A Study of Loading Capacity Increase in Modified Ductile Ring Fuse in Concentric Braces

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Abstract: Concentric braced frames are kinds of structural systems which are used more than other systems in multi-storey buildings. This is due to the ease of their construction and their capability of economizing the projects. Concentric braces contain sufficient lateral stiffness but they don’t have adequate ductility. Various methods have been suggested to increase the ductility of these braces by researchers. One of these methods is to dissipate the energy by using a ring which is installed at the end of the brace members. Researches indicate that performance of this element result in ductility increment in concentric braces. However loading capacity of the ring element is limited and its ductility decreases by increment of its diameter and it may also limit some architectural aspects in the braced span. In this article the possibility of increasing the loading capacity of the ring by adding ductile steel plates has been studied, so that the new element acts as a fuse for different ranges of loads and prevents other members of the structure to enter the non-linear phase. The stresses and deflections have been studied by using a non-linear finite elements analysis under cyclic loadings. Resulted hysteretic curves indicate that added plates have effectively increased the ring’s loading capacity whilst providing desirable ductility.

Keywords: CBF, ductility, hysteretic curves, nonlinear static analysis, steel structures

Introduction

The earthquake-resistant design philosophy is a three-tiered approach. First, the structures must have adequate lateral stiffness to control the inter-story drifts such that no damage would occur to nonstructural elements during minor but frequently occurring earthquakes. Second, during moderate earthquakes, some damage to nonstructural elements is permitted, but the structural elements must have adequate strength to remain elastic so that no damage would occur. Third, during rare and strong earthquakes, the structure must be ductile enough to prevent collapse, although one should aim for repairable damage so that retrofitting would be feasible.

Providing the ductility of a structure is affected by non-linear behavior of its members and joints in the time of earthquake, its reconstruction cost after the earthquake is dependent on the number of resistant elements in the whole structure. Because of this, rehabilitation of moment resisting structural systems is very costly.

Concentrated braces do not have desirable ductility, but affected members against the earthquake are limited, hence their reconstruction is less expensive than MRFs (Chen et al., 2001; Tremblay et al., 2006). In order to obviate the deficiency of concentrated braces and providing a desirable ductility for them, several investigations have been performed by researchers in recent two decades, who tried to improve the ductility of concentrated braces (CBF).

Theory

One of the fuses is a new energy dissipater (Yielding steel) which is made in shape of a ring, and is installable in braced frames in order to increase the ductility and earthquake energy absorption. During earthquakes, this member dissipates a considerable amount of implied energy to the structure, by reaching to non-linear phase and forming plastic bending hinges. In this way, this member prevents other members to enter their non-linear phase, and also prevents or delays the buckling of brace members. These rings are designed in a way to enter the non-linear phase before the buckling of brace (Chen et al., 2001).

This kind of design causes the steel ring to play the role of a fuse to prevent the member from buckling. After the earthquake, the steel ring at the end of the brace will be damaged because of plastic deformations, and has to be repaired. But this act will be limited only to the joint at the brace corner and replacement of the steel ring. Placement of the ring in the braced frame is shown in figure 1.
Surveys indicate that the performance of this element result in increasing the ductility of concentrated braces, however the loading capacity of the element is limited and its ductility decreases by increment of its diameter, and it may also limit some architectural designs in the braced span. It was also observed that by increment of geometrical dimensions of the ring like its diameter, thickness and length, no considerable change was observed in the element loading capacity.

Therefore, this element is unusable in multi-storey buildings where large seismic loads are expected. For this reason, in this article a new assembly is proposed to increase loading capacity of this element by adding some ductile steel plates with different steel types next to the ring. The position of the plates in this assembly is important to increase the desirable effect of these elements as much as possible. The reliability of this new element -when the plates are installed parallel to the ring- is provable by a simple analysis (Tsai et al., 1993);

In sequential mode, we will have:

\[
\frac{1}{k_e} = \frac{1}{k_r} + \frac{1}{k_p} \Rightarrow k_e = \frac{k_r k_p}{k_r + k_p}
\]

While in parallel mode, we will have:

\[
k_e = k_r + k_p
\]

Where,

- \(k_e\): Equivalent stiffness of the element.
- \(k_r\): Bending stiffness of the ring.
- \(k_p\): Actual stiffness of the plates.

