Verification of Experimental Hysteresis Loops for Exterior Beam-Column Joint Under Lateral Cyclic Load

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Abstract. This paper presents the verification of experimental to modelled hysteresis loops for exterior beam-column joint tested under lateral cyclic loading. The reinforced concrete exterior beam-column joint was designed using Eurocode 8 and equipped with fuse bars as energy dissipators. The specimen was tested under lateral cyclic loading under controlled displacement (drift). The purpose of this study is to ensure a good agreement from both works is achieved. The exterior beam-column joint modelled hysteresis loops were carried out using HYSTERES Program which is one of the modelling programs under the Ruamoko 2D program. The verification was done by comparing the parameters of experimental hysteresis loops to modelled hysteresis loops. The response of the specimen was compared in terms of equivalent viscous damping, stiffness and ductility. Low percentage differences indicate good agreement between the two hysteresis loops.

1. Introduction
Seismic activity in Malaysia is rarely seen. Most of the earthquake activities in Malaysia was located in Sabah with the highest recorded magnitude of Mw 6.0 in 2015. The PGA of the 2015 Sabah Earthquake was estimated at 0.13g and 0.2g for 10% and 2% probability of exceedance, respectively [1]. Multiple seismic hazard assessment had also been made in local and South East Asia region to look into the potential seismic risk in Malaysia and Singapore and the neighbouring countries [2] [3]. Most of the findings point to mostly low magnitude earthquakes with a rare occurrence of a high magnitude earthquake. However, we do not know the level of damage that the buildings in Malaysia will experience when a large earthquake strike. Following that, a few types of modelling works had been done regarding the performance of local buildings under low to high earthquake excitations [4] [5] [6]. The works were carried out using the Ruamoko 2D program. The program was able to model the maximum displacement of the buildings under different earthquake excitations as well as predicting the damage region. However, results from experimental works are required to run the program.

This paper continues the work presented previously in [7] where it validates the hysteresis loops of corner beam-column joint. It is the first step in modelling the damage level of buildings under
different earthquake excitations. It is important to conduct a comparison to avoid errors in future works. This paper, however, focuses on the analysis of the response of reinforced concrete exterior beam-column joint tested under lateral cyclic loading. The exterior beam-column joint is a sub-assemblage of the two-storey school building. The same method from [7] is applied to verify the experimental hysteresis loops for exterior beam-column joint using Pampanin Reinforced Concrete Beam-Column Joint. The hysteresis loops from both experimental and modelled works were compared in terms of lateral strength, stiffness, ductility, and equivalent viscous damping.

2. Materials and methods

2.1. Experimental
The experimental part of this study consisted of lateral cyclic loading test on the exterior beam-column joint. The main objective of this test is to determine the yield strength as well as the seismic response of the beam-column joint. All elements were designed using Eurocode 8 with concrete Grade50 (fy = 50N/mm2) and high yield strength steel reinforcement bar (fy = 460N/mm2), and fuse bars were located in the joint as energy dissipator. The exterior beam-column joint consists of one reinforced concrete column (400mm x 400mm) and two in-plane beams (400mm x 400mm). The specimen was tested under lateral cyclic loading using the 500kN load actuator. This is to investigate the capability of the joint to adapt to lateral load, which mimics the real-life earthquake load. The exterior beam-column joint was tested under controlled displacements and expressed in terms of drifts. The specimen was tested under 11 sets of drifts which started at ±0.1%, ±0.2%, ±0.3%, ±0.4%, ±0.5%, ±0.6%, ±0.75%, ±0.8%, ±1.0%, ±1.75%, ±2.0% and ended at ±2.25. The lateral displacement of the foundation, column and beams was measured using LVDTs. A total of 7 LVDTs were placed on the specimen, as shown in Figure 1. Figure 2 shows the pattern of loading regime using control displacement applied to the beam-column joint.

