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DESIGN AND BEHAVIOR OF CONNECTIONS IN PRECAST CONCRETE SHEAR WALLS

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ABSTRACT

An experimental program is undertaken to enhance the knowledge base regarding seismic design of precast concrete shear walls. The “emulation design” and “jointed construction” philosophies are described, and an idealization of the behavior of precast shear walls is presented. Two connection details for horizontal joints in precast concrete shear walls are selected for further study. The connection details are proportioned for a prototype shear wall that is designed as part of a six-story precast concrete office building. A description of the test procedure is given, and highlights from two of the cyclic load tests are presented.

KEYWORDS

Cyclic tests; horizontal joints; lateral loads; precast concrete; seismic resistance; shear walls.

INTRODUCTION

Precast concrete members are seldom used for lateral load resisting elements in structures exposed to high seismic risk in the United States (U.S.). Current building codes require that precast systems be shown by experiment and analysis to have lateral load resisting characteristics that are equal or superior to those of equivalent cast-in-place concrete systems. This design philosophy, known as "cast-in-place emulation", has a tendency to undermine the cost-effectiveness of precast concrete systems. However, precast structures which do not emulate monolithic, cast-in-place concrete construction possess inherent characteristics that can be used for seismic resistance. In this design philosophy, known as "jointed construction", certain joints between precast members are allowed to deform inelastically, thereby providing deformation capacity, and, in some cases, energy dissipation capacity to the structural system.

This paper is a summary of an ongoing project at the Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST) which is supported in part by a subcontract from the University of Nebraska through a project from the National Science Foundation PRESSS (PREcast Seismic Structural Systems) program. The overall goal is to advance the concept of jointed construction by investigating the seismic performance of connections in precast concrete shear walls.

PRECAST SHEAR WALL CONSTRUCTION AND BEHAVIOR

Due to their high initial stiffness and lateral load capacity, shear walls stand out as an ideal choice for the lateral load resisting system in precast concrete buildings. Furthermore, inelastic deformation of connections offers the potential for high ductility and energy dissipation capacity in jointed construction. The present study, which addresses the behavior of connections between panels in slender precast shear walls, is centered about a prototype wall that was designed as part of a building system under study in the

University of Nebraska PRESSS project (Tadros et al., 1993, Tadros et al., 1994), and the test specimens in the NIST program were configured to represent portions of this prototype wall. The prototype shear wall (Fig. 1) comprises the precast panels of a stairwell, and two such panels are erected side-by-side with two more panels stacked above the first pair. The wall features both vertical joints and horizontal joints, and it is rather slender with a height-to-length aspect ratio equal to 3.9. The panels were configured such that the shear wall included both vertical and horizontal joints, and it employs 3 x 12 m panels that can be easily transported to the construction site.

It is tacitly assumed in this project that relative movement between adjacent precast panels is inevitable unless monolithic construction is emulated. Because of wall slenderness, and by virtue of the flexibility of the connections between panels, the idealized response of the prototype wall is assumed to be dominated by rocking. This rocking motion is a rigid body rotation which is mobilized by opening and closing of horizontal joints between panels. An element of strategy in jointed construction is to utilize parts of the connection hardware (i.e. the connectors) to provide deformation capacity and energy dissipation capacity to precast shear walls while simultaneously maintaining the lateral load resistance required by design. A secondary goal is to minimize damage to the concrete and anchorages (i.e. bars, plates, welds and bolts).

SELECTION OF CONNECTION DETAILS

The initial task of this project was a search through the technical literature for potential connection details for vertical and horizontal joints in precast shear walls (Schultz, 1992a, Schultz, 1992b). The objective was to identify connections that promise improved seismic performance, while maintaining the cost-effectiveness of precast construction. The final selection had to include connections suitable for regions of both moderate and high seismicity. This selection was made with participation from the U.S. precast construction industry, which was fostered at three levels. First, an Industry Advisory Group was formed, including precast producers, engineering consultants, and a building official, to provide guidance at early stages of the project. Second, continuous communication with other PRESSS researchers provided advice. Third, the research team utilized the 1993 and 1994 PRESSS Industry Seismic Workshops (*PRESSS*, 1994) as a forum whereby potential connection details received critical evaluation.

