Validation of Corner Beam-column Joint's Hysteresis Loops between Experimental and Modelled using HYSTERES Program

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ABSTRACT

The beam - column joint is an important part of a multi-storey RC building as it caters for lateral and gravitational load during an earthquake event. The beam-column joints should have a medium to high ductility for transferring the earthquake load and gravity load to the foundation. By designing multi-storey RC buildings using Eurocode 8 can avoid any diagonal shear cracks in column which is a major problem in non-seismic design buildings using British Standard (BS8110). This paper presents the experimental hysteresis loops of monolithic corner beam-column joints of multi-storey building which had been designed using Eurocode 8 and tested under in-plane lateral cyclic loading. The experimental hysteresis loops of corner beam-column joint was compared with modelled using the HYSTERES program. The full-scale corner beam-column joint of a two story precast school building was designed, constructed, tested and modelled is presented herein. The seismic performance parameters such as lateral strength capacity, stiffness, ductility and equivalent viscous damping were compared between experimental and modelled hysteresis loops. The experimental hysteresis loops have similar shape with the modeling hysteresis loops with small percentage differences between them.

Keywords: Corner beam-column joint; hysteresis loops; seismic design; ductility; stiffness; equivalent viscous damping

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Introduction

Malaysia is one of the countries which is located in South East Asia and it is classified as a low seismic region because only a few earthquakes activities occurred in this region. However, due to the recent earthquake events such as the 2014 Banda Aceh Earthquake and the 2015 Sabah Earthquake, the local and government authorities have started to look at this matter seriously. Moreover, East and West Malaysia are located at the peripheral of the Pacific Ring of Fire and located closed to Indonesia and the Philippines. Both of these countries had undergone severe and devastating seismological activities in the past few decades [1]. Due to frequent earthquake occurrences in these countries, the possibilities of Malaysia being thrust by moderate earthquakes cannot be ignored. Recently, a few activities of earthquakes had happened in Sabah especially in Tambunan, Kota Marudu, Kudat, Beluran, Kunak and Keningau while two earthquakes had occurred in Belaga, Sarawak [2]. These events proved that earthquakes can happen in Malaysia and the preventive measures must be taken so that the buildings will save under moderate or strong earthquakes. One of the best option is to design the reinforced concrete and steel buildings using Eurocode 8 and to repair and strengthened the buildings using Carbon Fibre Reinforced Polymer (CFRP) and enlargement of the structural components.

Before seismic code of practice such Eurocode 8 was introduced and implemented in Malaysia, most of the reinforced concrete buildings were designed using BS8110 which is non-seismic code of practice. These buildings performed quite well under gravity loads but performed badly during the 2015 Sabah Earthquake where most of these building damages and required major repaired and strengthening. One of the failure mechanism in RC buildings which designed using BS8110 is soft-story mechanism due to weak-column and strong-beam design concept. The soft-story mechanism occurred because the column tends to fail earlier than the beam under severe or strong ground motion [3]. This type of failure is very common with medium or high rise building with a large opening at the ground floor, which typical design for condominiums, apartments and flats in Malaysia. Some of this failure can be observed during the 2015 Ranau, Sabah Earthquake. This earthquake was recorded with magnitude of 5.9 scale Richter and caused severe damage to the Ranau hospital with spalling of concrete and buckling of reinforcement bars. This building has a large opening at ground floor and brick infill walls from the first floor until tenth floor. Thus, the stresses were highly concentrated at the bottom column located on the ground floor and caused large diagonal shear cracks on column at ground floor, which is known as soft-storey mechanism [4]. Therefore, it is recommended to design multi-storey buildings using Eurocode 8 where it is one of the ways to prevent structural damages and soft-storey mechanism.

