Precast Concrete Connections to Develop Moment Resistant Frames

Dean E. Stephan
President Charles Pankow Builders
Los Angeles, California, USA

Background

Precast concrete moment frame construction is not used extensively in the United States despite the economics, quality and efficiencies inherent with prefabricated construction. This is largely due to the lack of test data on precast concrete moment resisting frames, the lack of development of moment resistant joinery, and building code provisions oriented towards monolithic detailing requirements and provisions. In addition, in the United States the precast concrete industry's traditional market is shear wall braced, lowrise buildings which do not require moment resistant frames. Industry and researchers began to recognize the potential advantages and uses for precast concrete moment resistant frames in the mid 1980s.

The critical element in successfully utilizing precast concrete in moment resistant frames was the development of economical joinery. Because of the seismic considerations in many areas of the United States, industry and researchers also recognized the desirability of developing joinery that could accommodate cyclic loading and inelastic response. As a result, in 1987 private industry through the Precast/Prestressed Concrete Industry (PCI) and government through the National Institute of Standards and Technology (NIST) instituted an experimental program to examine the behavior of one-third-scale model precast concrete beam-column connections subjected to cyclic loading which caused an inelastic response. The object of the program was to develop recommended guidelines for the design of an economical precast concrete moment resisting beam-to-column connection. The joinery was to be suitable for use in all regions of the United States including those of high seismic risk. The concept investigated was the use of high strength post-tensioning steel to connnect the precast elements. The clamping forces of the post-tensioned steel exerted through the joint provided the required shear and moment resistance to applied dead, live and cyclic seismic loads. The hinge occurred at the beam to column interface (Figure 1). The research was completed in 1991. It demonstrated the feasibility of such joinery, but revealed substantial slippage in the hysteresis loops and a low lever of energy absorption. (Cheok and Lew, 1990; Cheok and Lew, 1991). Independent work at the University of California at San Diego demonstrated similar results (Priestley, 1992; Priestley and Tao, 1993)

In 1990 the National Science Foundation (NSF) and the Japanese Ministry of Construction initiated a joint USA/Japan program known as Precast Seismic Structural Systems (PRESSS) to develop precast concrete joinery for use in seismic regions. The participants from Japan were primarily large construction companies possessing major internal research and development capabilities. In an effort to stimulate industry involvement by the United States precast concrete industry, NSF established an industry advisory board composed of structural engineers, precast concrete manufacturers and contractors. In addition to the advisory board, NSF sponsored workshops around the country to solicit industry input regarding the areas of investigation deemed desirable. The actual United States participants in PRESSS were researchers from leading research institutions and a limited number of structural engineers. Through involvement on the advisory committee, Charles Pankow Builders was exposed to the work of PCI/NIST and the research at the University of California at San Diego and became interested in developing a precast concrete joint that would qualify under the Uniform Building Code (UBC) for a special moment-resisting frame (SMRF) for use in mid and highrise building construction in the highest seismic risk regions defined by UBC, Zone Number 4.

In most cases, the UBC monolithic detailing applicable to the cast-in-place concrete SMRF cannot easily achieved in a purely precast concrete system. Thus, structural approaches to precast concrete structures are undertaken under the UBC category of 'undefined structural system'. Under this approach, such systems must be shown to be equivalent to monolithic concrete SMRF's dynamic characteristics, lateral force resistance and energy absorption capacity.

Under current seismic design approaches, buildings protect themselves by dissipating energy through inelastic action with the resulting significant damage to the framing components (Figures 2 and 3). Collapse is avoided by the concept of ductility withough regard to the economic impact of the resulting and potentially severe structural damage on the future use of the building.

Pankow decided to attempt to develop a precast concrete joint between frame beams and columns which would substantially separate the functions of moment resistance and energy dissipation to address the issue of property damage as well as life safety. The connection to be studied was designated as a hybrid precast concrete connection. The hybrid connection contains mild steel and post-tensioning steel, both of which contribute to the joint's moment resistance. In addition, the mild steel undergoes inelastic action serving as an energy dissipater while the post-tensioning functions in its elastic range, providing the clamping force between the beam and the column, allowing beam shear at the interface to be resisted by friction.

