6th Canadian Conf. Earthquake Engineering / Toronto / 1991 / 6ème Conf. Canadienne Sismique

Seismic performance of existing reinforced concrete frames designed primarily for gravity loads

Attila Béres[I], Stephen P. Pessiki[II], Richard N. White[III], and Peter Gergely[IV]

ABSTRACT

Full scale beam-column joint region specimens of lightly reinforced concrete frames were tested to study the seismic behavior of structures designed primarily for gravity loads. Details commonly used in the past were examined, including low percentages of longitudinal reinforcement, lap splices immediately above floor levels, widely spaced ties, and discontinuous positive beam reinforcement embedded in the beam-column joint. Fourteen interior and five exterior joints were loaded under combined constant gravity loads and reversing cyclic loads to and within simulate earthquake effects. Significant damage was concentrated close to the joint region. Interior specimens with discontinuous beam bars experienced a gradual decrease of load carrying capacity when this reinforcement pulled out. In exterior specimens, the pull-out was combined with joint shear failure and severe cracking along the splice exhibiting a less ductile behavior.

[I]Graduate Research Assistant, School of Civil and Environmental Engineering, Cornell University, Ithaca, NY, 14853.

[II]Assistant Professor, Department of Civil Engineering, Lehigh University, Bethlehem, PA, 18015.

[III]James A. Friend Family Professor of Engineering, School of Civil and Environmental Engineering, Cornell University, Ithaca, NY, 14853.

[IV]Professor of Structural Engineering, School of Civil and Environmental Engineering, Cornell University, Ithaca, NY, 14853

INTRODUCTION

There are many thousands of multi-story reinforced concrete frame structures in North America that were designed since the early 1900s without regard to significant lateral forces. The lateral load resistance of these structures is considered to be suspect for moderate to severe earthquakes because the details used are in sharp contrast to those now used in modern seismic design. In order to develop reliable seismic evaluation techniques for such frames, a research program is underway at Cornell University as part of a multi-university effort under the auspices of the National Center for Earthquake Engineering Research. The major goal is to provide a better understanding of the behavior of these kind of structures, by studying the effects of the critical parameters that influence (a) deterioration of load carrying capacity, (b) degradation of stiffness, (c) ductility, and (d) energy dissipation. Results will be used to improve inelastic dynamic analysis programs and to develop repair and retrofit schemes.

EXPERIMENTAL PROGRAM

Identification of critical details

Characteristic reinforcing details widely used in the past building construction were identified by review of ACI detailing manuals and design codes from the past five decades, along with input from practicing structural engineers. The following details were found to be typical and judged to be potentially critical to the safety of lightly reinforced concrete structures in an earthquake (Fig. 1).

1. Lapped splices of vertical column reinforcement located at the maximum moment region just above the construction joint at the floor level.
2. Widely spaced column ties which provide little confinement to the concrete.
3. Little or no transverse reinforcement within the joint.
4. Low percentage of longitudinal reinforcement in the columns and discontinuous positive beam reinforcement with a 6" embedment length into the column.

Test Plan and Variables Studied

A total of 19 specimens have been tested to date. The results from the tests of the first 10 specimens were reported previously by Pessiki, et al. (1990); a report on the remaining results will be published in 1991.

Six interior specimens (I1-I6) had continuous bottom beam reinforcement through the beam-column joint. These specimens were detailed to investigate the influence of the amount of the joint reinforcement and column bar arrangement on joints with spliced and unspliced vertical column rebars. Eight interior specimens (I7-I14) had discontinuous positive moment reinforcement extending into the columns. Variables studied included size of embedded reinforcement, column axial force level, and transverse confinement of the joint region by perpendicular stub beams.

Five experiments (E1-E5) have been conducted on exterior joints to study the effect of column axial force, transverse confinement, and ties within the joint.

Specimen Configuration and Loading Arrangement

Specimens were loaded in a computer-controlled testing facility constructed at Cornell (Pessiki, et al., 1988). Forces representing the gravity load (dead and service load) were applied to the column and at the ends of each beam, followed by reversed cyclic forces at the beam ends. The cyclic forces were controlled by a preset load history until the peak resistance was reached. After this point, the experiment was deformation-controlled, using measured rotations.

Specimen Geometry and Fabrication Details

Critical specimen dimensions were: 14"x24" beams with #3 (0.375" diameter) stirrups at 5' spacing, 16"x16" columns with 2% reinforcement and #3 ties at 16" spacing (with the first tie placed 8" above the joints as specified in earlier ACI Codes), extra #3 ties at the lower bending point of the offset vertical reinforcement, and 1.5" cover over ties and stirrups. Material strengths were $f'_c = 3500$ psi and $f_y = 60000$ psi. Some specimens had post-tensioned transverse beam stubs to simulate the presence of lateral confinement and 3-D frame effects in a real building.

EXPERIMENTAL RESULTS

Interior Joint Regions with Continuous Bottom Beam Reinforcement

Results from these 6 experiments have been summarized by Pessiki, et al. (1990a). A typical hysteresis and cracking pattern plot is shown in Figs. 2(a,b). In all specimens, damage to the column at the splice location was concentrated in a zone below the first column tie located 8 inches above the joint. In columns made with 8#7 bars, loss of cover in this zone contributed to the eventual failure by buckling of the offset reinforcement. Most of the energy dissipation and stiffness loss that occurred in the columns was also attributed to this region adjacent to the joint.

All specimens had extensive shear cracking in the joints at failure (Fig. 2(c)). The joint shear stresses at peak load (computed according to the guidelines of ACI352R) were in the range of 11.8 - 13.4 $\sqrt{f'_c}$, with negligible influence of column bar size and arrangement.

Providing 2#3 ties within the joint distributed the cracks within the joint and shifted the failure zone from the joint to the splice region and decreased the rate of strength loss, but it did not increase the peak resistance significantly because of the weakness of the lightly confined splice zone.