There are a lot of research which had been conducted on beam-column joint which design using BS 8110 [5,6,7], repaired and retrofitted beam-column using CFRP, SFRC, steel plate and enlargement of column [8,9,10], modelled hysteresis loops and behavior of beam-column joint using Ruaumoko 2D [11,12,13] and designed beam-column joint in accordance to Eurocode 8 by incorporating fuse-bars [14,15]. Thus, this study will focus on the seismic performance and behavior of corner beam-column joint in two-storey school building which had been designed using Eurocode 8. The analysis of hysteresis loops will be given the first priority because all the parameters of the seismic performance for the RC buildings can be extracted from them. These parameters are lateral strength capacity, yield lateral displacement, elastic stiffness, secant stiffness, equivalent viscous damping and ductility. For validation purpose, the experimental hysteresis loops will be compared with modelling hysteresis loops using HYSTERES Program which can be obtained from Ruaumoko 2D folder. The Ruaumoko 2D and 3D software are based on finite element method where it is capable of providing a step-wise time history non-linear analysis of two or three dimensional structure. HYSTERES program which is included in Ruaumoko Program was used as the preliminary program to model the inelastic behavior of interior beam-column joint [5]. The program can also be used to acquire the mode shape, hysteresis loops, moment rotation, damage indices and also energy dissipation [16]. The Ruaumoko 2D and 3D program is designed to carry out the analysis of structures, in particular buildings or bridges, subjected to earthquake and other dynamic excitation [16].

Design and Research Methodology

Design corner beam-column joint using Eurocode 8

Figure 1 shows the plan view of the two-storey school building which was designed in accordance of Eurocode 8 together with the locations of interior, exterior and corner beam-column joint. The interior beam-column joint is labelled as BC2-3I, exterior beam-column joint is labelled as BC3-2E and interior beam-column joint is labelled as BC1-2C. A prototype specimen of corner beam-column joint which labelled as BC1-2C will be designed, constructed, tested and analyzed under in-plane lateral cyclic loading. Meanwhile, Figure 2 shows the location of corner beam-column joint at first floor of two-storey RC school building. Whereas, Figure 3 shows the detailing of the corner beam-column joint which had been designed using Eurocode 8 and the seismic loading which represent by peak ground acceleration (PGA=0.3g)

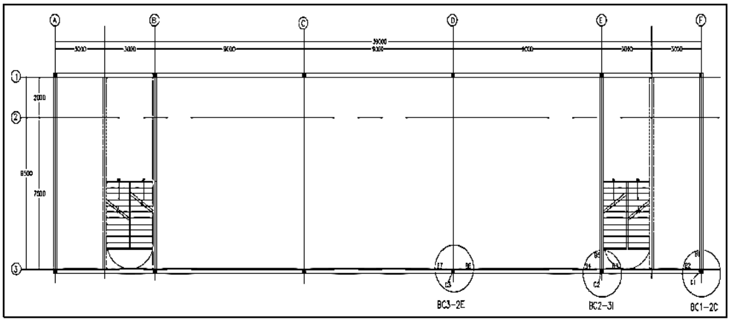

Figure 1: Plan view of two-storey RC building

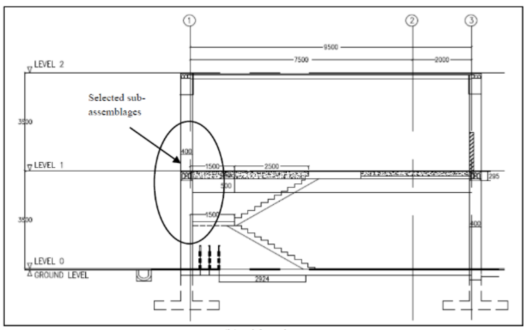

Figure 2: The location of corner beam-column joint at two-storey school building.

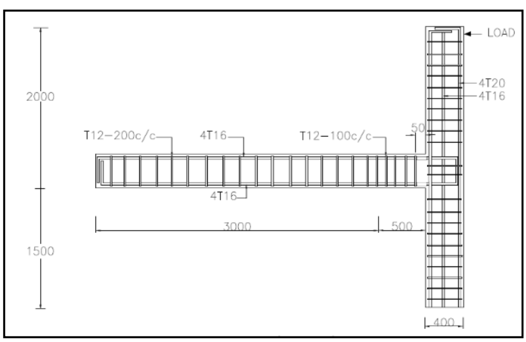

Figure 3: Detailing of corner beam-column joint.

