Ninth Canadian Conference on Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

EVALUATION OF BOND-SLIP MODELS FOR R/C JOINTS

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ABSTRACT

An experimental study was conducted on a full-scale exterior reinforced concrete beam-column joint primarily designed for the gravity load. The beam-column joint specimen was tested under reversed cyclic loading. The experimental results had revealed that drift capacity of the test specimen mainly depended on the anchorage capacity of the shortly embedded beam bottom longitudinal reinforcement bars into the column which is one of the common deficiencies in the structures designed prior to 1970s. Comparisons are made between experimental results, and an existing bond stress-slip model in the literature. Based on the observed behavior, in general, analysis results using the developed backbone curve for bond stress-slip relationship pertaining only to this study was in good agreement with experimentally obtained moment-slip rotation results.. The effect of cyclic loading on the slippage of the reinforcing bar within the same drift was more pronounced as compared to monotonic loading.

Introduction

Several studies have been performed on the bond strength between the steel reinforcing bars and the concrete (Alsiwat and Saatcioglu 1992; Cho and Pincheira 2006; Harajli and Mabsout 2002). Some of the common parameters affecting the bond strength between concrete and reinforcing bars in the beam-column joints include the anchorage length of the beam longitudinal reinforcement within the joint, confinement of the joint region, and the type and magnitude of applied loadings. The objective of the present study is to investigate the bond stress-slip relationship of reinforced concrete beam-column joints designed with shortly embedded beam bottom longitudinal reinforcement bars into the column and inadequate lateral reinforcement spacing within the joint which are some of the common deficiencies in the structures designed prior to 1970s. The beam-column joint specimen was subjected to combined constant axial and lateral cyclic loadings. Furthermore, a numerical bond stress-slip model deducted from the experimentally obtained values for the tensile reinforcing bar strain versus its corresponding slip was developed and implemented within the sectional analysis code.. A comparative analysis was performed between present experimental study and corresponding numerical results with an existing analytical model in the literature to understand various relationships such as moment-curvature, bond stress-slip, and moment-slip rotation of the beam-column joint.

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Beam-Column Joint Eperimental Setup

The representation of the beam-column joint subassembly in a typical building frame is shown in Fig. 1(a). The joint specimen was designed and detailed according to pre-1970 practices in the United States with short anchorage length at the bottom reinforcement and inadequate stirrup spacing within the joint region as seen in Fig. 1(b). The concrete had an ultimate strength of 24 MPa. The steel bars yield strength and strain were 422 MPa and 0.0021, respectively.

The experimental setup, which was suggested by ACI Committee of Acceptance Criteria for Moment Frames Based on Structural Testing, ACI T1.1-01 2001, for the beam-column joint is shown in Fig. 2. A lateral cyclic force was applied at the tip of the free end of the column by a 250 kN capacity dynamic actuator, which was attached to a strong reaction wall. The column was also subjected to a constant axial load through a 1000 kN capacity static actuator. The axial load was applied directly to the column and thus the hinge support did not have any reaction from this particular load. The bottom of the column was fixed to the strong floor with a pinned hinge support. The beam end was supported by a rigid link, which was also attached to the strong floor by means of a hinge support to simulate a roller support condition just below the beam free end. Several displacement transducers and strain gauges were mounted on the specimen to measure the lateral displacements in the beam and the column, slip in the positive beam reinforcement, and strains in reinforcing bars.

The specimen was loaded with a constant axial load of 700 kN which corresponded to approximately 25% of the column's ultimate axial load capacity. The positive beam reinforcement had an embedment length of 150 mm, and the flexural ratios between the beam and the column were approximately 1.9 and 1.3 for push and pull direction, respectively.

The lateral applied force at the column tip created reactions at the supports as shown in the free body diagram of the beam-column joint specimen (Fig. 3). The axial loads P and P' were equal to each other since these forces were applied to the column only. On the other hand, when the specimen was displaced, the cyclic lateral force F had an angle β with the horizontal axis, hinged end of the column had two reactions, C_x and C_y, and B_x and B_y, were produced at the beam end due to circular movement of the rigid link. A MATLAB code was developed, considering all these forces in the free body diagram, to calculate the envelope for the moment-curvature relationship at the face of the beam where the strain gauges were located. Since the measured force Bx was not significant (less than 1% of F) this reaction was omitted and the roller support condition was assumed.