Figure 1. Location of LVDTs on exterior beam-column joint.
2.2. Modelling

The modelling of the seismic response of structures can be simulated using various available software. However, currently, HYSTERES Program of the RUAUMOKO2D software is the most user friendly as the parameters are easy to defined. It generates a force-displacement curve or hysteresis loop model, using parameters from experimental results. The modelling works for the modelling of analytical hysteresis loop for the exterior beam-column joint is considered as initial work. The Pampanin Reinforced Concrete Beam-Column Hysteresis rule (IHYST 44), as shown in Figure 3, was chosen as the Hysteres model. The input parameters for the program were calculated and tabulated in Table 1. The results yields in the form of force and displacement. They were then plotted and compared to the experimental result.

![Figure 3. Pampanin Hysteresis for IHYST 44](image)

**Figure 2.** The loading regime pattern for testing.

| IOP | As1 | Xi | Au1 | Au2 | DeltaF | Beta |
|-----|-----|----|-----|-----|--------|------|
| 2   | 1.5 | 1.5| -0.9| 0.3 | 49     | -0.5 |
3. Theoretical Background

Three main parameters are involved in this paper. They are equivalent viscous damping, ductility and stiffness. These parameters are the key factor in determining the capacity of the beam-column joint under different drifts.

3.1. Stiffness

In seismic design, it is important to have sufficient lateral stiffness to ensure the deformation of the structure is under control and hence save it from failure [8]. It presents the total load (F) required to push the building by a certain displacement (Δ), and it is expressed as F/Δ [9]. In the elastic region, the stiffness is referred to as preliminary effective stiffness (Ke), and the value becomes lesser with increasing damage [10],[11]. When entering the inelastic region, it becomes secant stiffness (Ksec). Both Ke and Ksec are expressed in Equation 1 and 2.

\[ Ke = \frac{\text{Yield Load, } H_y}{\text{Yield Displacement, } \Delta_y} \]  
\[ Ksec = \frac{\text{Ultimate Load} - \text{Yield Load, } H_u-H_y}{\text{Ultimate Displacement} - \text{Yield Displacement, } \Delta_u-\Delta_y} \]

3.2. Ductility

Ductility is the ability of a structure to undergo large amplitude cyclic deformations in the inelastic range without a substantial reduction in strength [12]. Based on Figure 3, the displacement ductility is taken for the ideal elasto-plastic behaviour. It is expressed by the following Equation 3.

\[ \text{Ductility, } \mu = \frac{\Delta_u}{\Delta_y} \]

Where the ultimate displacement (Δu) is defined as the displacement corresponding to a 20% strength degradation of the maximum strength (P_{max}) [9], the details and the ductility of the structure will affect the ability of a building to resist collapse during seismic activity.

3.3. Equivalent Viscous Damping

Seismic performance of a building highly depends on equivalent viscous damping and energy dissipation [13]. The total energy dissipated by a system when the lateral cyclic load is applied calculated using Equation 4 [14].

\[ \xi_{eq} = \frac{1}{4\pi} \times \frac{E_D}{E_{SO}} \times 100\% \]

E_D is energy dissipation and while E_{SO} is the strain energy. Value of ED is calculated as the area under the graph (hysteresis loops).

4. Results and Discussion

By comparing the analytical results from HYSTERES Program to the results from the experimental test, several conclusions can be made. Since the hysteresis does not consider the properties of the material, but rather history-dependent, the results of the displacements show that HYSTERES Program is capable of modelling different structural configurations. This is proven by the generally good agreement and soundness of the hysteresis loops presented in Figure 4. Experimental and modelled hysteresis loops were represented by the solid line and dotted line, respectively. Each hysteresis loops were compared based on the overall shape of the responses, the ultimate force and displacement values as well as yield force and displacement values.
Table 2 shows the comparison of stiffness, ductility and equivalent viscous damping in pushing and pulling direction. The comparison is made for ±0.75% drift, ±0.80% drift, ±2.0% drift, and ±2.25% drift since these are the points at which yield force and ultimate force falls into. The ranges of percentage differences of lateral strength between both hysteresis loops in pushing and pulling directions are 2.17% to 5.12% and 4.73% to 20.54% respectively. Meanwhile, for ductility, the percentage of differences fell within the range of 3.17% to 6.84% for pushing direction and 3.92% to 17.40%. As for stiffness, the discrepancies for pushing and pulling direction vary between 0.26% to 18.11% respectively.

