Comparative study of reduced beam section modelling on SMRF steel structure

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Abstract. RBS (reduced beam section) as part of SMRF (special moment resisting frame) is designed to absorb energy release during earthquake. Reducing beam section force plastic hinge occur away from beam column connection. Comparative study of RBS modelling using two finite element software, OpenSEES and ETABS were conducted. OpenSEES is an open source software intended for earthquake simulations. The software provides various element and material details to ensure that the model built can represent the real structure. However, the simulation using this software is very complex. Simplified analysis of RBS using commercial software ETABS was proposed. It is found that the method has similar result with OpenSEES.

Keywords: Reduced beam section, Special moment resisting frames, OpenSEES

1. Introduction

Failure of beam to column moment connections in steel moment-resisting frame (MRF) were observed during the Northridge earthquake in 1994. Modification was proposed to safe the joint connection from damage due to seismic load. Several detail alternatives of steel frame connections were proposed that shift the plastic hinge away from the connection region by improving connection details or reduce beam section (RBS). The idea of RBS is to force beam yielding near to column face by utilizing circular radius cut in both top and bottom flange to reduce beam’s flange area at beam end. RBS is designed as a weaker part to form plastic hinge as energy dissipation during earthquake in order to let beam to fail firstly. Several research about RBS has been carried out since 1996 and during the last ten years the research still have been done to improve the performance of RBS [1] – [6].

Design guidelines of RBS can be found in FEMA 350 [7] and AISC [8]. According to these standards, RBS as part of special moment resisting frames (SMRF) is allowed to be adopted as seismic resistance building with unlimited height. During design process, building simulation and structural analysis process is conducted by finite element software. ETABS [9] is one of the commercial software employed by structural engineer consultant for high-rise building design. However, there is not much detail information available how to model the RBS in the design process. Comparative study were carried out to seek the simple way to model the RBS steel frames with ETABS but still represent the real RBS structures. The RBS frame modelled by OpenSEES Software [10] was chosen as a reference. OpenSEES (Open System
for Earthquake Engineering Simulation) is an open source software that is largely used by researchers. It provides various materials, elements and algorithm and hence the results can closely resembles the advanced analysis. However, structural analysis using OpenSEES are considered expensive. For that purpose, commercial software such as ETABS remain to be favoured. An adjustment in ETABS is needed so that the results can closely resemble advanced analysis conducted by openSEES. Hence, this research aims to find out the best way to modelled RBS in ETABS so that the result can be identical as the OpenSEES.

2. Research Methodology
2.1. Model Validation
The study start with validation model to ensure that built model in openSEES can represent the real structure. Experimental and numerical study of RBS steel structure done by Stella [11] as shown in Figure 1 was used as reference. According to the experiment, steel material is modelled as bi-linier stress strain curve without strain hardening with yield strength 430 MPa [11]. The experiment used circular cut to form the RBS beam with a distance 115 mm from column face as can be seen in Figure 1b. Uniaxial material bilinear is assigned at beam and column where the plastic hinge is concentrated at the centre of RBS and elastic beam element is assigned at beam and column where the plastic hinge is not occured. Properties of plastic hinge were defined by rotational spring based on Ibarra Modified Krawinkler (IMK) [2],[12] to describe the nonlinear behaviour of the frame. Beam is divided into three elements as shown in Figure 1c, two small elements at the beam end represent RBS and one element between two rotational springs. Panel zone is modelled according to Jun Jin [13] based on hysteresis curve obtain from experimental test where ratio of shear force between RBS and panel zone shear force was 0.7 (recommended value is 0.7 – 0.9)[1].

It is known that panel zone is one of important component that affect non-linier behaviour of beam, rigid panel zone will result greater non linier deformation in the beam [14]. The appearance of plastic hinge in RBS is a function of plastic moment value (\(M_{pb}\)) determined based on Eurocode 8 part 3 [15] equations as follow:

\[
M_{pb,RBS} = Z_{RBS} \cdot f_{yb}
\]

where \(Z_{RBS}\) = effective plastic modulus at plastic hinge location (at the centre of RBS section for radius cut)

\[
Z_{RBS} = Z_b - 2.\, g \cdot t_f \cdot (d_b - t_f)
\]

\(f_{yb}\) = yield strength of steel beam according to experimental test multiplied by CF (confidence factor).
Similar with experiment, horizontal cyclic loading was applied in openSEES model. Push over analysis was performed to represent the increment of loading during the test. Relationship between horizontal force and lateral displacement at top floor are plotted together with the experimental results. As mention earlier, Stella also conducted numerical model using ABAQUS. Figure 2 shows the curves obtained from Stella experiment and numerical results and from openSEES. As can be seen, the curve attains from openSEES agree well in the initial stage with the experiment but has lower maximum capacity. However, the results is very close to numerical model built by ABAQUS. It can be concluded that, numerical model using openSEES can represent behaviour of the real RBS and hence the model is considered valid. Here after, the element type, the panel zone model and the hinge properties used in validation model are used in next study and results from openSEES are considered as advanced analysis.