Numerical Evaluation of Moment Curvature and Slip Rotation Using MATLAB Software

In this study, the flexural behavior of the reinforced concrete beam was determined using the following assumptions:

- The strain distribution over the depth of the section was linear and thus the strain in the reinforcement was linearly proportional to the strain in concrete.
- The tensile strength of concrete was neglected.
- The compressive concrete stress-strain relationship was adopted from a model by Hognestad (1951).
- The stress-strain relationship used for the reinforcing steel was assumed to behave linearly in the elastic and yield portions, forming a bilinear relationship, whereas the strain-hardening portion was defined by a parabolic function (Yalcin and Saatcioglu 2000). Behavior in both tension and compression were assumed to be the same, i.e., no buckling effect in reinforcing bars in compression was considered.
- For the embedded portion of the rebar, a uniform bond stress was assumed.

Algorithm for the Moment-Curvature Analysis

The input data included the cross-section of the specimen, the area and location of the longitudinal reinforcing bars, and the material properties. The bond stress-slip model, which was developed for this particular study, was also used as an input data.

Using well-known sectional analysis methodology, the resulting moment-curvature relationships were determined considering the above-mentioned assumptions. The analysis, without considering any reinforcing bar slippage or shear deformation, was compared to Response-2000 (Bentz and Collins 2000) and COLA (Yalcin and Saatcioglu 2000) and excellent agreement was obtained.

The algorithm of this program was such that the moment-curvature relationship was obtained by incrementing the concrete strain in the extreme compression fiber until the reinforcing bar in tension started to slip. Up to this point in computation, regular sectional analysis procedure was followed. The slip occurred when the reinforcing bar in tension reached its maximum tensile stress, obtained from the developed bond stress-slip model. After this point, the calculation procedure continued by decreasing the strain in the tensile reinforcing bar incrementally. The corresponding top compressive fiber concrete strains and the internal forces were calculated using equilibrium. Fig. 4 illustrates the progression of strains within the compressive and tensile zones of the cross-section. It should be noted that after the first slippage of the reinforcing bar, the moment-curvature curve traces the ascending portion of the backbone curve towards its initial starting point. This behavior is quite reasonable, since the strains within the reinforcing steel could not increase after the slippage occurs. The progression of the deformation is schematically shown in Fig. 5.

Algorithm for the Moment-Slip Rotation Analysis

When the slippage occured, for each increment of strain in the tensile reinforcing steel, the compression depth was calculated and its corresponding slippage value was determined. Assuming a uniform bond stress distribution between the concrete and the steel, the reinforcing strain was determined through the bond stress-slip model, incorporated in the program. During the analysis, the slip rotation was simply calculated from the following equation, which was adopted from another study (Alsiwat and Saatcioglu 1992):

$$\theta_{SLIP} = \frac{\delta_{SLIP}}{d - c} \tag{1}$$

where θ_{SLIP} is rotation due to slip, δ_{SLIP} is the slippage of the reinforcing bar, d is the effective depth and c is the compression depth of the section.

Analysis of Moment-Curvature, Bond Stress-Slip and Moment-Slip Rotation Results

As shown in Fig. 6, the backbone envelopes obtained from the experimental cyclic beam moment-curvature results and the sectional analysis were in good agreement. Additionally, the failure was controlled by the slip of positive reinforcing bar in the push side and the early shear failure within the joint in the pull side. The strain gauge readings indicated that none of the reinforcing bars in the beam had reached the yield value of 0.0021.

An average bond stress-slip backbone model was developed from the results of two beam column joint test specimens, having similar test parameters as described in the above experimental setup section. In addition to the moment-curvature relationship, comparisons were also made for the bond stress-slip (Fig. 7) and moment-slip rotation relationships (Fig. 8) between the results of the present experimental study and an existing bond stress-slip model in the literature proposed by Harajli and Mabsout (2002). Figs. 7 and 8 illustrate the comparative analysis of bond stress versus slip, and moment versus slip rotation curves obtained through analytical model developed by Harajli and Mabsout and the current experimental study. As it is observed, the model by Harajli and Mabsout underestimated the slip at the same drift levels. This may be due to the fact that their developed model was based on monotonically loaded reinforcing bars. However, in the present experimental study, the reinforcing bars were subjected to the cyclic loading. It is worth to mention that from the current experimental study plot of bond stress versus slip in Fig. 7, the maximum bond stress of only 7.1 MPa was achieved at drift level of 0.5% while the maximum slip of 12.2 mm was occurred at 1.75% drift.