Both the design and the construction components of the construction industry in the United States do not perform or have a significant involvement in research due to structural market impediments. As a result Pankow did not have any experience regarding contracting for services, funding or embarking upon the research and testing activities necessary to develop a precast concrete SMRF and to introduce code changes and design procedures necessary for its acceptance and widespread application. In the United States contractor initiated research pertaining to buildings is very limited. The industry research that has been done is primarily limited to investigations bearing upon means and methods of construction and is generally related to specific projects.

Two avenues were explored for performing the required research, university research laboratories and the Building and Fire Research Laboratory of NIST. The university laboratories had highly qualified researchers and the necessary facilities but their ability to respond was severely limited by the needs and structures of their graduate studies program. In addition, their orientation and usual deliverable was a published technical paper. This fell far short of the need to develop design procedures and addressment of code issues and required code changes necessary to transfer the technology to practice. In the United States there is not a clear history of efficiently transferring construction related research from university laboratories to practical application. Th ecause of this seems to be due to the lack of private industry involvement in research activities and their funding. Much of the university-based construction research funding comes from NSF, with a technical paper being the deliverable. A notable exception is research funding by government agencies to address specified needs of their construction programs.

Because of the perceived problems of university-based research, Pankow elected to sponsor the desired investigations at NIST. In addition, NIST offered to reduced Pankow's investment risk by cost sharing. NIST funded their estimated overhead and Pankow funded the estimated direct cost of performing the research. NIST possessed qualified researchers, the physical testing facilities and their research activities were not restricted by graduate program needs and academic year time constraints.

Due to the lack of experience in contracting for and participating in research, Pankow funded its portion of the estimated research cost as a donation to the American Concrete's Institute's (ACI) Concrete Researchand Education Foundation (ConREF). In turn, ConREF contracted with NIST and provided a volunteer oversight committee of experts from the membership of ACI. In addition, Pankow directly engaged the services of Professor John Stanton, a researcher at the University of Washington, to participate in establishing the necessary investigations, to consult in evaluating the research results and to provide essential assistance to Pankow in understanding and defining the technical issues. The collaboration was later expanded to include financial, technical and material contributions from material suppliers and the participation of a structural design practitioner to perform the tasks necessary for code evaluation/acceptance and to participate in the development of design procedures.

Research results

The research portion of the development of a successful precast concrete SMRF based upon a hybrid joint was commenced in 1992 and successfully concluded in 1994. The investigation was divided into two phases. The initial phase explored different locations and configurations for the cross-joint steel, different steel materials and different configurations of the energy absorbing mechanism. The second phase consisted of multiple testing of the prototype joint (Figure 4) developed as a result of the first phase explorations. The second phase of testing developed test data concerning energy absorption and data upon which to base design procedures. The research procedures and the results of the research has been widely reported through published technical papers (Cheok *et al.*, 1992; Cheok and Lew, 1993; Cheok and Stone, 1994; Stone *et al.*, 1995).

The performance of the hybrid joint developed has met all of the research team's expectations. The prototype hybrid precast concrete moment resistant joint displayed behavior that, in almost every way, was significantly superior to conventionally reinforced monolithic joints constructed in accordance with UBC requirements for Zone 4 special moment-resisting frames that were tested for reference. The conclusions of the investigation are:

1. A hybrid precast concrete system can be designed to have the same flexural strength as a conventional monolithic system.