Experimental work

The selected sub-assemblage of corner beam-column joint is consisting of one column with one in-plane beam and one out-of-plane beam as designed using Eurocode 8. Both of the beams were pin-jointed at the end using two steel plates and tightened together using four high yield bolts and threaded rods. The column is constructed using monolithically cast-in-situ to foundation beam and then bolted to the strong floor using highly threaded rod. The dimensions of the column and beam are 4m x 0.4m x 0.4m and 3.5m x 0.4m x 0.4m, respectively and the experimental setup is shown in Figure 4. The whole sub-assemblage of corner beam-column joint were constructed using concrete Grade (f_{cu}=50MPa) and high steel bars with f_y=460N/mm^2. After construction and curing of the concrete, the specimen was tested under lateral cyclic loading. The specimen was tested until the specimen reaches the ultimate load and eventually experience strength degradation. Nine LVDTs were used to measure the lateral displacement of the beams, column and foundation. Five numbers of LVDTs is placed on one side of column and two LVDTs placed on the foundation beam and one LVDT located at the end of the beam. Thirteen sets of drifts that starts with ±0. 01%, ±0. 05%, ±0. 1%, ±0. 2%, ±0. 5%, ±0. 75%, ±1. 0%, ±1. 15%, ±1. 25%, ±1. 35%, ±1. 5%, ±1. 75% and ±2. 0% were applied at the top of the column.

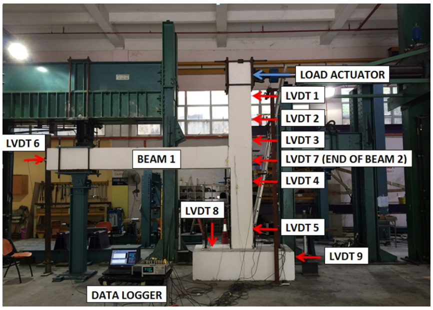

Figure 4: Experimental set-up of corner beam-column joint

Modelling

After an experimental analysis was taken placed, the hysteresis loops of LVDT1 was plotted under load versus displacement. The Hysteresis Rule was chosen based on the closest condition and shape of hysteresis loop available in Ruaumoko 2D Manual. Based on the experimental hysteresis loops which had been plotted shown that it has a slip in the loop and the Hysteresis Rule number 25 was chosen to represent it. The number 25 hysteresis rules represent the TAKEDA with SLIP as shown in Figure 5. There are some parameters which need determine based on the experimental results before using the HYSTERES program. Some values of the parameters were calculated based on the experimental hysteresis loops which has a similar shape of TAKEDA with SLIP requirement. Table 1 shows the values of parameters as data input for number 25 hysteresis loops.