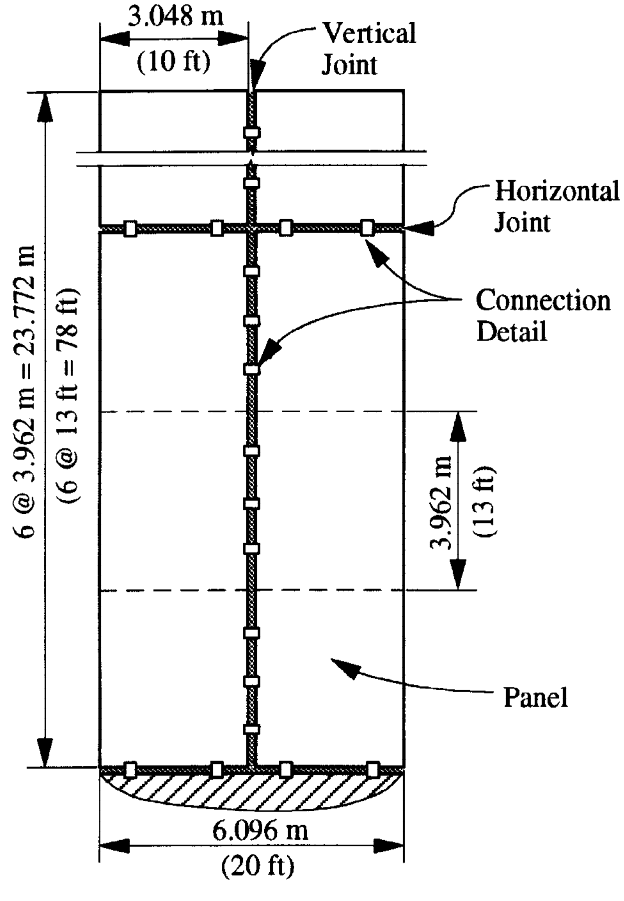

Fig. 1. Prototype shear wall

EXPERIMENTAL PROGRAM

The experimental program includes four connections, two of which are reported in this document. For these two connections, vertical reinforcement is spliced using either grouted sleeves or post-tensioning hardware. The connections were incorporated in specimens that simulate portions of precast concrete shear walls along horizontal joints. The panel specimens were constructed using typical materials, including concrete with a 34-MPa (5000 psi) compression strength, non-shrink grout and Grade 60 reinforcing bars (414 MPa). Proprietary grouted splice sleeves and post-tensioning hardware were used for the connections. The horizontal joint specimens were tested in the NIST Tri-directional Test Facility (Woodward and Rankin, 1984) using cyclic drift histories that simulate seismic motions. The drift history used for the tests was specifically tailored for the U.S. PRESSS program (*Report*, 1992), and it comprises groups of cycles, the pattern of which is repeated until the end of the test. The peak drift of the pattern of drift cycles is increased monotonically among successive groups of cycles.

The horizontal joint test setup is shown schematically in Fig. 2. The specimen represents a portion of the prototype wall, including the panel above the joint and a stub representing the panel below the joint. Vertical loads are applied to the top crosshead, the sense and magnitude of which is determined as needed to define a vertical stress equal to 0.69 MPa (100 psi) representing dead loading, and a continuity moment equal to 50% of the overturning moment at the base of the panel. This last feature is necessary to properly model the lower portion of a shear wall. This paper describes the horizontal joint connection details, and highlights from the experiments of the first two horizontal joint connection tests are given.

SPECIMEN DESIGN

The two horizontal joint connection details in this document are shown in Fig. 3 and 5. The gross dimensions of both specimens are identical, including the 152-mm (6-in.) thickness. Panel reinforcement in all specimens is nominally identical except for the type of vertical reinforcement, and the connection-specific hardware in the vicinity of the joint. As in the vertical joint series, two sheets of WWF6 x 6 - W3.5 x W3.5 welded wire fabric were used to provide shear strength to the panels, and properly-lapped #4 deformed bars were used along the edges of all panels. In addition, three overlapping wire spirals are used along each jamb to confine the concrete and mitigate compression damage from cyclic loading.

