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PERFORMANCE OF DUCTILE CONNECTIONS IN PRECAST CONCRETE FRAMES

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ABSTRACT

Tests were conducted at the University of Minnesota to investigate the behavior of ductile connections between precast beam-column frame elements. Four connections were tested to characterize the behavior of nonlinear-elastic and tension-compression yielding connection concepts. The connections were found to perform well through design level drifts of 2%. Some strand fractures occurred at larger drifts (>4%). In addition, bar fractures were observed near mechanical couplers at locations which required large deformation demands. The nonlinear-elastic connection concepts had a "self-righting" nature. Minimal residual drifts remained at the end of the loading history relative to the tension-compression yielding details. The hysteretic force-deformation response obtained from the subassemblage experiments was used to model the connections in an analytical study of multistory precast frames subjected to earthquake ground motions.

KEYWORDS

Precast concrete, connections, seismic, ductile, nonlinear-elastic, frames

INTRODUCTION

Precast concrete construction represents a viable alternative to construction methods utilizing cast-in-place concrete. Advantages related to the use of precast techniques include higher quality control that can be obtained in the precast plants, speed of erection, and freedom in the architectural form of the members. Despite these well-recognized advantages, the use and development of precast concrete construction in seismic areas of the United States has been limited by the lack of code specifications about the seismic resistant design of these structures. The Uniform Building Code (UBC, 1991), as an example, refers the designer to regulations applicable to monolithic lateral force resisting systems, without addressing the possibility of using precast concrete frames as such systems. To satisfy these requirements, when precast concrete members are used in areas of high seismicity, they are generally joined using cast-in-place techniques. This practice greatly reduces the advantages of precast over cast-in-place construction, namely the speed of erection and the economy.

With the ultimate objective to develop code regulations regarding the use of precast systems for areas of high seismicity, the coordinated Precast Seismic Structural Systems (PRESSS) program was initiated between the United States and Japan. The work presented in this paper refers to the part of the PRESSS project on beam-column connections for ductile-joint frames that was conducted at the University of Minnesota in conjunction with researchers at the University of Texas at Austin (Saqan, 1995). Objectives of this project were the development of ductile connection concepts between precast elements, laboratory tests of the proposed connection concepts to characterize their behavior, numerical investigations of complete precast frame systems using the idealized connection concepts, and finally the development of code specifications based on the experimental and numerical analyses.

The objective was to develop connections capable of accommodating the deformations within the connection region rather than in the precast members. The degradation of the precast members was therefore expected to be greatly reduced. The proposed connections were expected to exhibit good energy dissipation characteristics and/or be capable of undergoing significant deformations without loss of load carrying capacity. In the initial part of this study, connection concepts representing different behavior categories were identified, sized, and detailed. The connections were representative of four different connection categories: nonlinear-elastic, tension and compression yielding, energy dissipating, and shear yielding. The nonlinear-elastic connections were characterized by the elastic behavior of precast members and connection components; since inelastic action was excluded, upon removal of loading the connection was intended to return to its original undeformed configuration. The tension and compression yielding connections relied on yielding in tension and compression of connection components for energy dissipation. The energy dissipation category included connections that relied on means other than yielding for energy dissipation; for example, a connection utilizing friction devices could be classified as energy dissipating. In these three categories the deformations of the connection components, and the energy dissipation phenomena were mainly related to flexural forces. The connections of the shear yielding category also relied on inelastic behavior of some of the connection components, but unlike the previous cases shear deformations were associated with the energy dissipation characteristics of the connection.