2. Prior to mild steel bar fracture, the hybrid system suffers no strength degradation.
3. The behavior of the hybrid precast concrete joint was predictable. The ratio of the experimental moment to the predicted moment was 1.055 for the hybrid system versus 1.14 for the monolithic system.
4. The hybrid system is self-centering and displays essentially no residual drift from inelastic action.
5. The hybrid system has very large drift capacities. It suffered negligible damage at drifts of 6%; the maximum throw of the test equipment. No cracks reached 1 mm in width. The cracks closed completely upons removing the load. The damage was limited to minor spalling that occurred in the concrete cover (Figure 5).
6. The hybrid system dissipated more energy per cycle than the monolithic system for drifts up to 1.5%. Thereafter, the energy dissipated was approximately 75% of the conventional system (Figure 6 and 7).
7. The hybrid system exhibited durability in excess of 40 cyclical loadings. A cyclical loading number far in excess of the number of cyclical loading which characterize seismic events.
8. Failure was defined as loss of 80% of the maximum restive moment. The hybrid joint did not experience brittle failure, even at the 6% drift level.
9. Strains in the transverse steel remained below 0.15 fy and no sign of shear distress was detected. This was in contrast to the monolithic system which suffered severe cracking and was beyond repair at the end of the tests.
10. The hybrid joint surpassed the drift capacity of steel special moment-resisting frames currently in use (Figure 8).

Current status

The testing and analytical phase of the research is over except for some minor testing of debond reinforcing steel under cyclic loading. Design procedures have been developed by the researchers in conjuction with a practicing structural engineer and are currently being reviewed by the ConREF oversight committee. Acceptance criteria for the joint's performance has been submitted to International Conference of Building Officials (ICBO) for approval. Recommended code revisions to the ACI 'Building Code Requirements for Reinforced Concrete and Commentary' and NEHRP 'Recommended Provisions for the Development of Seismic Regulations for New Buildings' are being drafted by a task committee established by ACI to facilitate the transfer of the technology to practice through timely code modifications. The precast concrete moment-resisting frames developed are being used to resist lateral forces in a multi-story parking structure currently under construction in a region of low seismicity.

The Northridge earthquake which occurred near Los Angeles, California in 1994 emphasized the urgent need for the development of special moment-resisting frames capable of meeting the demands of a major seismic event. Prior to the Northridge event, steel SMRFs were the preferred lateral restraining system and deemed to possess sufficient ductility to withstand maximum credible earthquakes. Northridge shattered this assumption due to the widespread brittle failure of steel SMRFs. Subsequent testing revealed that the frames could not meet the rotational demands that resulted from the Northridge ground motion.

Due to the magnitude of property damage resulting from the Northridge event ($20 billion, US) and the high cost and uncertainty of repair procedures for existing structural frames, insurers, lenders, owners and investors are demanding that building designs for seismic regions recognize property damage as a criteria in addition to life safety. Research into ways to dissipate the ground motion energy from earthquakes, other than intentionally inflicting damage to the structural frame, is very timely and responsive to society's needs.

Conclusions

Pankow deems its investment in non-proprietary research to be a qualified success. Close cooperation between industry, practitioners and researchers and their exchange of information during the investigations focused the ideas and explorations on cost effective and constructable solutions, and data and procedures useful to practitioners. All parties benefited from the diverse knowledge base represented on the team. Pankow was able to introduce the manufacturing, erection and construcability constraints into the investigation and to keep the focus on the goal of developing a useful and economical precast concrete joint for use in seismic regions. The practitioner was able to introduce the constraints on variables and compelxities in the desing procedures that reflectged the sophistication and capabilities represented in practicing structural engineers' offices. The researchers posed the probing questions that needed answering and established the testing procedures and analysis that would provide the answers. Pankow provided the champion necessary for the transfer of the technology to practice.

Pankow's venture into non-proprietrary colloborative research revealed two major problems and impediments to future research investment by the company. The first is the cost efficiencies and organization of research laboratories.

1. The research organizations, be they government or university, have extremely high overhead structures and charges.

2. Research is performed without apparent regard for schedules or understanding of industry's need for timely results.

3. The manufacture of test specimens was grossly inefficient. This resulted in wasteful costs being incurred and caused long delays in the testing program.

4. Research organizations are not structured to respond to customer needs. They respond to their internal structure such as academic schedules and publication needs.

Pankow produced the phase 2 specimens in California with construction tradesmen and shipped them some 4200 km to Virginia for testing by NIST at approximately 1/8 the cost and 1/3 the time of producing them at NIST. There remains some minor testing related to the bonding of reinforcing steel during cyclical loading. The cost of manufacturing and testing these specimens at a testing laboratory is 1/4 the cost at the research laboratory.

