Modelling and Validation of Seismic Performance for Corner and Interior Beam-column Joint Using HYSTERES Program

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Abstract. The validation between experimental and modelled hysteresis loops is a preliminary work in determining the dynamic behaviour of the beam-column joints under earthquake excitations using Ruaumoko 2D program. However, this paper only focuses on accurately modelling the hysteresis loops of corner and interior beam-column joint using the HYSTERES Program. The corner and interior beam-column joints were designed using Eurocode 8 and equipped with unbonded fuse-bars which act as passive energy dissipators. The hysteresis loops were modelled based on the input parameters obtained from the experimental hysteresis loops. From the HYSTERES program, the Pampanin Reinforced Concrete Beam-Column Joint was chosen to represent the hysteretic behaviour (load versus displacement) for overall seismic behaviour of these joints. The lateral strength capacity, stiffness, ductility and equivalent viscous damping from experimental and modelled hysteresis loops were then compared, and the percentage difference from both hysteresis loops was calculated. Based on the outcomes, there are some parameters which have shown good agreement, and this proves the effectiveness of using HYSTERES program in modelling the hysteresis loops of the beam-column joints.

Keywords: corner joint, interior joint, stiffness, ductility, equivalent viscous damping

1. Introduction
Recently, there are a lot of studies have been conducted on non-seismic of beam-column joints under earthquake excitations which contribute to structures damage and collapse. Different damage or failure modes are expected to occur in beam-column joints depending on the types of joint and the adopted structural details (such as the presence of transverse reinforcement in the joint; use of plain round or deformed bars; alternative bar anchorage solutions) [1]. Many laboratories testing had been conducted in the heavy structural laboratory on non-seismic RC beam-column joints under in-plane lateral cyclic loading [2-5]. Evidently the non-seismic design buildings in Malaysia are vulnerable under seismic load. Most of the buildings in Malaysia were designed and constructed using a non-seismic code of practice known as BS8110, where there is no provision for earthquake load at all [6]. Past studies analyzed the dynamic behaviour of the RC buildings in Malaysia under various real earthquake excitations using Ruaumoko 2D program [7-9]. It was found that the non-seismic buildings which were design using BS8110 did not sustain Ranau Earthquake (PGA=0.12g), which is the highest recorded earthquake excitation in Malaysia. By assessing the dynamic behaviour of the buildings, researchers can understand and predict the overall seismic behaviour of the building when earthquakes with similar excitations strike. Ruamoko 2D is a notable tool in seismic analysis, and it provides a wide variety of
modelling options. One of them is the HYSTERES program which is a program used to determine the best choice of loop parameters to obtain the most suitable hysteresis loop for use in a Ruamoko analysis [10]. The program provides a list of hysteresis loops model for various types of structures, and it has proven accurate in modelling works. The modelling work done using HYSTERES program is considered as preliminary work in determining the overall dynamic behaviour of the structure. Therefore, it is important to model the hysteresis loops precisely to avoid error in future modelling work.

Generally, most of the beam-column joints were designed in accordance with Eurocode 8 (EN 1998-1:2004) by considering the seismic loads and applying weak beam and strong column designed philosophy. By applying this design philosophy, the joint will be ductile and therefore, can sustain higher lateral load compared to conventional non-seismic design. However, it was found that the provisions provided in Eurocode 8 for RC beam-column joint lead to “over-strength” design and steel congestion in the beam-column joint region [11-13]. Therefore, the use of energy dissipator in seismic design beam-column joint is one of the methods to explore to provide additional damping and increase the ductility of the beam-column joints. In this study, the hysteretic behaviour of seismic design corner and interior beam-column joints with unbonded fuse bars was evaluated. The beam-column joints were a part of the RC buildings which were designed per Eurocode 8. The joints were equipped with unbonded fuse bars as Passive Energy Dissipator to enhance the energy dissipation capacity and increase the damping ratio of the structure. The joints were tested under lateral cyclic loading, and their hysteresis loops (load vs displacement curve) were plotted. Following that, the modelled hysteresis loops were established. Both hysteresis loops were then compared, and the difference of lateral strength capacity, stiffness, ductility and equivalent viscous damping were analyzed.