**2.2. Comparative Numerical Study**

As mention earlier, the objective of this study is to find out a simple RBS model in commercial software ETABS that represent the actual RBS steel frame. Results from openSEES analysis is assumed as reference. RBS steel frame similar with Stella experiment as shown in Figure 1a will be modelled and analysed by ETABS. Simplification of circular cut of RBS detail is presented in Figure 3. Circular cut of RBS in Figure 1b is approach as rectangular cut as presented in Figure 3. The effect of RBS depth and length are studied to look for the precise size that represent the real circular cut.
Based on Figure 3, number of elements to describe the RBS detail was varied, 3 elements as similar to openSEES model shown in Figure 1c and 5 elements as shown in Figure 4. Discretization of 5 elements consist of 3 elements for RBS with different depth, 120mm and 84mm. The results are presented in Figure 5. As can be seen, varying 3 or 5 RBS elements have similar results but 5 elements is more accurate since the graph is closer to openSEES.

Since ETABS does not provide menu to describe panel zone as detail as OpenSEES, hence it is defined by rigid end factor. This factor describes the stiffness of beam column joint and the ability of the panel zone to deform. The value is between zero to one (0-1), and in this study it is varied 0, 0.3 and 1. The comparative study was also conducted on three dimensional (3D) frame lay out which are 1x1 bays_2 stories (3D2S_1x1), 1x1 bays_3 stories (3D3S_1x1), 3x2 bays_2 stories (3D2S_3x2), 3x2 bays_3 stories (3D3S_3x2) and 3x4 bays_3 stories (3D3S_3x4). All frames have the same column distance as 3m and story level as 1.7 meters.
3. Results

3.1. Variation of RBS length and depth in ETABS model

The study was conducted according to Stela experimental frame as shown in Figure 1. Length of circular cut RBS is based on formula proposed by Charter [1] and Eurocode 8 part 3 as presented in equation 3 – 5.

\[
\frac{3d}{8} \leq l < 0.50d \quad (3)
\]
\[
0.25d \leq c < 0.50d \quad (4)
\]
\[
g \leq 0.25b_f \quad (5)
\]

Since depth \(d\) of circular cut is 114mm, hence the variation of RBS half-length must be in range of 42.75mm to 57mm whereas the RBS width \((tf-g)\) must be upper than 60 mm. and for \(c\) must be in range 28.5mm to 57mm. Hence, length of simplified RBS is varied to 86, 90 and 100mm while width is varied to 70, 84 and 100mm.

Figure 6 and Figure 7 shows study results by varying length and width of RBS according to Figure 3. As can be seen, variation of length as 86, 90 and 100mm do not significantly affect behaviour of frame. However, width variation has similar result in the elastic stage, then the effect is significant after plastic hinge form in RBS. Among 3 different size, width of 84mm has the closer results to openSEES. Hence, it can be concluded that circular cut section of RBS can be approach as rectangular with length and width as 86 mm and 84 mm, respectively as shown in Figure 3.

![Figure 6. Base shear vs drift with length variation](image)

![Figure 7. Base shear vs drift with width variation](image)

3.2. Geometric Approach of RBS in ETABS in Various frame lay out

Comparative study of RBS model in ETABS was also conducted on three dimensional (3D) frame lay out which are 1x1 bays_2 stories (3D2S_1x1), 1x1 bays_3 stories (3D3S_1x1), 3x2 bays_2 stories (3D2S_3x2), 3x2 bays_3 stories (3D3S_3x2) and 3x4 bays_3 stories (3D3S_3x4). All frames have the same column distance as 3m and story level as 1.7 meters. Push over analysis was conducted and results are shown in base shear versus drift ratio and presented in Figure 8 to Figure 12. Drift ratio is the ratio between top lateral displacement and overall height of the building. As mentioned earlier, panel zone in ETABS model is approach by using rigid zone which is varied from 0, 0.3 and 1.

Based on Figure 8 and Figure 9 it can be seen that for one storey frame with 1x1 bay, rigid zone factor 0.3 has the closest result to openSEES. The more number of spans such as frame with 2x3 spans rigid zone factor as 0 is represent the actual RBS frame as shown in Figure 10 to 12. It can be concluded that slenderness of the buildings affects rigid zone factor to be used in ETABS model. It is known that rigid end factors / rigid zone factor as 0 to 1 describe the stiffness of the beam column connection which is the
ability of the panel zone to deform. Usually, for steel structure the value is taken as 0 since the structure is more ductile with significant shear deformation capacity.

Figure 8. Base shear vs drift of 2 stories with 1x1 spans

Figure 9. Base shear vs drift of 3 stories with 1 x 1 spans

Figure 10. Base shear vs drift of 2 stories with 3 x 2 spans

Figure 11. Base shear vs drift of 3 stories with 3 x 2 spans

Figure 12. Base shear vs drift of 3 stories with 3 x 4 spans
4. Conclusions
Based on the simulation and analysis that has been done with various structural models it can be concluded that ETABS model with more element discretization in RBS area has accurate results. The study also found that proposed length and width of rectangular cross of RBS as an approach of circular cut section can represent the real RBS frame as conducted in the experiment. The chosen RBS length and width is equal to the smallest section of the circular cut of RBS measured from center of the circular cut. Panel zone can be approach by using rigid end factor as 0 for frame with bays more than 1x1 and 0.3 for frame with more slender.

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