13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 518

Effect of Modeling Features on Response of Reinforced Concrete Frames

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SUMMARY

In reinforced concrete structures, failure of beam-column joint has been as one of the major causes of damage or even collapse of these structures during earthquakes. Non-ductile detailing of reinforcement in terms of inadequate shear reinforcement in the joint panel or insufficient anchorage of the beam bars within the joint region are the main causes of deficiency in the performance of the joints during earthquakes. The objectives of this study are to compare different aspects of modeling the nonlinear behavior of exterior beam-column joints and also to propose a new model for the shear behavior of the exterior joints. The advantages of using different models for beam-column joints in reinforced concrete structures are discussed. It is shown that the behavior of exterior beam-column joints can be predicted with reasonable accuracy using an element consisting of diagonal struts in combination with fiber elements.

INTRODUCTION

Non-ductile detailing of reinforcement in the joint in terms of inadequate shear reinforcement in the joint panel, or insufficient anchorage of the beam bars within the joint region are the main causes of deficiency in the performance of the beam-column joints during an earthquake. Under severe loading and if the connection is adequately designed, the beam could be expected to achieve significant post-yield flexural strength while the column flexural demands could be expected to approach values associated with nominal flexural strength. These actions imply substantial shear loading of the connection, which could result in connection damage or failure. It has been found that inelastic deformations within a joint during cyclic reversed loading may lead to rapid loss of both stiffness and strength.

Loading of connection core concrete comes through transfer of the concrete stress developed in beam and column flexural compression zones and through transfer of reinforcing steel compression and tension stress as distributed to the connection core through bond. Under severe reversed cyclic shear loading,

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concrete in the connection core may crack under high principal tensile stress, or crush under high principal compression stress. The main objective of any design method is the assessment of the safety and the serviceability of the structure during different loading history. Because of the economic feasibility of using analytical model instead of obtaining data from destructive experimental tests, there is a need for an efficient and reliable analytical model, which predicts the behavior of such structures, and gives comparable results to experimental evidence. The more the nonlinear behavior of beam-column joint is known and predictable, the better such undesirable damages could be prevented, and the appropriate retrofitting scheme could be selected. Estimates of the demands can be established through dynamic inelastic analyses of appropriate models. The model should be based on accurate nonlinear dynamic analysis and real behavior of the elements. A number of nonlinear models have been developed for predicting the behavior of different structural elements during earthquakes. Most of the nonlinear models assume the beam-column connection to be rigid, regardless of the real behavior of the joint during shear degradation and bond deterioration. The behavior of the joint is then simulated by means of several inelastic springs, which have been calibrated by the results of experimental data. Since the contribution of the joint deformation to the overall performance of the structure is difficult to predict, therefore the mentioned model may not yield accurate results.

NON-LINEAR MODELLING

There are two major categories for the nonlinear dynamic analysis of reinforced concrete structures. One is to present the overall behavior of each structural component in terms of a macro-model. The second is to discretize each structural component into smaller units and then capture the overall behavior of the component in terms of the behavior of those smaller units.

A major aspect in modeling the nonlinear behavior of the components is how to consider the regions which yield and the regions which remain elastic in the structural components during the dynamic analysis. One common model (lumped plasticity model) is to consider the yielding of the element to be localized in the zero length regions in the elements' ends, which are called plastic hinges. The idea behind the other model (spread plasticity model) is to assume the plastic hinges to form in the members' ends but allows some parts of the length of the element to go into inelastic deformation. DRAIN-2DX (Allahabadi and Powell [1]) is a computer program for static and dynamic analysis of inelastic plane structures. The concept of lumped plasticity is implemented in this program (plastic hinge beam-column element). Yielding occurs only in the plastic hinges, that is; the element consists of an elastic beam, and two plastic hinges at the ends of the beam, and optional rigid end zone. The element has serious limitation. The inelastic axial deformation is not considered, and plastic hinges are assumed to yield only in bending. Thus using such element in the event of significant P-M interaction is not theoretically correct. For the accurate analysis of the structure, the true force-displacement relationship for the beam-column joint should be known. Moreover modeling the behavior of reinforced concrete with lumped-plasticity idealization is not accurate, since inelastic deformation is observed throughout the non-zero length in the members' end.

IDARC2D is another computer program which has been developed for inelastic damage analysis of structures (Reinhorn et al. [2]). It has the capability of using both lumped plasticity, and spread plasticity concepts. The formulations are based on macro-models in which most of the elements are represented as a comprehensive element with nonlinear behavior. Columns and beams are macro-model with inelastic flexural deformation and elastic shear deformation. The beam unlike the column does not take axial deformation. The load-deformation of the structure is simulated by versatile hysteretic models, which are implemented in the program and are mainly controlled by parameters indicating the stiffness degradation, strength deterioration, and pinching of the hysteretic loops.

Based on the mentioned concepts, the nonlinear dynamic analysis of a structure or a part of a structure relies on simplified method. There were no consideration of the actual behavior and deformation of the joint. Thus for prediction of the behavior of the structure during an earthquake by each model, there are many unknown parameters which should be defined. These include; load-deformation relationship in the members' end, stiffness degradation, strength deterioration, and pinching factors, and so on.

