the length of reduced section. The notations in Figure 1, which schematically shows a longitudinal profile of balanced brace, will be used to study the tensile behavior of Balanced Braces.

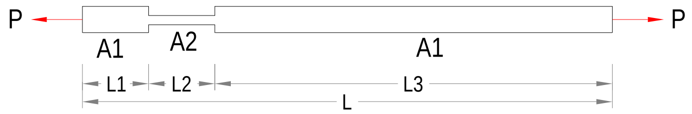

Figure 1 Notations for studying the tensile behavior

The tensile behavior of a balanced brace can be investigated in three steps. In the first step, both the reduced and the complete area (A1 and A2) behave elastically. In the second step, the reduced area will yield while the complete area is still elastic and finally in the third step, the whole length of brace is yielded. The relation between axial force and axial displacement in the second step is given in Eqn. 2.1.

$$IF \quad A_2F_y < P \leq A_1F_y \ : \ \delta = \frac{P(L_1+L_3)}{EA_1} + \frac{F_yL_2}{E} + \frac{(\frac{P}{A_2} - F_y)L_2}{E'} \tag{2.1}$$

E and E' are the elastic and the post yield stiffness of steel material respectively, δ is the axial displacement, P is the axial force and F_y is the yield stress of steel. For the third step, Eqn. 2.2 relates the axial displacement and axial force.

$$IF \quad P > A_1F_y \ : \ \delta = \frac{F_yL}{E} - \frac{F_yL}{E'} + \frac{\frac{P}{A_1}(L_1+L_3) + \frac{P}{A_2}L_2}{E'} \tag{2.2}$$

In Figure 2 the axial force – displacement diagram for different lengths of the reduced area and for the ratio of post yield to elastic stiffness of 0.01 is shown. In this figure it is assumed that area of the complete section is 2700 mm^2 and the ratio of the reduced to complete area is equal to 0.5. According to this figure, after yielding of the reduced area, the slope of the force – displacement diagram, decreases. The amount of reduction in inclination is related to the reduced area and to the length of the reduction. In the third step, in which the total length of the brace yields, the inclination will reduce significantly.

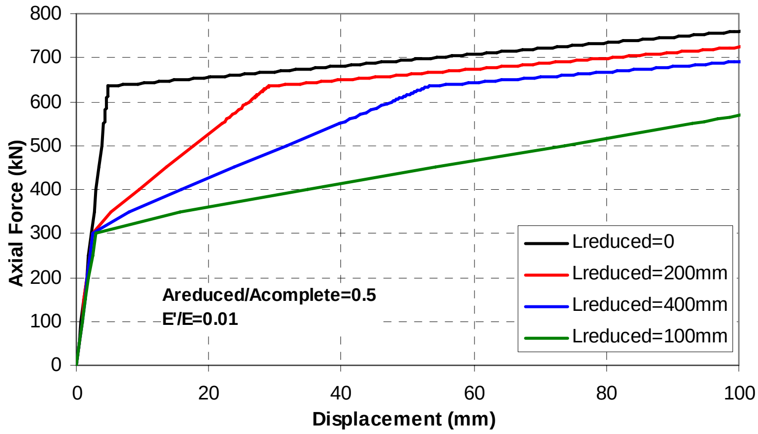

Figure 2 Force-Displacement diagrams for a brace with reduced section and with different lengths of reduction.

In Figure 3 the axial force–displacement diagram in tension, for braces with different reduced areas and total reduced length of 400 mm is plotted. It can be seen that the more the reduction in area, the more the reduction in the post yield stiffness of the force – displacement diagram.

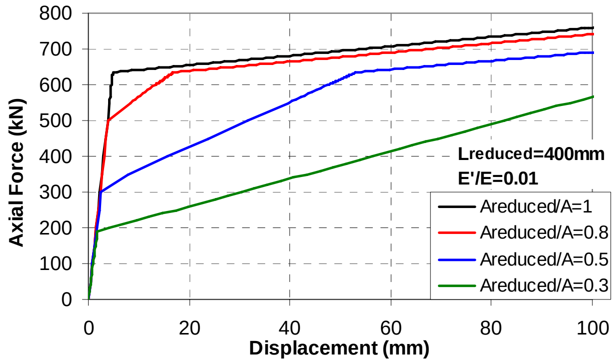

Figure 3. Force-Displacement curve for a brace with different reduced areas and an equal reduced length.

Apparently the amount of reduction in tensile capacity is also dependant on the post yield stiffness of steel material. The results of finite element analysis are the same as those obtained above.

3. COMPRESSIVE BEHAVIOR OF BALANCED BRACES

Length of the reduced area, its location through the length of the brace, the amount of reduction in area and the method of reducing the area will affect the compressive behavior of the balanced brace. In this paper, the elastic and inelastic buckling behavior of balanced braces is studied.