Conclusions

The following conclusions were deducted from the experimental and numerical analysis of bond slip model for the reinforced beam-column joint with short embedment length and inadequate lateral reinforcement at the joint:

1. It was observed that the cyclic loading increases the slippage of the reinforcing bar within the same drift level.
2. In general, the developed numerical model for this study and the experimental results were in good agreement. However the existing bond stress-slip model proposed by Harajli and Mabsout underestimated the experimental bond stress-slip results and the resulting rotations due to slip.
3. The present study contributes to the understanding of bond behavior of the beam-column joint subassemblies when subjected to realistic loadings scenario including cyclic loading.

Acknowledgments

The financial supports for this project have been provided by the National Science Foundation (USA) grant number OISE-0352947, TUBITAK (Turkey) grant number ICTAG-I597, and Bogazici University Research Fund grant number 05A401.

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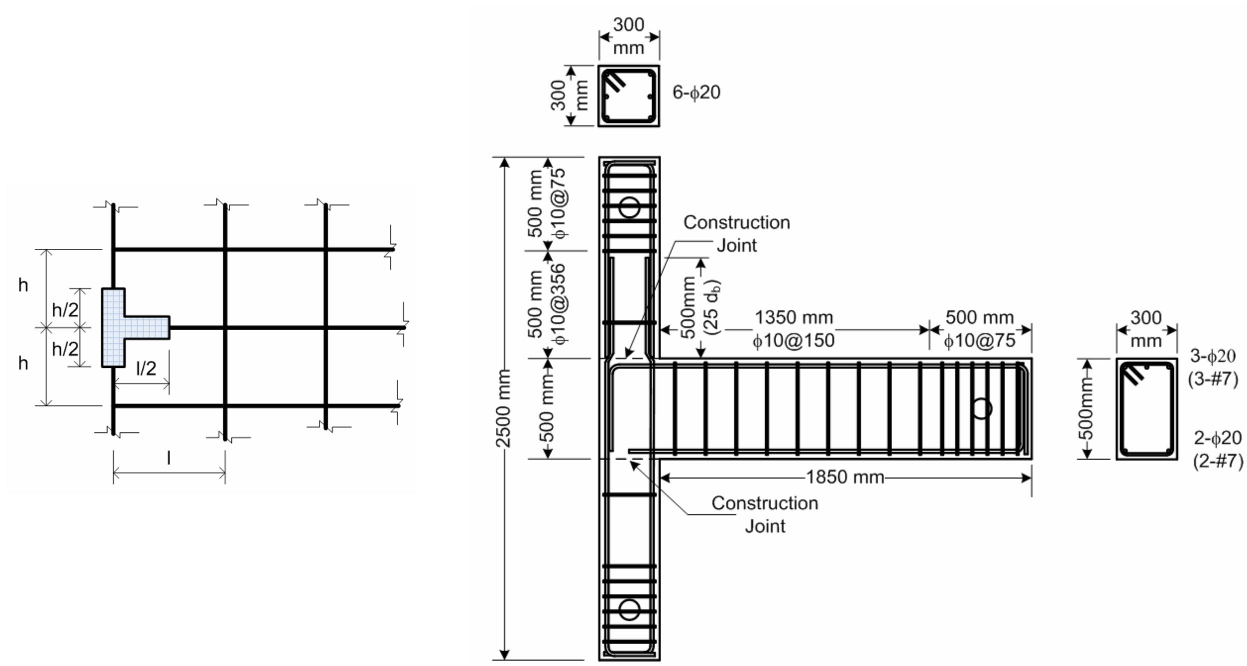

(a) Side-view of the beam-column joint in a typical building frame

(b) Reinforcement detail

Figure 1. The specimen and reinforcing details.