Lastly, the differences for equivalent viscous damping goes from 6.55% to 13.56%. Since the hysteresis loops were modelled well, most of the results calculated are within the acceptable limit. Although, generally, the results in pulling directions gives higher differences. This is because the experimental hysteresis loops are not symmetrical creating smaller loops in pushing direction and bigger loops in pulling direction. Meanwhile, the modelled hysteresis loops are symmetrical, and HYSTERES Program tends to overestimate the slope of hysteresis loops in both directions. Nonetheless, the results are still good to use for determining the mode shape of the building since the condition depends on the selection of the final shape of the hysteresis loops. Overall, these hysteresis plots show that HYSTERES Program is justifiable in modelling the hysteresis loops of reinforced concrete exterior beam-column joint. Therefore, the Pampanin RC Beam-Column Joint hysteresis can be used for modelling two-storey school building using Ruaumoko 2D software as shown Table 3 and Table 4.

**Table 2. Lateral strength, ductility and stiffness and its percentage difference in pushing direction**

| Parameters | Drift (%) | Pushing Direction | Model (kN) | Exp (kN) | Difference (%) |
|------------|-----------|--------------------|------------|----------|----------------|
| Lateral    | 0.75      |                    | 113.00     | 119.42   | 5.52           |
|            | 0.80      |                    | 144.60     | 137.78   | 4.83           |
| Parameters | Target Drift (%) | Pulling Direction |
|------------|-----------------|------------------|
|            | Model (kN)      | Exp (kN)         | Difference (%) |
| Lateral    | 0.75            | -121.30          | -105.28        | 14.14 |
| Strength   | 0.80            | -148.20          | -120.59        | 20.54 |
|            | 2.00            | -250.00          | -238.45        | 4.73  |
|            | 2.25            | -300.00          | -266.91        | 11.67 |
| Ductility  | 0.75            | 1.30             | 1.25           | 3.92  |
|            | 0.80            | 1.39             | 1.33           | 4.41  |
|            | 2.00            | 1.86             | 1.63           | 13.18 |
|            | 2.25            | 2.15             | 2.56           | 17.40 |
| Stiffness  | 0.75            | 8.23             | 7.42           | 12.66 |
|            | 0.80            | 7.42             | 6.43           | 14.29 |
|            | 2.00            | 5.08             | 3.97           | 24.53 |
|            | 2.25            | 4.57             | 3.56           | 24.00 |

Table 3. Lateral strength, ductility, and stiffness and its percentage difference in pulling direction

| Equivalent Viscous Damping |
|----------------------------|
| Target Drift (%) | Model (%) | Exp (%) | Difference (%) |
| 0.75            | 8.39      | 9.61    | 13.56         |
| 0.80            | 10.33     | 11.03   | 6.55          |
| 2.00            | 17.95     | 19.75   | 9.55          |
| 2.25            | 19.13     | 21.71   | 12.63         |

Table 4. Percentage differences for equivalent viscous damping
5. Conclusions
The percentage difference indicates the discrepancy in values that could have been the result of many factors. These included ill-fitting of reinforcement bars and friction formed between the machine and the beam-column joint during testing. However, the discrepancies do not solely depend on the experimental only. In HYSTERES Program, the basic section properties and material properties were not defined. If a detailed requirement is needed in modelling the hysteresis loops, potentially more accurate hysteresis loops can be achieved. This paper presented the comparison of hysteresis loops between experimental results and modelling results using HYSTERES program for exterior beam-column joint. Based on the percentage differences calculated, all three parameters mentioned exhibit good agreement. Additional work can be executed using RUAUMOKO2D and DYNAPLOT to conduct a thorough analysis of mode shape and response of the two-story school building under various earthquake excitations.

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