Energy Based Seismic Design and Evaluation Procedures for Reinforced Concrete Bridge Columns

by John Mander

Abstract

This project is concerned with the experimental determination and computational micromodeling of energy absorption or cyclic fatigue *capacity* of reinforced concrete bridge piers The results are used with a new smooth hysteretic rule to generate seismic energy *demand* spectra. By comparing the ratio of energy capacity to demand, inferences of column damageability can be made.

This seismic capacity analysis of bridge piers is developed starting from the basic principles of micromechanics Constitutive models that predict the hysteretic behavior of mild and high strength steel reinforcing bars are dealt with in detail; stability, degradation and consistency of cyclic behavior is explained, and an energy based low cycle fatigue model is proposed. A hysteretic model for confined and unconfined concrete subjected to either cyclic tension and/or compression is advanced.

A column analysis program, UB-COLA, is developed to predict the behavior of columns when subjected to large inelastic cyclic deformation. The axial, flexure and shear deformations are modeled and all of the various failure modes such as longitudinal bar or transverse hoop fracture, or concrete crushing and bar buckling are captured. Flexural deformations are modeled using a fiber element routine. Shear deformations are modeled by developing a new Cyclic-Inelastic-Strut and Tie (CIST) model. This computational model was validated through experiments on bridge piers typical of construction in the eastern and central United States. These experimental studies included cyclic loading tests on models of entire piers (at reduced scales of 25 to 33%) as well as full size subassemblage tests on column-to-cap connections retrieved from prototype bridge structures.

A smooth rule-based hysteretic model was developed to simulate bridge pier behavior Using this model, nonlinear dynamic analyses were conducted to assess seismic energy *demand* and the associated inelastic energy based fatigue spectra. Seismic analysis and design recommendations regarding the assessment of fatigue energy are made based on the nonlinear dynamic analysis. A methodology for the evaluation of existing bridge structures is proposed, this incorporates traditional strength and ductility aspects and fatigue energy demand. The relevance of fatigue aspects for the seismic design of new bridge structures is also demonstrated. It is shown that the present code use of force reduction factors that are independent of natural period, are unconservative for short period stiff structures. Recommendations are made for force reduction factors to be used in fatigue resistant seismic design

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Objectives and Approach

This research is being performed to develop seismic evaluation procedures for bridge columns using energy based analyses that implicitly account for the duration effects of earthquakes. The evaluation first assesses the hysteretic energy absorption *capacity* of bridge columns and then compares this with the *demand* imposed by a critical earthquake.

A dual experimental-theoretical approach is adopted whereby the energy absorption *capacity* of typical bridge columns is determined by laboratory testing. The test results are used to validate computational models that are based on the hysteretic micromechanical behavior of confined and unconfined concrete and reinforcing steel. From hysteretic macro models that are validated by the experiments as well as the associated analytical micromodeling predictions, the hysteretic energy and cyclic loading *demand* is determined for historically recorded earthquakes.

This research task is part of NCEER's Highway Project. Task numbers are 91-3412 and 10693-E-5.2.

Accomplishments

Traditional (ATC-6-2, 1983) and more recent (Chai, Priestly and Seible, 1991 and NCEER, 1993) seismic evaluation procedures compare displacement ductility capacity with demand. If for a given peak ground acceleration the capacity exceeds the demand, the structure is considered to be able to survive the entire earthquake; however, no recognition is made in these analyses regarding the length or energy content of earthquake ground motions. This research has focused on using energy as the principal means of determining the damage potential of bridge columns. The proposed energy-based damage evaluation procedure is a three-step process as follows: (a) evaluate the hysteretic energy and cyclic loading *capacity*, (b) evaluate the seismic energy *demand*, and (c) compare the energy capacity/demand ratio, and if this is less than unity, incipient failure is expected and the bridge pier should ideally be retrofitted.