3.1. Elastic Buckling

To investigate the change in critical buckling load of balanced braces, the elastic buckling of a brace is studied with the aid of Energy method. In the Energy method, an approximate value for the critical buckling load is determined by examining the variation and balance of energies before and after buckling.

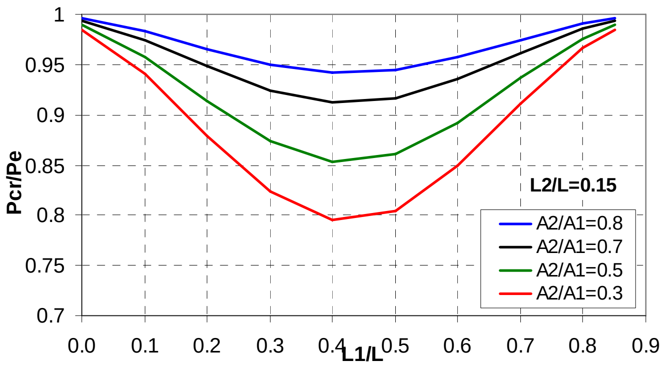

Figure 4. Elastic buckling of balanced braces

3.2. Inelastic Buckling and Post Buckling Behavior

Buckling and post buckling of the braces shown in Figure 5 are presented in this paper. In model "I" three 100 mm slots are provided at each end of the brace, giving the total reduced length of 600 mm. In model "II" a through plate is used for connection of the brace to the gusset plate and the reduced area is provided in the through plate. To eliminate the un wanted buckling modes, a restraining system, which is the continuation of the main brace section, is provided around the through plate but a length equal to half of the possibly imposed drift is considered without any restraining system to reduce any interference with axial displacements of the through plate. In model "III" the free length is also restrained by the restraining system, but special details are provided to help the free axial displacements of the through plate.

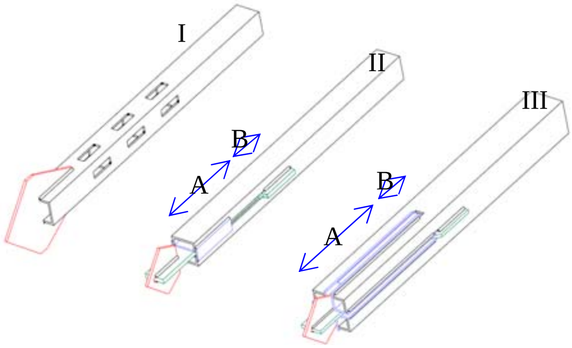

Figure 5. Studied models of Balanced Braces

To study the local and global buckling behavior of balanced braces with finite element programs, an initial imperfection shall be applied to the model to initiate the buckling. In model "I" the finite element model consist of SHELL elements while in models II and III, solid and contact elements are used.

As stated previously, the reduced length of brace in model "I" is 600 mm and the total length of the brace is 4 m. The area of the complete section is 2700 mm^2, while the area of the reduced section is 70% of the complete area. Different mode shapes of eigenvalue buckling and their combination are applied to the model and finally it is concluded that when the length of each reduced section is kept around 100 mm and less, the local buckling will not dominate the behavior and the global buckling behavior does not differ significantly with the usual complete braces.

In model "I", the length of the reduced area is small, which results small decrease in tensile capacity of the brace and finally the difference between the tensile and compressive capacity will not decrease significantly and the difficulties in the brace behavior due to buckling of the compressive brace remain unchanged.

In model "II" it is possible to consider an adequate length for reduction in area, because undesired buckling modes are eliminated with the aid of buckling restraining systems. In this model, the length of the reduced area is 1 m, and the area of the reduced section is 40% of the complete area which is equal to 2700 mm^2. The finite element model which is built with the aid of 8-node solid elements in ANSYS Finite Element program is shown in Figure 6. The connection of the through plate is simplified with a rigid plate on which the loading is applied.

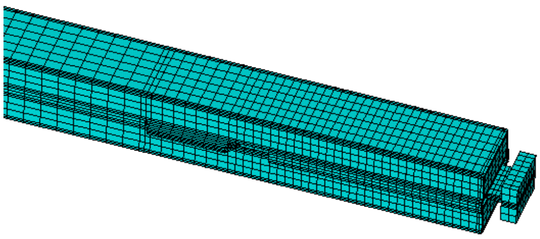
Figure 6. Finite element mesh of model "II"

The monotonic compressive and tensile behavior of this model is shown in Figure 7. In this figure the force-displacement model of the complete brace is also shown for comparison. It can be seen that yielding of the through plate will happen before the global buckling of the brace. Changing the area and length of the reduced section and the moment of inertia of the complete section can lead to a combination in which the buckling will not happen until the required storey drifts.

Reduction in tensile capacity of the brace at displacements of about 50 mm is due to necking phenomena in the through plate.