Interior Joint Regions with Discontinuous Bottom Beam Reinforcement

Specimens I7-I14 were constructed with bottom beam reinforcement discontinuous 6 inches into the column. The cyclic load applied to each specimen was controlled by the values of the forces applied to the beams, with the "reference" position being 20 kips constant dead load on each beam. Three load cycles were applied to the beam ends at paired force levels of 30 and 10 kips, 40 and 0 kips, 50 and -10 kips (upward force), and 60 and -20 kips. Low-level cycles (30 and 10 kips) were applied after each set of 3 cycles. Loading beyond peak resistance was controlled by the values of positive beam rotation measured over a distance of 11 inches from the beam column joint.

Figs. 3(a,b) show plots of bending moment versus rotation measured close to the joint of a typical specimen (I-11). The individual hysteric loops are not symmetric since the reversing load cycles produce the superposition of the symmetric gravity loads and the antisymmetric loads simulating the lateral action.

Failure of each specimen with discontinuous beam reinforcement was by pullout of this reinforcement from the beam-column joint. At load cycles of 40 and 0 kips cracks appeared on the face of the joint in the vicinity of the embedded bars. These cracks further progressed at higher load levels to merge with diagonal cracks formed at lower load levels (Fig. 3(c)). Subsequent cycles gradually opened the cracks further causing loss in strength and stiffness. In a few cases, the cracks at the embedment zone did not progress towards the diagonal cracks, but proceeded vertically along the beam-joint interface. Spalling of concrete cover over a distance of 3-4 inches above and below the joint, and vertical cracking up to the first tie, occurred in the top column but the splices performed well. Joint shear stresses at the peak upward force were 20-40% less than in interior specimens with continuous reinforcement.

The column axial force was the most significant variable. Specimens loaded with larger axial force (350 kips) exhibited a significant increase of load bearing capacity at relatively low rotation levels, and had increased energy dissipation capacity and higher overall specimen stiffness at the beginning of the load history.

The size of the embedded reinforcement size (3/4" and 1" diameter) did not influence significantly the peak strength values, but rotations were larger in specimens with the smaller bars.

Three specimens had transverse beam stubs to simulate the possible lateral confinement by beams perpendicular to the plane of the main load bearing frame. Near the bottom of each stub, a 50 kips prestressing force was applied over an 8 by 14 inch area to simulate gravity load action in a 3-D framing system. The beam stubs produced no marked effect on the hysteresis envelopes nor on capacity.

Exterior Joint Regions with Embedded Bottom Beam Reinforcement

Five specimens (E1-E5) have been tested to study the behavior of exterior joints, using a load history that facilitated comparison with results from the interior joints.

A moment-beam rotation plot for a typical specimen without transverse beam stubs is given in Figs. 4(a,b) Initial cracks appeared on the face of the joint in the vicinity of the embedded bars during early load cycles. Under increasing loads, these cracks progressed diagonally across the joint into the splice region, and as cracking extended along the entire length of the splice, the load carrying capacity dropped suddenly. Additional load cycles induced a large opening of the construction joint above the beam. In addition, the cracks along the splice progressed vertically downwards toward the bottom column. The prying action of the bent-down beam reinforcement produced full separation of the 30-50 inch high concrete cover layer opposite the beam, as shown in Fig. 4(c). In contrast to the interior joints, downward loading on the beams had a major contribution to the failure of the exterior joints.

Specimens with transverse beam stubs showed a similar failure mechanism; however, cracking was less severe. Pullout of the bottom beam bars occurred at about the same load as intensive cracking occurred at the splices. Transverse confinement (either by beam stubs or by 2#3 ties) increased the peak load capacity by 25-40% and provided a more gradual strength degradation.

Only one specimen was tested at the higher level of column axial force (350 kips). It had no extra joint ties or transverse beam stubs, and experienced a very sudden failure at a relatively low rotation value.

The peak load capacity of exterior joints was nearly the same as obtained for interior joints. However, strength degradation of exterior joints was more rapid because of higher levels of damage to the splice region. Further analysis of data and the results of additional experiments will lead to firm conclusions about the behavior of joint regions with discontinuous embedded reinforcement.

SUMMARY

Experimental results have been presented on the seismic resistance of typical details of interior and exterior beam-column connection regions in existing lightly reinforced concrete frame structures designed primarily for gravity loadings. These experiments have provided new insight into damage mechanisms, failure mechanisms, and the influence of primary variables on connection region strength, stiffness, and ductility. The results show that these non-seismically detailed joint regions have significant initial strength and moderate ductility under simulated seismic loadings. Specimens with discontinuous positive beam reinforcement experienced considerable strength loss. At the same time these beam-column subassemblages became increasingly flexible reducing the demand for strength.

The measured bending moment-rotation hysteresis relations for these joint regions are complex and unsymmetrical, and point to the need for analytical models that properly incorporate strength deterioration, stiffness degradation, and pinching effects.

ACKNOWLEDGEMENTS

This research was sponsored by the National Center for Earthquake Engineering Research, SUNY Buffalo, NY. The Center is funded by NSF Grant No. ECE 86-07591 and by other sponsors including the State of New York. Advice on existing building details from Jacob Grossman, Raymond DiPasquale, and Glenn Bell is greatly appreciated. Opinions expressed herein are those of the authors only and not of the sponsors.

REFERENCES

ACI Committee 352, "Recommendations for Design of Beam-Column Joints in Monolithic Reinforced Concrete Structures", (ACI 352R-85), American Concrete Institute, Detroit, MI, 1985.

Pessiki, S.P., Conley, C., Bond, T., Gergely, P., and White, R.N., "Reinforced Concrete Frame Component Testing Facility - Design, Construction, Instrumentation, and Operation", Technical Report, NCEER-88-0047, National Center for Earthquake Engineering Research, State University of New York at Buffalo, New York, 1988.