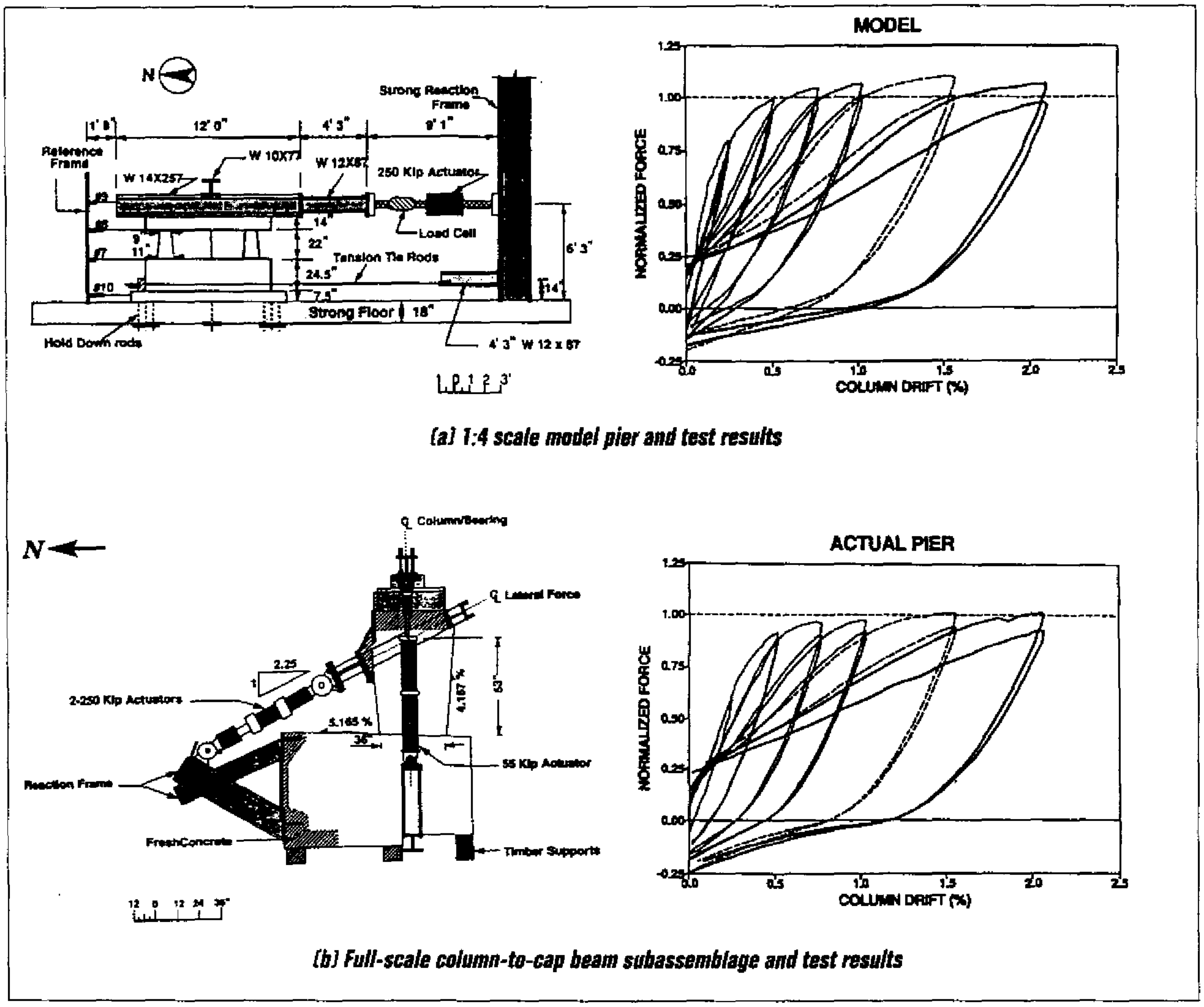
In what follows in this paper are the results of research associated with the determination of hysteretic energy capacity and demand with a particular emphasis on non-ductile bridges in the eastern and central United States.

Evaluation of the Hysteretic Energy Capacity of Bridge Piers

This phase of the research has used a dual experimental-analytical approach for the determination of hysteretic energy capacity. Several reduced scale model bridge piers, as well as full scale subassemblages, have been tested in the laboratory under quasi-static reversed cyclic loading. These experimental studies have been used to validate computer programs that have been developed to derive the hysteretic energy capacity using the principles of micromechanics.

Experimental Studies

A 25% scale model of a shear-critical bridge pier with twin 36 inch square columns was constructed and tested under cyclic loading. The model was based on the Jewett-Holmwood Road



(a) 1:4 scale model pier and test results

(b) Full-scale column-to-cap beam subassemblage and test results

■ **Figure 1**
Pier Experiments of Jewett-Holmwood Road Bridge Crossing of East Branch of Cazenovia Creek.

bridge crossing of the east branch of Cazenovia Creek at East Aurora, New York. This specimen had 1.0% longitudinal steel and only nominal hoops (#3 @ 12 inch *crs* in the prototype). The gravity axial load on the columns was $P = 0.05 f'_c A_g$. The prototype bridge piers were demolished as part of an Erie County bridge rehabilitation scheme. The opportunity was therefore taken to retrieve a column to cap beam connection and test this full-size specimen under reversed cyclic lateral load in the University at Buffalo seismic laboratory. Figure 1 presents the experimental specimens together with the normalized test results. It is evident that the experimental results demonstrate reasonably good ductile behavior despite poor transverse steel detailing.