To fill the gap between these analytical models and a finite element method model, a new model for the shear behavior of exterior joints is presented. The model is based on fiber formulation concept (DRAIN-2DX /element type 15). In fiber element material nonlinearity can spread through the whole length of the element. The deformable part of the element is discretized into parallel fibers that are assumed to be stressed and strained uniaxially in the direction parallel to the direction of the longitudinal axis of the element.

In the proposed model, the joint region is considered to be the connection between the column and the beam end. The beam bar anchorage is assumed to be perfect. Thus bond slip of the beam bars is ignored and the shear is resisted only by a diagonal concrete strut mechanism. The local response mechanisms that control connection behavior are defined by the behavior of plain concrete, and reinforcing steel under general reversed-cyclic loading. Consideration of material behavior associated with development of the local response mechanisms defines the required material modeling capabilities of the proposed model. Connection response is determined by the applied loading at the connection perimeter as controlled by flexural demand in the beams and column, and the behavior of the reinforced concrete constituent materials.

FIBER ELEMENT

The fiber model corresponds to a large level of discretization, where each structural member is modeled by single element, but the stress-strain history of a large number of points, for both steel and concrete, is evaluated during the analysis at several cross-sections inside the element (Spacone et al. [3]). The fiber model allows for accurate modeling of the cross –section geometry. The area of the cross section, the material, and spacing of cross-sections can be varied along the member to represent the nonlinear behavior of the critical regions more accurately. In fiber model, the beam-column element is divided into a discrete number of cross sections (segments). The model assumes constant fiber properties over each segment length, based on the properties of the monitored slice at the center of each segment. The non-linear behavior of the element is monitored at these control sections, which are in turn discretized into longitudinal fibers of plane concrete and reinforcing steel. The non-linear behavior of the section is then captured from the integration of the non-linear stress-strain relationship of the fibers. This feature permits the modeling of any type of structural element with irregular cross-sections and different sectional areas, such as the case of the circular column. Regardless of the high memory demand and increasing computational cost, the accuracy of the model increases with the number of fibers in each cross section.

Material Models

The material model for concrete considers cracking and crushing and tension stiffening. The concrete material properties are defined as points in the stress-strain curve shown in Figure 1. There is a maximum of 5 points for defining the stress-strain relationship in compression, and 2 points for defining the stress-strain relationship in tension.

The point with coordinates (S1C, E1C) refers to the cracking of the concrete and the point (S2C, E2C) refers to the maximum compression strength of the concrete. The point (S3C, E3C) defines the ultimate strength of concrete under high strains. The horizontal branch shows the ability of concrete to sustain some strength at very large strains.

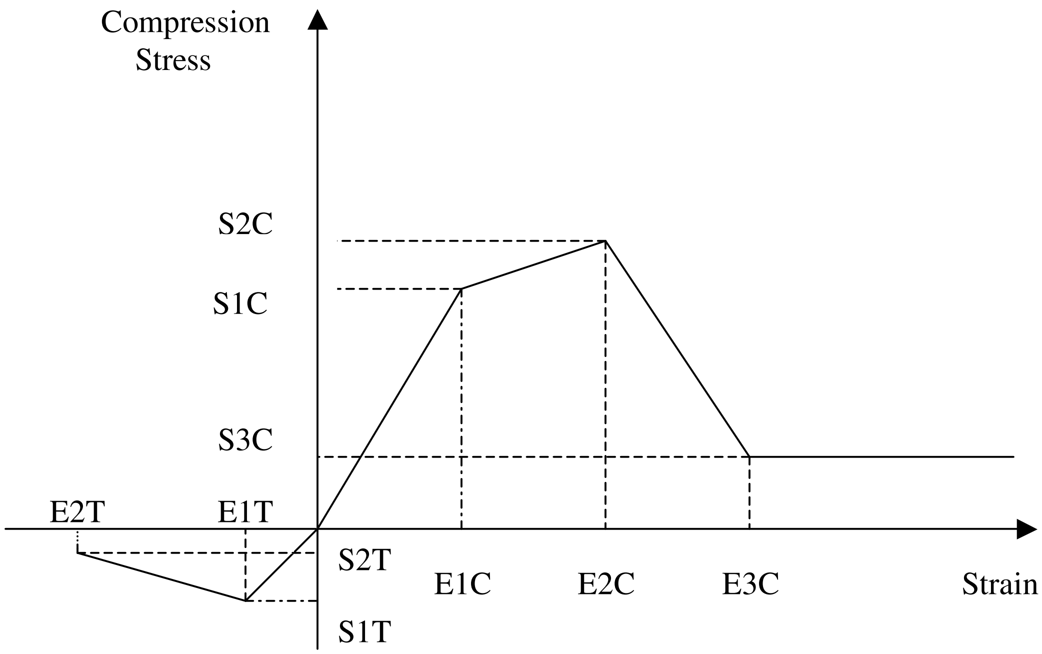


Figure 1. Properties for Concrete (DRAIN-2DX)

For concrete in compression, the curve proposed by Kent and Park [4] and for concrete in tension, the relationship developed by Vebo and Gali [5] have been adopted in this study.