Pessiki, S.P., Conley, C., White, R.N., and Gergely, P., "Seismic Behavior of the Beam-Column Connection Region in Lightly-Reinforced Concrete Frame Structures", Proceedings of the Fourth U.S. National Conference on Earthquake Engineering, EERI, Palms Springs, 1990a, Vol.2, pp.707-716.

Pessiki, S.P., Conley, C., Gergely, P., and White, R.N., "Seismic Behavior of Lightly-Reinforced Concrete Column and Beam Column Joint Details", Technical Report, NCEER-90-0014, National Center for Earthquake Engineering Research, State University of New York at Buffalo, New York, 1990b.

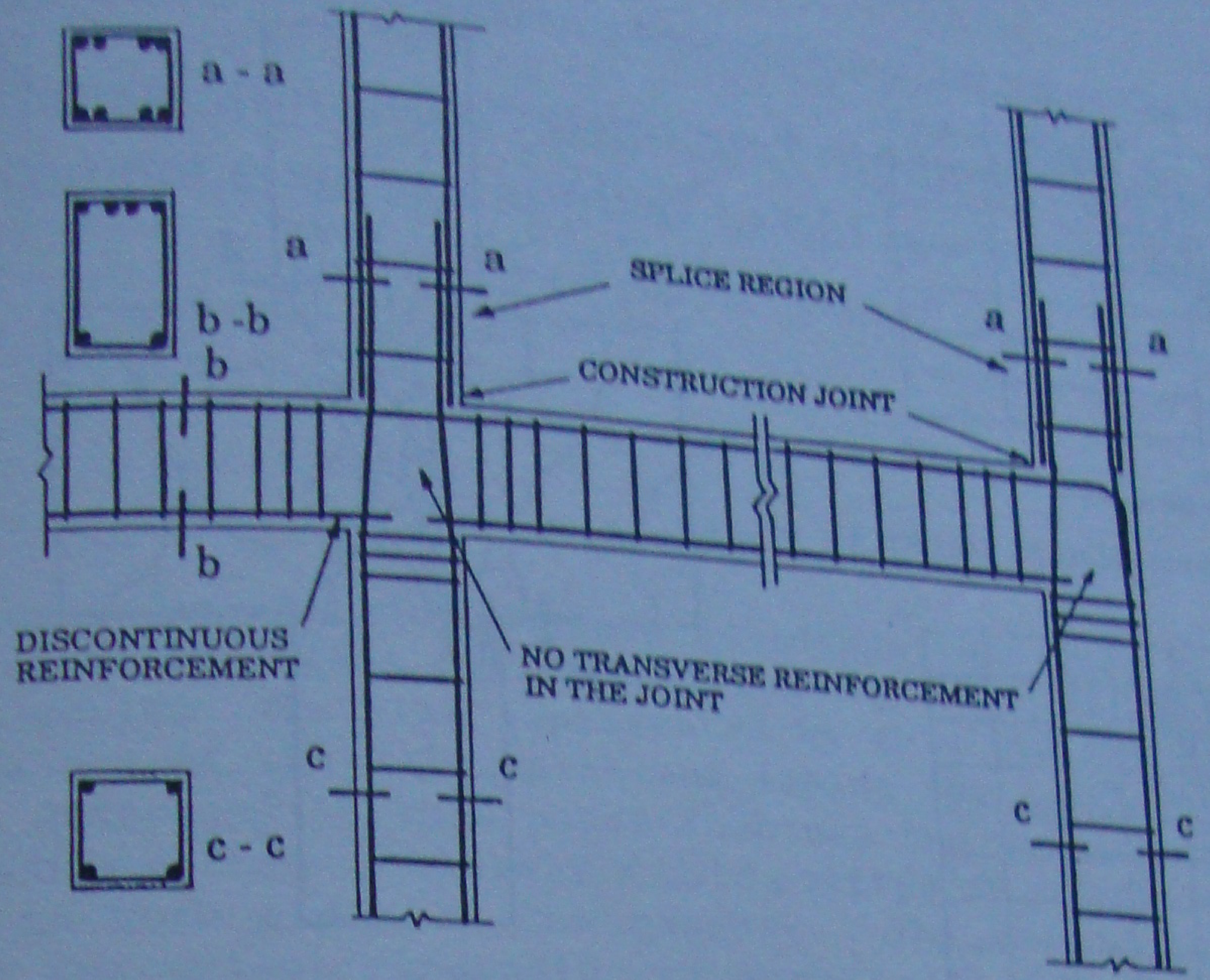
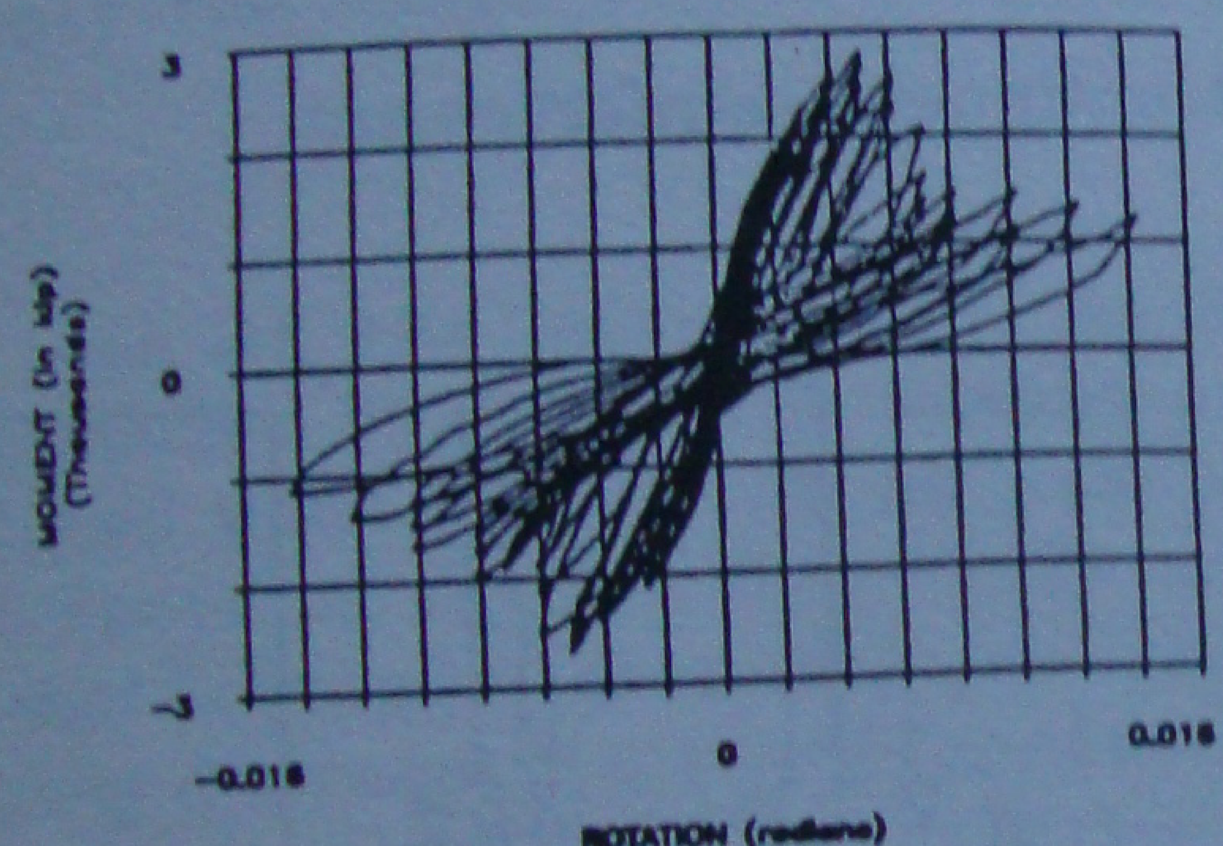
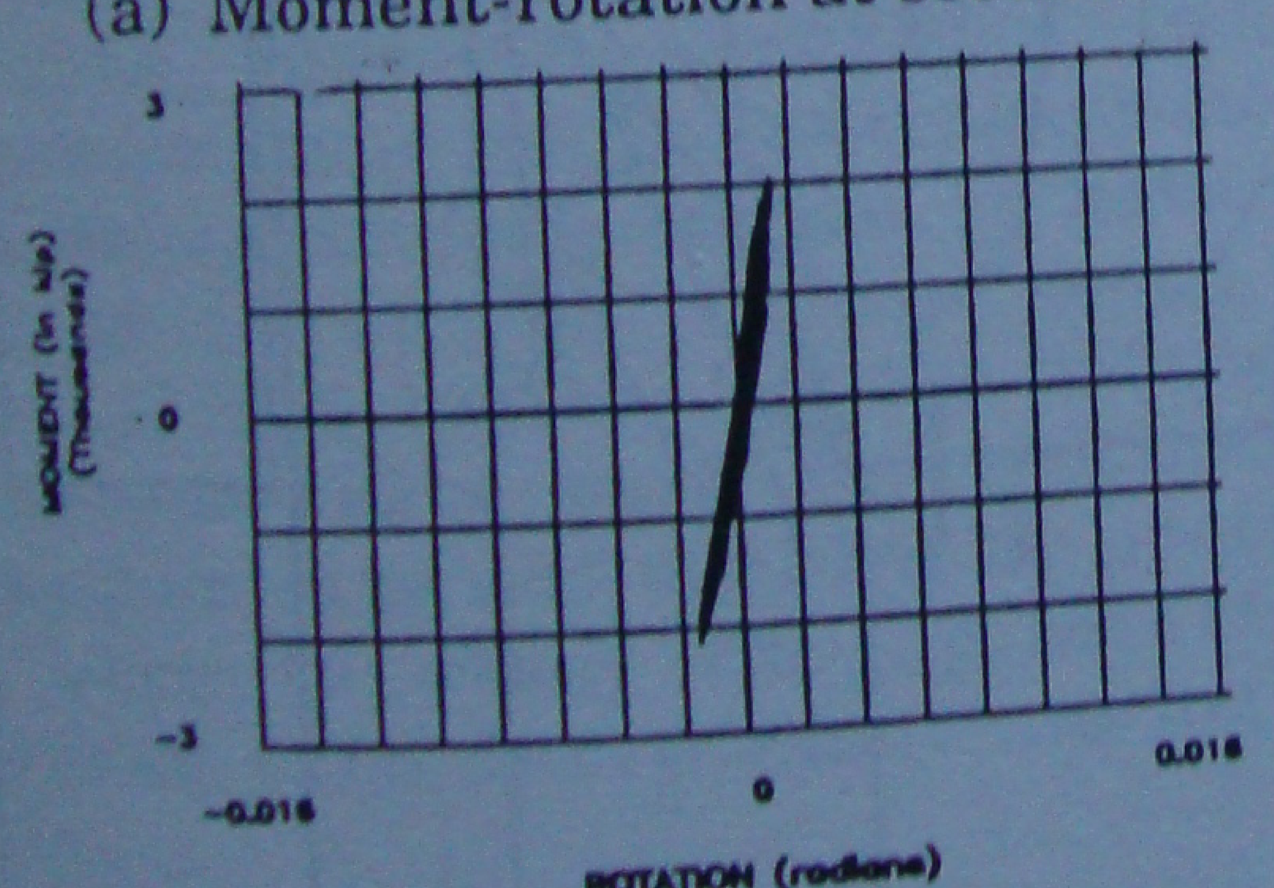
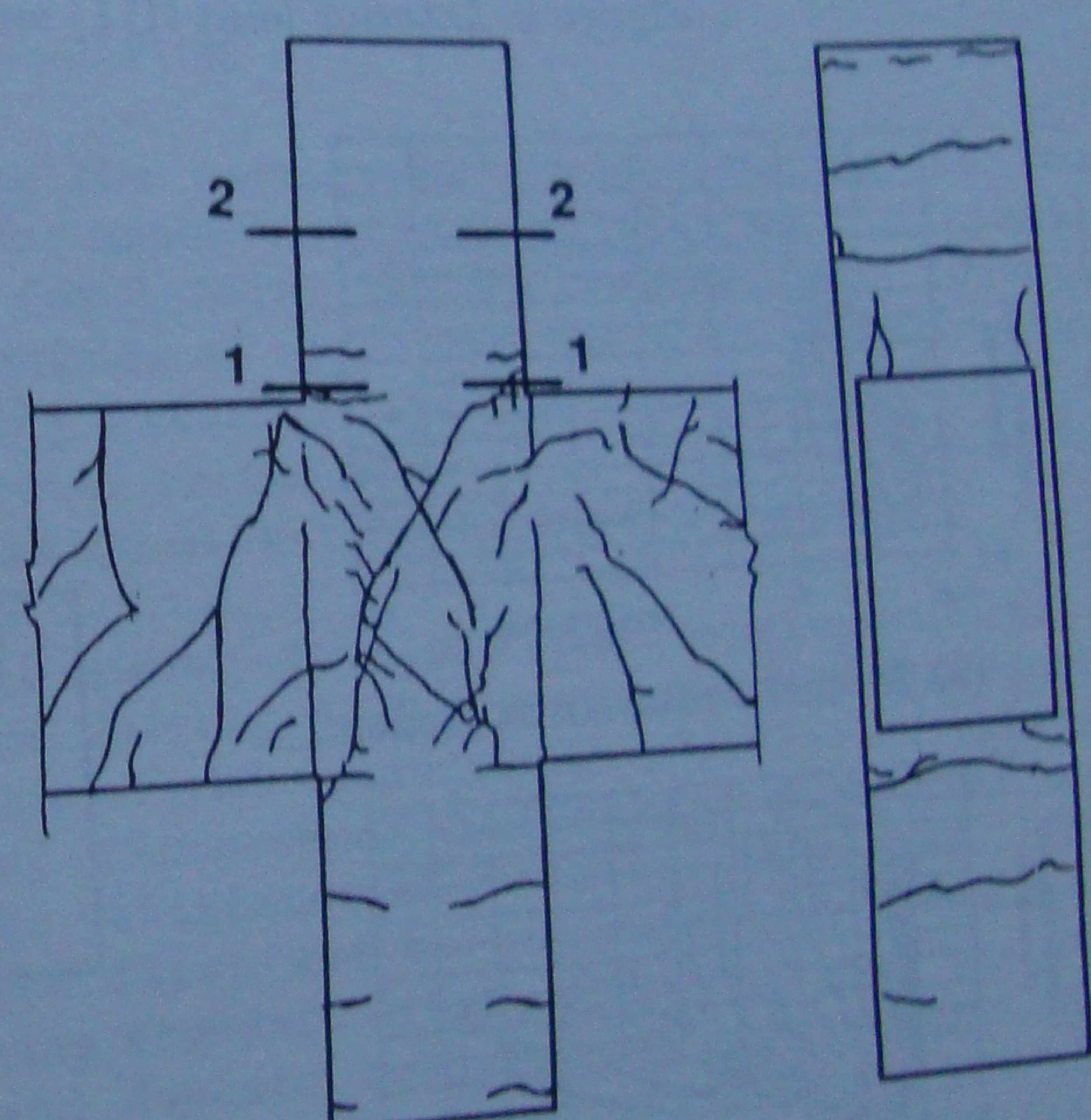


