Energy Dissipation of RC Interior Beam-Column Connections and Hysteresis Model

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SUMMARY:
Under earthquake loading, the cyclic response of beam-column joints significantly affects the overall response of the reinforced concrete moment frames. In the present study, cyclic test results of 54 interior beam-column joint specimens were investigated to evaluate the energy dissipation capacity. The energy dissipation capacity of the joints correlated well with the bond resistance of the beam re-bar at the joint. On the basis of the results, the energy dissipation capacity of the RC joints was defined as a function of the bond resistance at the joint. Then, a simplified hysteresis model for the joints was developed in a manner such that the actual energy dissipation ratio was the same as the predicted energy dissipation ratio. For verification, the proposed model was compared with the existing test results for interior joint specimens.

Keywords: RC beam-column joint, Energy dissipation capacity, Simplified hysteresis model

1. INTRODUCTION

In reinforced concrete (RC) moment-resisting frames, the overall earthquake resistance is significantly affected by the behavior of the beam-column connections. According to previous studies(Leon, 1989; Soleimani et al., 1979), the connection behavior is significantly affected by bond-slip of the beam re-bars, and diagonal shear cracking at the beam-column joint. When bond-slip and diagonal cracking occur, unloading/reloading stiffness and energy dissipation are significantly degraded. In the present study, the design parameters that are closely related to the hysteretic energy dissipation were investigated by using existing test results. Then, the load-deformation relationships of beam-column connections were defined with the design parameters.

2. RELATIONSHIP BETWEEN ENERGY DISSIPATION AND BOND RESISTANCE

In current design code ACI 318-11, the bond resistance of deformed bars is defined as the ratio of the embedment length of the beam re-bars and square root of concrete strength $\sqrt{f'_c}$ (MPa) to the bar diameter d_b and strength of the beam re-bars f_y (MPa). The embedment length indicates the column depth h_c for interior connections.

For interior beam-column connections,

$$h_c \geq \alpha \frac{f_y}{\sqrt{f'_c}} d_b \tag{2.1}$$

Where α = coefficient related to the deformed bars in compression and tension; (= 0.24 ~ 2.04). In Eq. (2.1), the major design parameters that are involved in the bond resistance of beam re-bars are

$(h_c/d_b)(\sqrt{f_c'}/f_y)$ for interior beam-column connections.

By investigating existing test results of beam-column connections, the relationship between hysteretic energy dissipation and the design parameters relevant to bond resistance was studied. Existing cyclic test results of 54 cruciform beam-column connections satisfying $\Sigma M_{nc} / \Sigma M_{nb} \geq 1.2$ were used for the investigation. The concrete strengths were f_c' = 24.0 ~ 88.2 MPa. The yield stresses and diameters of beam re-bars were f_y = 276 ~ 710 MPa and d_b = 9.5 ~ 35.8 mm.

Fig. 1 shows the definition of the energy dissipation ratio κ of a beam-column connection. The energy dissipation ratio κ is defined as the ratio of the actual energy dissipation E_{II} per load cycle to the idealized elastic-perfectly plastic energy dissipation E_{ep}. According to ACI 374.1-05, the energy dissipation ratio κ was calculated using E_{II} corresponding to the third load cycle at the lateral drift ratio $\delta \approx$ 3.5 %. When the number of load cycles repeated at δ = 3.5 % was less than three, the energy dissipation ratio was calculated for the first or second load cycle. When a specimen failed before δ = 3.5 %, or when the peak strength of the second or third load cycle was less than 90 % of that of the first load cycle, the energy dissipation ratio was evaluated at a lateral drift ratio less than δ = 3.5 %. In the calculation of E_{ep}, the yield stiffness k_y was defined as 75 % of the positive and negative peak strengths, $0.75P_P$ and $0.75P_N$ (Park, 1988).

