Finite element analysis of eccentrically braced frames with a new type of bolted replaceable active link

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ABSTRACT: Five years after the devastating series of earthquakes in Christchurch, New Zealand, the structural engineering community is now focussing on low damage design by either proactively reducing the possibility of significant damage to primary steel members (i.e. developing seismic resisting systems that will deliver a high damage threshold in severe earthquakes) or by improved detailing of the primary steel members for rapid replacement. This paper presents a development of Eccentrically Braced Frames (EBFs) with replaceable active links. It uses the bolted flange- and web splicing concept to connect the active link to the collector beam or column. Finite element analyses have been performed to investigate the behaviour and reliability of EBFs with this new type replaceable active link. The results show a stable hysteretic behaviour and more significantly easier replacement of the damaged active link in comparison with conventional EBFs.

1 INTRODUCTION

The steel Eccentrically Braced Frame (EBF) is a relatively new structural system for providing seismic resistance of buildings, which employs the structural fuse concept in a ductile building design (i.e. which is designed to undergo controlled damage in a severe earthquake). In the EBF, the active link (see Figure 1) is the structural fuse.

Figure 1 - Member terminology applied to a V-braced EBF (NZS3404 Figure C12.11.2)
The conventional steel EBFs are expected to sustain significant damage during a design level earthquake through repeated inelastic deformation of their active links. In these EBFs, the active link is traditionally made continuous with the collector beam and supports the floor slab, although it is not made composite with the floor slab. This continuity of active link with the adjacent collector beam or beams implies that following yielding of the active links, a costly and disruptive repair is expected, even if the structure has met its goal of providing life safety during an earthquake. Five years after the devastating series of earthquakes in Christchurch, New Zealand, the structural engineering community is now focussing on low damage design by either proactively reducing the possibility of significant damage to primary steel members (i.e. seismic resisting systems that will deliver a high damage threshold in severe earthquakes) or by improved detailing of the dissipative parts for rapid replacement. This paper presents a development of EBF systems with a new type of bolted replaceable active links. To investigate the inelastic seismic behaviour of this system, cyclic quasi-static finite element analyses were performed. The active links exhibited a very good ductile behaviour, developing repeatable and stable yielding.

2 FINITE ELEMENT MODEL OF EBF WITH A REPLACEABLE ACTIVE LINK

The principal objective of these finite element analyses was to answer the question whether the proposed new type of bolted replaceable active link suppresses inelastic demand away from the link, allowing the rest of the structural system to remain essentially elastic under severe earthquake excitation. It was also intended to answer, as best is possible in advance of experimental testing, whether the link is able to deliver rotation capacity not smaller than 0.08 rad, as required by the most modern seismic design codes.

2.1 Description of the proposed replaceable active link

The replaceable active link configuration that was investigated has a built-up cross section comprised of wide and thick flanges and relatively thin web. It uses the bolted flange- and web splicing concept to connect the link to the collector beam or column i.e. the link is connected to the collector beam through top and bottom flange bolts to transfer the bending moment, while the shear is transferred through concentrically loaded web-bolted connections. The connections were designed to transfer and sustain the maximum forces that can be delivered by the fully yielded and strain hardened active link.

As shown in Figure 2, the depth of the replaceable active link is less than the collector beam depth. It was intended for the replaceable link not to interact with floor slab, so that it can be easily replaced. For easy replacement, the top flange bolts and the collector beam must not develop any permanent deformation, such that the top flange bolts can be left in place when the active link is replaced.

![Figure 2 - Proposed replaceable active link](image-url)
2.2 General overview of the analyses

Three dimensional (3D) finite element (FE) models were developed to study the seismic behaviour of EBFs with replaceable links. SIMULIA/Abaqus (ABAQUS 2013, Analysis User’s Manual) was used for modelling and analysing the models. Abaqus is a general purpose finite element program well suited to advanced numerical modelling of non-linear applications involving structural steel.

![Figure 3 - FE model of the one storey EBF with replaceable active link](image)

Figure 3 shows the FE model of a single storey of a realistic structure, with detailed modelling of the active link region and with the elements away from the active link modelled as beam elements which remain elastic. A quasi-static dynamic implicit procedure was performed taking into account second order effects. The simulations were performed in two dynamic implicit quasi static steps. Three different FE models were created. The first one was a bare steel EBF, while, in the second and third models, a composite concrete slab was added. The reason for performing two models with a composite slab was that the slab contributes to the shear strength of the EBF system by resisting shear in parallel with the active link. Although the slab was lightly reinforced, it will crack in shear and is expected to develop a maximum shear resistance approximately twice that was predicted by NZS 3101. Hence, the first set of results with the “concrete” Young’s modulus of 20.8 GPa was valid up to about the 57th loading cycle. Following this cycle cracking was expected in the slab, which was not captured by the FE analysis. Therefore, the second numerical simulation was performed with a much softer slab with Young’s modulus of 3.56 GPa – there results were valid from about 58th cycle to the end of cyclic loading applied in this study. This approach was first implemented by Nandor Mago (Mago, 2013) upon the request of the second author of this paper.