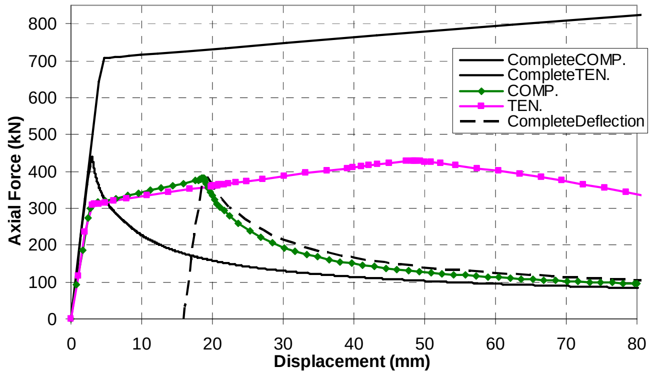

Figure 7 Force – displacement diagram of model “II”

Figure 8 shows the deformed shape and von misses stresses in the modified model “II”, in which the moment of inertia of the complete section is increased to overcome the buckling phenomenon up to axial displacements equal to 60 mm. In this model the area of the complete section increases to about 3800 mm^2. Figure 8 shows the stresses at axial displacement of about 70 mm, in which buckling has happened. The buckling happens when the rigid plate at the end of the model get in contact with the brace and the axial capacity of the brace increases significantly and then the brace buckles globally and the compressive capacity reduces.

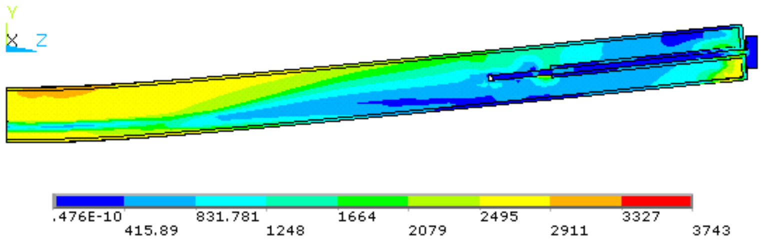

Figure 8 Von misses stresses in modified model “II” at axial displacement of about 70 mm

Applying the cyclic load according to AISC seismic provisions to the modified model “II”, shows that the undesired buckling in the through plate will happen, when the compressive displacements are applied after the increase in the free length of the through plate in tension, as shown in Figure 9. The initial free length of the through plate was about 30 mm at each end, which increased to 50 mm at cycles with axial displacement of 40 mm. This unsupported length together with the fact that the through plate is yielded in axial force, lowers the bending capacity of the through plate and causes the plate to buckle.

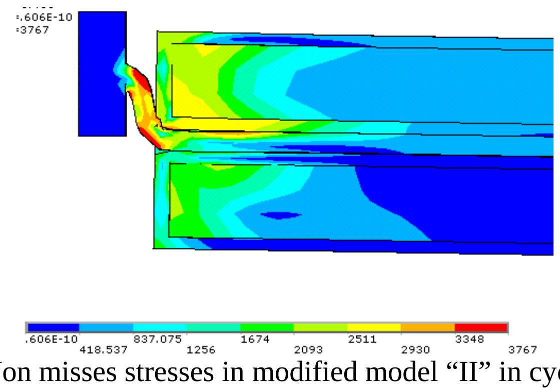

Figure 9 Von misses stresses in modified model “II” in cyclic loading

To overcome this problem, model “III” of Figure 5 was considered, in which there is no unsupported length. Using a simplified model for the finite element analysis shows that the behavior of this model is satisfactory and the brace will yield both in tension and compression in the range of displacement demands applied to the brace. Figure 10 shows the hysteretic curve of model “III”.

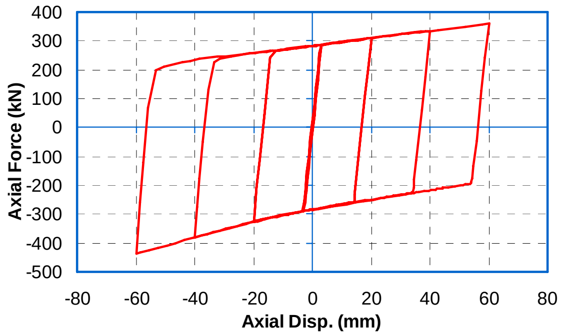

Figure 10 Hysteretic curve of Balanced brace, model “III”

4. CONCLUSION

In this paper, tensile, compressive and cyclic behaviors of Balanced Braces are studied with the aid of finite element analysis. According to the obtained results, to reach a favorable behavior and to reduce the unbalanced force, the length of the reduced area shall be adequate. On the other hand, this length shall be considered in a way that undesired buckling modes do not happen in compressive loading. In model “III”, shown in Figure 5, buckling of the brace in compression is postponed and displacement control actions are yielding in both tension and compression. The cyclic behavior of this model is stable and difficulties due to buckling in compression are eliminated. Additional studies, including more comprehensive finite element models and experimental studies are required to verify this model.

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