The material model for steel reinforcing bars is shown in Figure 2 in which it accounts for yielding of steel, as well as strain hardening.

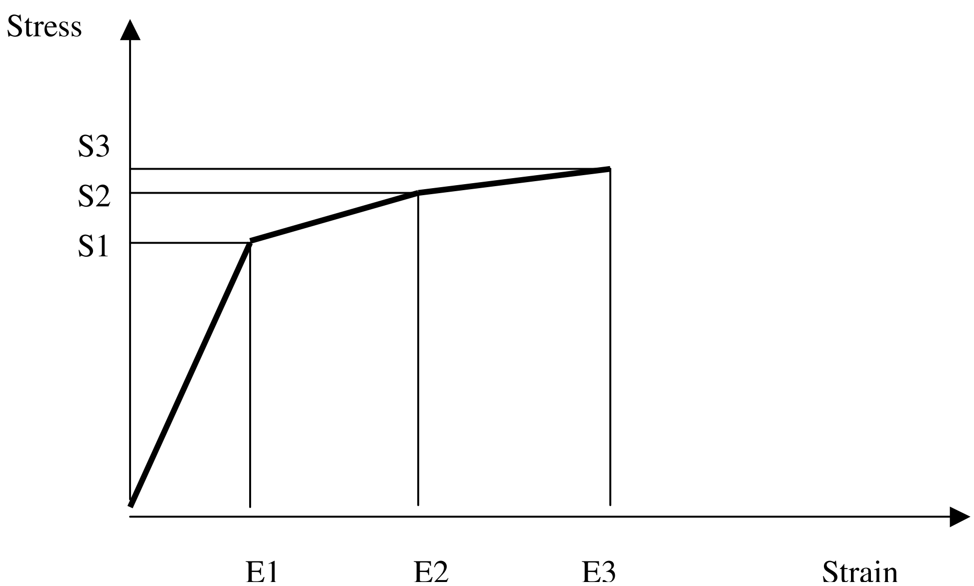


Figure 2. Properties for Steel (DRAIN-2DX)

Effect of the Number of Fibers in the Cross-Section

There are no limits specified for the number of fibers in the cross section or the number of segments in an element. It may be appropriate to specify a large number of fibers for a small analysis model consisting of one or two elements. However, if several such elements are specified as part of a large model, the execution time may get long. Although the large number of fibers increases the accuracy and also the execution time, there must be a compromise between accuracy and time of execution. For better understanding of the problem, the results of analysis of a rectangular section moment of inertia (I) with different number of fibers are compared to the calculated value obtained using the equation, I = b*h3/12 (for a rectangular section with b = h = 400 mm, I = 4004/12 = 2.1333 E9 mm4).

Figure 3 shows the result of the analysis of the same section with different number of fibers in the cross section (slice), and the theoretical value for moment of inertia, which is shown by a horizontal line.

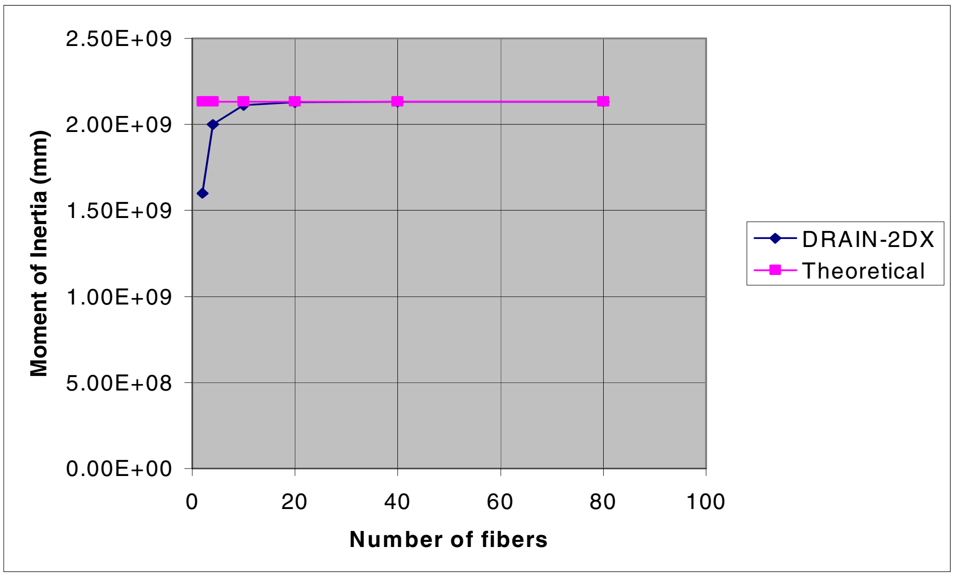


Figure 3. Effect of Number of Fibers on Moment of Inertia of the Cross- Section

It is observed that for the number of fibers of more that about 20, there is a negligible difference between the analytical value obtained from DRAIN-2DX, and the theoretical value of the moment of inertia. For smaller number of fibers, the results may become inaccurate.