2.3 Idealisation strategy

Solid elements C3D8R were used to model the active link region, which was connected to beam elements B31 via kinematic coupling. The beam 31 and solid C3D8R elements were tied to the bottom face of the shell S4R modelled slab representing shear studs. Detailed 3D bolt modelling and tightening was performed, as well as detailed welds modelling. For all interacting surfaces of cover plates with the active link, collector beam and bolts was defined interaction behaviour. The normal behaviour was specified as a hard contact with no penetration, while a friction coefficient of 0.35 was set for tangential behaviour. This is a minimum value for steel on steel friction, which is appropriate for these bolted connections which are required to be no-slip. The total number of variables in the model is 2476653. Figure 4 shows the meshed geometry as well as the above mentioned features of the FE model.
2.4 Material models

Standard stress-strain values were used, with the materials’ true stress versus plastic strain values listed in Table 1.

<table>
<thead>
<tr>
<th>Grade</th>
<th>$t_{\text{max}}$</th>
<th>$E$ [MPa]</th>
<th>$f_y$ [MPa]</th>
<th>$f_u$ [MPa]</th>
<th>$e_{\text{pl}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>≥20mm</td>
<td>210,000</td>
<td>280.37</td>
<td>507.40</td>
<td>0.163039</td>
</tr>
<tr>
<td>300</td>
<td>&lt;20mm</td>
<td>210,000</td>
<td>300.43</td>
<td>507.40</td>
<td>0.163039</td>
</tr>
<tr>
<td>300</td>
<td>≤12mm</td>
<td>210,000</td>
<td>310.46</td>
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</tr>
<tr>
<td>300</td>
<td>≤8mm</td>
<td>210,000</td>
<td>320.49</td>
<td>507.40</td>
<td>0.163039</td>
</tr>
<tr>
<td>350</td>
<td>≤20mm</td>
<td>210,000</td>
<td>350.50</td>
<td>350.99</td>
<td>0.122664</td>
</tr>
<tr>
<td>350</td>
<td>≤8mm</td>
<td>210,000</td>
<td>360.51</td>
<td>360.99</td>
<td>0.122664</td>
</tr>
<tr>
<td>30</td>
<td>≥17mm</td>
<td>280.37</td>
<td>662.07</td>
<td>480.16</td>
<td>0.167319</td>
</tr>
<tr>
<td>8.8</td>
<td>≥11mm</td>
<td>320.49</td>
<td>854.90</td>
<td>480.16</td>
<td>0.167319</td>
</tr>
<tr>
<td>8.8</td>
<td>&lt;11mm</td>
<td>310.46</td>
<td>364.20</td>
<td>480.16</td>
<td>0.167319</td>
</tr>
</tbody>
</table>

The steel material was modelled as a bilinear. A combined hardening was used for the cyclic quasi-static analyses. The combined isotropic/kinematic hardening model provides a more accurate approximation to the stress-strain relation than the linear model. It also models other phenomena such as relaxation of the mean stress and cyclic hardening. The concrete slab was modelled as an elastic medium without reinforcement. If the concrete had been modelled as an inelastic material, e.g. through using the concrete damaged plasticity (CDP) option in ABAQUS, the analyses would have taken an order of magnitude longer, as very small time increments are needed to capture concrete cracking that are anticipated at larger loading cycles (Mago, 2013).

2.5 Boundary condition and Loading protocol

The columns were fixed at the bottom, while Z-symmetrical boundary condition were applied to the side of the 1m wide slab to provide a lateral restraint of the frame. Cyclic enforced displacements were applied on the left and right collector beam to column connections as shown in Figure 5. The duration of Step-2 is 76, with each unit of time representing one peak displacement.
3 RESULTS AND VERIFICATION

The following figures display plots from the last cycle when total link rotation of 0.0927 rad was reached.

