EFFECT OF LOADING HISTORY ON SEISMIC PERFORMANCE OF NON-DUCTILE BEAM-COLUMN JOINTS

FA. I. Refaie ¹ and W. M. Hassan ²

ABSTRACT

Unreinforced beam-column joints in existing concrete structures are believed to have caused older building collapses due to losing their axial load carrying capacity during past earthquakes. In quasi-static cyclic tests of beam-column joints, different researchers use different loading protocols and number of displacement cycles per amplitude. In most cases, the selection of such protocols is arbitrary. Different backbone curves and strength and stiffness degradation profiles may be resulted for the same joint configuration due to this arbitrary choice of loading protocol. This leaves future researchers who work on numerical modeling of such joints to define cyclic backbone curves in the dilemma of selecting the most representative test protocols to adopt their test results. The present study experimentally investigates the effect of the number of displacement loading cycles as well as a near-fault and a subduction zone earthquake scenarios’ displacement protocols on the performance of shear critical unreinforced beam-column joints. As a part of the current study, the test program presented in this paper consists of 2 two-third scale specimens with joint beam to column depth ratio of 1. The specimens were tested under axial load ratio of 45%. The number of cycles used is 1 and 3 cycles for each drift level. The test results confirm that increasing the number of cycles in shear critical joint tests significantly increases post-peak strength and stiffness degradation and limits the deformation capacity of such joints. Residual joint axial capacity following shear failure was also reduced when using three displacement cycles.

¹ Assistant Professor, Housing and Building National Research Center, Cairo, Egypt, (fatma_alz@yahoo.com)
² Associate Professor, Housing and Building National Research Center, Cairo, Egypt,(whassan@berkeley.edu)

Effect of Loading History on Seismic Performance of Non-ductile Beam-Column Joints

FA. I. Refaie and W. M. Hassan

ABSTRACT

Unreinforced beam-column joints in existing concrete structures are believed to have caused older building collapses due to losing their axial load carrying capacity during past earthquakes. In quasi-static cyclic tests of beam-column joints, different researchers use different loading protocols and number of displacement cycles per amplitude. In most cases, the selection of such protocols is arbitrary. Different backbone curves and strength and stiffness degradation profiles may be resulted for the same joint configuration due to this arbitrary choice of loading protocol. This leaves future researchers who work on numerical modeling of such joints to define cyclic backbone curves in the dilemma of selecting the most representative test protocols to adopt their test results. The present study experimentally investigates the effect of the number of displacement loading cycles as well as a near-fault and a subduction zone earthquake scenarios' displacement protocols on the performance of shear critical unreinforced beam-column joints. As a part of the current study, the test program presented in this paper consists of 2 two-third scale specimens with joint beam to column depth ratio of 1. The specimens were tested under axial load ratio of 45%. The number of cycles used is 1 and 3 cycles for each drift level. The test results confirm that increasing the number of cycles in shear critical joint tests significantly increases post-peak strength and stiffness degradation and limits the deformation capacity of such joints. Residual joint axial capacity following shear failure was also reduced when using three displacement cycles.

Introduction

Old structures which were built without adequate seismic resistance design are considered a cause of disasters during earthquakes. Understanding the seismic behavior of these structures will increase the usefulness of information that can enhance the seismic assessment and rehabilitation standards and guides such as ASCE/SEI 41 [1] and ACI 369 [2].

1 Assistant Professor, Housing and Building National Research Center, Cairo, Egypt, (fatma_alz@yahoo.com)
2 Associate Professor, Housing and Building National Research Center, Cairo, Egypt, (whassan@berkeley.edu)

Testing reinforced concrete structural elements and subassemblies in the laboratories is essential to know the behavior of these components under seismic loading. Generally the type of loading and loading histories have a significant effect on the behavior of the tested specimens. The thoughtful selection of displacement amplitudes and number of cycles helps to investigate the critical behavior of test specimens. According to ACI 374.2 [3], two cycles at each deformation level are sufficient if the expected specimen degradation is rapid and three cycles are suitable for gradual degradation. As shown in Fig. 1, the selected drift ratios are functions of the yield drift.