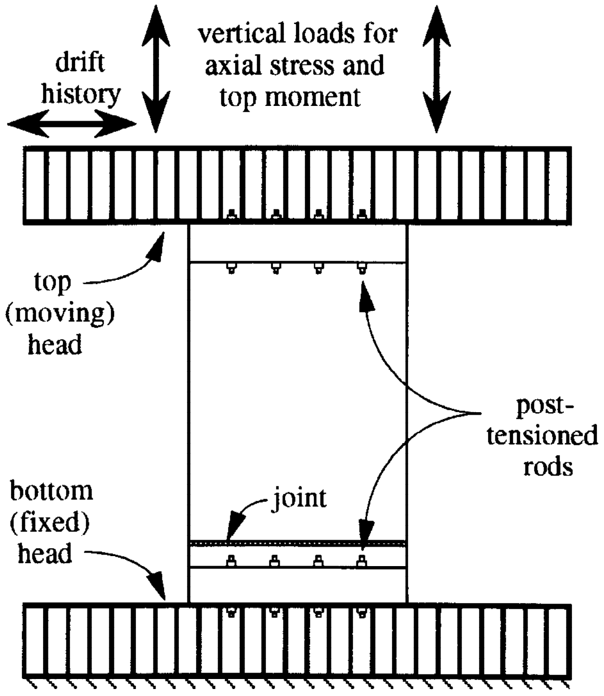

Fig. 2. Test setup for horizontal joint connection specimens

In proportioning the connectors for the horizontal joint details, it was assumed that first yield is the design limit state, and vertical reinforcement in all panels was proportioned to develop a nominal capacity of 320 kN (72 kips) provided by two #7 Grade 60 bars or equivalent. In addition, it was deemed important to avoid the use of blockouts, as these reductions of the compression zone can curtail the flexural capacity of the walls. Furthermore, blockouts require placement of dry-pack grout following erection of the panels.

GROUTED SPLICE SLEEVE (GSS) CONNECTION

This detail is a relatively simple connection (Fig. 3) that is common in the precast industry. Vertical rebars are spliced using proprietary sleeves (Splice Sleeve) and grout (Master Builders). These splice sleeves allow rebar stresses to be transferred across the joint, enabling the reinforcement to yield under lateral loading and form a plastic hinge at the base of the panel. Aside from the splice sleeves and the necessary grout tubes, this detail also features a 190-mm (7.5-in.) debonded length of rebar in the panel below the joint. By debonding the bar, the length of reinforcement that can deform plastically and dissipate energy is increased. In addition, the concrete surrounding the portion of vertical rebar that is likely to undergo large plastic deformations is isolated from the associated bond stresses and strains, thus mitigating cracking damage to the panel.

The force-displacement response of specimen GSS is shown in Fig. 4. The specimen responded to the cyclic strain histories in a stable manner, exhibiting moderately wide force-displacement hysteresis loops. Stiffness decayed quickly with cracking of the joint and panel, and the flexural capacity of the panels deteriorated gradually once peak load was attained. However, the panel and connection exceeded the target design strength. The only distress noted during the test was inclined cracking of the panel and crushing of the grout in the horizontal joint. Yet, neither of these effects was marked, and the test was stopped when the stroke capacity of the load actuators was reached. It was also noted that the concrete above the grout at the jambs was not affected by vertical compression. During the test, strains of the vertical reinforcement in the footer exceeded values of 0.06.