Figure 6 - Von Mises stresses (Pa) following the 76th cycle and link rotation of 0.0927 rad

Figure 7 - Active yield flag telling whether the material is yielding or not, following 76th cycle.
The development of equivalent plastic strain (PEEQ) as a cumulative measure of material’s inelastic deformation due to cyclic loading for the 76th cycle is shown in Figure 8. The maximum PEEQ of 176% is well below the predicted cumulative plasticity demand necessary to initiate fracture in an EBF constructed from a seismic grade of steel, which is 280% (Clifton G.C. and Ferguson, W.G., 2015).

![Figure 8 - Equivalent plastic strain contour for the 76th cycle.](image)

In Figure 9 is shown the history of the total horizontal force versus lateral displacement.

![Figure 9 - Hysteresis loop with the total horizontal force versus lateral displacement](image)

The link’s rotation history is presented in Figure 10. The total link rotation of 0.0927 rad was reached at 76th loading cycle which is greater than the required 0.08 rad. The analysis was restarted from the last cycle with four additional cycles. At the 80th cycle the link underwent a total of 0.134 rad rotation and with a cumulative plasticity demand of 224% which is close to that associated with initiation of link fracture.
The ultimate strength of the link estimated by NZS 3404 section 12.11 was $V_{\text{link}}^{0} = 731 \text{ kN}$. A value of $V^{*} = 737 \text{ kN}$ shear force for 76th cycle (or 0.0927 rad) was derived in the presented FE analysis which could be considered as a confirmation of the above mentioned code provision. The difference between code and numerical analysis is 0.82%. This means that proposed design procedure for EBFs with replaceable active links is satisfactory as long as it is designed in compliance with NZS 3404. Thus, the designers can be assured with a high degree of confidence that the brace has the required strength and stiffness. Further, the inelastic demand away from the active link was suppressed.

Figure 10 - Link’s rotation (rad) versus cyclic loading

3.1 Validation of finite element analyses

At the time this paper is being written there is an ongoing experimental program at the University of Architecture, Civil Engineering and Geodesy, Sofia, Bulgaria. Two tests of a single storey full-scale EBF structure will be carried out. The first active link will be monotonically loaded while for the second one will be subjected to cyclic loading according to AISC 2010 loading protocol. The aim of these tests is to prove the concept of the proposed new type bolted replaceable active link for EBFs. The test rig of the EBF is shown in Figure 12.

Figure 11 - Component forces (N) normal and tangential to the cross section A-A through the replaceable active link for the 76th cycle
4 CONCLUSIONS

The key points from above reported analyses are that:

- The proposed replaceable active link has rotation capacity of up to $\theta_p = 0.134$ rad, which is greater than required by most modern seismic design codes of $\theta_p = 0.08$ rad and satisfies the requirement that the active link should be able to develop 1.5x the specified rotation at the design ultimate limit state to resist stronger than ULS design level earthquakes.

- For active link rotation angle of 0.094 rad the maximum frame interstorey drift is 1% of the frame height. Hence, “damage limitation requirement” is considered satisfied.

- The proposed bolted design procedure is satisfactory in suppressing inelastic demand in all components except the active link.

- The bolt tension forces do not increase which means bolt failure will not occur during an earthquake excitation.

- There is no sliding on the bolted surfaces of the model, meaning the no-slip condition is met.

- The welded web stiffener attracts significant local plastic strain and demonstrates the potential benefit of a bearing sandwich stiffener which allows the web to deform plastically independent of the stiffener.

A bolted replaceable active link can be used to facilitate replacement of damaged active links after a moderate to strong earthquake, which reduces repair costs. The conventional design of the active link is interlinked with the design of the collector beam, which often results in a significant over-design for this member. This new type of bolted replaceable active link allows the link element to be fabricated from a lower steel grade, or modified section dimensions, thereby assuring an elastic response of the collector beam outside the replaceable link element.

The use of the proposed new type bolted replaceable active links for EBFs would also have the advantages reported in the other replaceable links. The replaceable link concept would:

- Allow designers to size the replaceable active links with desired cross-section dimensions and different steel grade, if needed. In this way the designer has greater flexibility to choose a section that best meets the required strength, without automatically changing the floor collector beam section;
• Allow for independent control of frame stiffness and required strength, resulting in more efficient structures;
• Allow for quick inspection and easy replacement of yielded and damaged links following a major earthquake, significantly minimizing the disruption time to reoccupy the structure;
• Allow self-centring of the structure to its undeformed configuration by disconnecting the distorted replaceable links from the structure;
• Allow shop welding of critical elements and field bolting of the replaceable links to be done, thus considerably improving quality and reducing erection time and cost;
• Allow for elements spanning multiple stories to be fabricated in the shop and assembled through these links on site, further reducing erection time.

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