The other major impediment to investment in research by industry is the difficulty of having the research results and application evaluated and approved for use.

1. Current code evaluation procedures are oriented to construction products and do not adequately address changes in design procedures or code prescribed details and restrictions.

2. Concrete design codes in the United States are produced by the consensus process of the volunteer members of the professional organization, the American Concrete Institute

(ACI). By nature, this process tends to be inefficient and results in a code which severely lags technological development.

3. Current codes are besed primarily on experience rather than a combination of experience and science. This makes the evaluation and acceptance of technology resulting from research an undefined process that is excessively time consuming and expensive. The result is an inefficient transfer of innovations resulting from research to practice.

These problems, which seem to exist to a much greater extent in the United States as compared to Europe or Japan, have been recognized by the three model code bodies, ACI and the Civil Engineering Research Foundation (CERF) and methods are aggressively being developed to try to address these issues.

Recommendations

The benefits to the building industry and the value accruing to the users of the constructed social infrastructure in the United States demands that there be increased involvement and investment in research by industry. This industry driven research activity will emphasize development and application rather than acquisition of knowledge. Timely performance and cost efficiencies will be essential and the use of the results will be the deliverable. As industry and the research community forge their future alliances both parties need to understand the needs of the other so the relationship can be productive. To facilitate the changed nature of the resulting research, the following is recommended:

1. All parties must learn to accurately forecast probable research cost and schedule.

2. Traditional research deliverables must be expanded to include information and procedures necessary for application of the technology.

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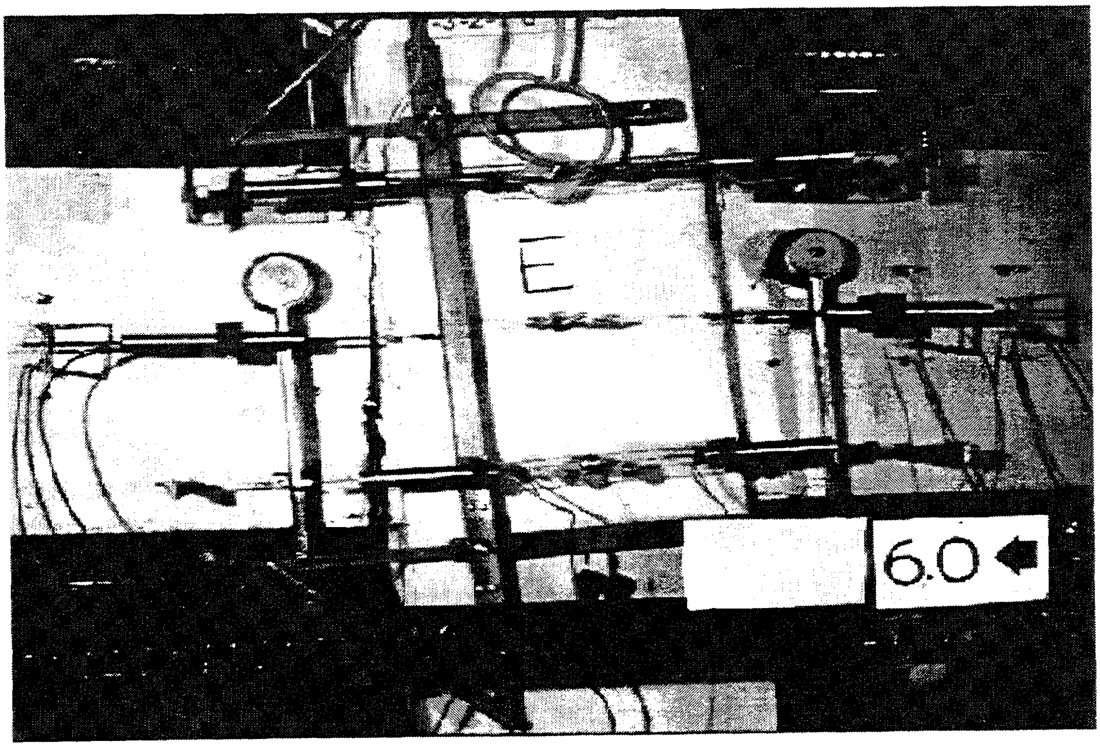

