Analysis of rc frames with cracked interfaces 
beam-column joints under earthquake excitations
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Abstract

The analysis of rc structures subjected to earthquake ground motion is carried out. After the cracking of the interface, the beam-column joints are modelled with rotational connections with stiffness depending on the bond-slip of the anchored bars in the joints and on the plastic strains of the rebar. Although the attention is principally focused to the modelling of the beam-column joints, all structural members are considered with elasto-plastic stress-strain laws. The moment-rotation envelope of the rotational connections obtained from the dynamic analysis can be utilised to evaluate the slip of the reinforcing bars in order to avoid bond damage in the joints.

1 Introduction

During severe earthquake it is an accepted design philosophy to allow structure to exceed elastic limit so that a considerable amount of energy is dissipated by inelastic behaviour.

In reinforced concrete structures the cracking of the interfaces of mating members causes slip of the anchored bars in the joint and hence beam fixed-end rotations. These fixed-end rotations
contribute significantly to the overall deflection of the structure [1-2]. This problem is more marked for interior beam-column joints since the top and bottom anchored bars of the beams, running through the joint, are simultaneously pulled and pushed at the opposite sides of the joint (the moments of the beams in each joint are simultaneously clockwise or counter-clockwise (see Fig.1)).

![Figure 1: Interior beam-column joint.](image)

Due to the moment reversal bond damage of the anchored bars occurs. The bond damage process increases with increasing cycles magnitude tending to destroy the anchorage. To prevent collapse it is important to avoid greater slip of the bar anchored in the joint since to greater slip correspond greater values of the bond damage [3]. The hazardous condition of destroyed anchorages is not considered in this study since the major attempt is to provide a better interpretation of the behaviour of earthquake resistant structures after the cracking of the concrete at the beam-column interface joints.

2 Beam-column interface model

In the process of the pull-out bar anchored in the beam-column joint the concrete around the bar between the lugs is subjected to strong compression stresses and cracks, inclined of about 40-45° from the
bar axis, arises from the lugs [4]. These cracks, in the unconfined concrete region of the joint, can reach the cracked interface of the beam-column joint. Hence, a pull-out concrete cone arises with depth depending principally on the width of the concrete cover (unconfined concrete) [5]. In this cone the bond is completely destroyed and for a bar working in tension beyond the yield stress plastic strains characterise the end slip of the bar if the bond damage has not been occurred in the confined concrete region of the joint. In this case, the end slip due to the plasticity of the bar is about 80% of the total slip and the remaining part is due to the bond-slip in the confined concrete region of the joint.

With reference to Fig.1, the relative rotation, \( \vartheta \), of the beam with respect to the column face is given

\[
\vartheta \approx \frac{u_t - u_b}{h}
\]  

where \( u_t, u_b \) = end slip of the pulled and pushed bar respectively; and \( h \) = distance between top and bottom bars.

By neglecting the slip of the pushed bar because is very small [5] the relative rotation is given

\[
\vartheta \approx \frac{u_t}{h}
\]  

Taking previous considerations into account, the slip of the pulled bar is given by

\[
u_t \approx \frac{\varepsilon l_s}{0.8}
\]

where \( \varepsilon \) = steel strain of the pulled bar and \( l_s \) = depth of the concrete cone.

The rotation equilibrium at the interface provides

\[
M = \sigma A_l z
\]
where $M$ = moment; $\sigma$ = steel stress; $A_f$ = area of the pulled bars; and $z$ = distance between the pulled bar and the centroid of the compression force of the cracked section, that can assumed approximately to be equal to $h + \frac{c}{2}$ being $c$ the concrete cover of the beam.

By considering a bilinear stress-strain relationship for the steel reinforcement, Eq.4 becomes

$$M = E_0 \varepsilon A_f h \quad \varepsilon \leq \varepsilon_y$$

(5)

$$M = \left[E_0 \varepsilon_y + E_1 (\varepsilon - \varepsilon_y)\right] A_f h \quad \varepsilon > \varepsilon_y$$

(6)

where $\varepsilon_y$ = yield strain of the steel; and $E_0, E_1$ = elastic and strain hardening moduli.