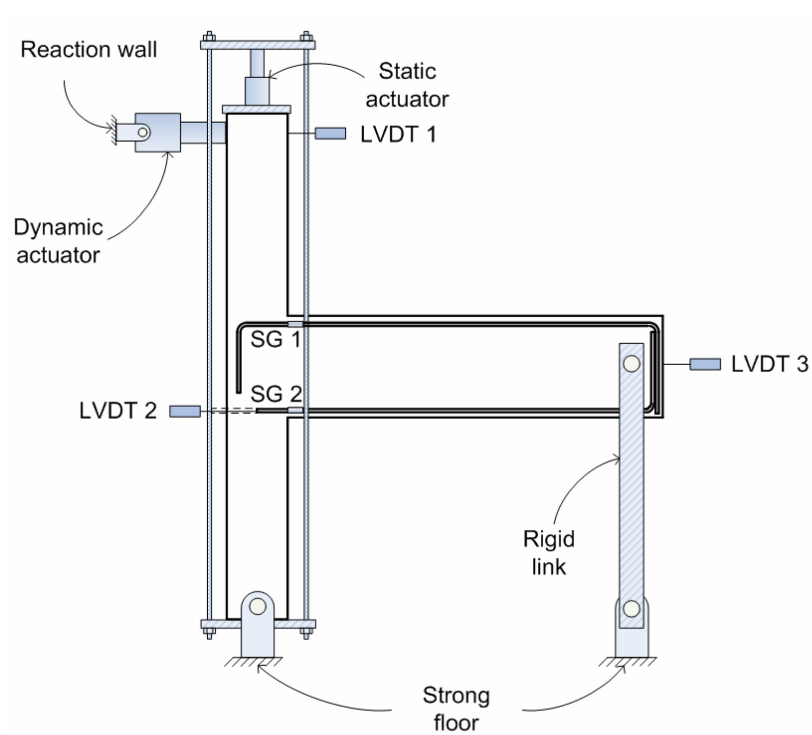

Figure 2. Test-setup and instrumentation details.

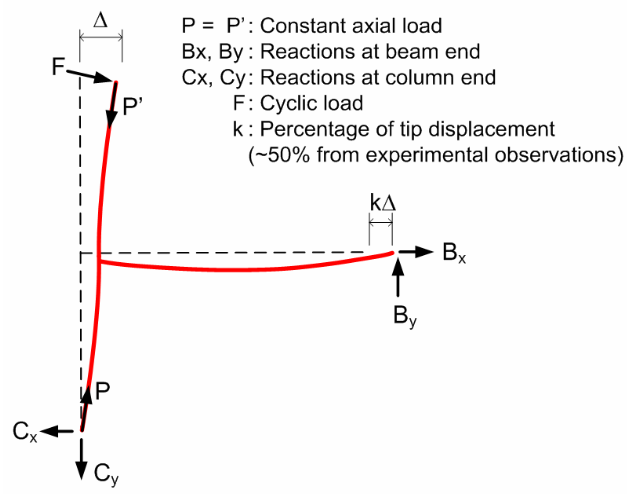

Figure 3. Free body diagram of test specimen.

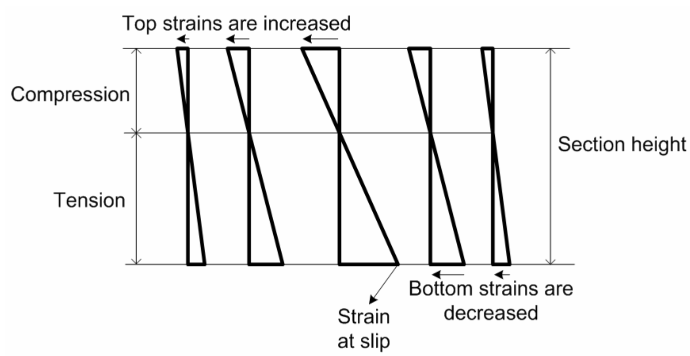

Figure 4. Progression of steel strains along the cross-section.

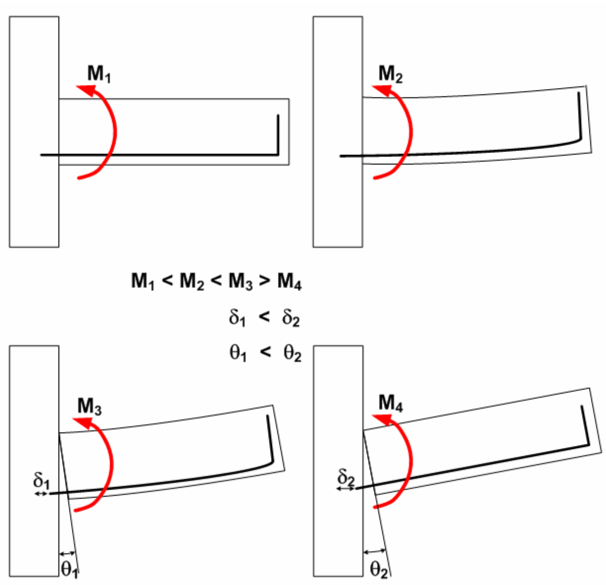

Figure 5. Progressive deformed shape of the beam member.