A second set of model and prototype pier studies were undertaken on a bridge that had a typical three circular column frame pier bent. The prototype bridge, located at Niagara Falls, New York, was a two-span overpass. The central pier had three 33 inch diameter columns 20 feet long. Each column possessed a longitudinal steel volume of 0.019 with #4 circular hoops at 12 inch centers and carried an average gravity axial load of $0.03 f'_c A_g$. Prototype and model specimen details are presented along with the experimental results in figure 2. Again, test results show that in spite of poor (non-ductile) detailing, there is a fair degree of ductile response. Damage was mostly located in the connections (beam column joints) of these two specimens.

These prototype test results provide added confidence to the above-mentioned reinforced concrete model studies and basically confirm that well-conducted experiments on reduced scale physical models down to 25% in size show little difference when compared to their full-size companions.

Analytical Studies

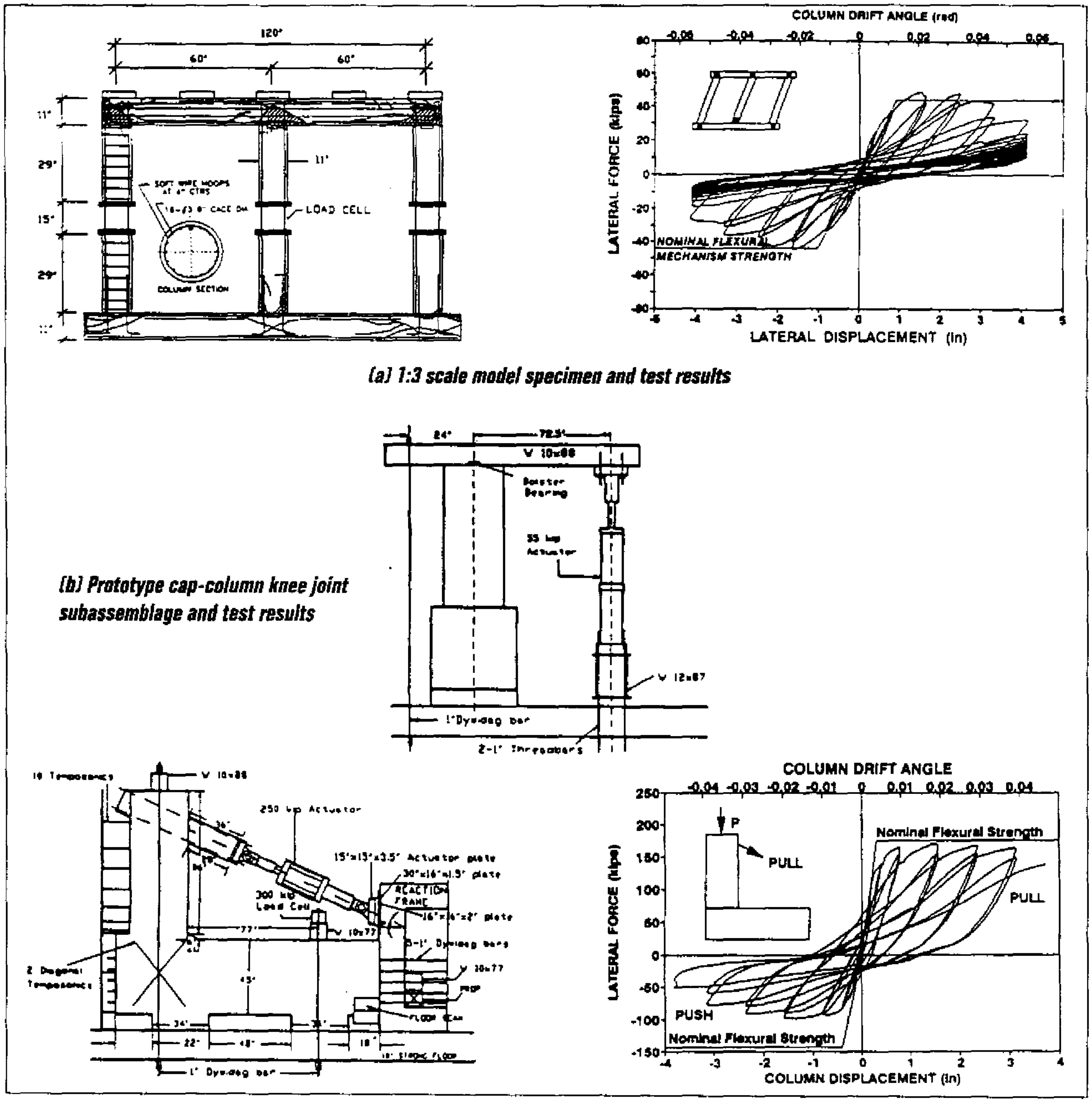
The seismic capacity of the aforementioned piers was evaluated using existing (ATC-6-2, 1983; Chai, Priestley and Seible, 1991; NCEER, 1993) recommendations. The first of these approaches, ATC 6-2, dates back to research work done in the 1970's following the 1971 San Fernando earthquake (ATC-6-1, 1983).The focus of that approach is on the flexural and shear ductility of columns, with no recognition of possible column-to-cap beam joint vulnerability. Due to the very conservative assumptions made based on the paucity of test results at the time, shear-brittle columns are generally predicted Thus, by using these recommendations engineers may be tempted to either demolish or retrofit a bridge pier for the wrong reasons.

