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Cyclic Behaviour of Lightly Reinforced Beam-To-Column Joints

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SUMMARY

To clarify the effect of joint detailing on the seismic performance of lightly reinforced concrete frames, an experimental study was undertaken. The parameters studied were the effect of joint rotation, column axial load, cross-reinforcement in the joint, the percentage of longitudinal reinforcement in the beam and the loading history. It was found that allowing free joint rotation leads to an increase in the ductility and energy dissipation capacity of RC frames. The cross-reinforcement in the joint reduced the damage in the joint region but stiffens the joint leading to crack formation at the column face thereby reducing the ductility and energy dissipation capacity of the frame. The ductility and energy dissipation capacity increase with a decrease in the percentage of longitudinal reinforcement. The presence of axial load in the column not only increases the strength and ductility but also reduced the damage in the joint region. A damage index based hysteretic model is proposed. The model can simulate the degradation of strength and stiffness as well as the pinching effect. The advantages of the proposed model over other existing models are highlighted.

INTRODUCTION

Reinforced concrete frames are designed as per Capacity design Philosophy wherein ductile failure modes are preferred as against brittle failure modes. At the structure level this translates into a preference for the so-called global failure mechanism wherein plastic hinges form in the beams rather than in the columns thereby minimising the curvature ductility required at the sections and maximising the total energy dissipation capacity of the frame. One way of achieving a global failure is to go for a strong column-weak beam (SC-WB) design. At the member level, the same philosophy requires that brittle failure modes such as shear and bond failure are precluded. Thus, additional shear reinforcement at the hinging location and additional bond lengths can be used.

Although the principles of capacity design are well understood, translating them into practice can be quite difficult, if not impossible. Beam-column joints are critical regions in frames and are subjected to complex shear and bond forces. Failure of the joint region can not only damage the column load paths but also adversely affect the ductility and energy dissipation capacity of the frame as a whole. The size of the

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members and joints and the amount of reinforcement required to obtain a desired level of ductility are difficult to determine. Some work in this direction has been done with respect to Ductile Moment Resisting Frames (DMRF) which are used in regions of high seismicity. However, in regions of low seismicity, frames with limited (restricted) ductility are used where the member and joint sizes as well as the amount of reinforcement are moderate. Further, the free rotation of the joints in such frames is often restricted by strong in-fill walls. Such frames are likely to develop problems in their joint regions, which need to be understood. Thus, it is necessary to study the inelastic cyclic behaviour of lightly reinforced beam to column joints.

Several experimental studies have been carried out in the past to understand the behaviour of beam-to-column joints,. Bertero[1] summarized the results of available experimental studies and advocated closely spaced stirrups and extra anchorage lengths to prevent shear and bond failures. Uzmeri[2] carried out tests on beam-column joint subassemblages by applying axial load to the columns. He also observed cracking at the beam-column joint line. Lee[3] studied the cyclic behaviour of reinforced concrete T-joints with light and heavy shear reinforcement in the joint region. They also studied the effect of column axial load on the damage pattern. Based on the test results, they concluded that the specimens with heavy shear reinforcement in the joint had less load degradation compared with the one with light joint reinforcement. They also found that axial load in the column reduced the damage in general and reduced damage in joint region in particular. Paulay[4] and Leon[5] studied the cyclic performance of interior beam- column joints and arrived at the conclusions that shear and bond failure of the joint is primary causes for concern. They can be however be minimized by providing adequate shear reinforcement and bond lengths. More recently Murty[6] tested reinforced concrete T-joints with various anchorage and shear reinforcement detailing. In addition they varied the relative size of beam and column and found that a bigger column size gives well-rounded hysteretic loops. Their work also emphasizes the need for extra shear reinforcement in the joint.

In order to clarify the hysteretic behaviour of lightly reinforced beam to column joints, an experimental programme was undertaken. The effect of joint rotation, column axial load, cross-reinforcement in the joint and the percentage of longitudinal reinforcement in the beam on the ductility and energy dissipation capacity of the frames were studied. The damage sustained is evaluated and correlated with observed damage. A damage index based hysteretic model is proposed and guidelines are given to calibrate the model for use in inelastic cyclic analyses. The model can simulate the degradation of strength and stiffness as well as the pinching effect. The response obtained from the model is compared with reported test results. The advantages of the proposed model over other existing models are highlighted.