As it’s shown, for any amount of \(k_r\) and \(k_p\), equivalent stiffness will be more in the parallel mode. Therefore the plates were placed in parallel with the ring to recuperate for the stiffness loss caused by the ring element. These equations are also applicable for damping.

The installation form of the plates is shown in figure 2. This element can play the role of a fuse to prevent the buckling of the braces in range of various loadings.

Figure 1. Placement of the ring in the braced frame.

Figure 2. Proposed model.
Geometrical And Mechanical Properties Of The Members

In every analysis, the ring used is made of seamless pipes with 22 cm diameter, 1.2 cm thickness and 14 cm length. The plates used in this research were LYS, ST37 and 304, with 42 cm length and 6 cm width. Investigations on thickness of 0.8, 1 and 1.2 cm and their effect on loading capacity tolerance of the element were performed.

Plates’ lengths were based on ring’s diameter and required length of welding for linking to gasket plate of the brace. Calculations confirmed that 42 cm of length satisfied these conditions.

Mechanical properties of the members were obtained by performing a simple tension test on the ring, ST37 and 304. The results for mentioned samples and LYS (Chen et al., 2001) are shown in table 1.

<table>
<thead>
<tr>
<th></th>
<th>module of elasticity $\frac{kg}{cm^2}$</th>
<th>Ultimate Strain $\epsilon_u$</th>
<th>$F_y$ $\frac{kg}{cm^2}$</th>
<th>$F_u$ $\frac{kg}{cm^2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ring</td>
<td>$2 \times 10^6$</td>
<td>0.2</td>
<td>3000</td>
<td>4800</td>
</tr>
<tr>
<td>LYS</td>
<td>$1.95 \times 10^6$</td>
<td>0.4</td>
<td>1000</td>
<td>3000</td>
</tr>
<tr>
<td>St37</td>
<td>$2 \times 10^6$</td>
<td>0.26</td>
<td>2400</td>
<td>3700</td>
</tr>
<tr>
<td>304</td>
<td>$1.56 \times 10^6$</td>
<td>0.47</td>
<td>2800</td>
<td>6350</td>
</tr>
</tbody>
</table>

Modeling And Study Of Element Performance

In order to study the performance of the element under the influence of cyclic loads, a 3-D FE model of the ring was constructed using ANSYS; first alone, and then by adding the plates with the mentioned properties.

Three dimensional element “Solid 185” with 8 nodes –which each node has three degrees of freedom was used for modeling. This element is able to show all the stresses, internal forces and in-plane and out-of-plane loadings in non-linear analysis. The multi-linear kinematic hardening model was used to model the stress-strain curve and hardening circumstance of the members. Non-linear static analysis was used to study the behavior of the model. Loading and supports were defined within a 10 cm width on the brace joint plate in order to provide conformity between loading of the model and actual loading. Applied loading diagram which starts with little displacements (0.05 mm) is shown in Figure 3.
Results and hysteretic loop of the ring

The steel ring with 22 cm diameter, 1.2 cm thickness and 14 cm length, as described, was modeled in ASYS software under cyclic loads. Force response diagram to induced displacement, and hysteretic loop of loading-displacement of the ring, are respectively shown in figures 4 and 5.
As it is shown, hysteretic loops are pretty wide which shows the energy absorbing capacity of the ring. The force-ring deformation diagram which is derived from hysteretic loop is shown in figure 6. The first plastic hinge was formed under the load of 9.1 tons and the model bore 12 tons in the last step of loading.

Results and hysteretic loop of the proposed element (the ring and the plates)

The element, as described, was modeled in ANSYS software for three different types of steel (LYS, ST37 and 304) and under cyclic loads.