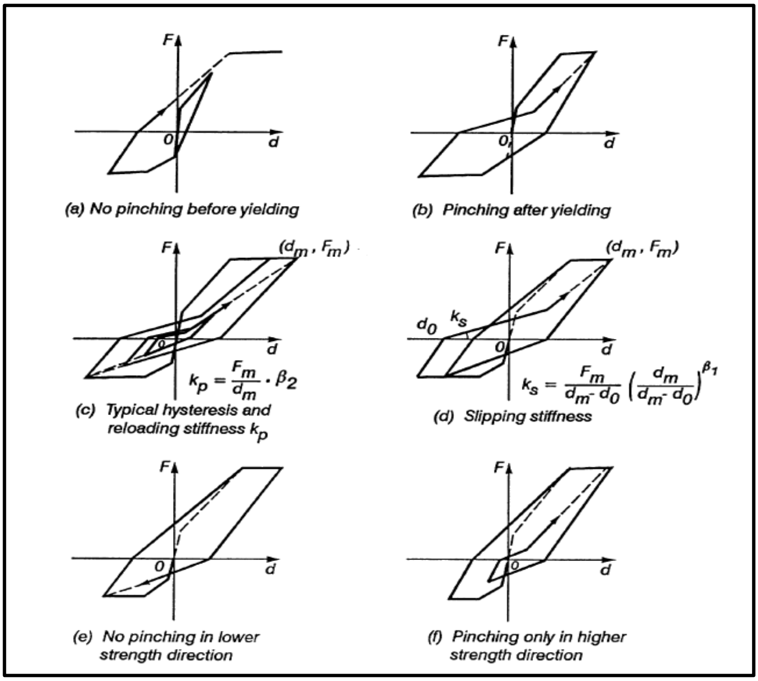

Figure 5: TAKEDA with SLIP hysteresis

Table 1: Parameters for number 25 hysteresis loops

Parameters	Data Input
Stiffness average, Ke	8.71
Bilinear factor, r	0.0612
Positive yield force, P+	90.39
Negative yield force, P-	-102.66
Strength Degrading Choice (ILOS)	1
Ductility at degradation begins	1.86
Ductility at degradation stops	3.21
Final fraction of strength	0.1
Ductility at 0.01 initial strength	0
Unloading Degradation Parameter, α	1.54
Slipping Stiffness Parameter, β2	1.73
Reloading Stiffness Parameter, β2	0.94
Cracking Force for Component, FC	67.79
Cracking Displacement for Component, RC	20.45
Plot sub-divisions	5
Initial Displacement	0
History Choice and Scale	1

Parameters for Analysis

Hysteresis Loop

Hysteresis loop measures the behavior of a structure from elastic to non-elastic. The graph of the hysteresis loops which is load vs displacement was plotted for both cycles for each drift starting from ±0.01%, ±0.05%, ±0.1%, ±0.2%, ±0.5%, ±0.75%, ±1.0%, ±1.15%, ±1.25%, ±1.35%, ±1.5%, ±1. 5% and ±2.0% drift. From hysteresis loops, the parameter such as lateral displacement, stiffness, ductility and equivalent viscous damping can be determined accordingly. Hysteresis loop can be associated with viscous damping and it is a result of dynamic hysteresis. Figure 3 shows a hysteresis loop with indication of energy dissipation (E_D) and strain energy (E_{SO}).

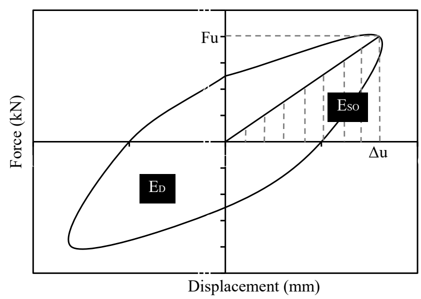

Figure 6: Hysteresis loop with indication of energy dissipation (ED) and strain energy (E_{so}).

Stiffness

Stiffness are defined as rigidity of an object to the extent of which it resists deformation in response to an applied force. The stiffness in the linear elastic region, K_e and stiffness in inelastic region, K_{sec} is expressed by equation 1 and 2 [19] while the differences of elastic stiffness (K_e) and secant stiffness (K_{sec}) is illustrated in Figure 7. Yield load is loaded at the point where the specimen starts to deform plastically while yield displacement (Δ_y) is the displacement at the yield point. Ultimate load, however is the maximum load that the specimen can withstand before failing.

$$K_e = \frac{F_y}{\Delta_y} \tag{1}$$

$$K_{sec} = \frac{F_u - F_y}{\Delta_u - \Delta_y} \tag{2}$$

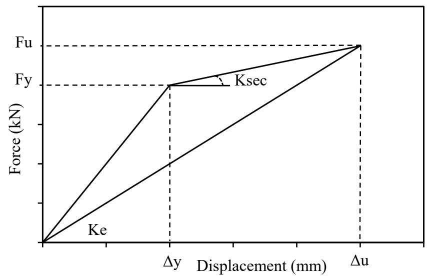

Figure 7: Differences between $K_{elastic}$ and K_{secant},

Ductility

Ductility is described as the ability of a structure or its components to resist the inelastic domain of response [21]. The displacement ductility factor can be defined as the ratio of lateral displacement (Δ_x) and yield lateral displacement (Δ_y). The displacement ductility factor is expressed in equation 3 [20].