Verification of Fiber Element

To demonstrate the ability of fiber elements in the analysis of structures, a circular cantilever column tested by Stone and Cheok [6] under the application of axial load and horizontal quasi-static load reversals on the column’s top is studied. This example has also previously been used for the verification of the IDARC-2D program.

The column analyzed in this investigation is a full-scale circular bridge pier measuring 30 feet in height with an aspect ratio of 6.0 to exhibit flexural failure (Figure 4). The tests were performed using a displacement controlled quasi-static history as shown in Figure 5, while the axial load equal to 1000 kips held constant. The column was made of 5.2 ksi concrete (measured compressive strength at 28 days) and had a modulus of elasticity of approximately 4110 ksi.

The longitudinal reinforcement consisted of 25 D6 #14 (Grade 60 steel with an actual yield stress of 68.9 ksi and diameter of 0.552 inch) and modulus of elasticity of 27438 ksi. The steel exhibited good ductility in the material testing with a 2% strain and a strain hardening of 1454 ksi before actual rupture. The purpose of this analysis is to simulate the characteristics of the hysteretic behavior and compare it with the experimental recorded response.

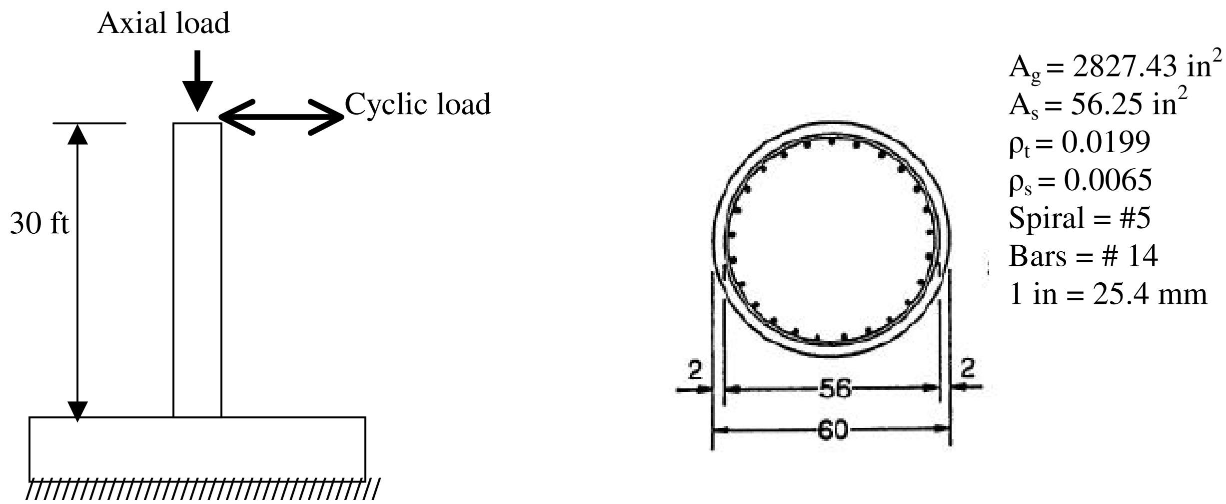


Figure 4. Configuration of Full-Scale Bridge Pier

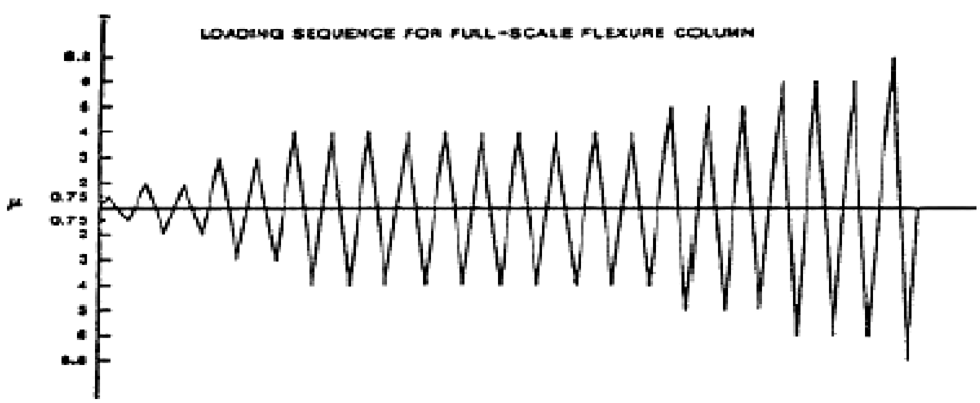


Figure 5. Loading Sequence for Full-Scale Flexure

In DRAIN-2DX (Fiber element), there is no provision for circular sections. Instead of approximating the circular section by an equivalent rectangular section, the circular section was divided into 40 fibers with equal width. The non-linear behavior of the reinforced concrete element derives from the stress-strain relationship models of concrete and steel as discussed earlier. The effect of concrete confinement due to the presence of transverse reinforcement was considered by modifying the strain softening slope in the monotonic envelope. The result of the DRAIN-2DX analysis in terms of the relationship between shear force and displacement is shown and compared with the experimental results and that obtained using

IDARC-2D program as shown in Figure 6. Good correlation between the analytical and experimental results is noticed.