Force response diagram to induced displacement, and hysteretic loop of loading-displacement of LYS with 1 cm thickness, are respectively shown in figures 7 and 8.
Figure 7. Force response diagram to induced displacement of LYS with 1 cm thickness

Figure 8. Hysteretic loop of loading-displacement for LYS with 1 cm thickness

The force-deformation diagram which is derived from hysteretic loop, is shown in figure 9.
The first plastic hinge was formed under the load of 26 tons and the model bore 45 tons in the last step of loading. The slope of the diagram changes in two points. The first change is because of forming of the plastic hinge in the plates. And the second one is related to forming of the plastic hinge in the ring and in the link to the brace joint. Diagram of energy-loading cycle and diagram of cumulative energy-loading cycle are shown in figures 10 and 11 respectively (Shih and Sung, 2004).

Energy in the last elastic cycle: $E_E = 209 \text{ N.m}$
Energy in the last loading cycle: $E_P = 25408 \text{ N.m}$

Ratio: $\frac{E_P}{E_E} = \frac{25408}{209} = 121.6$
Total energy in 2 loading cycles (N.m): 
\[ \sum_{i=1}^{2} E_i = 392 \]

Total energy in 32 loading cycles (N.m): 
\[ \sum_{i=1}^{32} E_i = 317708 \]

Average energy in each of the loading cycles in plastic zone (N.m): 
\[ \overline{E_p} = \frac{\sum_{i=1}^{32} E_i - \sum_{i=1}^{2} E_i}{32 - 2} = \frac{317708 - 392}{32 - 2} = 10577 \]

Average energy in each of the loading cycles in zone (N.m): 
\[ \overline{E_e} = \frac{\sum_{i=1}^{32} E_i}{2} = \frac{392}{2} = 196 \]

Ratio of average plastic energy to average elastic energy in each of the loading cycles: 
\[ \frac{\overline{E_p}}{\overline{E_e}} = \frac{10577}{196} = 54 \]

As it is shown, the energy of the last loading cycle is 121.6 times more than the last elastic cycle. Average energy of each element loading cycle, in the last cycle is 54 times more than the average energy of each loading cycle in the elastic zone. This comparison indicates the high capacity of the element in absorption and dissipation of earthquake energy.

Ratio of energy in the last loading cycle for the ring accompanied by the plate, to one without the plate was (Young et al., 2001):
\[ \frac{(E_p)_{\text{with-plate}}}{(E_p)_{\text{without-plate}}} = \frac{25408}{7190} = 3.53 \]

As it is shown, amount of dissipated energy is 3.53 times increased, which indicates the ductility increment. The diagram of force-ring displacement (with and without the plates) is presented in order to show the increment in bearing capacity.
As it is shown, at similar displacements, the bearing capacity is improved because of added plates and increment of axial stiffness of the element. Besides, as a result of using ductile plates, energy has also been dissipated.

As stated before, analysis was performed for three steel types and three thicknesses that are presented in figures 13 to 15 to show the differences between the force-displacement diagrams of the models, which are derived from their hysteretic loops, and diagrams of cumulative energy-loading cycles.
Figure 13-b. Diagram of cumulative energy-loading cycles of LYS with different thicknesses

Figure 14-a. Diagram of force-displacement of ST37 with different thicknesses

Figure 14-b. Diagram of cumulative energy-loading cycles of ST37 with different thicknesses
Figure 15. Diagram of cumulative energy-loading cycles of 304 with different thicknesses

Conclusion

It can be deduced from the investigations and studies that:

It is possible to increase the bearing capacity of the ring element by adding ductile plates. Also because of the ductility of this element and its high energy absorption, it can be expected to absorb significant portion of plastic energy in structures. Since the bearing capacity of the element is dependent on the thickness and steel type of the plates, designer can decide about the range of loading more freely. Besides, bearing capacity of the proposed element can be controlled by decreasing the number of plates and forming a symmetrical model. The suggested element has a simple implementation and does not need professional workforce to be utilized.

References