The second recommended seismic evaluation procedure is based on more recent work by Priestley and his co-workers at the University of California, San Diego (Chai, Priestly and Seible, 1991). Recommendations have now been made for assessing joint strength and ductility capacity. These tend to agree quite well with the aforementioned experiments. New shear recommendations have also been developed, but these are still based on displacement ductility amplitude.

This research project has returned to the fundamentals of micromechanics in an attempt to predict the energy absorption capacity of bridge columns. Bridge pier failure is defined as that state in which the columns are unable to sustain the gravity load of the superstructure, that is, the onset of collapse. Incipient pier collapse may occur when: (a) the longitudinal bars fracture due to low cycle fatigue; (b) the transverse hoops fracture, thus leaving the column unconfined; (c) the lateral capacity is reduced to zero due to either shear strength deterioration, P–delta effects, or both For columns with a moderate-to-high axial load intensity, failure modes (b) and (c) generally prevail. Most bridge columns, however, have low levels of axial load, thus either failure modes (a) or (c) occur depending on the reinforcing steel detailing.

The analytical portion of this study is concerned with modeling the energy absorption (fatigue) *capacity* of reinforced concrete bridge columns using a cyclic dynamic Fiber Element computational model. The complete analysis methodology for bridge column capacity is developed starting from the basic principles of micromechanics. The hysteretic behavior of ordinary mild steel, as well as high strength threadbar prestressing reinforcement, was dealt with in detail by modeling cyclic stress-strain behavior and accounting for stability, degradation and consistency of cyclic behavior. An energy-based, universally-applicable low cycle fatigue model for such reinforcing steels is proposed. This new damage modeling approach using energy obviates the need for cycle counting and its use is therefore attractive for random loading situations.

A hysteretic model for confined and unconfined concrete subjected to both tension or compression cyclic loading was advanced. Such sophisticated modeling was found necessary to enable the assessment of inelastic shear deformations under *cyclic* loading. This concrete stress-strain model is an enhanced version of the well-known model of Mander, et al (Mander, Priestley and Park, 1988). The model has been enhanced to predict the behavior of high strength concrete, and is also capable of simulating gradual crack closure under cyclic loading A fiber element based column analysis computer program, UB-