The tests performed at the University of Minnesota were representative of two of the described connection categories: the nonlinear-elastic, and the tension and compression yielding concepts. The laboratory tests were conducted on beam-column subassemblages using the displacement history prescribed by the PRESSS program: set of three cycles to increasing displacement levels were alternated with a single cycle to approximately 75% of the load reached during the previous set. The intermediate cycles were used to evaluate the stiffness degradation of the specimen throughout the test. The connection responses observed during the laboratory tests were analyzed and compared in terms of moment versus rotation characteristics (moments and rotations were calculated at different locations including the beam-column interface), stiffness degradation, residual deformations, and shear transfer mechanisms across the joint. For the different concepts, the observed response in the form of moment-rotation curves was modeled and adopted in the formulation of connection elements to be included in the finite element program DRAIN-2DX. These connection element models were incorporated into models of complete 5- and 15-story frame systems (representative of buildings with different fundamental periods) which were then subjected to a variety of ground motion records. The selection of the earthquake records was done with the intent to cover a wide range of acceleration characteristics: the 1940 El Centro, N-S; 1968 Hachinohe, Japan, N-S; 1989 Loma Prieta (Corralitos), N-S; and the 1985 Vina del Mar, Chile, S-20W. The El Centro earthquake record was scaled to obtain a peak ground acceleration of 0.4g, the maximum value implied by the UBC code for zone 4. The remaining records were scaled to obtain values of spectral intensity equivalent to the one of the scaled El Centro record. The results from this numerical investigation were analyzed and compared in terms of base shear, base moment, hinge distributions, roof displacement histories, story displacements envelopes, interstory drift envelopes, and ductility demands for both precast members and connection elements. Discussion and comparison of experimental and numerical results will be presented in the next paragraphs.

SPECIMEN DESCRIPTION AND TEST RESULTS

A total of four connections were tested at the University of Minnesota (Palmieri, 1996). Two of the specimens, PTB and PTS, represented the nonlinear-elastic concept. Both specimens, shown in Figure 1,