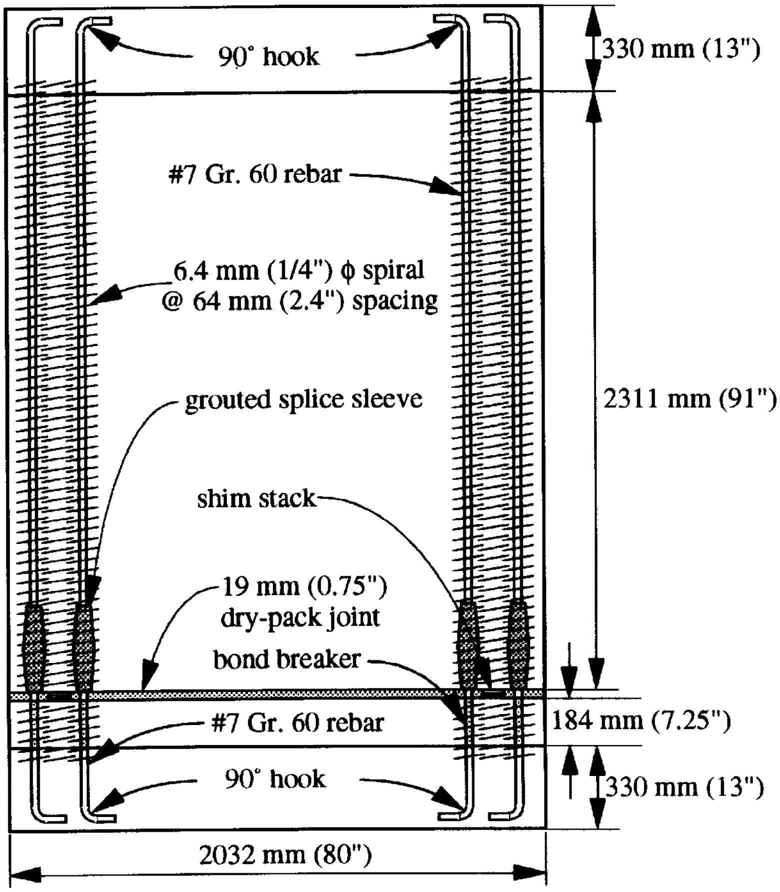

Fig. 3. Grouted splice sleeve (GSS) specimen detail

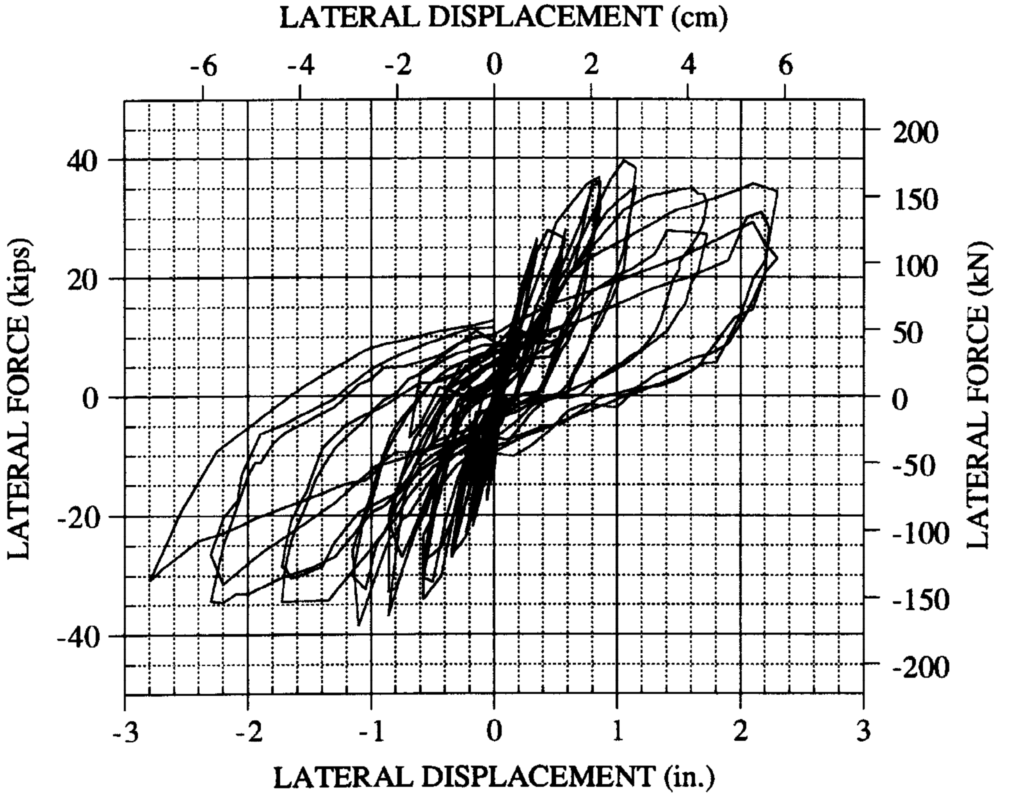

Fig. 4. Force-displacement response for specimen GSS

POST-TENSIONED TENDON (PTT) SPECIMEN

If sizable energy dissipation is not necessary, and if gravity stresses are low in the panels, the post-tensioned tendon connection (Fig. 5) is quite attractive. Vertical reinforcement is provided in the form of high-strength prestressing bar, and these are spliced using standard couplers. Like the GSS detail, there are no grout pockets in this connection. Because the tendon is not grouted, it is not bonded to the panel, and this feature is deemed necessary to protect the tendon from inelastic strains that can reduce the effective prestress in the panels. The expected mode of response for this connection is transfer of lateral loads by flexure across the joint. Energy dissipation is not likely to be large, but the debonded tendon should allow ample inelastic displacement of the panel.

Prestressing strand can also be used, and it offers a much larger linear strain capacity than does bar. However, bar (Dywidag Systems) was selected because it is easier to handle and place in a vertical member. The uniformly-spaced tendons are a compromise between the performance-based strategy of protecting the tendons from large strain increases due to rocking and the construction-based need to provide some reinforcement along the jamb for placement of the panels and to limit out-of-plane “walking” as the panel rocks during ground shaking.