Figure 1 Hinge at Column/Beam Interface, 6% story drift

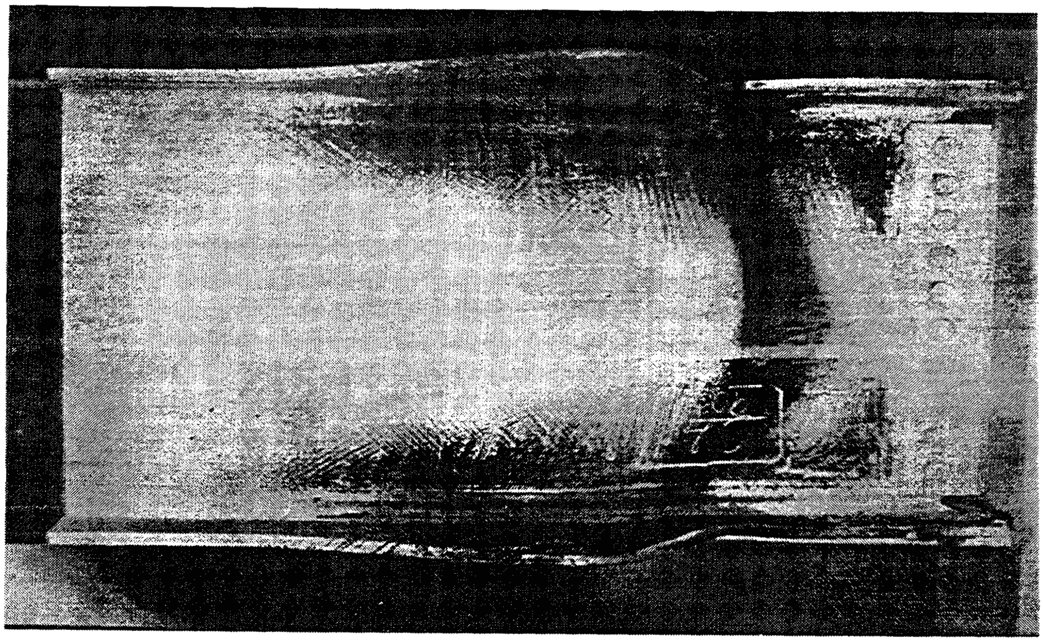

Figure 2 Structural STeel SMRF, 3.5% story drift

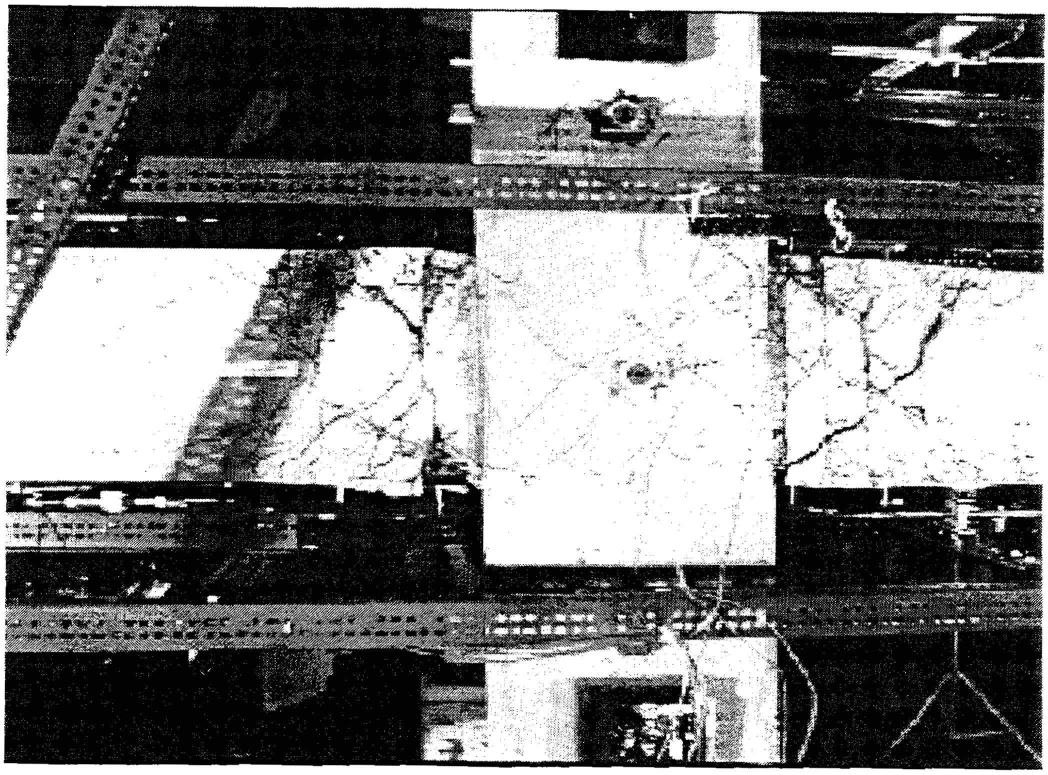