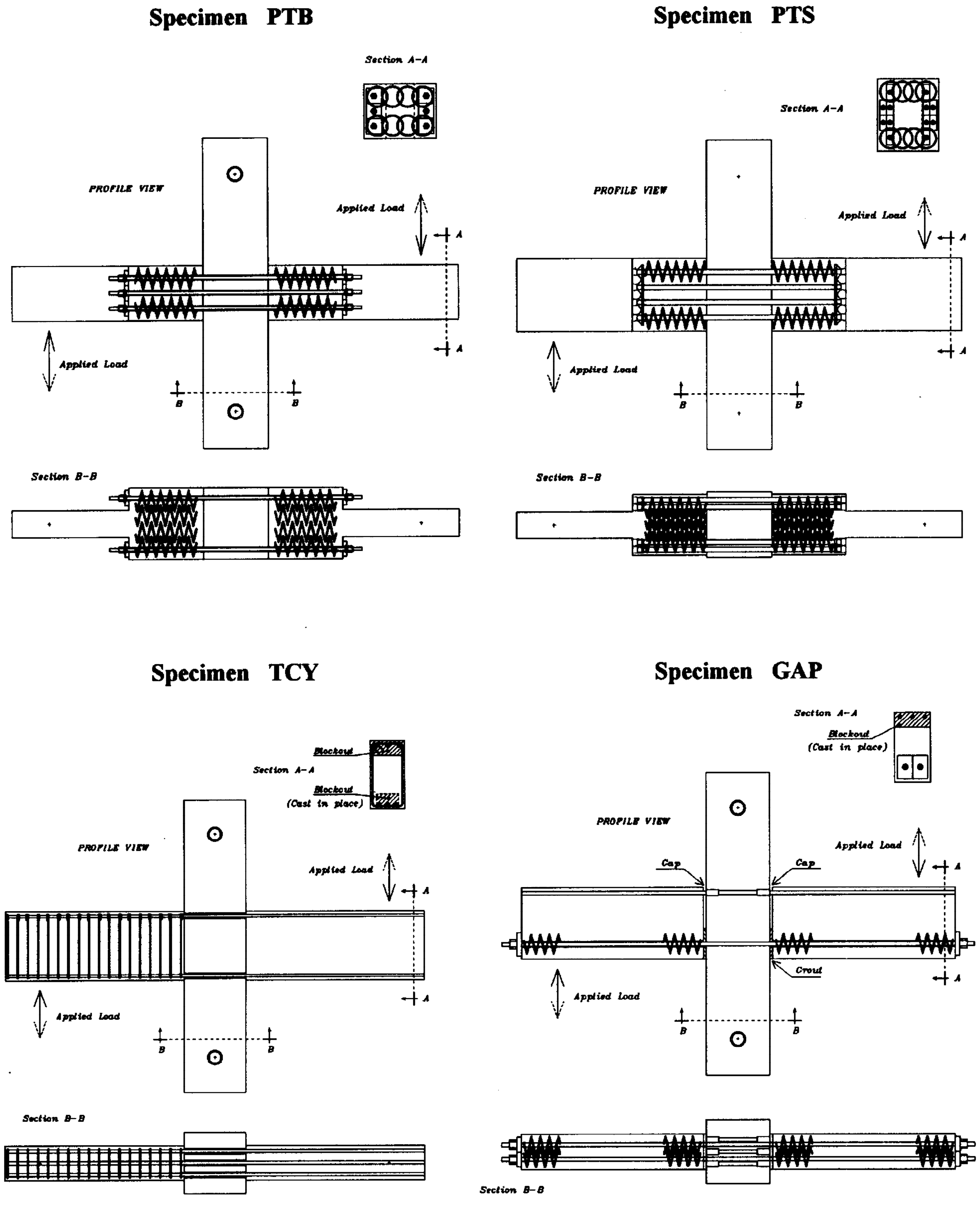

Fig. 1. Connections Tested at the University of Minnesota.

utilized debonded post-tensioning steel as the connecting element between the precast members. Dywidag bars were used in specimen PTB, and monostrands were used in specimen PTS. For this type of connection, the deformations are accommodated by the opening and closing of a crack at the beam-column interface. The unbonded post-tensioned reinforcement is lightly prestressed to insure that in accommodating the deformations at the interface, the post-tensioning steel does not undergo any inelastic deformation. In this regard the connection reinforcement remains elastic. This insures that upon removal of load the connection will return to its original undeformed configuration. To insure that the post-tensioning reinforcement remains elastic, the initial applied post-tensioning force is just sufficient to resist gravity and wind loads, and the post-tensioning steel is located as close as possible to the beam centroid. Since precast members and connection components were supposed to remain elastic, low energy dissipation characteristics were anticipated in the use of this type of connection. Both connections were designed utilizing the method proposed by Priestley and Tao (1993).

Specimen TCY represented a tension and compression yielding concept (Figure 1). The longitudinal beam reinforcement was kept continuous through the joint and served as the connection reinforcement. Under reversed cyclic loading, the longitudinal reinforcement was intended to yield in tension and compression at the beam-column interface providing energy dissipation characteristics. The simplicity of this connection was reflected in its low cost (related to the absence of any particular hardware), and in the absence of eccentricities in the load transfer paths that are often related to failures observed in connection components.

Specimen GAP (Figure 1) also represented a tension and compression yielding concept. The post-tensioning steel in the lower part of the connection provided the necessary clamping action between the precast members; proper choice of the initial post-tensioning force insured elastic behavior of the steel throughout the test. The deformations were accommodated by a 1 in. wide gap at the top part of the beam-column interface. The resistance was provided by tension and compression yielding of longitudinal beam reinforcement which spanned the gap and was mated to tapered threaded couplers in the joint at the beam-column interface. The gap-type system has several advantages. Placing the gap at the top of the beam-column interface may facilitate the constructability of the connection in the field by enabling the erectors to place the beams and then work from the top down to construct the connection. A gap located at the bottom of the beam may enhance the system performance by concentrating the rotations at the bottom of the interface. In this situation, the precast floor panels should remain relatively undamaged; whereas in the case of the gap at the top, cracks would form in the floor panels along the beam-column interface. The gap also serves to reduce concrete degradation at the interface by accommodating the compression resistance through yielding of the reinfocement. The yielding of the mild reinforcement in tension and compression was intended to provide the energy dissipation characteristics anticipated in the use of this type of connection.

Typical moment-rotation curves measured at the beam column interface (rotations were measured within 6 in. from the interface) are shown in Figure 2 for the nonlinear-elastic concept (specimen PTB). From the plots it can be observed that some energy dissipation was observed in the case of PTB. This hysteretic response actually enhances the connection behavior by reducing the demands through energy dissipation. The minimal residual deformations observed throughout the entire test are also of importance. Superimposed upon Figure 2 is the anticipated behavior of the connection evaluated according to the Priestley and Tao model (Priestley and Tao, 1993). The value for s in the figure represents the assumed spalling depth (0.75 in. represents the concrete cover; 1.5 in. represents the depth to the concrete confined by additional spiral reinforcement). It can be seen that the model provides a good envelope to the connection response. Figure 3 refers to the tension and compression yielding concept (specimen TCY). The wider hysteresis loops relative to the tension and compression yielding connection indicated good energy dissipation characteristics. The inelastic behavior of this connection was evident in the substantial residual deformations that are observed in the plot.