![Drift Ratio](image)

**Figure 1. Deformation history for specimens with two cycles at each deformation level [3]**

FEMA 461 [4] recommended the loading history shown in Fig. 2. It recommended that the lowest damage state occurred after first 6 cycles or the first drift ratio could be around 0.0015.

![Drift Ratio](image)

**Figure 2. Deformation history for specimens with two cycles at each deformation level [4]**

The standard displacement history of Pacific Earthquake Engineering Research Center (PEER) applies three cycles at each of increasingly large displacements, Fig. 3. It is worth mentioning that this deformation history is the most common in the experimental studies.
The displacement history could have different patterns through the loading stages of the specimens as illustrated in Fig. 4, specially in shear critical elements. At earlier stages of the test the displacement history consists of two cycles per displacement amplitude while at later stages of loading, with larger inelastic displacement demands after severe degradation of the tested specimen, each displacement amplitude consists only of one cycle [6]. The effect of long duration earthquake could be presented by applying many cycles in the constant drift ratio as shown in Fig. 5 [5].

Figure 3. Deformation history for specimens with three cycles at each deformation level [5]

Figure 4. Different number of cycles at different loading stages [6]
The behavior of beam-column connections is significantly influenced the seismic performance of reinforced concrete frames. The majority of beam-column connections in old structures do not have proper transverse reinforcement and behave in non-ductile manner, see Fig. 6. Many experimental studies were conducted to evaluate the seismic behavior of that type of connections. A recent NEES grand challenge research experimental program suggested that corner and exterior joints lacking transverse reinforcement can sustain up to 2.5% drift under high axial load ratio of 45% [6, 7 and 8]. A joint axial capacity model was then suggested based on a limited data set. The assessment of the effect of loading history on the cyclic performance of such joints is very limited in the literature, [5, 9 and 10], although many of these joints are shear critical and believed to be prone to significant strength and stiffness degradation with more rigorous displacement-based protocols.
This paper presents a part of a research program aiming to evaluate the effect of the loading history on the behavior of non-ductile exterior beam-column joints.

**Research Program**

The research program of the current study consists of testing two-third scale exterior beam-column joints. The main goal is to evaluate the effect of different cyclic quasi-static displacement protocols on the behavior of non-ductile joints. Thus, this parameter was varied in the tests while column axial load, was kept as close to constant as possible. The specimen designations are J45-C1 and J45-C3; where "J" refers to J-Failure type as defined in [7] and [8], "45" refers to the axial load ratio and "C1 and C3" refer to the number of cycles at each displacement amplitude.

**Description of Specimens**

The test specimen design philosophy incorporated seismic details in both beam and column, along with strong column-weak beam failure scenario to prevent premature failure of the sub-assemblage due to a seismic detailing deficiency other than the absence of the transverse reinforcement of the joint, hence to enforce joint shear failure.

Fig. 7 shows detailing of geometry and reinforcement of the beam-column joints. Ends of columns represent the contra-flexure points at the middle of floor heights. Columns have rectangle cross section of 400 mm × 300 mm and height of 2000 mm. Longitudinal reinforcement of columns consists of four corner bars of 25 mm diameter and two intermediate bars of 12 mm diameter. Transverse reinforcement consists of 10 mm diameter hoops spaced at 75 mm. The end point of the beam represents the inflection point at the mid span. The beam length is 1650 mm and it has rectangle cross section of 250 mm width and 400 mm depth. Beam is reinforced with four top and bottom longitudinal bars of 25 mm diameter and 10 mm diameter stirrups spaced at 75 mm. The actual cylinder compressive strength of the specimens is 19.3 MPa resembling the prevailing strength in older construction.