OUTLINE OF EXPERIMENTS

The tests reported in this paper were carried out in two series. In the first series, four specimens were tested by resting the column on the strong floor while in the second series, six specimens were tested by allowing free joint rotation. Both monotonic and cyclic tests were carried out. The experimental programme is summarized in Table 1.

The specimens were T-shaped beam-column sub-assemblages, designed and detailed as per the code IS 13920[7] so that shear and bond failures can be prevented. Both the beam and the column sizes were kept identical with width b equal to 150 mm and depth D equal to 200 mm. They were also doubly-reinforced with identical reinforcement on either side. Two-legged stirrups made of 6 mm mild steel were used throughout at a spacing of 100 mm. The letter X in the specimen name indicates that additional cross-reinforcement was provided in the joint as shown in Fig. 1.

Table 1 Experimental Programme

Test	Specimen	Displacement history	Joint rotation	Other details
1	DB312M	Monotonic	Restricted	-
2	DB312C	Cyclic	Restricted	-
3	DB212116C	Cyclic	Restricted	-
4	DB212C	Cyclic	Restricted	-
5	DB212XM	Monotonic	free	-
6	DB312C	Cyclic	free	cross reinforcement in joint
7	DB312XC	Cyclic	free	cross reinforcement in joint
8	DB212116XC	Cyclic	free	cross reinforcement in joint
9	DB212AC	Cyclic	free	axial load.
10	DB312AC	Cyclic	free	axial load.

*Note: *DB212XM – Doubly reinforced beam with 2 No.s 12 mm ϕ bars with cross-reinforcement.*

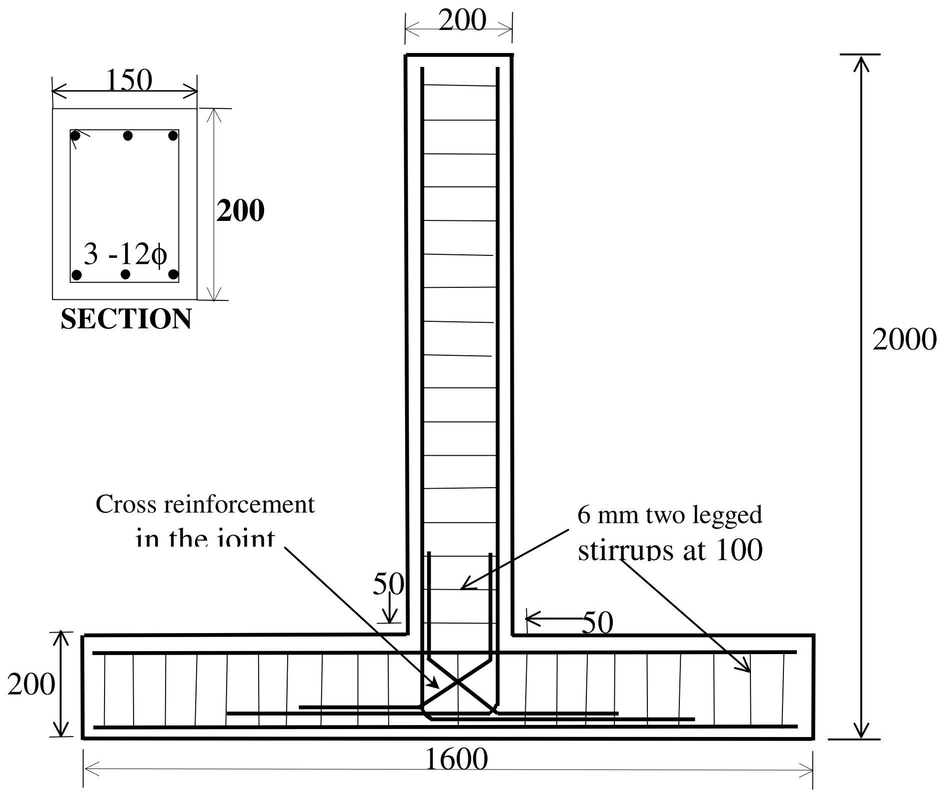

Fig. 1 Specimen Details

A nominal mix was used for concrete with the intention of obtaining a strength of around 20 MPa. Somewhat higher strengths were obtained for the second series of specimens due to higher fineness modulus of the fine aggregate. All longitudinal reinforcement was cold-rolled HYSD bars while the transverse reinforcements were made of mild steel. The average strength of concrete, as obtained from cube tests along with the yield strength of steel as obtained from tension tests are shown in Table 2.