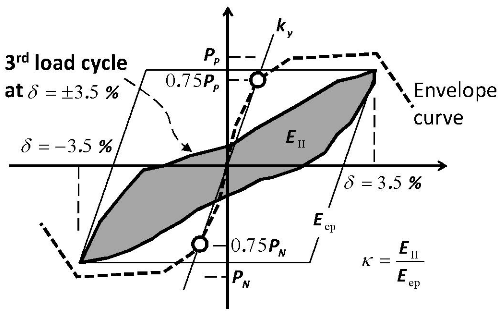

Figure 1. Definition of hysteretic energy dissipation (ACI 374.01-5)

Fig. 2 shows the relationships between the bond resistance and energy dissipation ratio κ for the interior beam-column connection. As shown in Fig. 2, the energy dissipation ratio κ correlated with the bond resistance.

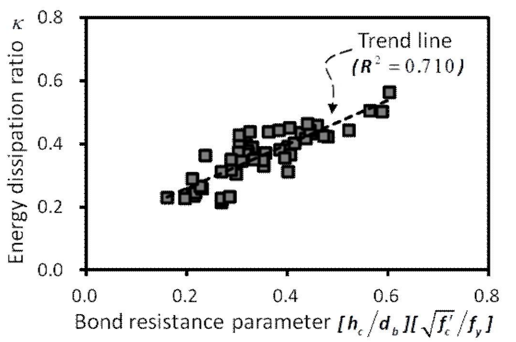

Figure 2. Relationship between bond resistance and energy dissipation ratio

On the basis of the result shown in Fig. 2, the energy dissipation ratios κ of the interior beam-column connection was defined as the functions of the bond resistance.

$$0.16 \le \kappa = 0.70 \frac{h_c}{d_b} \frac{\sqrt{f'_c}}{f_y} + 0.118 \le 0.56 \tag{2.2}$$

In Eq. (2.2), on the basis of the test results, the minimum and maximum energy dissipation ratios κ were proposed as 0.16 and 0.56 for the interior connections.

3. HYSTERESIS MODEL

Fig. 3 shows the proposed models for structural analysis of interior beam-column connections. The proposed model consists of an elastic beam-column element and a plastic rotational spring element. The elastic beam-column element describes the elastic flexural responses of beams and columns. The plastic rotational spring element represents the overall plastic deformation angle.

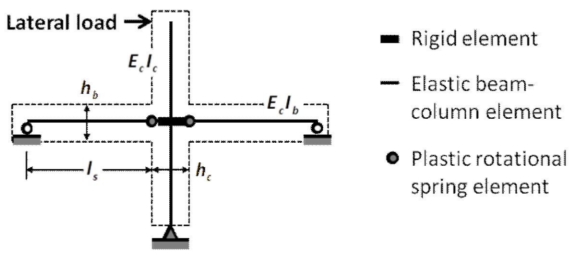

Figure 3. Simplified model for interior connections

The energy-based hysteresis model was defined such that the predicted hysteretic energy dissipation of the connection is the same as the area enclosed by a load cycle of the cyclic curve. The proposed model was developed by modifying the Pinching4 model in OpenSees.(Mazzoni et al., 2006) The hysteresis model consists of an envelope curve(Fig. 4) and a cyclic curve(Fig. 5). The envelope curve is defined as the moment-plastic deformation angle relationship by monotonic loading, addressing the initial cracking, yielding, and post-yield strain hardening behavior of the beam-column connection. The cyclic curve describes the unloading/reloading behavior and the stiffness- and strength-degradations during repeated cyclic loading.

Fig. 4 shows the characteristic points defining the envelope curve. EC, EY, EU, and EF denote the initial cracking, yield, ultimate, and failure points, respectively. The flexural cracking moment M_{cr} and nominal flexural capacity M_n at the critical section of the beam are used for the moments at EC and EY, M_c and M_y, respectively.

$$M_c = M_{cr} = 0.63\sqrt{f'_c}\, I_g / y_t \tag{3.1}$$

where y_t = distance between the neutral axis and the far tension end

$$M_y = M_n \tag{3.2}$$

The moment M_u at EU and the residual strength M_f at EF can be defined as functions of the nominal flexural capacity M_n.

$$M_u = \beta_u M_n = 1.25 M_n \tag{3.3}$$

$$M_f = \beta_f M_n = 0.2 M_n \tag{3.4}$$

For simplicity, $\beta_u \approx$ 1.25 can be used, by assuming the strain-hardening stress $\approx 1.25 f_y$.(ACI 318, 2011) The residual strength of the connection was determined as β_f = 0.2 according to FEMA 356.