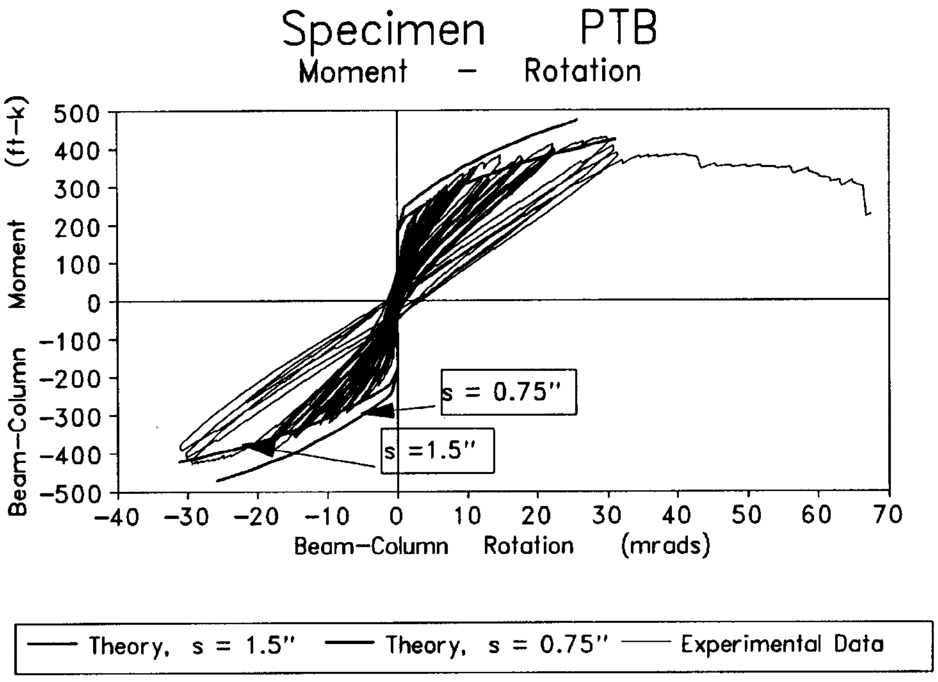

Fig. 2 Specimen PTB: Moment versus Rotation at Beam-Column Interface.

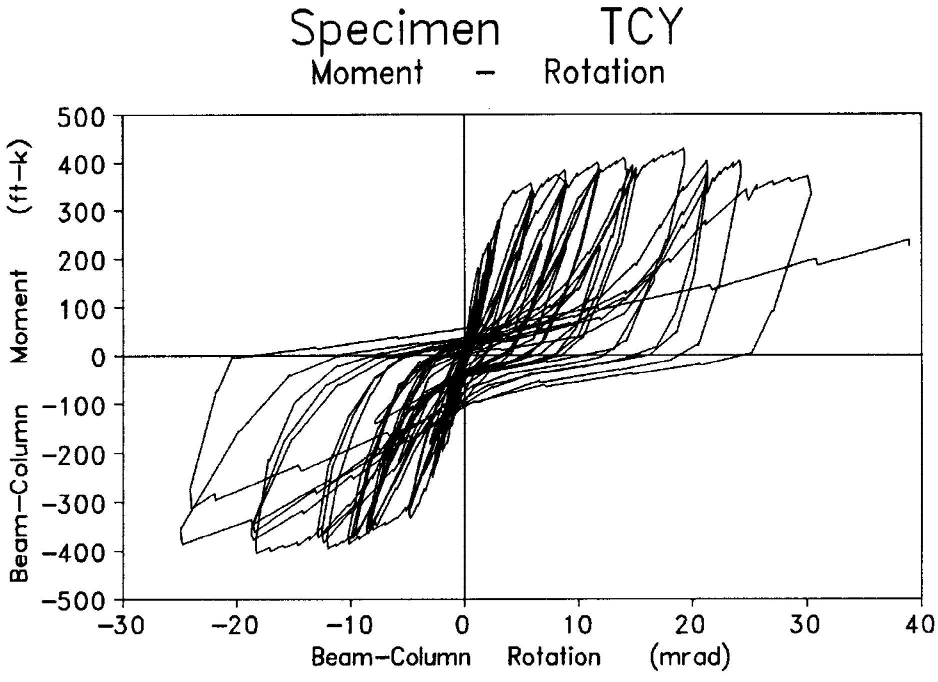

Fig. 3 Specimen TCY: Moment versus Rotation at Beam-Column Interface.