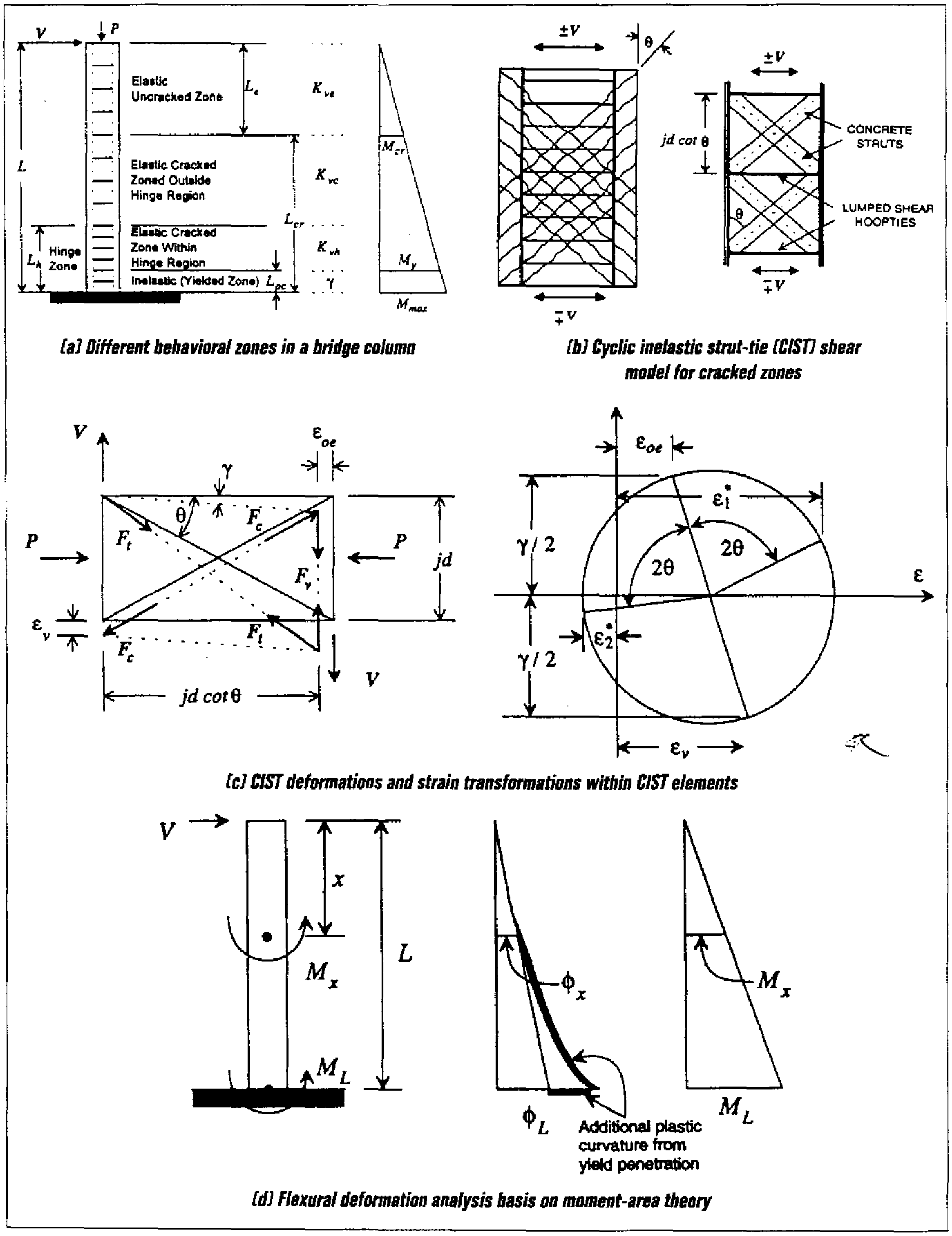


(a) 1:3 scale model specimen and test results

(b) Prototype cap-column knee joint subassemblage and test results

Figure 2
Niagara Parkway Overpass Bridge Pier Experiments.