2. A Prototype Two-storey RC Building

A two-storey reinforced concrete school was designed in accordance with Eurocode 8 equipped with fuse bars at the joint were constructed, tested, analyzed, modelling and validation in this study. Figure 1 shows the side view of a prototype two-storey building with a total height of 7000mm, width of 9500mm and 1500mm depth of the stump together with pad footing. Meanwhile, Figure 2 shows the plan view of the two-storey RC school building, which had been designed using Eurocode 8 under Ductility Class Medium (DCM) with PGA=0.3g. The three types of joints are shown in Figure 2 which labelled as EJ-2B, IJ-3B and CJ-2B. EJ-2B means exterior beam-column joints with two beams, IJ-3B denotes as interior beam-column joint with 3 beams perpendicular with each other, and finally, CJ-2B designates as corner beam-column joint with two beams which located at the corner of the first floor of this prototype building. However, only two joints, namely IJ-3B (interior joint) and CJ-2B (corner joint) will be explained, testing, modelling and testing in this paper.
Figure 1. Side elevation of prototype two-storey RC school building

Figure 2. Plan view of the two-storey RC school building

Figure 3 shows the three dimensions and side elevation view of the corner joint, which labelled as CJ-2B joint. The corner joint with two beams and one column was seated on the foundation beam. The dimension of the column is 3500x400x400mm, sizes of the beam are 3500x400x400mm, and a dimension of foundation beam is 1800x900x500mm. Figure 4 shows the three dimensions and front view of the IJ-3B specimen with one column and three beams. The dimensions of column and beams are similar to corner joint labelled as CJ-2B. These corner joint and interior joint with two beams and three beams, respectively seated on foundation beam will be constructed in the heavy structural laboratory starting from ±0.01% until ±2.5% drift as listed in Table 1. These two joints were equipped with fuse-bars as energy dissipators which dissipate to the surrounding when the movement of the column from left to right and back to the original position. The work done by this movement can be determined by calculating the area under the hysteresis loops using area of trapezium between two drifts. Figure 5 shows the fuse-bars with 600mm length and reduction of diameter from 25mm to 20mm at the centre with 200mm length only.
Figure 3. Three dimensions and side elevation view of CJ-2B joint

Figure 4. Three dimensions and front view of specimen IJ-3B joint

Figure 5. The total length of fuse-bars of 600mm with reduce diameter at centre
Table 1. Specific target drift and displacement in pushing and pulling direction for CJ-2B and IJ-3B

| Pushing Direction | Pulling Direction |
|-------------------|------------------|
| Target Drift (%)  | Target Drift (%) | Lateral Displacement (mm) | Lateral Displacement (mm) |
| +0.01             | -0.01            | +0.38                      | -0.38                      |
| +0.05             | -0.05            | +1.90                      | -1.90                      |
| +0.10             | -0.10            | +3.80                      | -3.80                      |
| +0.20             | -0.20            | +7.60                      | -7.60                      |
| +0.50             | -0.50            | +19.00                     | -19.00                     |
| +0.75             | -0.75            | +28.50                     | -28.50                     |
| +1.00             | -1.00            | +38.00                     | -38.00                     |
| +1.15             | -1.15            | +43.70                     | -43.70                     |
| +1.25             | -1.25            | +47.50                     | -47.50                     |
| +1.35             | -1.35            | +51.30                     | -51.30                     |
| +1.50             | -1.50            | +57.00                     | -57.00                     |
| +1.75             | -1.75            | +66.50                     | -66.50                     |
| +2.00             | -2.00            | +76.00                     | -76.00                     |
| +2.25             | -2.25            | +85.50                     | -85.50                     |
| +2.50             | -2.50            | +95.00                     | -95.00                     |

3. Equipment and Instrumentation

Upon the complete construction of specimen CJ-2B and IJ-3B, these two joint samples need to paint with white colour for easy marking of the cracks observed during testing at a different level of drifts. Furthermore, these specimens require installing equipment and instruments such as LVDTs (linear potentiometers), strain gauges, loading cell and data logger. Figure 6 shows a total number of five LVDTs were placed along the column, one LVDT on Beam 1 and two LVDTs on the foundation beam of specimen CJ-2B. LVDT 1 to 5 was located on the column in the x-direction (in-plane) to capture the lateral displacement at different point of the column. LVDT 6 was placed at the end of Beam 1 and LVDT 7 at the end of Beam 2, to observe the movement of the beams in x-direction and y-direction (out-of-plane) respectively.