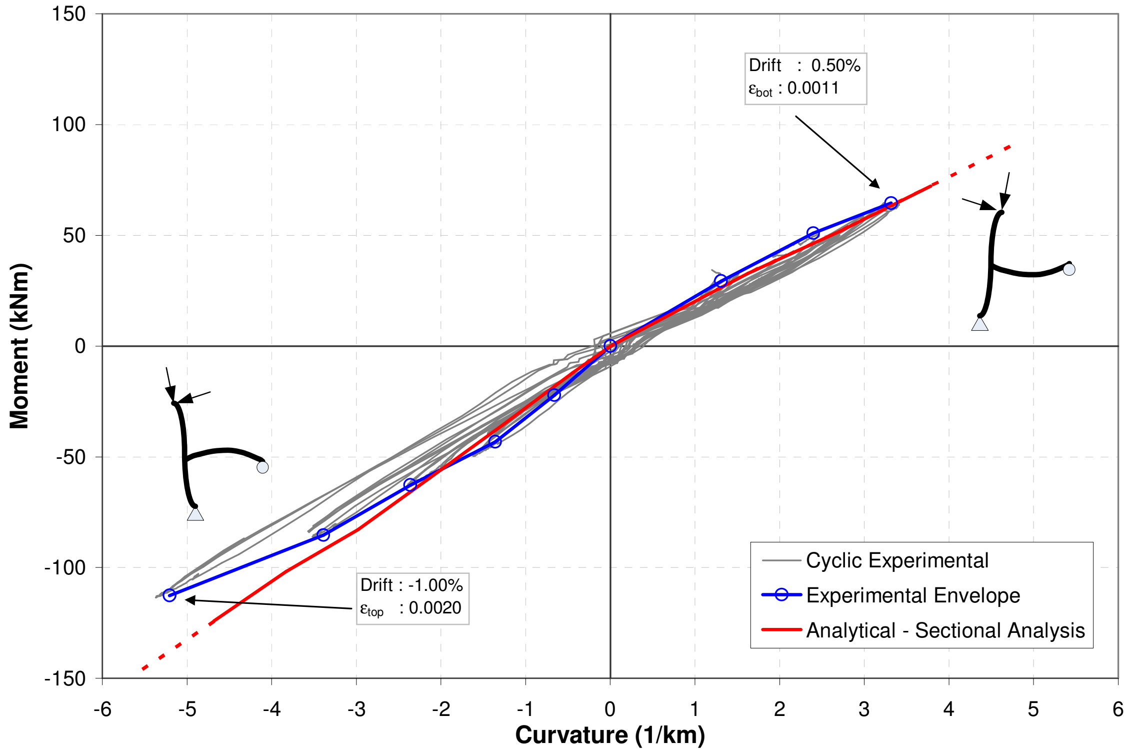

Figure 6. Moment-curvature relationship.