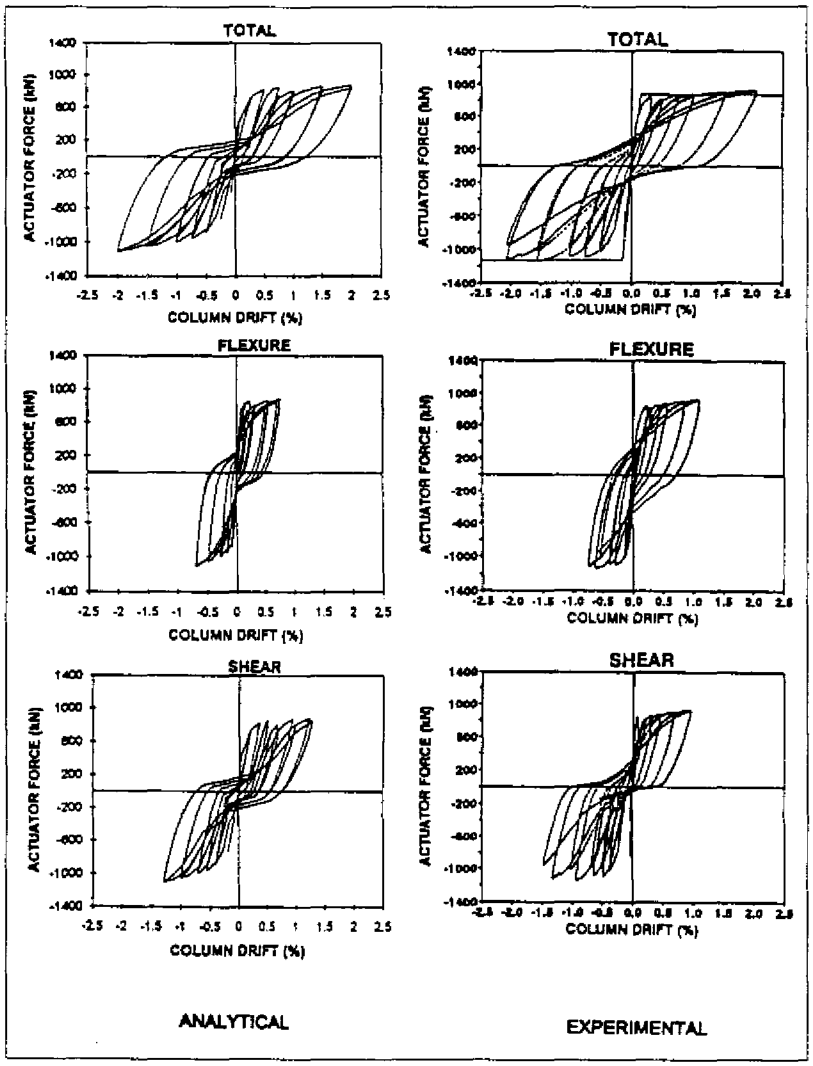
COLA, was developed for the purpose of accurately predicting the behavior of reinforcing concrete columns subjected to inelastic cyclic deformations. The axial, flexural and shear cyclic behavior are modeled, as well as the low cycle fatigue properties of reinforcing and high strength prestressing steel bars. Fracture of transverse confining steel is modeled using the energy balance theory of Mander, et al (1988). For assessing inelastic shear deformations under reversed cyclic loading, a Cyclic Inelastic Strut-Tie (CIST) model was developed which uses the new con-



■ Figure 3
Modeling of Shear and Flexural Deformations.

crete model. Figure 3 shows the essence of how shear and flexural deformations are captured in the analysis. First, the column is divided into cracked and uncracked zones, figure 3(a). Next, for shear computations, the cracked zone is modeled as with equivalent strut and tie elements, figure 3(b). Using energy methods and the cyclic constitutive relations for concrete and steel, the truss deformations (figure 3c) are computed on an incremental step-by-step shear force control basis. The resulting total shear deformations are added to the inelastic plus elastic flexural deformations, which are computed using the fiber element analysis and moment-area theory (figure 3(d)).

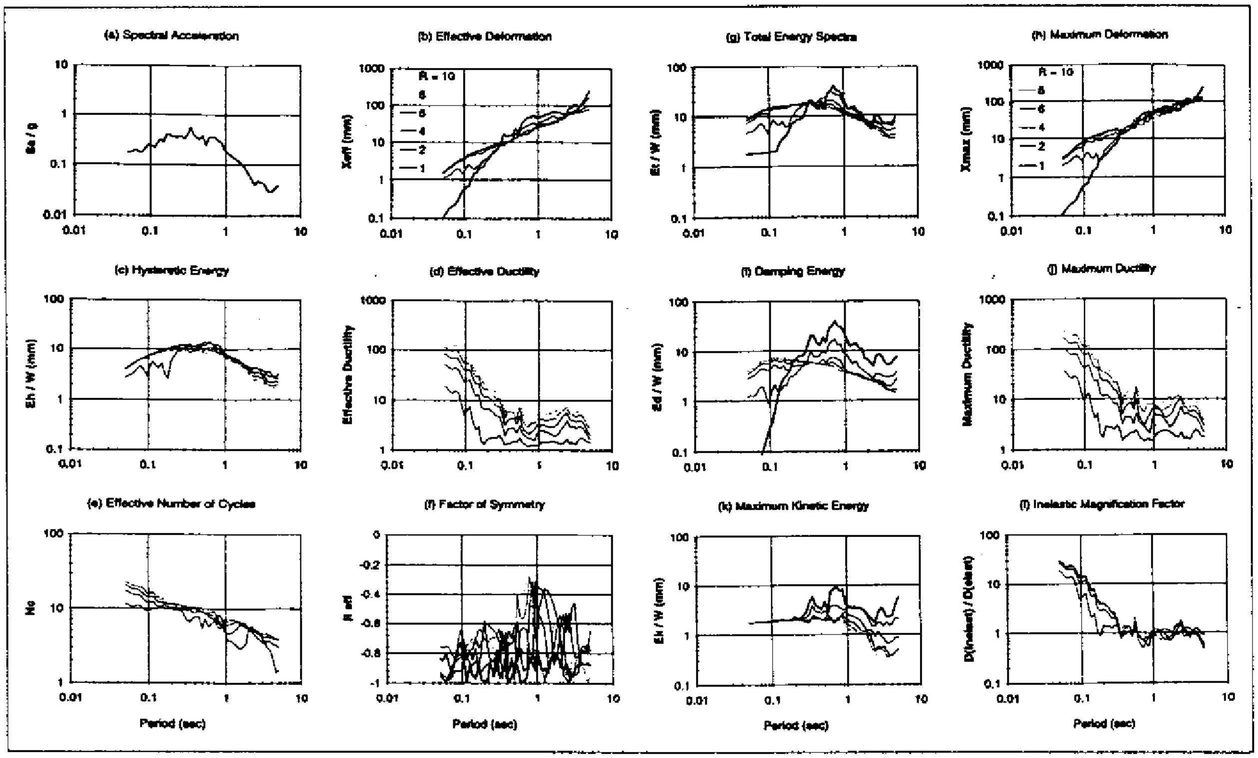
The program proved to be reliable in predicting the failure mode of either low axial load (low cycle fatigue of longitudinal reinforcement) or high axial load columns (fracture of confining reinforcement and crushing of concrete). For shear critical columns, the cyclic inelastic behavior is accurately simulated through the CIST modeling technique. An example of the predictive capabilities of the program UB-COLA is presented in figure 4 in which the prototype specimen previously shown in figure 1 is analytically modeled. Careful instrumentation of the laboratory experiments enabled a decomposition to be made of the flexure and shear components of total column displacements. It is evident that the modeling procedure is capable of capturing well both of these inelastic components of behavior.