Meanwhile, Figure 7 shows nine numbers of LVDTs and load cell are installed beside column and at the end of the beams for specimen IJ-3B. During testing, the displacement-controlled method was used and converted in terms of percentage drifts. According to ACI Committee 374 (2005), the drift can be defined as the ratio of lateral displacement over the height of the specimen, multiplied by 100. Whereby the unit is in the percentage of the total height drift is the ratio of lateral displacement over the height of the specimen in terms of percentage, and it is represented in Equation 1.

\[
\text{Target drifts (\%)} = \frac{\Delta x}{H_e} \cdot 100
\]  

\( \Delta x \) is the applied in-plane lateral displacement, and \( H_e \) is the effective height from top of strong floor to the centre of the double actuator with a value of 3800mm.
4. Experimental Results
From the experimental data, the load versus displacement graph, which is known as hysteresis loops, can be plotted for every drift recorded by LVDTs. However, only data from LVDT 1 was used for analysis and interpretation because it was positioned the closest to the actuator and measured the maximum lateral in-plane displacement. For each drift, two numbers of cycles were recorded and plotted for its hysteresis loop. Figure 8 presents the hysteresis loops using the data obtained from LVDT 1. The yield together maximum in-plane load and displacement, elastic stiffness, secant stiffness, ductility and equivalent viscous damping can be obtained from this hysteresis loops. It was observed that the lateral
displacement and its corresponding lateral load increases as the value of target drift increases. The symmetrical shape in the pushing and pulling direction of the hysteresis loops for both first and second cycle is similar for their respective drifts. Figure 9 shows the hysteresis loops for specimen IJ-3B obtained from data LVDT 1.

Figure 8. Hysteresis loop specimen CJ-2B obtained from data LVDT 1

Figure 9. Hysteresis loop specimen IJ-3B which obtained from data LVDT 1
5. Validation of Result and Discussion

The validation process involves analyzing the shape and calculating the parameters of the hysteresis loops for both experimental and modelling results. Selection of the best hysteresis loops representation was made from 57 numbers of Hysteresis Rules which are available in the Manual Appendices of the RUAUMOKO 2D. This involves multiple trial and error with two different Hysteresis Rule, which is Hysteresis Rule 4 (Modified Takeda Hysteresis) and Hysteresis Rule 25 (Takeda with Slip). Ultimately, Hysteresis Rule 44 (Pampanin Reinforced Concrete Beam-Column Hysteresis) was chosen since it is best represented the specimen. The Pampanin RC beam-column hysteresis includes bilinear unloading and slip-on reloading, as shown in Figure 10. Therefore, it is more suitable for defining the behaviour of reinforced concrete sections, as there are parameters that focused on the pinching and strength degradation behaviour. There are six main parameters, namely AlfaS1 (As1), AlfaS2 (Xi), AlfaU1 (Au1), AlfaU2 (Au2), DeltaF (DF) and Beta. Hysteresis Rule 44 was used to modelling both specimen CJ-2B and specimen IJ-3B.

![Analytical hysteresis for Hysteresis Rule 44 (Pampanin Reinforced Concrete Beam-Column Joint) [14]](image)

Figure 10. Analytical hysteresis for Hysteresis Rule 44 (Pampanin Reinforced Concrete Beam-Column Joint) [14]