BEAM-COLUMN JOINT

The behavior of the beam-column connections is complex and still not fully understood. The development of an analytical model, which has the capacity to account for the localized response mechanism that determines the global behavior of the structure, seems necessary for prediction of the response of the structures. The response of the joint is mainly dependant on shear mechanism of the joint panel and the bond condition between concrete and reinforcement, which have controlling effects on the hysteretic behavior of the joint under earthquake cyclic loading. Several mechanisms for joint load transfer during an earthquake have been proposed. The most common and well-known mechanism, which was first discussed by Paulay and Priestly [7] is based on the compressive capacity of the joint concrete.

The compression strut model assumes that after the bond is lost due to the level of damage, the tension forces in the longitudinal reinforcements of beams and column are anchored on the opposite corners of the joint panel as shown in Figure 7. This needs the assumption that the bond strength is mainly in the vicinity of beam and column flexural compression zone. These tensile forces are then combined with compression forces on each sides of the beam-column face and the resultants are then transferred through a diagonal compression strut. After the diagonal transferred shear exceeds the compressive strength of the cracked concrete in the joint, the joint shear resistance degrades. The transverse reinforcement has the role of confining the concrete core in the joint panel.

In exterior joints, a diagonal strut similar to that of interior joints will develop between the bend of the hooked top tension beam bars and the lower right hand corner of the joint The anchorage forces of the bars' end hooks; the bond stresses from the straight portion of the top bars, and the vertical forces introduced by the column above the joint will combine and form a diagonal compression force within the joint panel.