The strengths of concrete and steel in each specimen as obtained from test results, were used to calculate the yield and ultimate strengths of the beam section. The beams were analysed by the transformed section method to obtain the cracking and yield moments while the strain compatibility method was used to obtain the ultimate moment Park[8]. These were then converted to the corresponding loads at the level of load application. The yield displacement was calculated using the secant stiffness of the cantilever, at the yield level, as advocated by Paulay[9]. These are also shown in Table 2.

The experimental setup used for the second series of tests is shown schematically in Fig. 2.
Monotonic or cyclic displacements at the tip of the cantilever beam were imposed by means of a servo-hydraulic actuator mounted horizontally and fixed to the strong wall. More details of the experimental setup can be found in Kumar [10].

Table 2 Material and Section Properties

Specimen	F_{ck} N/mm^2	F_y N/mm^2	H_y kN	M_y kN-m	δ_y mm	H_u kN	M_u kN-m
DB312M	19.6	348	5.9	10.6	5.5	9.8	17.7
DB312C	18.5	348	5.9	10.6	5.4	9.8	17.6
DB212116C	17.3	348	8.1	14.6	6.2	12.2	21.9
DB212C	26.5	348	4.0	7.2	5.9	6.8	12.2
DB212XM	34.7	503	5.3	9.5	11.2	18.9	33.9
DB312C	25.9	503	7.7	13.8	8.7	19.6	35.4
DB312XC	27.0	503	7.7	13.8	8.9	20.1	36.0
DB212116XC	31.6	503	9.6	17.2	9.8	24.0	43.3
DB212AC	29.2	503	5.2	9.4	8.7	17.0	30.7
DB312AC	25.4	503	4.8	7.2	6.5	15.1	27.2

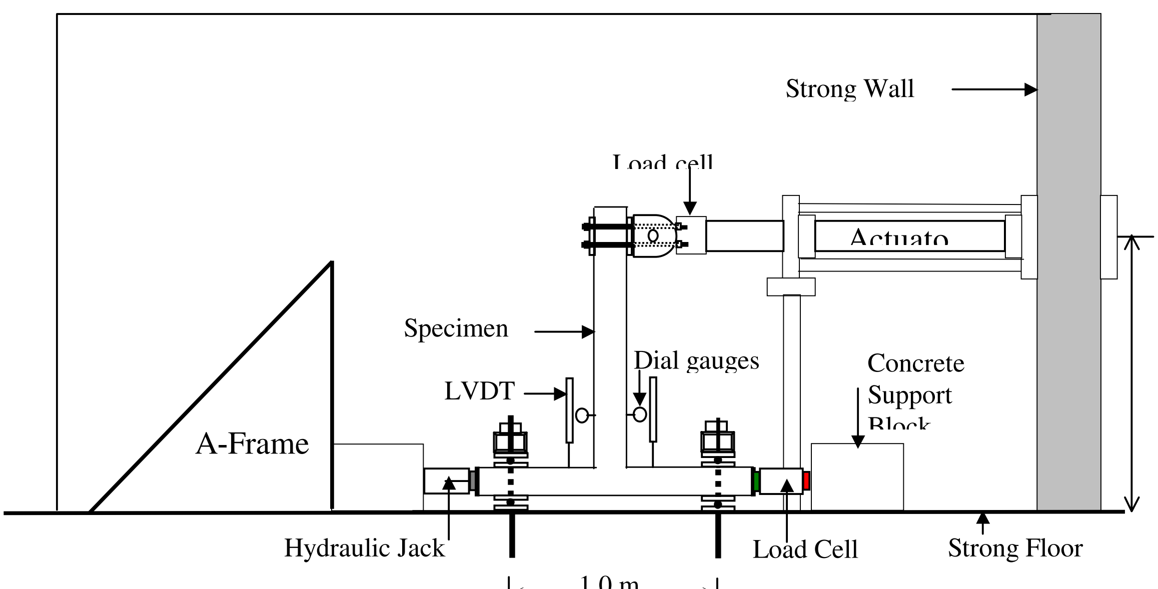

Fig.2 Experimental Setup

All the tests were done in a quasi-static manner. Test Nos. 1 and 5 were carries out by increasing the displacement monotonically. The cyclic tests were done as incremental cyclic tests. In Test Nos 2, 3 and 4, three cycles were imposed at each amplitude level after which the amplitude was stepped up to the next level. The cyclic tests in series two had only one cycle at each amplitude level but the steps were smaller than in series one. In the last two tests a constant axial load was superimposed over the cyclic load in the columns