The relative rotation of the beam with respect to the column is given by

$$\theta = \frac{u_t}{h} \equiv \frac{\varepsilon l_i}{0.8h}$$

(7)

The moment rotation stiffness of the rotational connection is given by

$$\frac{dM}{d\theta} = \frac{dM}{d\varepsilon} \frac{d\varepsilon}{d\theta}$$

(8)

Eq.8, by means of Eqs 5-7, provides

$$K_1 = \frac{0.8E_0 A_f h^2}{l_i}$$

(9)

$$K_2 = \frac{0.8E_1 A_f h^2}{l_i}$$

(10)
Where $K_1, K_2 = \text{stiffness of the rotational connection before and after the yielding of the reinforcement.}$ Before the cracking of the interface, the rotational connection is not activated. In the unloading stage the stiffness $K_1$ is used in similar way of the bilinear model of the steel. In Fig. 2 the moment rotation relationship of the beam-column interface is reported.

![Figure 2: Moment-rotation relationship of the cracked interface](image)

### 3 Analysis of rc frames

The analysis is carried out for the two frames reported in Fig. 3. For these structures is assumed (see Fig.3): $H=3000 \text{ mm}$; $L=5000 \text{ mm}$; and $T=4000 \text{ mm}$. All beams have cross-section 300 mm width and 500 mm depth with 4 symmetrical reinforcing bars of 14 mm diameter, whereas all columns have cross-section 300 width and 400 mm depth with 4 symmetrical reinforcing bars of 14 mm diameter. Concrete strength is 35 MPa whereas tensile strength of the concrete is 3 MPa. Concrete Young modulus is 35000 MPa. The distributed transverse load acting on the beam is 19.6 N/mm. By considering the depth of the cone 50 mm [5] we obtain $K_1 = 1.5 \times 10^{11} \text{ Nmm}$ and $K_2 = 7.5 \times 10^9 \text{ Nmm}$.

The El-Centro 1940 earthquake ground motion is assumed for the analysis.

In Fig. 4 for the simple portal frame of Fig. 3 envelope of the total shear at the base versus displacement of the top of the portal is reported. In Fig. 5 the moment-rotation envelope for the connections of the portal frame is reported.
Fig. 6 shows the envelope of the total shear at the base of the structure versus displacement of the second floor of the structure of fig 3 whereas, Fig. 7 shows the envelope moment-rotation of the left side connection of the interior beam-column joint at the second floor.

From the moment-rotation envelope we can calculate the slip of the bar (Eq.2). Taking into account that the slip at the transition between the confined and unconfined concrete regions is about 20% of the total slip, it is possible to evaluate if good bond conditions yet exists in the confined concrete region. To avoid not negligible bond damage it is necessary that the slip at the end of the cone near the confined concrete region is not greater than the 80% of the one corresponding to the maximum bond stress-slip relationship [3]. The maximum slip that not must be reached at the end of the confined concrete is about 0.65mm for usually reinforcing bars [6-7]. The slip at end of the confined concrete region of the joint of the portale frame is 0.051 mm, whereas for the joint of the structure
Figure 4: Total shear at the base versus displacement of the portale.

Figure 5: Moment versus rotation of the cracked interface.
at the second floor is 0.055 mm. These values of slip ensure that the bond damage in the confined concrete joint is negligible.

![Graph](image)

Figure 6: Total shear at the base versus displacement at the top.

### 4 Conclusions

A cyclic connection beam-column joint to model cracked interfaces based on bond-slip and plastic strains of the reinforcement anchored in the joint has been developed. The parameters which the model depends can be easily determined from the geometrical characteristics of the beam-column joint and from the mechanical properties of the reinforced concrete.

The model can be utilised after the dynamic analysis to evaluate the slip at the end of the confined concrete region of the joint in order to evaluate if bond damage occurs. The model can also be utilised to design anchorages of joints of earthquakes resistant structures.
Figure 7: Moment-rotation for the left side internal cracked connection at the second floor.

References