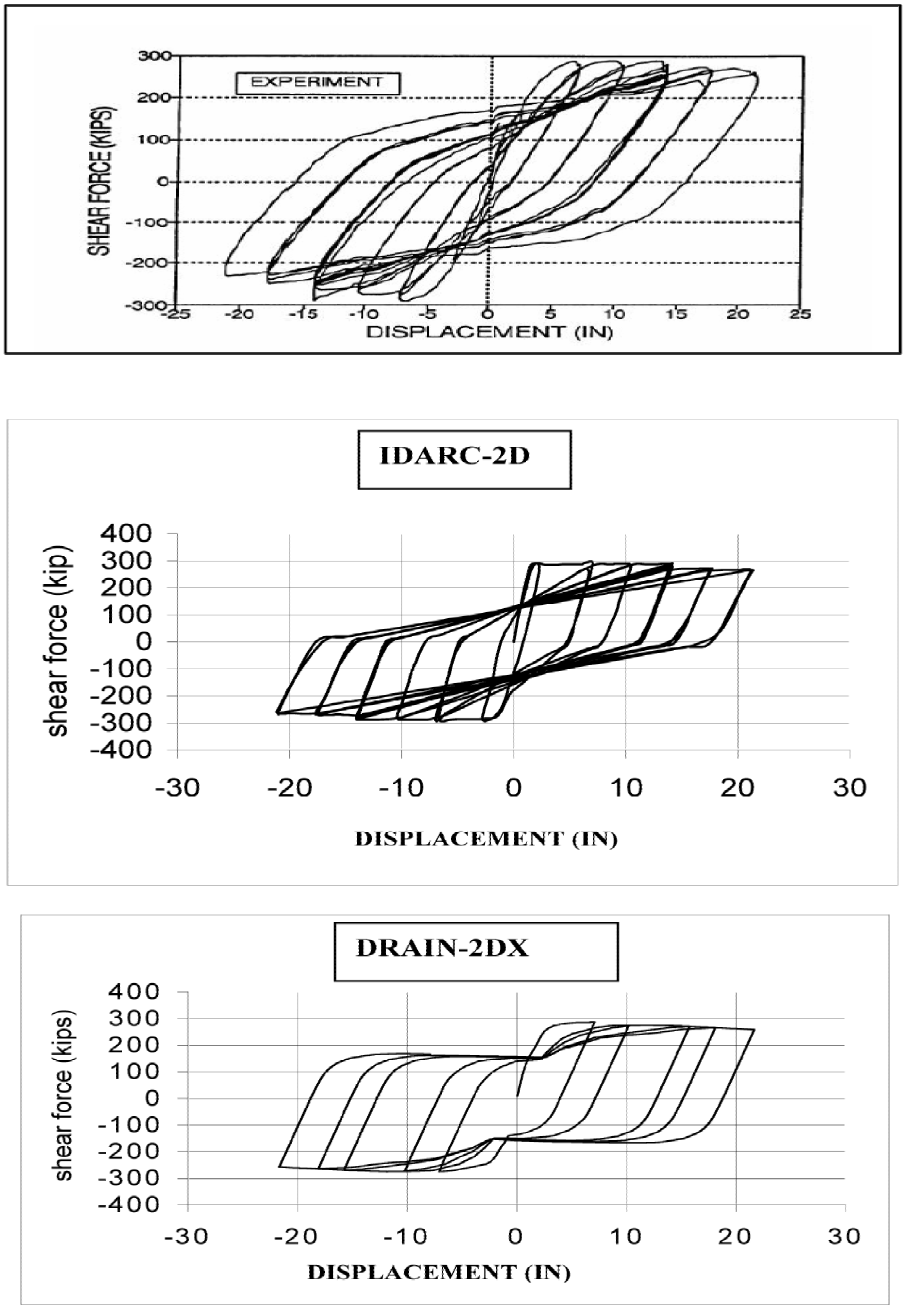


Figure 6. Response of the Bridge Pier

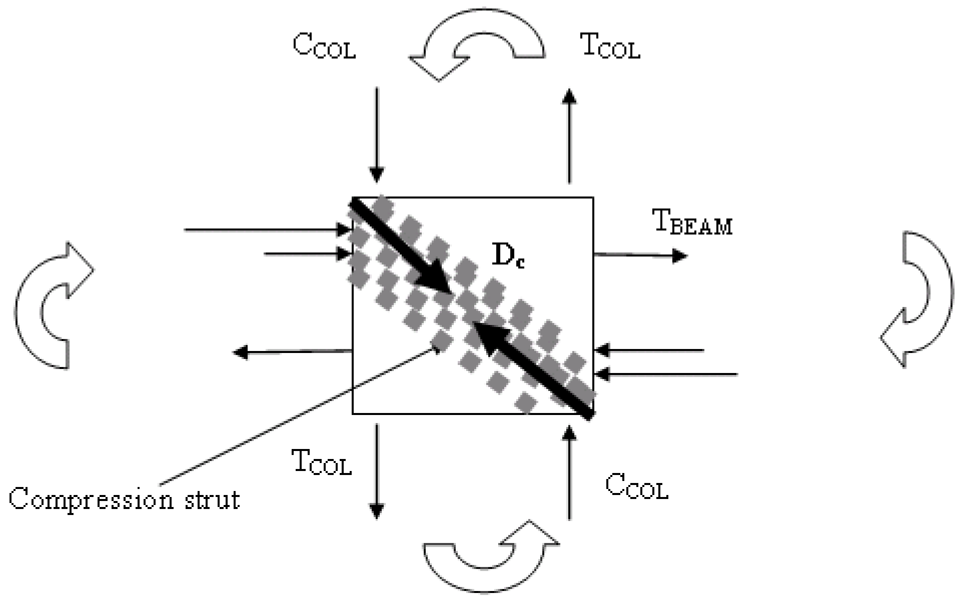
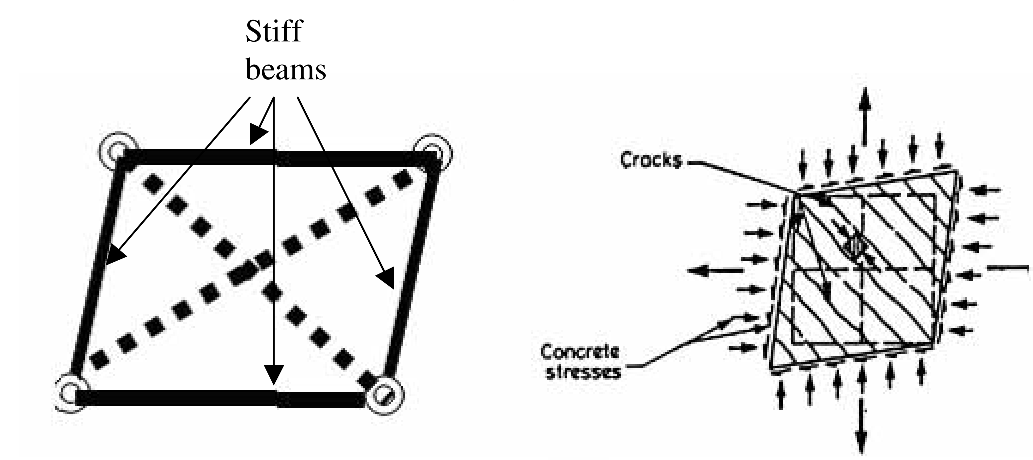


Figure 7. The Diagonal Compression Strut

Proposed Joint Model

A new model is proposed to simulate the behavior of the exterior beam-column joints in shear. The model is based on the fact that the shear resistance mechanism in the joint core without transverse reinforcement relies on the diagonal concrete struts, and the shear resistance capacity of the joint is determined by the compression strength of the concrete struts within the joint. The proposed model is implemented into the computer program DRAIN-2DX, using fiber element as discussed earlier. In this model, the external beam-column joint sub-assemblage is regarded as two separate elements. The beam and the column deformable parts have been discretized into a number of fibers.

Two diagonal connectors are used to represent the behavior of the joint as shown in Figure 8. Each connector is comprised of four identical stiff beams that are pinned to each other's end. The joint resistance capacity is determined by the compressive strength of the diagonal struts. Further details of the beam-column joint model are described by Sadjadi [8].