Figures 4 and 5 show a comparison of the test results in terms of stiffness degradation and residual displacements, respectively. The values of stiffness reported in Figure 4 are normalized for all the specimens with respect to the values calculated on the basis of linear elastic analysis. Comparison of the stiffness degradation characteristics for the four specimens shows similar trends, the higher stiffness degradation took place in the initial phases of the test due to the initiation of concrete cracking. In the case of specimens PTB, PTS, and GAP the shape of the loading curve was approximately linear, therefore the stiffness was calculated as the tangent of the line between the points corresponding to initiation of loading and the peak load reached during that cycle. This stiffness was termed as secant stiffness. In the case of specimen TCY, the loading curves could be represented as bilinear curves; the stiffness shown in Figure 4 for specimen TCY was calculated as the tangent of the first branch of this loading curve, and was therefore termed as tangent stiffness. A striking difference in the connection performance is shown in Figure 5. While specimens PTB and PTS exhibited minimal residual displacements throughout the entire test, in the case of specimens TCY and GAP these values increased dramatically when the specimens were subjected to drift levels in excess of 1%. As mentioned earlier, the nonlinear elastic systems tended to return the subassemblage to its undeformed position.

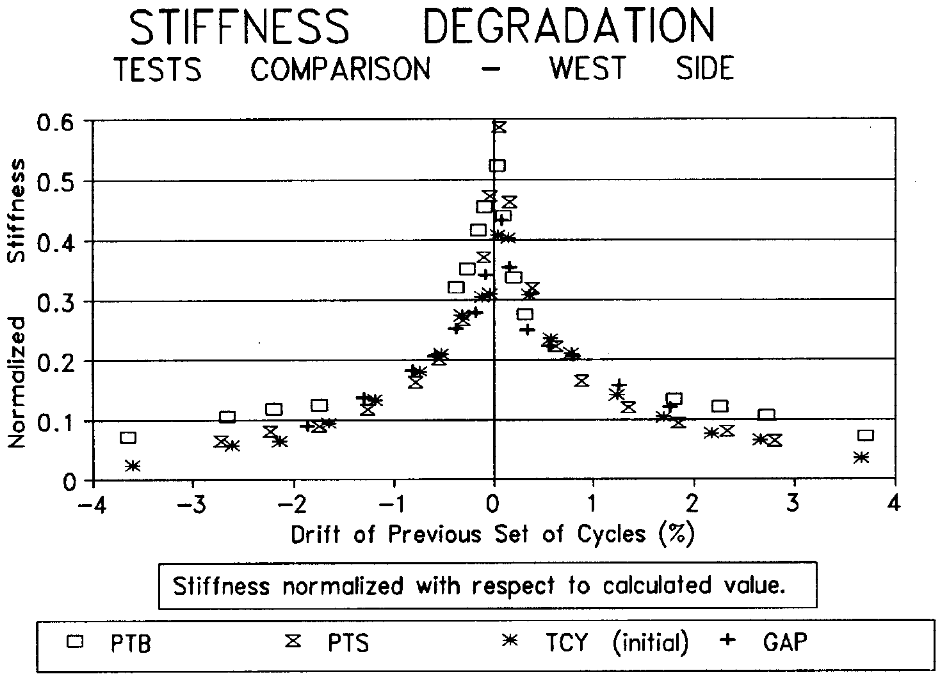

Fig. 4. Siffness Normalized with respect to Elastic Value: West Side Comparison.