$$Ductility, \mu = \frac{\Delta x}{\Delta y} \tag{3}$$

Equivalent Viscous Damping

Energy dissipation factor and equivalent viscous damping factor are the main factors that affect the seismic performance of a building [8]. Equivalent viscous damping is a way of measuring the response of a system to harmonic force at exciting frequency. The energy dissipation of a structure is low under exciting frequency, if the equivalent viscous damping factor is high. The energy dissipated in a vibration cycle of the structure can be determined by calculating the equivalent viscous system. An equivalent viscous damping factor can be calculated by using Equation 4 [17]. The formula given represents the area from one point to another. Therefore, a summation of the area under the hysteresis loop was calculated to represent a hysteresis loop for one drift.

$$\xi_{eq} = \frac{1}{4\pi} \times \frac{E_D}{E_{so}} \times 100\% \tag{4}$$

where E_D = energy dissipation represents the area under one hysteresis loop
E_{SO} = strain energy represents by the area of triangle at maximum displacement and maximum force.

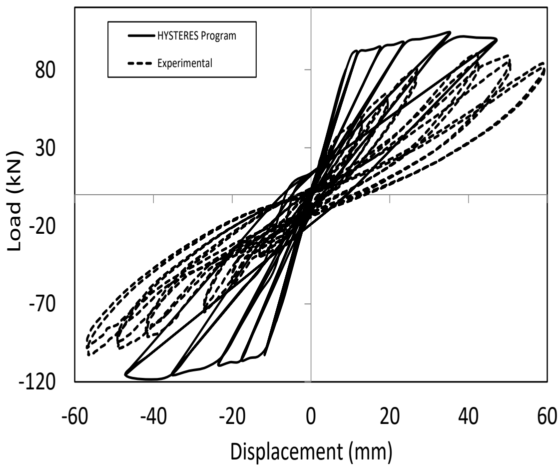

Figure 8: Comparison of hysteresis loops between experimental and modeling.

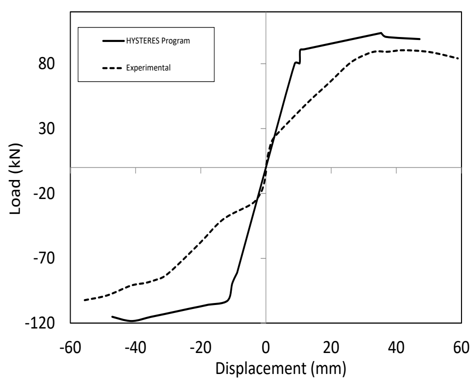

Figure 9: Lateral strength comparison between experimental and modeling.

Results and Discussion

To check the accuracy of the selection, comparison of hysteresis loops generated by HYSTRESES Program and the experimental results was compared as shown in Figure 8. The solid line represents the modeled hysteresis loops while the dotted line represents the experimental hysteresis loops. There are some similarities in some aspects between experimental hysteresis loops and modeling hysteresis loops for corner beam column joint.

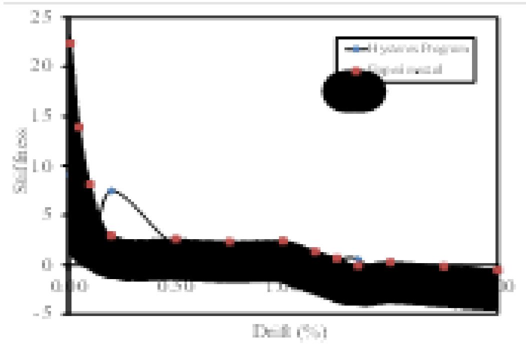

Figure 10: Stiffness comparison between experimental and modeling

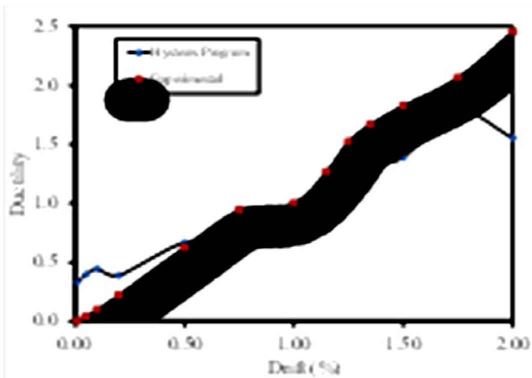

Figure 11: Ductility comparison between experimental and modeling

First, the shape of both experimental and modeling results has the similar patterns between each other’s. However, there are discrepancies between both of the results that resulted in the value of the modeling results higher than the experimental results in some certain areas. The modeled hysteresis loop exhibits a higher load with less displacement as compared to the ones from experimental.