Figure 3 Monolithic SMRF, 3.7% story drift

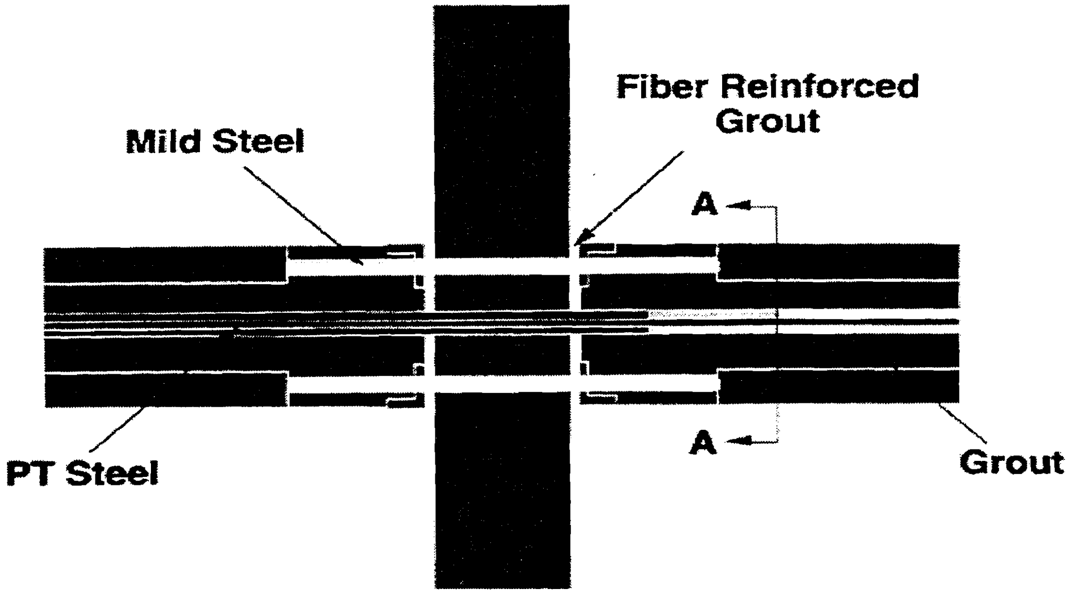

Figure 4 Prototype Hybrid Joint

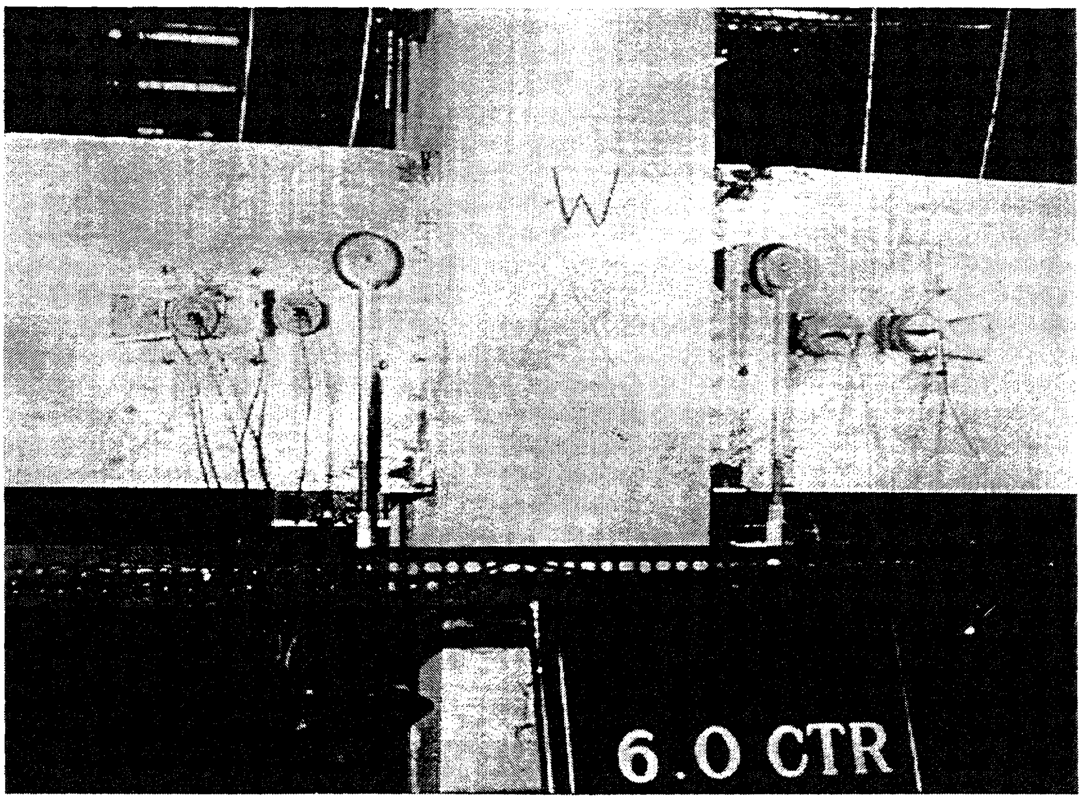