TEST RESULTS

In this section the test results are presented in the form of load-deformation hysteretic curves and the observations made during the test are briefly described. The hysteretic curves are non-dimensionalized using the yield load and yield displacement to make the comparison between the test results easy. Also in the case of tests where joint rotation was permitted (series 2), only the deformation due to the elastic rotation of the columns is deducted from the measured values and so the deformations due to the inelastic behaviour of the joint is included in the corrected deformations.

The load-deformation curve for the monotonic test on DB312M is shown in Fig. 3(a). The specimen attained its ultimate load at about $14\delta_y$ and thereafter its strength degraded and dropped back to the yield level at a displacement of $35\delta_y$. The specimen suffered damage in the form of a wide crack at the beam-column joint line and diagonal cracks in the joint region.

The hysteretic curves for specimens DB312C, DB212116C and DB212C are shown in Figs. 3 (b), (c), and (d) respectively. All these tests were carried out by resting the column on the strong floor which prevented free rotation of the joint. It can be seen that the curves are considerably pinched and degrading in strength and stiffness. The specimens failed by developing a major crack at the beam-to-column joint line and diagonal cracks in the joint region.

The load-deformation curve for the monotonic test on DB212XM is shown in Fig 3(e). The specimen attained its ultimate load at about $4\delta_y$ and thereafter its strength degraded and dropped back to the yield level at a displacement of $18\delta_y$. The specimen suffered damage in the form of a wide crack at a distance of d from the face of the column and the test was terminated when one of the reinforcing bars ruptured leading to a sudden drop in the strength. Although the specimen failed by developing a plastic hinge in the beam away from the joint as desired in capacity design, the formation of a single crack may not be a desirable failure mode.

The hysteretic curve for DB312C is shown in Fig. 3(f). The ultimate load is reached earlier at about $4\delta_y$ but the load is about 1.5 times the yield load on the positive side and twice the yield load on the negative side. The curve indicates moderate pinching but no degradation in strength. The specimen developed a minor crack at the beam-to-column joint line and also in the joint region. Comparison of the result with that for a similar specimen tested with restrained joint (Fig. 3(b)) indicates that joint rotation is beneficial and helps in reducing the damage in the joint.

The hysteretic curves for DB312XC and DB212116XC are shown in Figs.3(g) and 3(h), respectively. The ultimate load is reached at 3 to 5 times the yield displacement, but there is severe strength degradation leading to a reduction in the ductility. The curves are also more pinched than the one for DB312C indicating the increased stiffness of the joint due to the presence of the cross reinforcement. Both specimens developed cracks at the beam-to-column joint line but suffered minor damage at the joint itself. Since most columns will carry considerable axial load, one can expect that the damage in the joint region will be less even without the use of cross reinforcement. Therefore the use of cross-reinforcement may to limited to those columns where the axial load is low as in the top storeys.