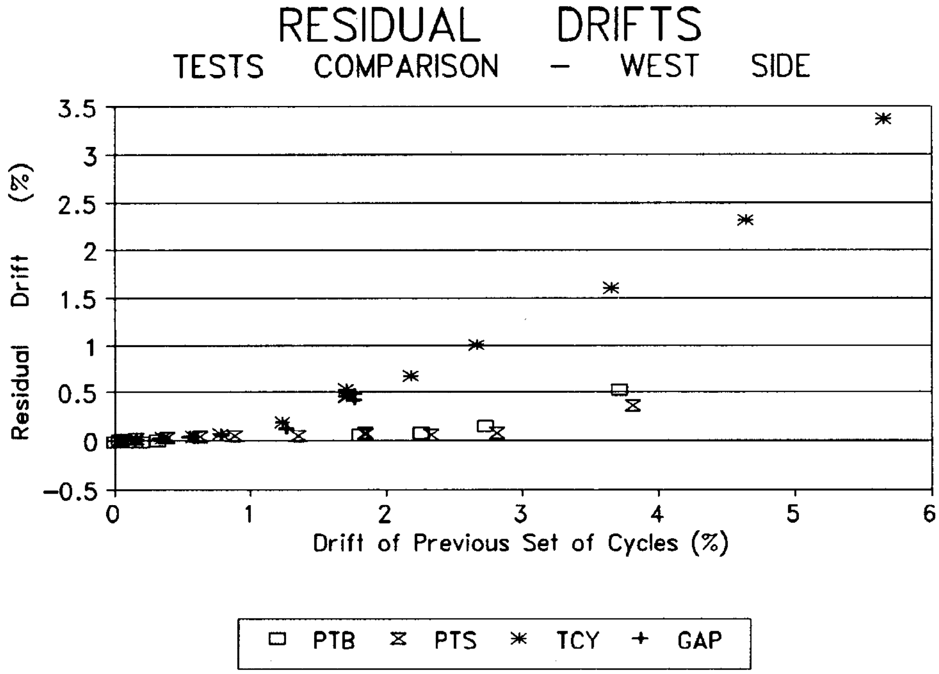

Fig. 5. Residuals Comparison: West Side.

NUMERICAL INVESTIGATION

The results of the numerical investigation showed that in all of the considered cases, the distribution of the plastic hinges was uniform through the frame, and that the hinges were concentrated in the connection regions rather than in the precast members. These characteristics were considered desirable, and satisfactory with respect to the objectives initially considered in the design of the proposed connections. In the cases of the El Centro and Hachinohe ground motions (the two earthquakes that appeared to bound the observed behaviors) frames utilizing monolithic connections were also investigated. It should be noted that the model used for the monolithic connection was not obtained from test results. The initial stiffness of the monolithic system was taken equal to that of the gross cross section. This assumption was used to provide a conservative comparison of the displacement response of the precast systems relative to the monolithic system.

In general, the response of the 5- and 15-story frames subjected to the mentioned earthquake records indicated that the structural behavior was dependent on both the type of connection utilized and the characteristics of the ground motion. Considering for instance the response in terms of story displacement envelopes for the 5-story frames subjected to the El Centro earthquake (Figure 6), it can be observed that the different precast frames exhibited comparable response. The similarity of the response was related to the similarity in the hinge distributions and ductility demands (intended as the ratio between the maximum observed deformation and the deformation corresponding to yielding of the element) for the different cases. It was also related to the fact that the El Centro earthquake did not generate large permanent deformations in the connection elements. The Hachinohe ground motion appeared to be more demanding on the structures. Higher values of connection ductility demands generated permanent deformations that differentiated the behaviors among the different frame types as shown in Figure 7. In all cases the self-righting nature of the nonlinear-elastic connection resulted in minimal residual deformation of the precast frames utilizing such connections at the end of the applied ground motion. This characteristic is particularly appealing since it minimizes deformation growth and results in a structure with less damage to repair following the earthquake.