Figure 1. Elevation view of an interior and an exterior beam-column connection region.



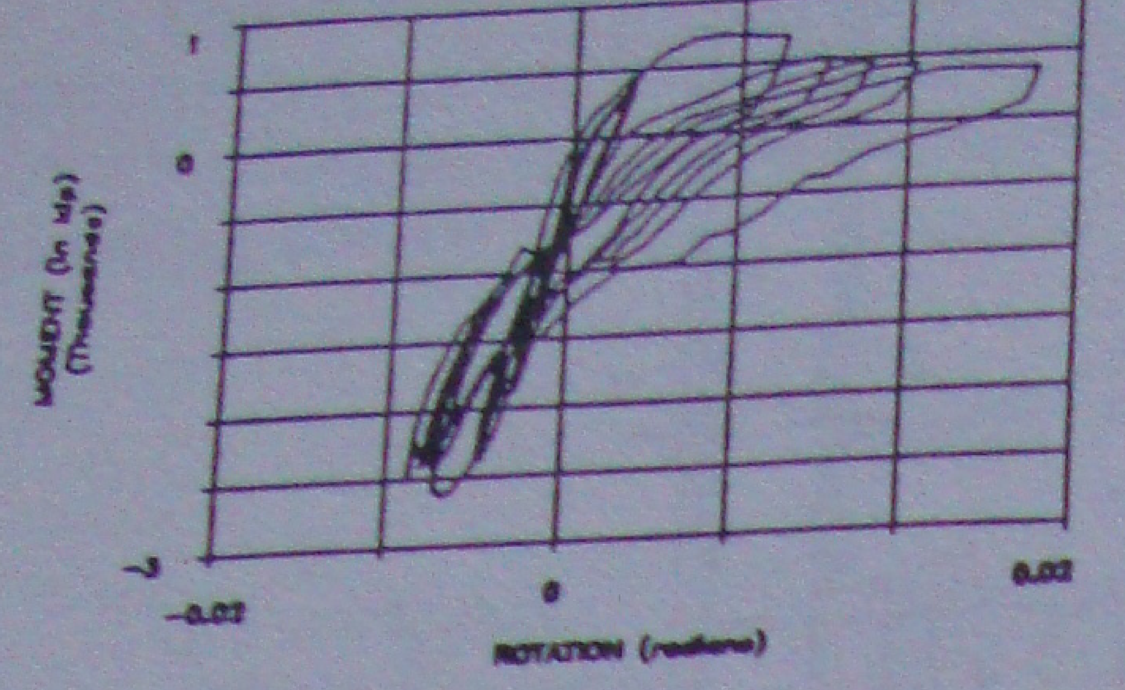
(a) Moment-rotation at section 1.