(a) The connector after the deformation (b) Shear deformation of the joint

Figure 8. Shear Deformation in the Beam-Column Joint

Verification with Experimental Results

To demonstrate the ability of the proposed joint model as described above, the results of previous experiments are compared with that of the proposed model.

As is typical of building frames in the structures that were built prior to 1970's, reinforced concrete structures have limited ductility and several performance deficiencies that prevent them from meeting the current seismic design criteria.

The beam-to-column connections targeted in this research suffer from lack of confining reinforcement in the joints. A typical exterior beam-column joint in a reinforced concrete frame built in 1964 is shown in Figure 9. This framing system was tested by Clyde et al. [9]. Four half-scale RC exterior joints were tested to investigate their behavior in a shear-critical failure mode. The joints were subjected to quasi-static cyclic loading, and their performance was examined for lateral load capacity, ductility, drift, and other performance criteria. There is no transverse reinforcement within the joint core to ensure the shear mode of failure in the joint, to prevail. The specimen dimensions and reinforcements for the test are shown in Figure 9 and Table 1.

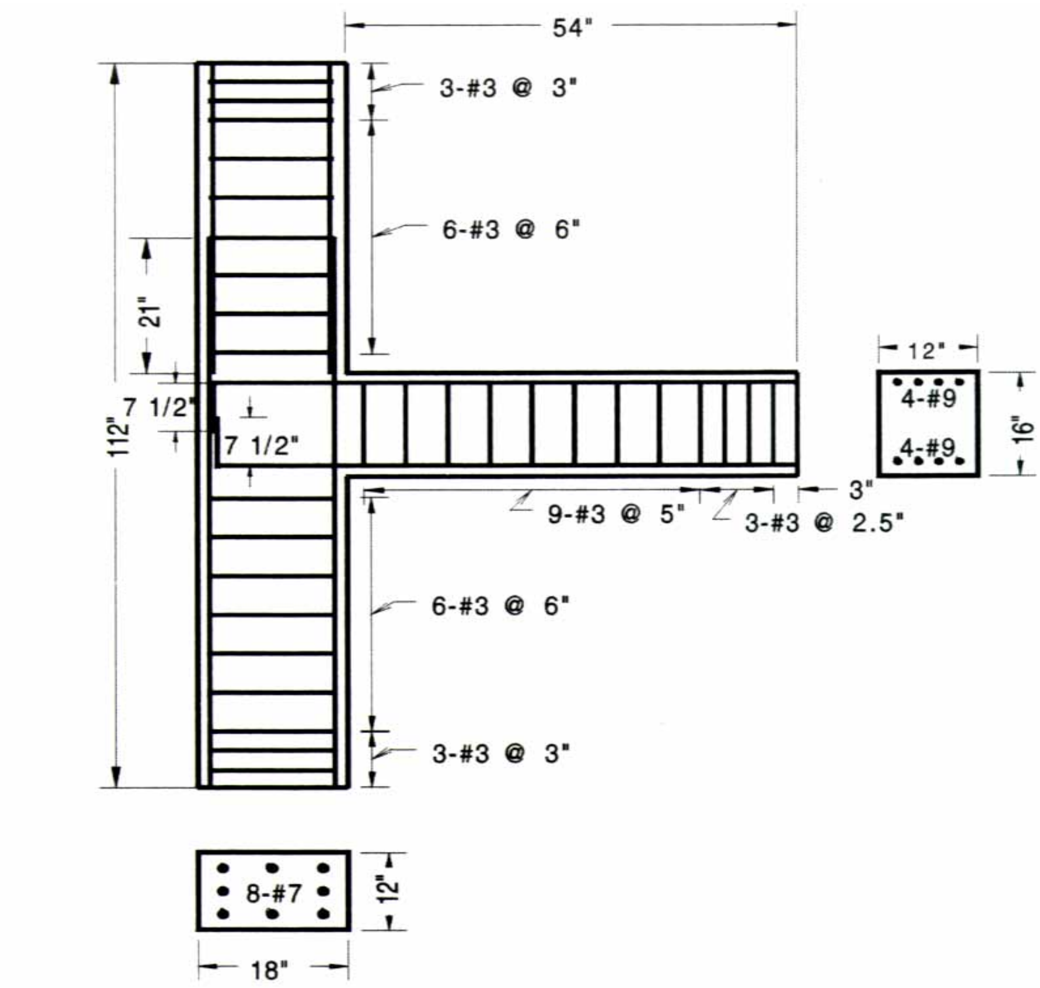


Figure 9. Specimen Dimension and Reinforcement Details (Clyde et al. [9])