■ **Figure 4**
Analytical Simulation of a Full Size Shear Critical Bridge Pier Tested by Mander, et. al. [1993] (see figure 1 for specimen details).

Hysteretic Energy Demand

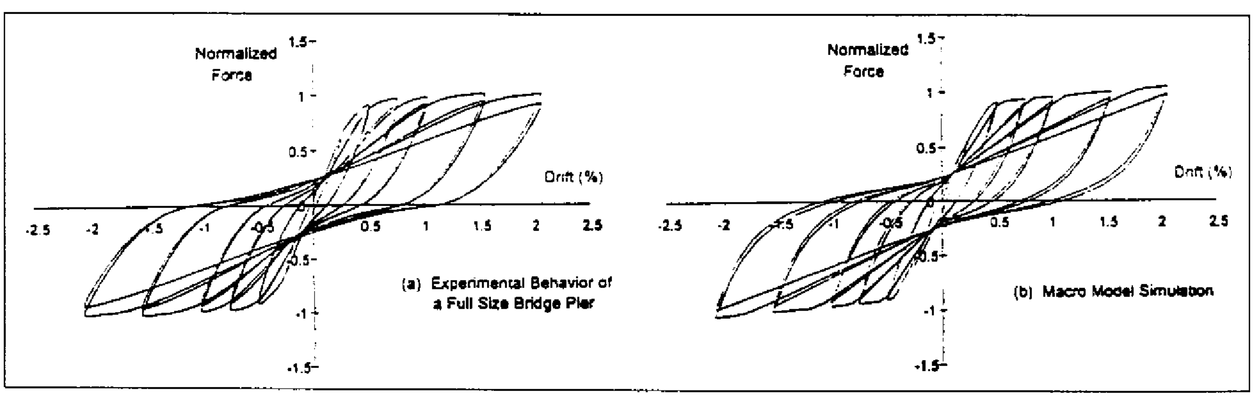
In order to assess the hysteretic energy and cyclic loading demand of reinforced concrete bridge piers, reliable hysteretic models that are representative of real bridge behavior are necessary. Therefore, a rule-based smooth hysteretic model was developed that is capable of capturing the behavior of bridge piers. The model parameters are determined automatically by using a system identification routine in conjunction with either (a) real experimental data from large scale laboratory tests, or (b) results generated from the reversed cyclic loading Fiber Element analysis computer program UB-COLA.