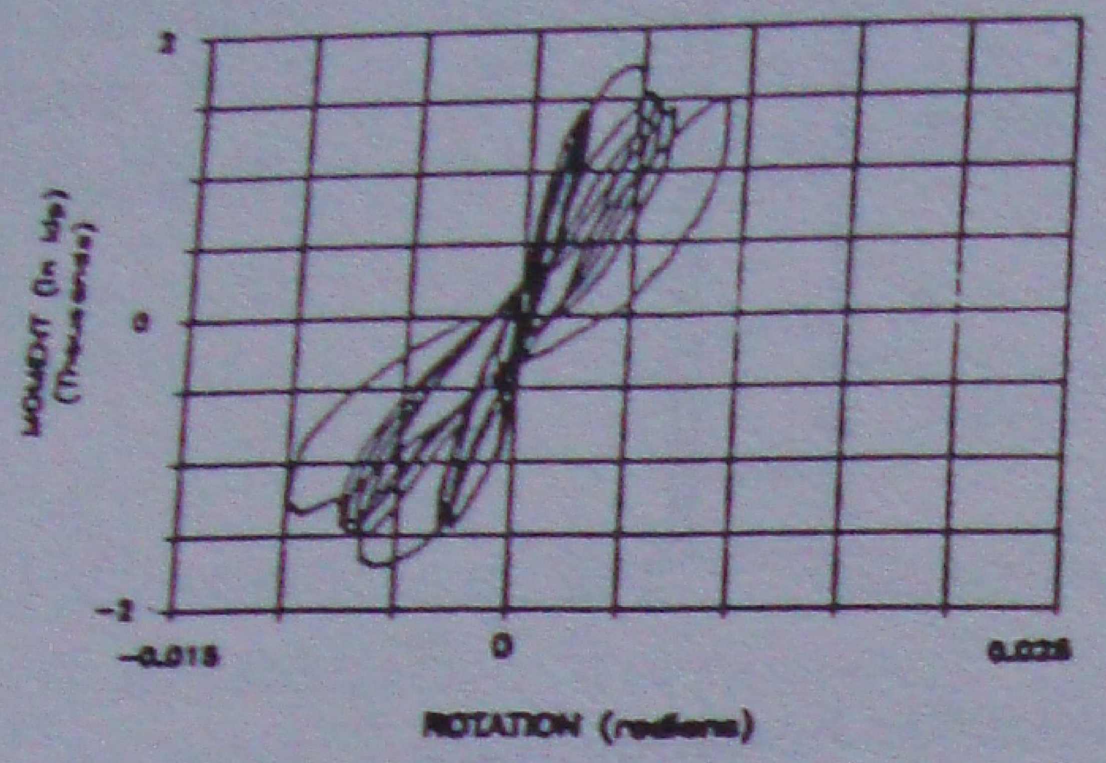


(b) Moment-rotation at section 2.

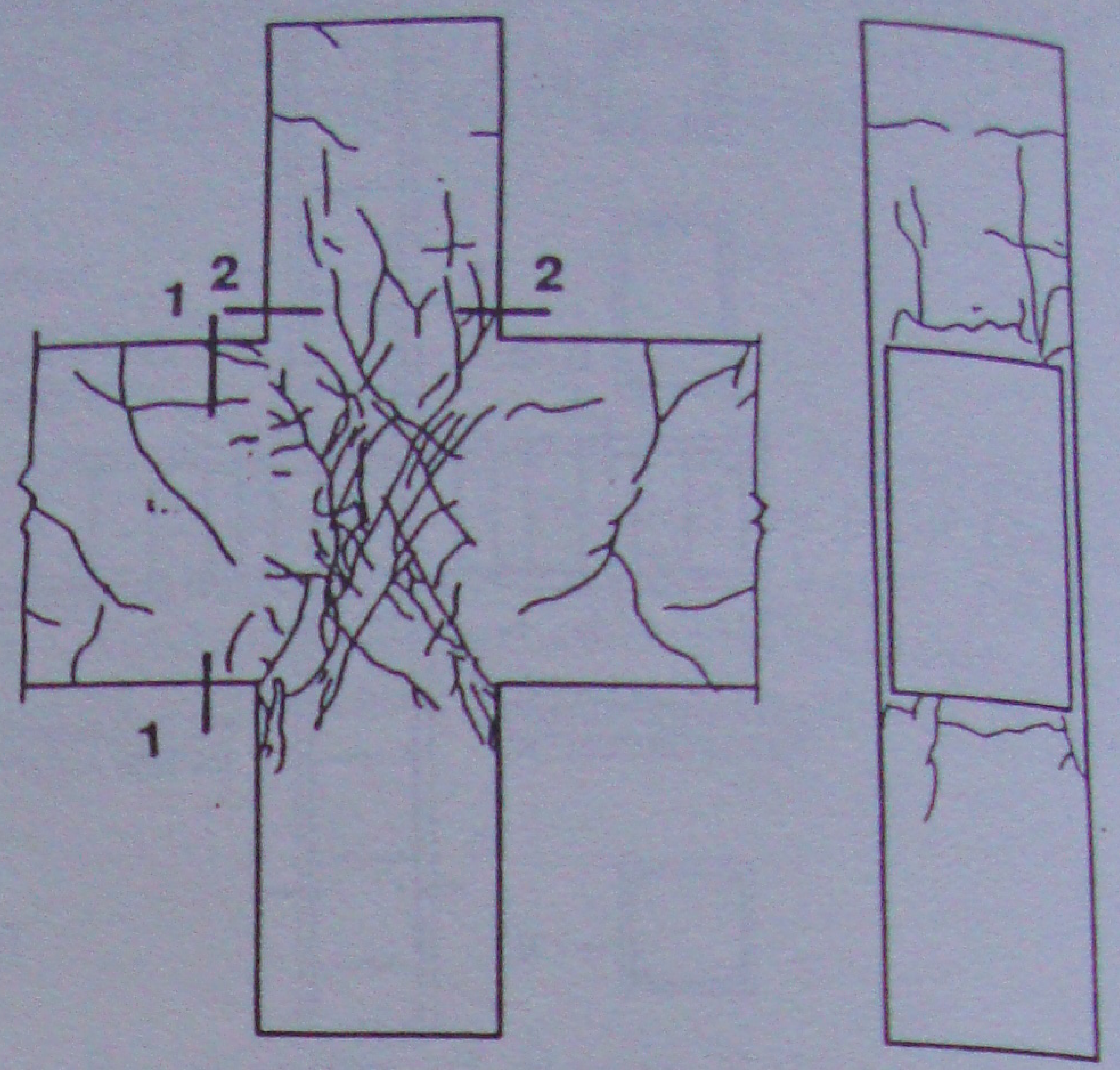
Figure 2. Interior joint (I2) with continuous reinforcement