Figure 5 No Load Self-Centering, post 6% story drift

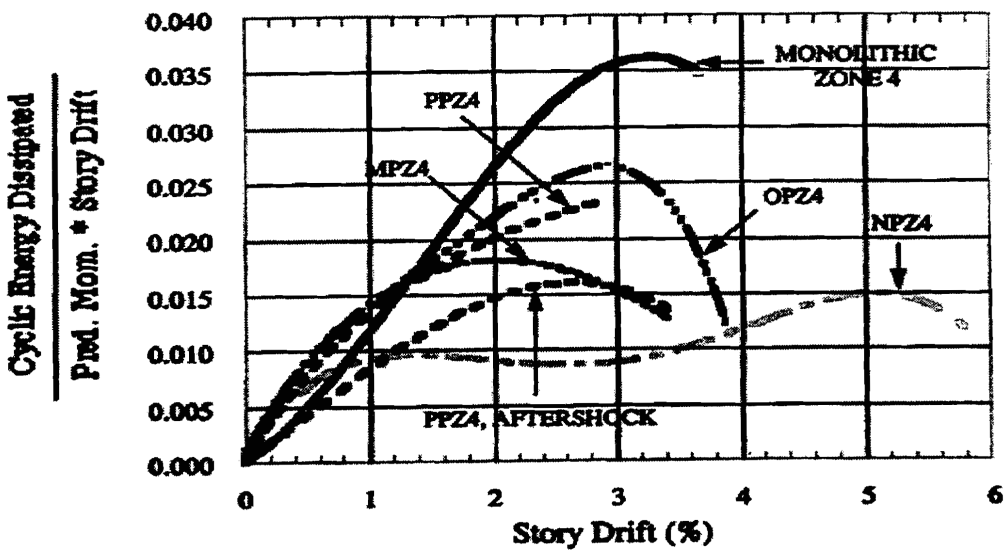

Figure 6 Comparative Energy Dissipation

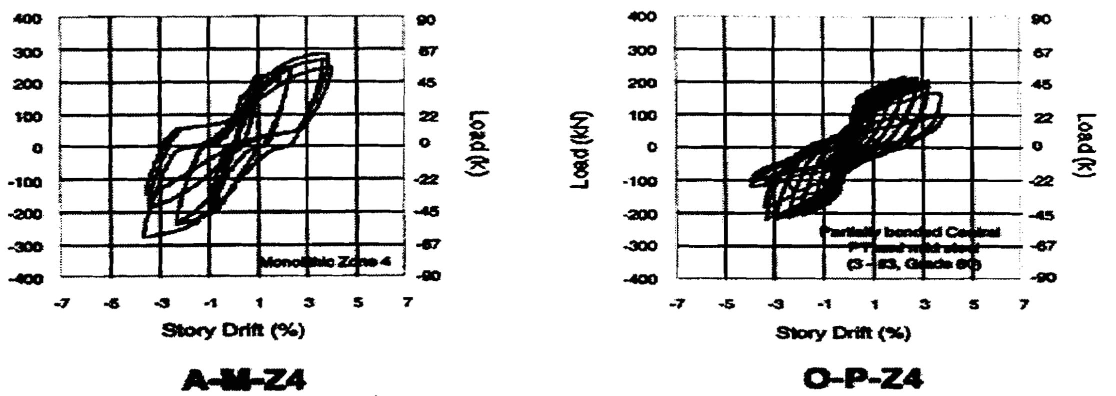