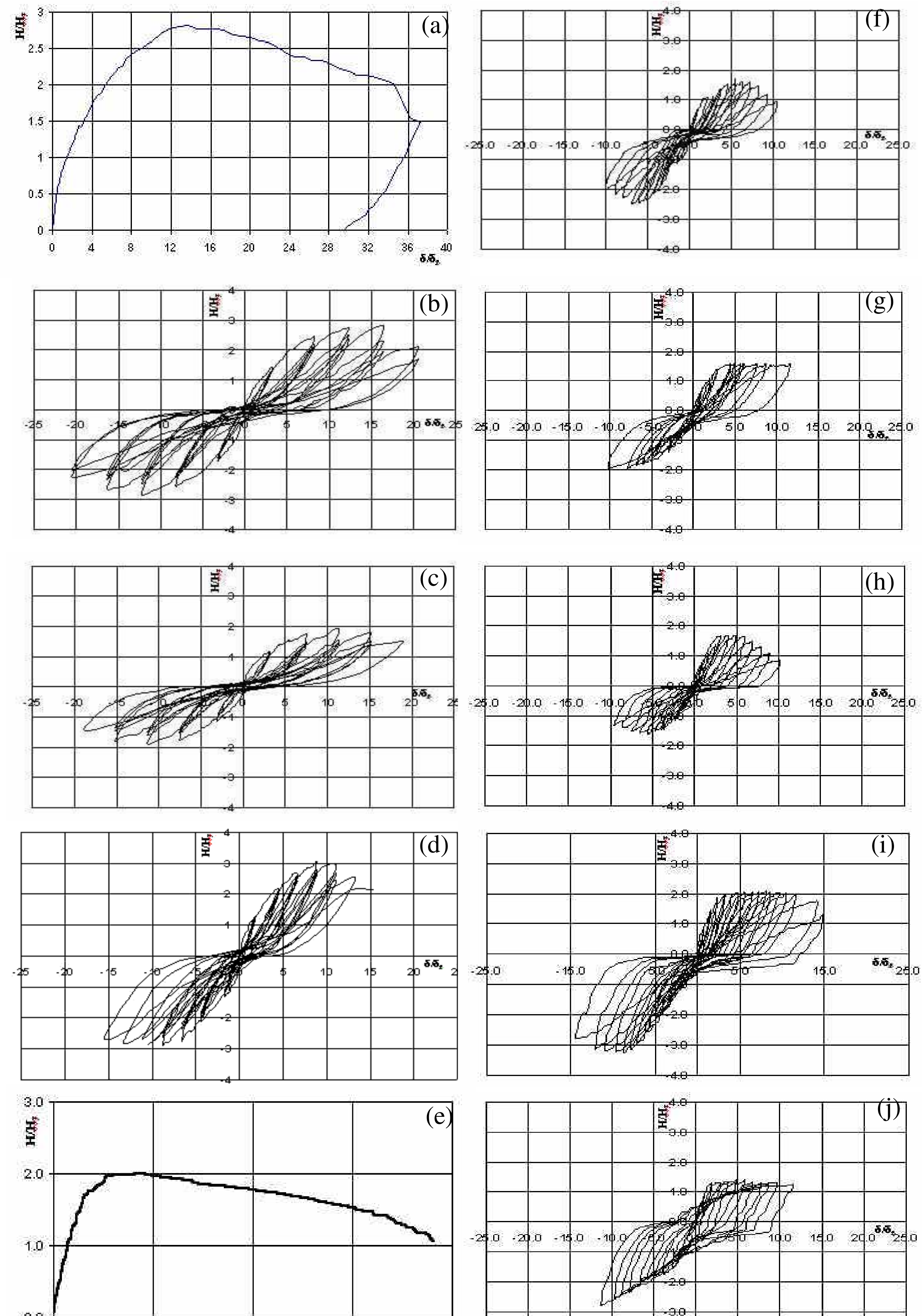

Fig. 3 Load-deflection curves – (a) DB312M (b) DB312C (c) DB212116C (d) DB212C (e) DB212XM (f) DB312C (g) DB312XC (h) DB212116XC (i) DB212AC (j)DB312AC

Comparison of the results for DB312C with DB212116 and also that for DB312XC with that for DB212116XC, indicates the well known fact that ductility increases with a reduction in the percentage of longitudinal steel.

The results of the last two tests on are presented in Figs. 3(i) and (j), respectively. While the curves for DB212AC show less pinching and no degradation, the curves for DB312AC are more pinched and exhibit some degradation at later stages. However, the presence of axial load reduced the damage in the joint region and increases the strength and ductility of the joint.

PROPOSED HYSTERETIC MODEL

It is useful to have a hysteretic model which can simulate analytically, the hysteretic behaviour of the joint. Since the degradation of strength and stiffness is a major phenomenon, it is important to be able to simulate them. Another important phenomenon is the pinching of the hysteretic loops due to the development of cracks. While most joints develop a major crack at the column face, the effect of cracks, developed elsewhere on the loop shape is also similar. However, it is well known that the rates of strength and stiffness degradation increase with increase in the damage.

The major requirements to be satisfied by any hysteretic model are that it should be easy to calibrate and it should enable the calculation of damage. Since the damage index is normalized to attain a value of unity at the assumed collapse point, the identification of the collapse point is also a major consideration.