(a) Moment-rotation at section 1.

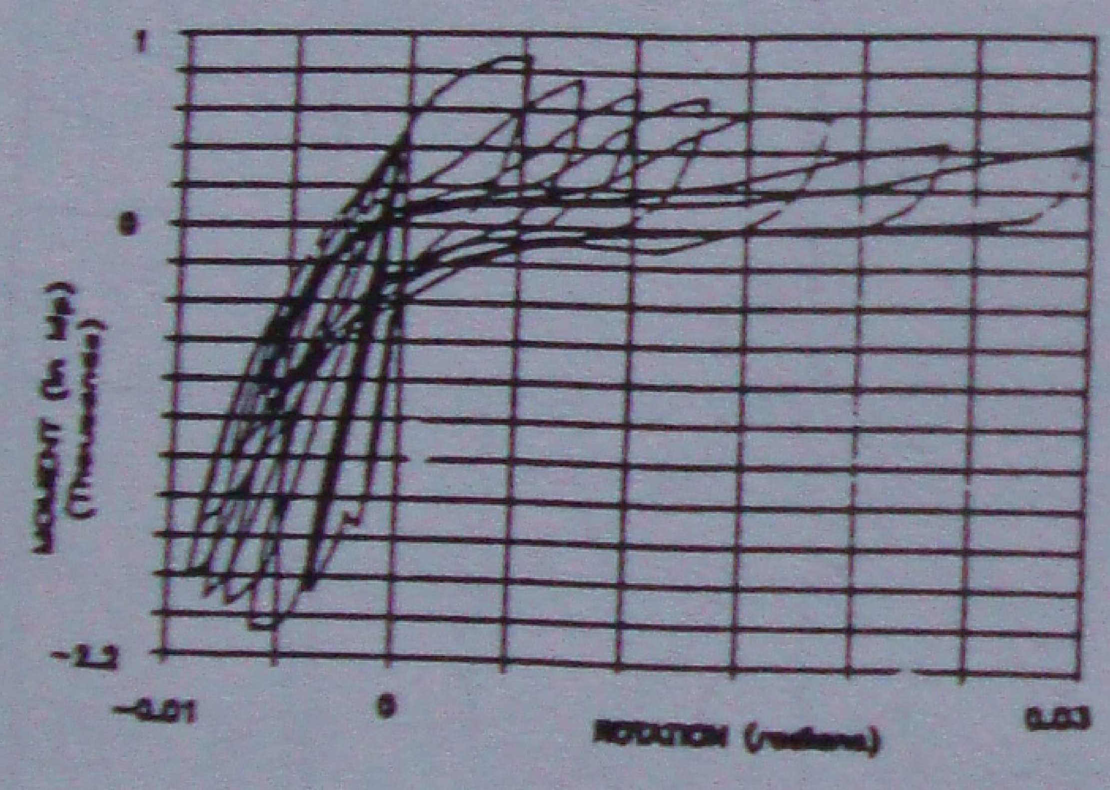


(b) Moment-rotation at section 2.