■ **Figure 5**

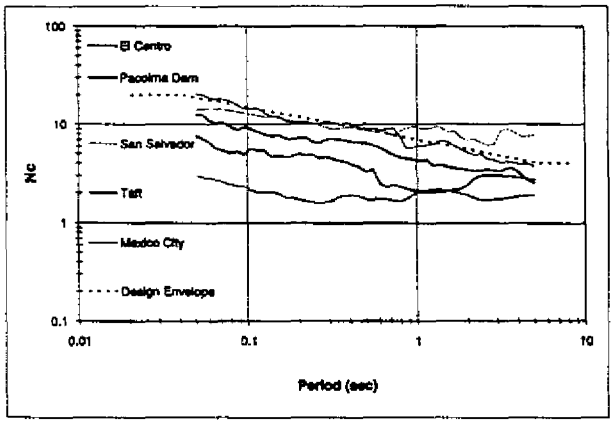
Energy, Ductility and Low-Cycle Fatigue Demand Spectra for Taft (1952) N21E, with 5% Viscous Damping Ratio Using the New Smooth Model.

A SDOF inelastic dynamic time-history analysis program was developed for using the new rule-based smooth model as well as more traditional hysteretic models such as the piece-wise linear Takeda model. Spectral results were produced by using the smooth model and an example of all the spectra generated for one earthquake are shown in figure 5. The smooth model was calibrated with the full-size bridge column experimental data to determine global parameters to simulate structural force-deformation behavior. The calibration is summarized in figure 6. The cyclic loading demand results from several analyses are summarized in figure 7, and the effective



■ **Figure 6**

Macro Model Simulation of a Full Size Bridge Pier Compared with Experimental Data.



■ **Figure 7**
Equivalent Number of Inelastic Full Reversed Cycles for $R_\mu = 6$.

dynamic magnification of displacement response depicted in figure 8.

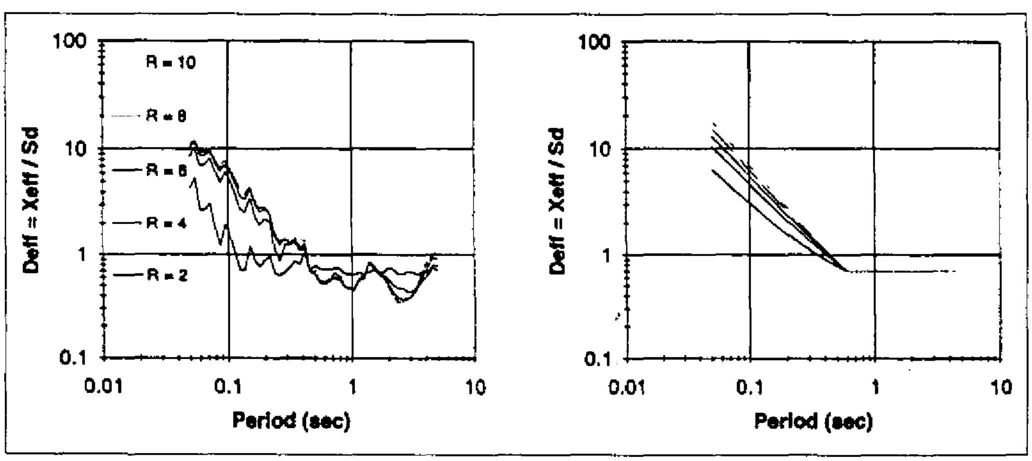
Conclusion

A complete methodology of seismic evaluation of existing bridge structures is proposed which incorporated the traditional strength and ductility aspects plus the fatigue energy demand. The relevance of fatigue aspects for the seismic design of new bridge structures is also demonstrated. Theoretical predictions using the new CIST-Fiber Element modeling techniques were validated by a combination of reduced scale and full size experiments on the reversed cyclic loading behavior of bridge piers.

It is shown that the present code use of force reduction factors that are independent of natural period are unconservative for short period stiff structures. Recommendations are made for force reduction factors to be used in fatigue resistant seismic design.

Personnel and Institutions

This work has been undertaken by Professor John Mander, of the University at Buffalo, and his graduate students, F.D. Panthaki, M.T. Chaudhary, S.M. Waheed and G.A. Chang. The following people have also collaborated on this project: Dr. S.S. Chen, University at Buffalo, with associated field work and the retrieval of the prototype specimens; Dr. P. Gergely, Cornell University, in critiquing the work; Dr. A.M. Reinhorn, University at Buffalo, on damage modeling of concrete elements; Dr. M. Saiidi, University of Nevada, Reno on experimental testing; Dr. J. Kulicki of Modjeski and Masters, Inc. on providing data on typical bridge piers in the eastern and central U.S.; Erie Country Department of Public Works on field testing and retrieval of prototype specimens; and Region 5, NYSDOT, on field testing and retrieval of prototype specimens.



■ **Figure 8**
Effective Inelastic Dynamic Magnification and Idealization.

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