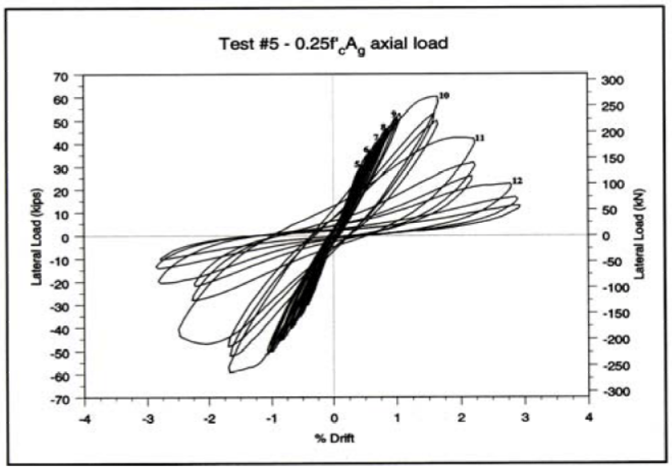
Table 1. Steel Reinforcement Details

Reinforcement Type	Bar Size	F_U ksi (MPa)	F_y ksi (MPa)
Beam longitudinal	9	108.2 (746.0)	65.9 (454.4)
Column longitudinal	7	107.6 (741.9)	68.1 (469.5)
Stirrups/ties	3	94.9 (654.3)	62.0 (427.5)

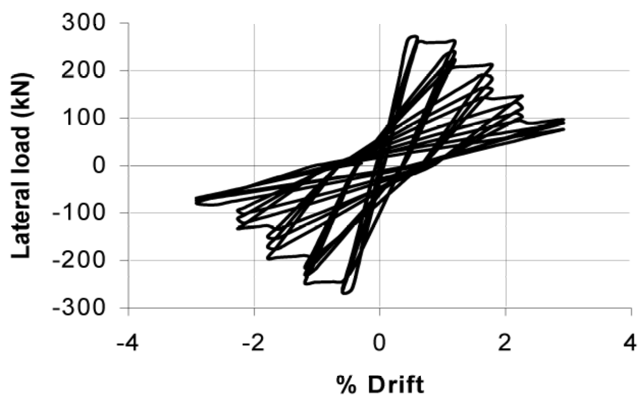
F_y **:** Yield strength of reinforcement
F_u **:** Ultimate strength of reinforcement

During the experiment, the column was mounted horizontally while an axial load equal to $0.1f'_cA_g$ (f'_c is the maximum compressive strength of the concrete and A_g is the gross cross-section of the column) for two of the specimens (specimen #2 & specimen #6), and 0.25 A_g f'_c for the other two specimens (specimen #4 & specimen #5), was applied using a small hydraulic cylinder. The compressive axial load was transferred to the column portion of the specimen through four threaded rods. The compressive axial load was set to an initial value and was then left to change at will, as the beam was subjected to load reversals. The lateral load was applied cyclically, in a quasi-static fashion, at the end of the beam through a loading collar.

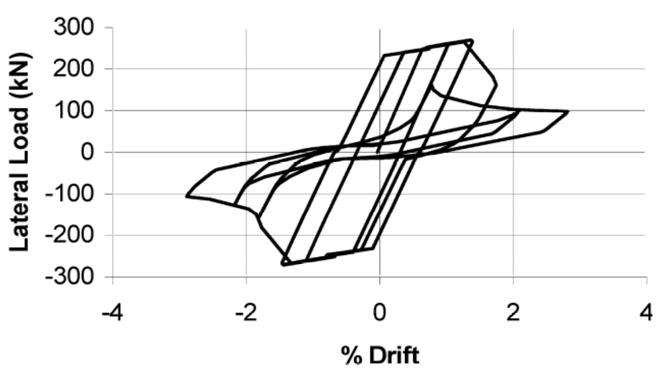
The first portion of the test was load-controlled. The lateral load was increased in 5 kip (22.2 kN) increments. At every load step, three cycles were performed, each cycle containing a push and pull segment. After the first yielding of the reinforcement, the testing was carried out using displacement control. Three cycles were performed at each displacement step, and the displacement was increased as a fraction of the initial yield displacement. The test continued until the lateral load dropped below 50% of its peak value.
The results in terms of lateral load versus the percentage of drift are presented in Figure 10. These results are for test specimen #5. The analytical results obtained using IDARC2D, and DRAIN-2DX (the proposed model), are shown for comparison in the same Figure. Good agreement between the proposed model and the experimental results is noticed.



(a) Experiment



(b) IDARC2D



(c) DRAIN-2DX

Figure 10. Comparison of the Experimental and Analytical Results (Test#5)

CONCLUSIONS

Based on the results of this study, the following conclusions are made.

1- The shear behavior of the external joint can be modeled by application of the well-known "diagonal compression strut model".

2- A macro-model using IDARC2D, although has limited features in modeling the joint zone, is able to simulate the hysteretic behavior, and degrading shear resistance mechanism of beam-columns. However, the simulation requires the exact values of hysteretic rule parameters, which are difficult to determine in the case of the prediction of behavior of elements. The main advantage of the program is its simplicity, and the speed in the analysis, which is important in the case of analysis of structures with several members.

3- The proposed new model using fiber element (DRAIN-2DX), is able to predict very comparable results to the experiment, by following a unified method for all specimens, and without the requirement of determining several unknown values for factors that govern the behavior. The main advantage of the model is its ability in the prediction of the behavior of the elements.

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