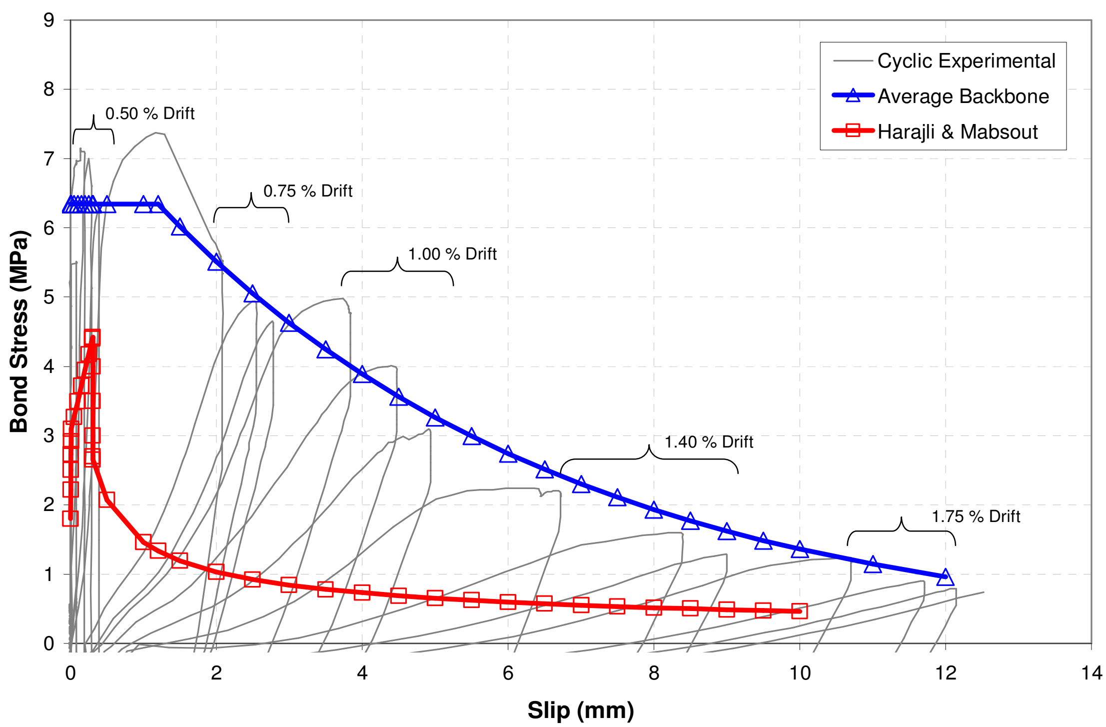

Figure 7. Bond stress-slip relationship.

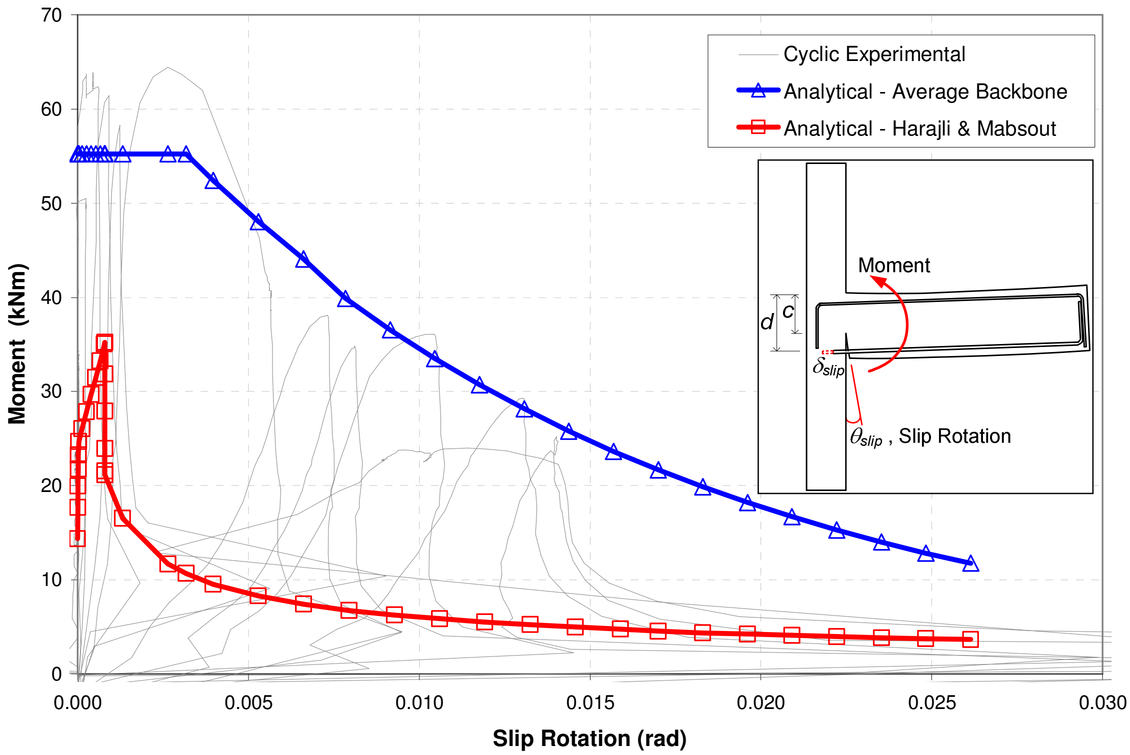

Figure 8. Moment-slip rotation relationship.