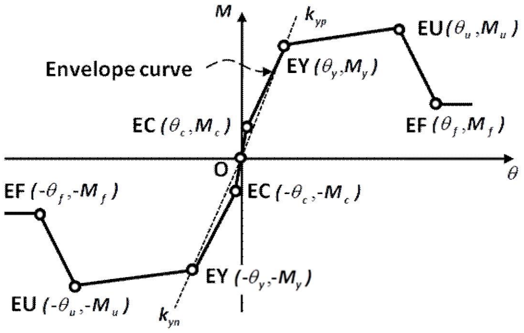

Figure 4. Envelope curve for a plastic rotational spring element

The plastic rotational spring element only represents the pure plastic deformation angle of the connection. On the basis of the existing test results, the cracking angle and yield rotation were determined as θ_c = 0.0002 rad and θ_y = 0.002 rad. FEMA 356 (FEMA 356, 2000) defines the plastic rotation angle at the beam plastic hinge θ_{bu} and the plastic shear angle at the beam-column joint θ_{ju} separately, depending on the re-bar detail and load condition. On the other hand, the plastic rotational spring element of the proposed model represents the overall plastic deformation angle of the connection. Therefore, θ_u at the ultimate point **EU** of the rotational spring element is defined as $\theta_u = \theta_{bu} + \theta_{ju}$. The plastic deformation angle θ_f at the failure point EF, defining the post-peak descending slope of the envelope curve, was defined as $\theta_f = 2.0\theta_u$.

Fig. 5 shows the cyclic curve of the moment-plastic deformation angle relationship, connecting six characteristic points CP, C1, C2, CN, C3, and C4. CP and CN denote the positive and negative peak points, respectively, where the unloading/reloading behavior begins. C2 and C4 denote the points where the unloading stiffness significantly decreases. C1 and C3 denote the points where the reloading stiffness is recovered. The unloading behavior continues from CP and CN to C2 and C4, respectively, where the moments are zero (M_{c2}=M_{c4}= 0). The unloading stiffnesses k_{up} and k_{un} are defined as

$$k_{up} = (1 - 0.05 \times i) k_{yp} \geq 0.2 k_{yp} \quad \text{and} \quad k_{un} = (1 - 0.05 \times i) k_{yn} \geq 0.2 k_{yn} \tag{3.5}$$

where k_{yp} and k_{yn}= secant stiffness connecting point O and the positive and negative yield points EY, respectively. In the present study, the degradation of the unloading stiffness is defined as the function of the number of load cycles, i (= 0, 1, 2, …), accumulated during entire loading history.(Mazzoni et al., 2006)

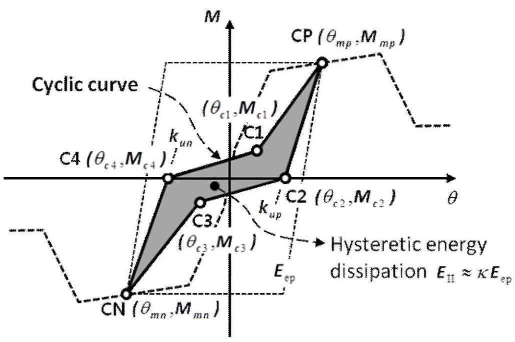

Figure 5. Cyclic curve for a plastic rotational spring element

As shown in Fig. 5, the values at C2-C3 and C4-C1 are affected by the hysteretic energy dissipation of the beam-column connection. Therefore, the moments and plastic deformation angles at C1 and C3 should be determined by the predicted energy dissipation capacity in Eq. (2.2). The values (θ_{c1}, M_{c1}) and (θ_{c3}, M_{c3}) are defined as follows:

$$\theta_{c1} = (-0.95\kappa + 0.5)\theta_{mp} \text{ and } \theta_{c3} = (-0.95\kappa + 0.5)\theta_{mn} \tag{3.6}$$

$$M_{c1} = (1.5\kappa - 0.12)M_{mp} \text{ and } M_{c3} = (1.5\kappa - 0.12)M_{mn} \tag{3.7}$$

Where (θ_{mp}, M_{mp}) and (θ_{mn}, M_{mn}) = plastic deformation angles and moments at the peak points CP and CN, respectively, where the unloading/reloading behavior starts; and κ is the energy dissipation ratio ($0.16 \le \kappa \le 0.56$).