![Figure 7. Specimen geometry and reinforcement details](image-url)
Instrumentations

Each test specimen was instrumented with 4 electric strain gauges as indicated in Fig. 8. The strain gauges are used to monitor beam bar longitudinal strains. The strain gauges are placed at 30 mm from the beam-column interface. Only exterior beam bar strains are monitored. The external instrumentations comprised 4 LVDTs on both joint faces to measure joint shear strains as shown in Fig. 8. In addition, a vertical LVDT was used to measure the beam tip displacement output.

Test setup

The test setup, Fig. 9, consisted of a loading frame where the beam-column sub-assemblage is vertically placed and the beam tip is loaded using displacement controlled hydraulic actuator of a 500 kN load capacity and 200 mm stroke capacity. The column is laterally restrained to develop
column horizontal reaction. The column base is also laterally restrained to the strong floor to develop the appropriate boundary condition. The axial load is applied to the column top using a 3000 kN capacity hydraulic jack. This loading arrangement simulates lateral loading on the beam-column sub-structure except for the P-Δ effect on the column since it is laterally restrained. This second order effect is insignificant in the joint area and ignoring it in the column leads to a more conservative joint test condition.

Figure 9. Test setup

Loading Protocol

The loading protocol comprises an increasing amplitude quasi-static displacement controlled scheme. The beam tip displacement amplitudes are functions of the predicted yield displacement for each specimen. The column axial load was held constant at an axial load ratio of 0.45 of the column’s gross concrete capacity. The axial load is monitored throughout the test and adjusted to its original value if load fluctuation occurred. The two specimens J45-C1 and J45-C3 have displacement histories with 1 and 3 cycles per drift ratio, respectively. The displacement histories are illustrated in Figs. 10 and 11.
Experimental Results

Cracking pattern and mode of failure

Cracking patterns were marked on each face of the tested specimens at the negative and positive peaks of each loading cycle. Figs. 12a-e show the cracking patterns for the two specimens after different drift amplitudes. Both specimens were confirmed to have failed in a J-Failure mode.

During 0.35% drift cycles, no cracking was observed. First diagonal cracks were observed in the two specimens at first negative peak of drift 0.69%. New cracks appeared and propagated at every new drift ratio. At both drift ratios of 0.69% and 1.33%, the second and third cycles of each drift ratio of specimen J45-C3 did not show new cracks and the existing cracks did not widen but slightly
extended. As shown in Figs. 12b and 12c, there is little difference in the cracking pattern of the two specimens until the end of drift ratio 1.33% cycles.

The real difference between the two specimens started to appear at drift ratio of 1.97%, Fig. 12d. At the second cycle of drift ratio 1.79%, concrete cover of specimen J45-C3 started to spall at the joint mid-point and the existing cracks widened. At drift ratio 2.97%, concrete cover started to spall in specimen J45-C1 while sever deterioration was observed in specimen J45-C3. At the second cycle of drift 2.97%, significant damage to the joint concrete is evident and the column longitudinal bars buckled. The same damage occurred in specimen J45-C1 but at drift ratio of 4.4% as shown in Fig. 12e.

![Cracking pattern after drift ratio of 0.69%](image1)

![Cracking pattern after drift ratio of 1.33%](image2)
c) Cracking pattern after drift ratio of 1.97%

d) Cracking pattern after drift ratio of 2.97%

e) Cracking pattern after drift ratio of 4.40%

Figure 12. Crack propagation in tested joints
Joint Axial Failure

The axial failure of joint J45-C1 took place during the cycle of 4.4% drift. At 1.6% drift toward positive 4.4% drift, the axial load dropped to 50% of its value. For joint J45-C3, at 1.46% drift of the third cycle toward the positive 2.97% drift, the axial load showed 39% dropping and axial failure took place. Thus the maximum drift capacity reached before axial failure is 4.4% and 2.97% for specimens J45-C1 and J45-C3, respectively. Inspection following the axial failure indicated that the axial failure was characterized by global spalling of joint concrete cover, severe buckling of column unconfined reinforcement within the joint, significant crushing of joint concrete core, breaking of the concrete wedge supported by column ties and longitudinal bars, and finally substantial dynamic instability of the subassembly represented by large side-sway of the column as shown in Figs. 13 and 14. It could be observed that the damage in concrete and the buckling of columns longitudinal reinforcement are more severe in joint J45-C3.