A large number of hysteretic models are available in the literature for predicting the cyclic behaviour of reinforced concrete members. The available models include those proposed by Takeda[11], Roufaiel[12], Kunnath[13] and Chung[14]. Some of the models use predefined rates of strength and stiffness degradation while others use complicated rules to calculate the same. While the former class of models are too simple and hence unable to simulate the actual behaviour with sufficient accuracy the latter are too complicated to be of practical use. In view of this, an attempt is made in the present study to develop a model which is simple and yet capable of giving sufficiently accurate simulation of the cyclic behaviour. The proposed model is similar to that of Roufial[12] but is based on a modified Park and Ang Damage Index[15]. Thus, the model is capable of evolving its own rates of strength and stiffness degradation.

The proposed model requires the calculation of the cracking, yield and ultimate moments and curvatures, as per standard theory. In addition, the ductility under monotonic loading needs to be calculated based on the stress-strain curves proposed by Kent and Park. For confined concrete. Collapse is assumed to occur at the ultimate deformation where the corresponding strength is taken equal to the yield strength. To account for the strain hardening of the tension reinforcement, a hypothetical initial strength of twice the yield strength is assumed at zero damage and the moment-curvature curve is extended beyond the point of ultimate moment until it intersects the strength degradation curve as explained in Kumar[16].

In the first cycle, the loading curve has a slope corresponding to the cracked elastic stiffness until it reaches the yield point. Thereafter, it proceeds towards the ultimate point as calculated above with the plastic stiffness and continues with the same slope until it intersects the degrading strength curve. Unloading occurs with a degraded elastic stiffness until the load becomes zero. Crack closing is such that the line points to the initial cracking point after which, reloading occurs with the degraded plastic stiffness until the degraded strength is reached. All the degraded values are calculated as $(1-\alpha D)$ times their initial values, where α is a degradation constant and D is the modified Park and Ang damage index.

The damage index is given by

$$D = (1-\beta)\frac{\delta_{max} - \delta_y}{\delta_u - \delta_y} + \beta\frac{\sum E_i}{H_y(\delta_u - \delta_y)}$$

where, δ_{max} is the maximum deformation experienced and E_i is the energy dissipated in i-th half cycle.

The proposed model was used to simulate the test results obtained for DB312XC and the result is shown in Fig. 4. The values of α were taken as 0.5, 0.75 and 0.5 for loading stiffness, unloading stiffness and maximum strength respectively. The ductility was 16.5 and the damage index parameter β was calculated to be 0.2. It can be seen that the model predicts the observed response with sufficient accuracy.

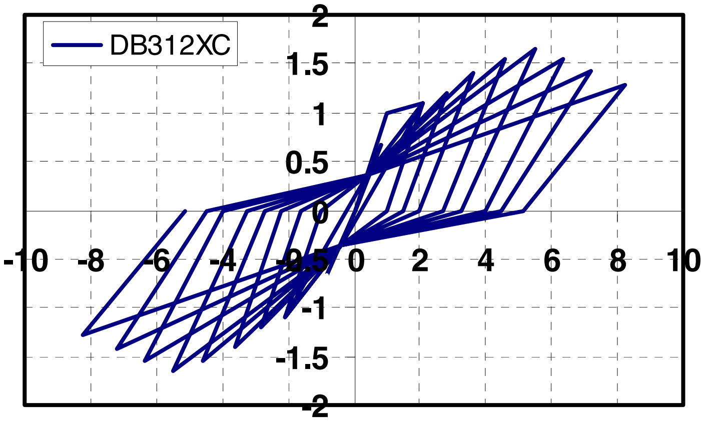

Fig. 4 Simulation of the test result using the proposed hysteretic model

CONCLUSIONS

The test results indicate that allowing free joint rotation is beneficial and leads to an increase in the ductility and energy dissipation capacity of RC frames. It also leads to a reduction in the damage in the joint region making the frames more safe and easy to repair. The ductility and energy dissipation capacity increases with a decrease in the percentage of longitudinal reinforcement as observed by other researchers in the past. The use of cross-reinforcement in the joint reduced the damage in the joint region but stiffens the joint leading to crack formation at the beam-to-column joint line thereby reducing the ductility and energy dissipation capacity of the frame. Therefore the use of such reinforcement may be limited to locations where the axial force in the columns is less. The presence of axial load in the column not only increases the strength and ductility but also reduced the damage in the joint region.

The proposed hysteretic model is simple and easy to calibrate and is able to simulate the major phenomena such as the degradation of strength, stiffness and the pinching of the hysteretic loops, observed in the cyclic response of the tested joints. In addition it gives damage indices consistent with observed damage and relates the degradation of strength and stiffness with the damage sustained.

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