Figure 7 Hysteresis plots of Monolithic Joint (left) and Hybrid Joint (right)

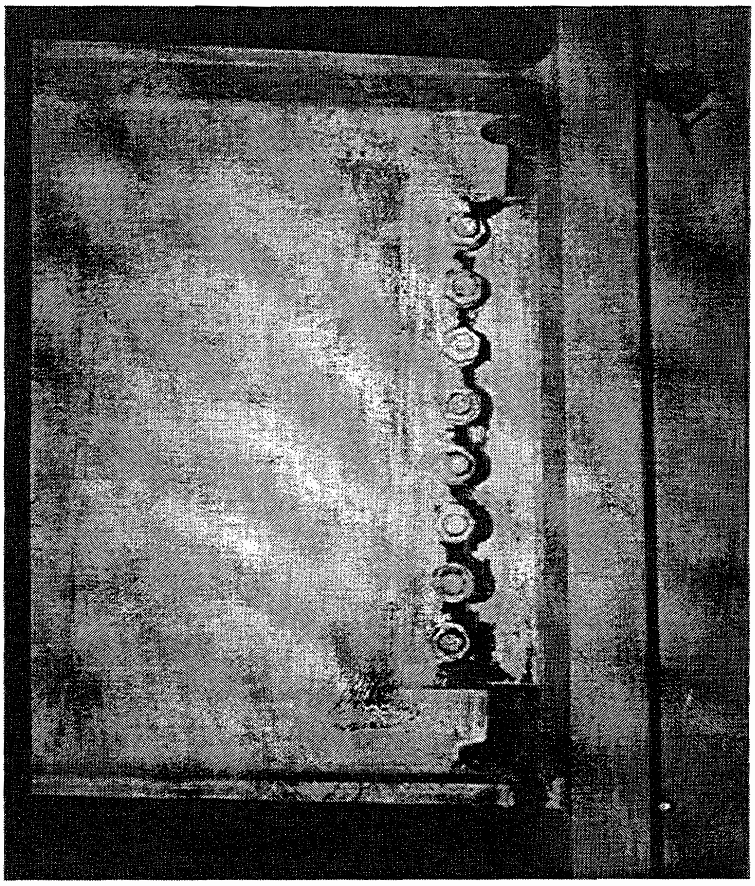

Figure 8 Structural steel SMRF, 0.75% story drift