Figure 11 shows the comparison of hysteresis loops between experimental and modelling for specimen CJ-2B which had been tested under in-plane lateral cyclic loading. The solid line represents the modelled hysteresis loops while the dotted line represents the experimental hysteresis loops. The rule incorporated allowed pinching, and therefore a good fit was achieved. Although a similar behaviour was shown between all the hysteresis loops, there are still some discrepancies between them. It was detected that the shape of modelling hysteresis loops is similar to the experimental hysteresis loops. However, the modelling hysteresis loops are a little bit fatter than the experimental hysteresis loops. This phenomenon occurs because during experimental work, a lot of energy was released to the surrounding under friction and kinetic energy. Figure 12 shows the comparison of hysteresis loops between experimental results and modelling results using HYSTERES program for specimen IJ-3B. These two graphs show good agreement and less disparity between experimental hysteresis loops and modelling hysteresis loops. From these graphs will be used to make the comparison between them for seismic performance parameters such as lateral strength capacity, stiffness, ductility and equivalent viscous damping. The comparison in term of percentage for these parameters will be presented in the next section.
Figure 11. Comparison of hysteresis loops between experimental and modelling results for specimen CJ-2B

Figure 12. Comparison of hysteresis loops between experimental and modelling results for specimen IJ-3B

6. Comparison between Experimental and Modelling Hysteresis Loops
Table 2 shows the comparison of lateral strength, ductility, stiffness and equivalent viscous damping between experimental hysteresis loops and modelling hysteresis loops in pushing direction for specimen CJ-2B. The lateral strength was taken as the in-plane lateral force, which contributes to the maximum
displacement for every drift tested in the laboratory. Based on the results, it can be seen that the percentage difference for lateral strength and stiffness are fairly low. In contrast, the percentage difference for ductility and equivalent viscous damping is higher. There is quite a big disparity between them because the modelling hysteresis loop is bigger than the experimental hysteresis loops which obtained directly from measurement data. However, this limit is within the acceptable range because only one specimen was conducted through this study.

Table 2. Comparison of lateral strength, ductility, stiffness and equivalent viscous damping for specimen CJ-2B

| Parameters          | Experimental | Modelled | Difference (%) |
|---------------------|--------------|----------|----------------|
| Lateral Strength (kN) | 90.39        | 93.71    | 3.54           |
| Ductility           | 2.22         | 2.76     | 19.57          |
| Stiffness (kN/mm)   | 1.43         | 1.56     | 8.33           |
| Equivalent Viscous Damping (%) | 8           | 9.83     | 18.62          |

Table 3 shows the comparison of lateral strength, ductility, stiffness and equivalent viscous damping between modelling and experimental for specimen IJ-3B in pushing direction. The results revealed that the percentage difference for lateral strength, stiffness and equivalent viscous damping is fairly low while the percentage difference for stiffness is quite high. This is because the experimental hysteresis loops are steeper than the modelled hysteresis loops. Overall, similar behaviour was shown between all the hysteresis loops but with some discrepancies between them. The HYSTERES Program tends to overestimate the results, however, the results are still reasonable to be used in Ruaumoko 2D for dynamic analysis since the requirement is only from the overall shape of the hysteresis loops. The limitations in the experimental work contributed to the difference between experimental and modeled hysteresis loops. During the experimental work, some of the energy was released to the surrounding under friction and kinetic energy. The untighten screw between a foundation beam and strong floor causes friction, and this contributed to smaller experimental hysteresis loops.

Table 3. Comparison of lateral strength, ductility, stiffness and equivalent viscous damping for specimen IJ-3B

| Parameters          | Experimental | Modelled | Difference (%) |
|---------------------|--------------|----------|----------------|
| Lateral Strength (kN) | 301.58       | 275.40   | 8.68           |
| Ductility           | 2.74         | 2.86     | 4.38           |
| Stiffness (kN/mm)   | 3.05         | 3.55     | 16.39          |
| Equivalent Viscous Damping (%) | 7           | 7.41     | 5.86           |

7. Conclusion and Recommendation

Based on experimental work, modelling hysteresis loops using HYSTERES program and validation between them, the following conclusion and recommendation are drawn:

1. It is important to validate the experimental and modelling hysteresis loops so that the seismic parameter can be determined and can be used for the design of RC buildings using Eurocode 8.
2. The parameters obtained from the modelling of hysteresis loops can be used to represent the actual behaviour of RC buildings and simulate them under different level of earthquake excitations using Ruaumoko 2D program.
3. It is recommended to use the parameters for Pampanin Reinforced Concrete Beam-Column Joint Hysteresis Model (Hysteresis Rule 44) in modelling any RC buildings using non-linear time history analysis and Ruaumoko 2D Programme.
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