Figure 13. Axial failure of specimen J45-C1

Figure 14. Axial failure of specimen J45-C3
Hysteretic Behavior

Figure 15 shows the beam shear-drift ratio hysteresis performance for specimens J45-C1 and J45-C3. It can be observed that at the small drift ratios, the response was almost elastic and with small residual displacement. Both specimens reached the peak shear at drift ratios 1.97%. At the following drift loading cycles after peak shear, specimen J45-C3 lost about 25% of its capacity while specimen J45-C1 lost 15% of its strength.

The subsequent loading cycles at the same drift ratio significantly affected the response of specimen J45-C3, especially after peak shear. At the same drift ratio, the second and third loading cycles do not show significant strength degradation until the peak shear is achieved. However, at drift ratio corresponded to the peak shear and the subsequent cycles, the loops clearly lose their stability and significant degradation of strength was observed. At drift ratio of 1.97%, strength degradation of second and third cycles was of 13% and 9%, respectively. While at drift ratio 2.97%, strength degradation was of 41% and 57%, respectively.

Figure 15. Shear-drift ratio hysteresis response of test specimens
Analysis of Test Results

Load Carrying Capacity and Displacement Ductility

The envelope curves of hysteresis loops for the two specimens are plotted, as shown in Fig. 16. With respect to specimen J45-C3, the envelope is corresponding to the response for the first cycle at each drift level.

Similar trends are observed during the elastic state. The envelope of specimen J45-C1 shows slightly higher load carrying capacity in push directions as compared to specimens J45-C3. Increasing of number of cycles from one to three in the same drift level does not significantly affect the load carrying capacity of the joint specimen.

The drift capacity at peak shear strength for both specimens was 1.97%. While the drift capacity of specimens J45- C1 and J45- C3 are 4.4% and 2.97%, respectively.

Displacement ductility factors are computed in order to estimate the ability of joint specimens to offer resistance in the inelastic domain. The displacement ductility is defined as the ratio between the ultimate displacement ($\delta_u$) to the displacement at yield ($\delta_y$). The ultimate displacement is estimated as the displacement at 20% load capacity after peak load. Yield displacement $\delta_y$ is computed as the secant stiffness at 75% of the ultimate load in equivalent elasto-plastic system.

Limited-ductility of the tested joints is confirmed by the displacement ductility values which are 2.5 and 1.8 for specimens J45-C1 and J45-C3, respectively. Increasing number of cycles at the same drift level negatively affects the ductility of the tested joints.

![Figure 16. Shear-drift ratio envelope response of test specimens](image-url)
Stiffness Degradation

The cycle stiffness of the specimen at certain drift level is considered as the average of the stiffness in the positive and negative directions. Fig. 17 illustrates the gradual degradation of the stiffness. Stiffness degradation is well noticed after reaching the specimens peak strength at drift 1.97%. It is also clear that increasing number of cycles at same drift level caused a more rapid decrease in the stiffness after the point corresponding to loss of shear capacity. The second and third loading cycles of specimen J45-C3 show significant stiffness degradation.

Figure 17. Stiffness degradation of test specimens

Conclusions

An experimental research program was developed to investigate the response of un-reinforced beam-column joints subjected to different displacement histories. Two types of loading histories were used, one cycle per drift level and three cycles per drift level. The experimental results showed that:

- The cyclic displacement history type influences the joint cracking behavior at different drift levels. More significant cracking were observed with increasing number of displacement cycles.
- Increasing load cycles at the same drift level does not affect the drift at the peak shear while it significantly decreases the drift capacity at axial failure.
- Increasing the number of cycles at the same drift level causes a more rapid decrease in the stiffness after peak shear strength. It also decreases displacement ductility substantially.

References

Concrete Institute, Farmington Hills, MI, 2011.