The result shows the value for both experimental and modeling has large differences in the elastic region, but later achieve similar strength as it entered the inelastic region. Based on Figure 8 and Figure 9, the beam-column joint for experimental hysteresis loops experience yielding at 0.75% drift. and continue to gain strength until 1.75% drift before experiencing strength degradation at 2.0% drift. The “pinch” effect showed throughout testing during reloading in pulling direction while little slip was shown. “Pinch” effect occurs when the structure experience a damage but still having its strength. The narrow hysteresis loops indicate the successive cycle the structure trying to achieve, but at a higher deformation. Since Takeda with Slip focuses more on hysteresis loops with major slip. The model is very sensitive to data inputs and it tends to estimate more than the actual hysteresis loop even though the exact parameters input was taken from the experimental hysteresis loop. The data obtained from Hysteres Program tend to be repetitive. Although it gave 13 sets of data that represents the 13 sets of drifts, it only gave data for one cycle as oppose to two cycles as per experimental. Therefore, it could be less accurate.

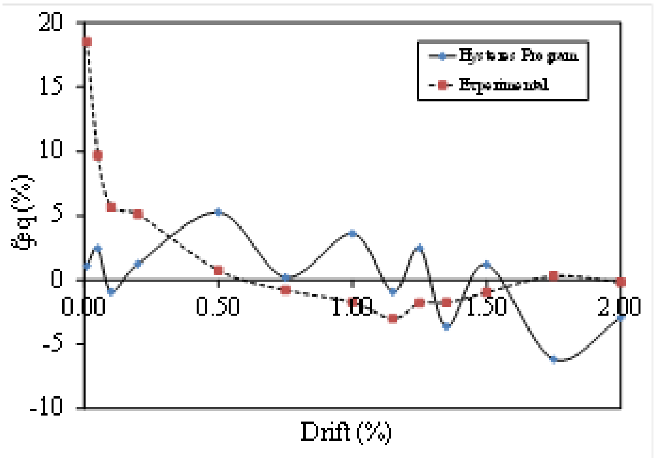

Figure 12: Comparison of equivalent viscous damping between experimental and modeling for each cycle of drift

Other than lateral strength, stiffness, ductility and equivalent viscous damping were also compared between them. Even though the shape of hysteresis loops showed higher estimation of lateral strength, the stiffness, ductility and equivalent viscous damping but it lies within the allowable limit. Stiffness and ductility exhibits a similar behavior, although there is small amount of differences which can be observed in Figure 10 and Figure 11. Initially at the first cycles of drifts, the stiffness has higher value but as the drift increases then the value of stiffness started to reduce drastically. Generally, the value exhibits that the effective stiffness for experimental was slightly higher than modeling, but later achieve similar stiffness degradation towards the end of the cycles. The values for equivalent viscous damping was calculated using equation 4 for each cycle for each drift using experimental and modelling hysteresis loops. Figure 12 shows the comparison of hysteresis loops between experimental and modelling. It can be observed that the equivalent viscous damping for modelling has slightly higher values than the experimental hysteresis loops. However, these values were within the allowable range and it can be used to design corner beam-column joint for higher peak ground acceleration.

Conclusions

This paper presented and validated of hysteresis loops between experimental and modeling of corner beam-column joint which had been designed in accordance to Eurocode 8. There is a good agreement between modeling and experimental hysteresis loops with small differences only. HYSTERES program was used to model and validate the hysteresis loops which can be used for modeling the two-storey RC school building under different level of earthquake excitations using Ruaumoko 2D program. The output file from Ruaumoko 2D program can be used to analyze different dimensions in terms of size and height of RC buildings without running experimental work in the laboratory using shaking table. It is suggested to use Hysteresis Rule number 25 for corner beam-column joint after validation had been made. Furthermore, it is recommended to use the value of parameters as listed in Table 1 for the purposes of modeling and designing corner beam-column joint for the future using different values of peak ground accelerations.

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