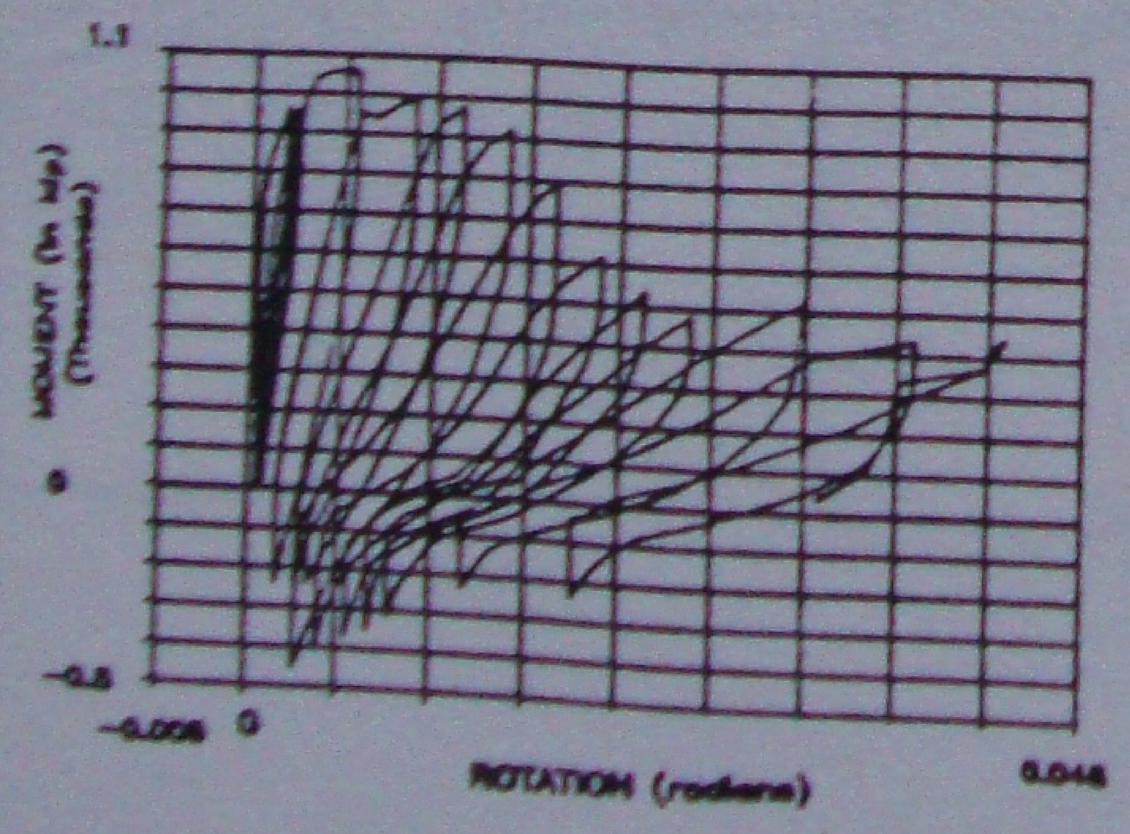


(c) Cracking pattern

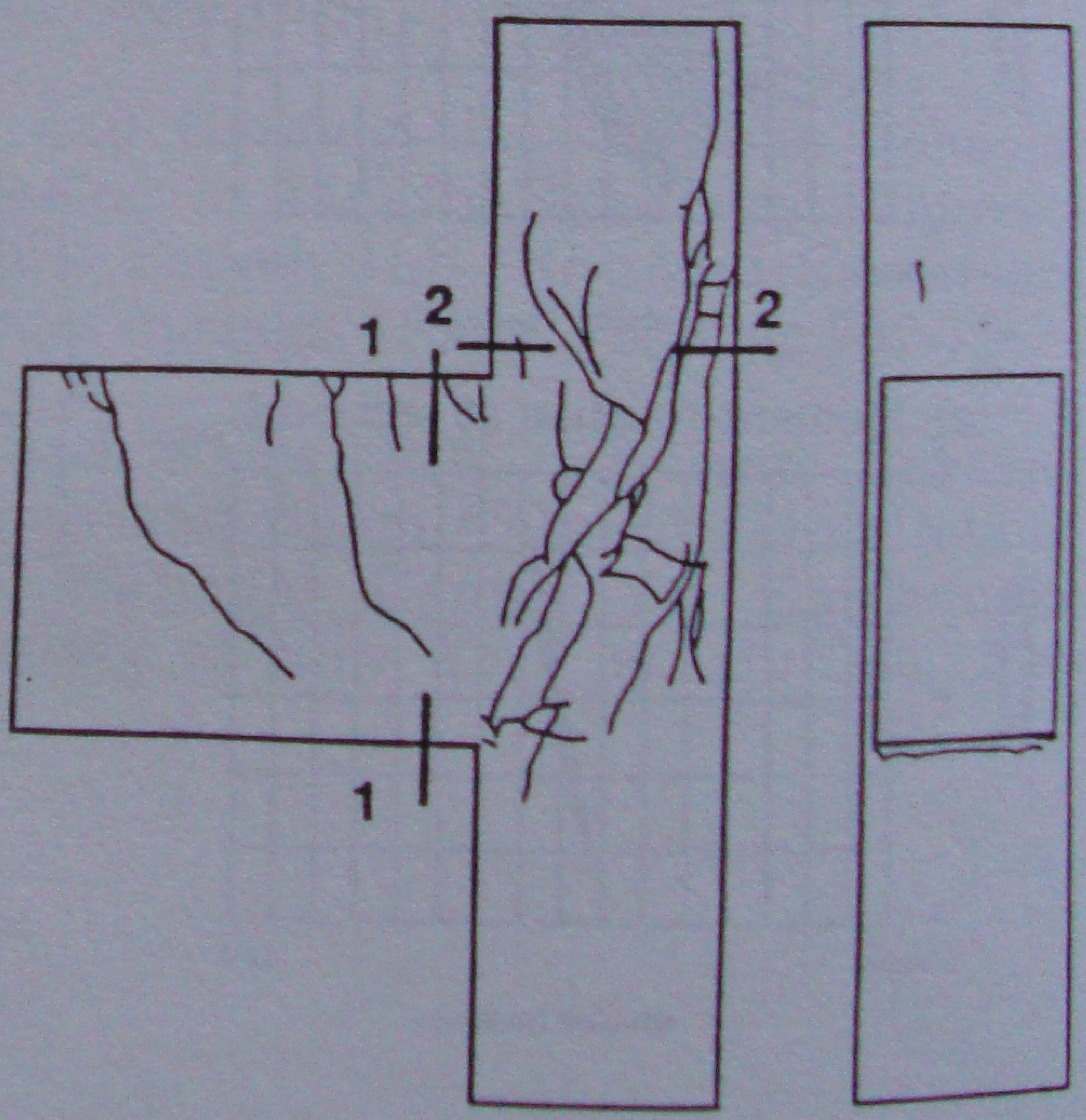
Figure 3. Interior joint (I11) with discontinuous reinforcement.



(a) Moment-rotation at section 1.



(b) Moment-rotation at section 2.



(c) Cracking pattern

Figure 4. Exterior joint (E1)