4. APPLICATIONS

The proposed hysteresis model was applied to existing interior connection specimens. The modeling parameters of the specimens are presented in Table 4.1. The connection specimens exhibited significantly different energy dissipation in the cyclic responses, depending on the bond resistance parameter $(h_c/d_b)(\sqrt{f'_c}/f_y)$.

Table 4.1. Modeling parameters for existing test specimens

Specimens		Bond resistance parameter	Modeling parameter			
		$\frac{h_c}{d_b}\frac{\sqrt{f'_c}}{f_y}$	κ [1)]	λ_θ	λ_M	θ_u (rad.)
Interior	Durrani S3	0.292	0.323 (0.324)	0.193	0.365	0.040
	Brooke 4B	0.324	0.345 (0.369)	0.172	0.398	0.040
	Xian U4	0.437	0.424 (0.416)	0.097	0.516	0.040

1) The values inside the brackets are the energy dissipation ratios calculated from the test results.

As shown in Fig. 3, the interior connection was modeled with elastic beam-column elements, plastic rotational spring elements, and rigid beam-column elements. In the elastic beam-column element, to consider the effect of flexural cracking, $0.35E_cI_g$ (E_c= modulus of concrete (= $4700\sqrt{f'_c}$) and I_g= second-order moment of inertia of the gross cross section) was used for the flexural rigidity of both columns and beams, as specified in ACI 318-11.

Fig. 6 compares the test results and the proposed cyclic responses. The figure shows the energy dissipation ratios $\kappa_{Pred.}$ and κ_{Test}. $\kappa_{Pred.}$ denotes the energy dissipation ratios predicted from Eq. (2.2) using the bond resistance parameter. The ratios of $\kappa_{Pred.}/\kappa_{Test}$ were 0.93 ~ 1.02, which indicates that the proposed hysteresis model describes the test results well. The results in Fig. 6 show that the simplified analysis model using elastic beam-column elements and lumped plastic hinges at the joint face can be used to describe the complicated cyclic response of the beam-column connections affected by flexural yielding of beams, bond-slip of beam re-bars, and diagonal cracking at the joint.

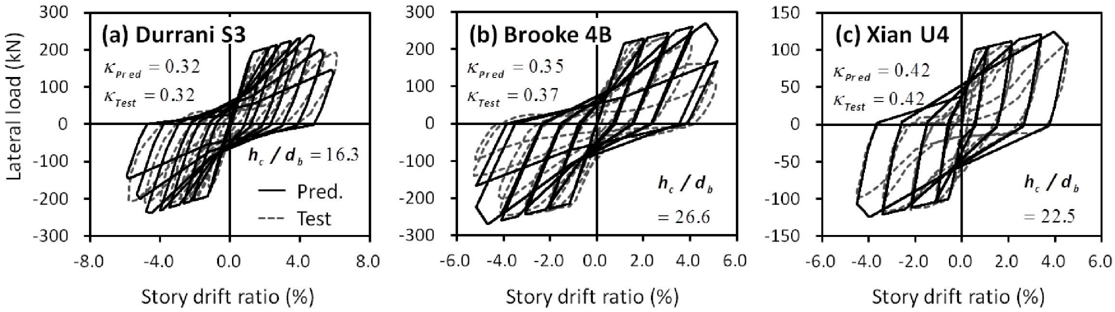

Figure 6. Cyclic responses for interior beam-column connections

5. CONCLUSIONS

The major conclusions of the present study are summarized as follows.

1) The hysteretic energy dissipation ratio κ of interior connections increased in proportion to the bond resistance parameters $(h_c/d_b)(\sqrt{f_c'}/f_y)$. The bond resistance parameters were defined as a function of the hysteretic energy dissipation demand, so that the function can be used for the performance-based earthquake design of beam-column connections.

2) The simplified analysis model using elastic beam-column elements and lumped plastic hinge elements at the joint face predicted the cyclic response of existing test specimens with reasonable precision. The proposed method can be conveniently used for inelastic numerical analysis of reinforced concrete moment frames.

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