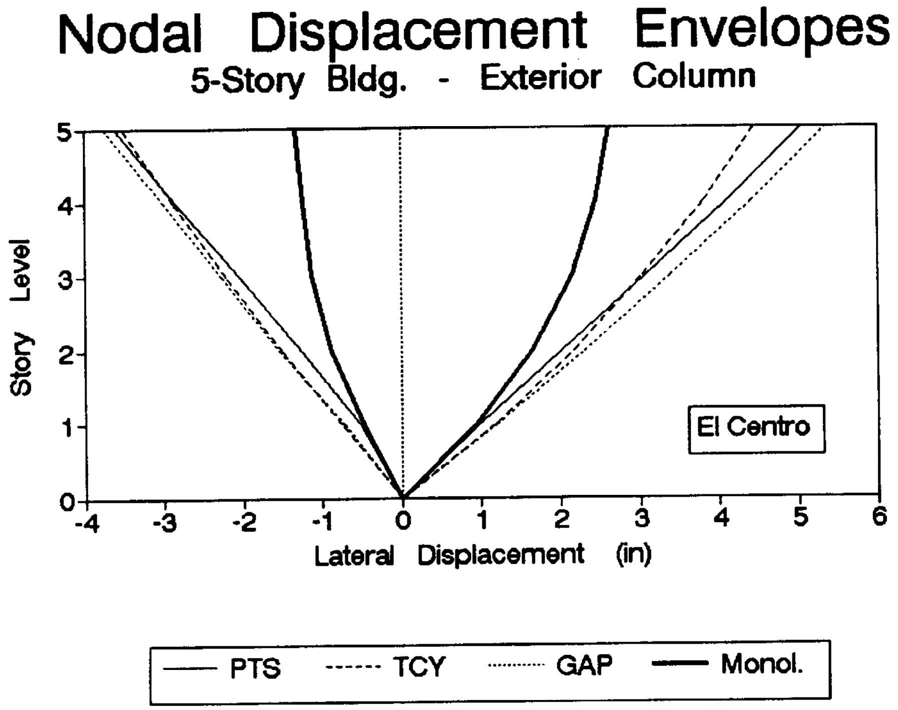

Fig. 6. 5-Story Frames: Story Displacement Envelopes for the El Centro Earthquake.

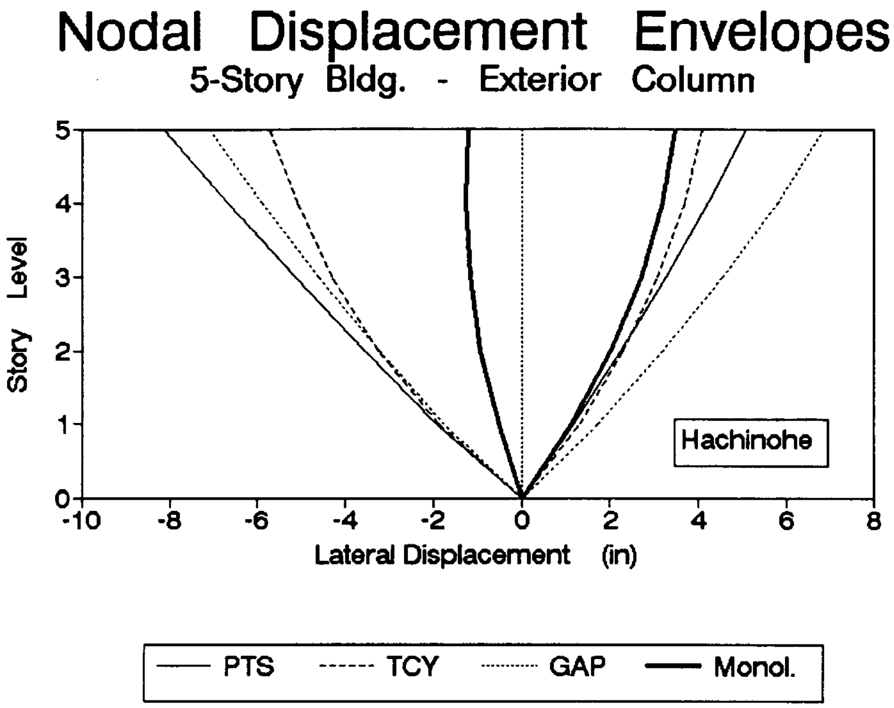

Fig. 7. 5-Story Frames: Story Displacement Envelopes for the Hachinohe Earthquake.

CONCLUSIONS

On the bases of the experimental and numerical investigations it was concluded that beam-column connections between precast members can be detailed and constructed to exhibit satisfactory behavior when used in the lateral force resisting systems of complete precast frames designed for areas of high seismicity. In terms of connection degradation under cyclic loading, the behaviors observed for the proposed connections were comparable if not better than the ones of equivalent monolithic concrete frames.

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