Equivalent Plane Stress FE Models for Grout-Filled Buckling Restrained Braces

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Abstract- In earthquake prone areas, buckling restrained braces (BRBs) are commonly used in buildings to absorb energy and improve structural response under seismic actions. Currently no detailed design guidance for grout filled buckling restrained braces (GFBRBs) exists. In order to address this, a greater depth of understanding of the behaviour of these elements is needed; hence this is an active area of research. Finite element modelling (FEM) offers an economic way to explore BRB behaviour. However, when BRBs are modelled using 3D FEM, significant computational effort can be required due to the various second order effects involved. Use of an equivalent 2D plane stress model has the potential to greatly reduce computational time while maintaining an acceptable level of accuracy. This paper presents two such models, an All-Steel Buckling Restrained Brace (ASBRB) and a GFBRB where global bending failure is simulated. The models are validated against experimental data [1, 2] and a comparison with 3D FEM is also presented. The 2D models are shown to capture the global failure of the studied BRBs with acceptable accuracy while reducing the computation time by as much as 94%.

I. INTRODUCTION
Numerical analysis has been shown to be an important and economically effective tool to analyse both All-Steel Buckling Restrained Braces (ASBRBs) [1, 3, 4] and Grout-Filled Buckling Restrained Braces (GFBRBs), however the analysis of the full device has usually only been conducted with 3D Finite Element Models which in turn require a large amount of computing resources to extract results. Key output such as the force-displacement and lateral thrust along the casing and the evolution of the core in higher buckling mode shapes [5] are required in order to understand the behaviour of the system.

Existing available numerical studies of GFBRBs fail to analyse the forces exerted on the inner surface of the casing due to the difficulty in quantifying this value experimentally, although some data exists for ASBRBs. Coupled with the relative lack of experimental data, the computationally expensive nature of 3D models remains one of the main obstacles in exploring BRB behaviour. Hence use of more efficient, equivalent 2D models represents an attractive alternative.

II. METHODOLOGY
Two experimental studies corresponding to an ASBRB and a GFBRB were used for validation purposes [1, 2] where a rectangular area equivalent to the flexural stiffness provided by the system’s structural section was obtained (Figure 1). In the case of the ASBRB, for the calculation of the second moment of area a single channel section UPN160 was calculated equal to 8.5E+05 mm$^4$ and transformed to a rectangular section, while maintaining a constant Young’s modulus. In the new section the base of the rectangle is equal to the width of the core (50 mm) and $h=59$ mm was calculated with Equation 1.

$$h = \sqrt[3]{\frac{12I_{UPN160}}{b}}$$  (1)

Where $h$ is the height of the equivalent rectangular cross section, $b$ the core width and $I_{UPN160}$ the second moment of area of a single channel section ($I_{UPN160}=850000$ mm$^4$).

For each case, 2 models were used (3D and 2D) in order to compare computational costs. In the case of the ASBRB 3D model, the curved corners/edges of the channel section were considered as right angles which resulted in minor modification (1mm) of the height of the rectangular section. The numerical results showed a good agreement with experimental data.
In the case of the GFBRB the equivalent cross section was found by following a three step procedure: i) find the Elastic Neutral Axis and the transformed section with the factor $n = \frac{E_{\text{concrete}}}{E_{\text{steel}}}$ ii) determine a rectangular cross section equivalent to the second moment of area of the transformed section iii) define a linked double beam system with half of the second moment of area value for each beam.

The Elastic neutral axis was found within the narrow grout section (gap) as shown in Figure 2a using the transformed section method, located at a distance of 34.38 mm measured from the top of the cross section.

Similar to the case of the ASBRB, equation 1 was used in order to determine a gross section with the same second moment of area with a width of 90mm (width of the core) and height of $h_{eq}$. The modelling method entails proposing a 2D linked beam system (see Figure 3) which avoids composite action in such a way that each beam provides half of the value of second moment of area with height $h_{1/2}$ using Equation 2.

$$ h_{1/2} = \frac{1}{\sqrt{2}} h_{eq} \quad (2) $$

Following generation of the equivalent 2 models, the results are used to compare axial force-displacement and lateral thrust against experimental data available. Also, computing time is compared with the 3D models.

### III. RESULTS OF NUMERICAL MODEL

The numerical analysis was conducted using the software ABAQUS assuming plane stress conditions with a dynamic implicit solver. The 8-noded quadratic elements CPS8R were used for the analysis. The 2D models used only a fraction of the number of elements in the 3D models, 12.2% (1120 elements) and 15.4% (3960 elements) for ASBRB
and GFBRB respectively. The material properties used to model the steel of the core were set as nonlinear with kinematic hardening with $\sigma_0=250$ MPa, $C_1=8000$, $\gamma_1=50$, $C_2=100000$ and $\gamma_2=1000$. The casing is assumed as a perfectly elasto-plastic material with $\sigma_0=282$ MPa; in both cases the Young’s modulus and Poisson’s ratio are considered as 200000MPa and 0.3 respectively. Figure 6 and Figure 7 show the results of the validated model of ASBRB. The model shows an overall good agreement with both experimental data and the experimenters’ own model; however some discrepancy between the experimental and numerical results can be observed. Clearly the idealisations of the equivalent 2D model, along with boundary condition and material simplifications all introduce a degree of inaccuracy. Some additional discrepancies may be introduced from the digitisation of the experimenters’ data. Note backbone curves which outline the extents of the hysteresis are used here for visual clarity.

In the case of the GFBRB Figure 8 compares the results of the hysteretic axial behaviour of the device obtained from the 2D and 3D models. The 2D and 3D model exhibit similar failure conditions which take place during the first cycle in the compressive range. However, the behaviour differs in the post failure range due to the assumptions made in modifying the geometry to an equivalent rectangular section and the distance from the elastic neutral axis to the outermost fibre.

### IV. CONCLUSION

It is possible to study stability of GFBRBs by conducting 2D analysis, taking advantage of significant reduction in computational cost. Table 2 shows the effective reduction of computing time for the 2 studies presented here. The 2D models were analysed in less than 10% of the time used by a 3D analysis and successfully captured the global behaviour and estimation of the lateral thrust from the core. However, there are clear limitations of this method when modelling post failure as the casing is transformed for elastic conditions. Figure 8 reveals an important loss of accuracy in the post failure range. Although the model is valid for global stability checks, local buckling such as bulging of the casing is unable to be captured. Improvement of these shortcomings will be investigated as part of the authors’ ongoing research.

### Table 2 - Reduction in computational time

<table>
<thead>
<tr>
<th>BRB</th>
<th>Model</th>
<th>CPU time [hrs]</th>
<th>Reduction time</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASBRB</td>
<td>3D</td>
<td>153.36</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>2D</td>
<td>2.61</td>
<td>98.3%</td>
</tr>
<tr>
<td>GFBRB</td>
<td>3D</td>
<td>89.01</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>2D</td>
<td>5.14</td>
<td>94.2%</td>
</tr>
</tbody>
</table>

### V. REFERENCES