The force-displacement response of specimen PTT is shown in Fig. 6. The specimen responded to the cyclic strain histories in a stable manner, exhibiting little energy dissipation capacity until the tendons were damaged. Stiffness did not decay until tendons were loaded beyond the proportional limit, at which time the force-displacement relation became markedly nonlinear. However, peak strength was maintained even after the tendons lost prestress. It is noted that the specimen behaved in an elastic manner (i.e. only small permanent displacements in the panel).

The anchor nuts used for five of the six tendons in specimen PTT were deficient and failed prematurely at drifts between 1% and 1.5% of wall height. These failures occurred at tendon loads between 147 kN (33 kips) and 156 kN (35 kips), and these loads represent 75% to 80% of the nominal strength of the threaded bars. These failures can be clearly seen in the force-displacement relation as marked drops in lateral load resistance. It is interesting that the specimen did not become unstable even when four of the six tendons had failed. Since the concrete panels were not heavily damaged, this specimen will be reassembled with different anchorages and retested.

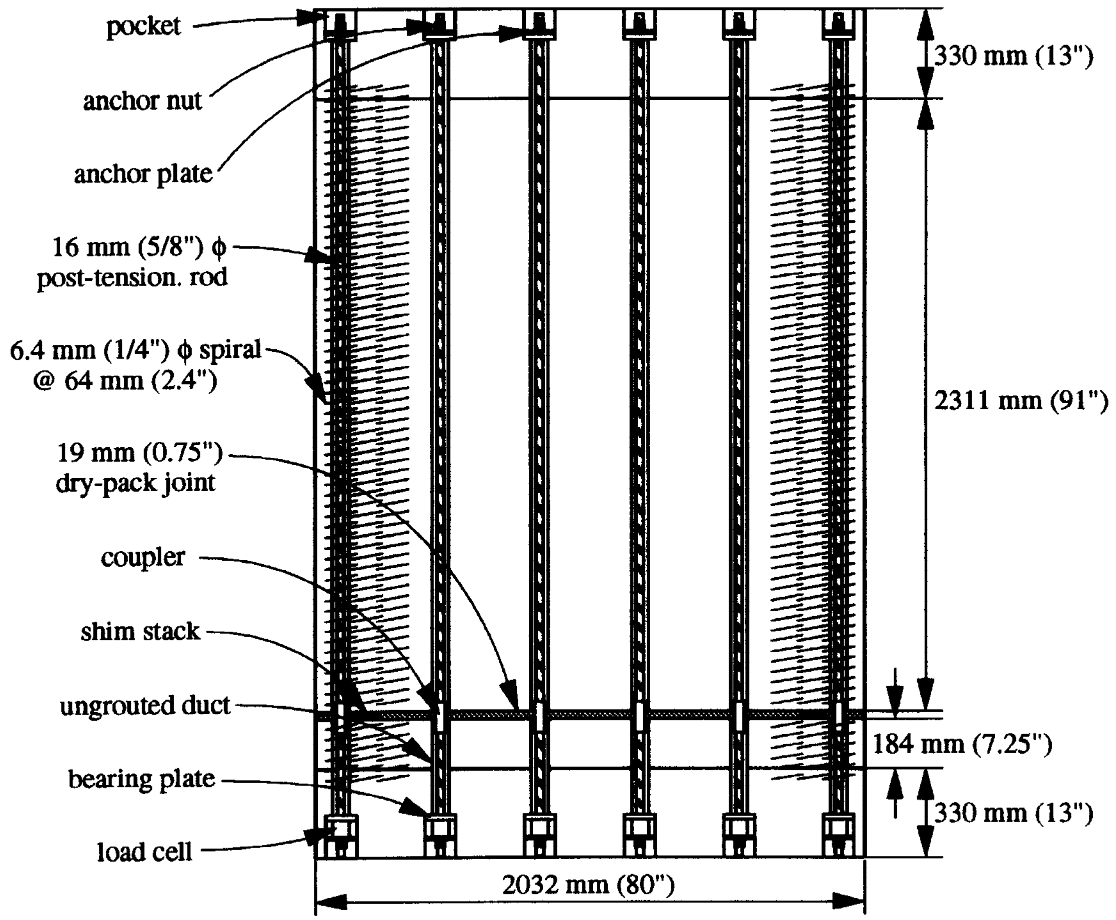

Fig. 5. Post-tensioned tendon (PTT) specimen detail

SUMMARY AND CONCLUSIONS

An experimental research program was undertaken with the goal of advancing the design of precast concrete shear wall connections according to the jointed construction philosophy. Four horizontal joint connections are included in the program. Preliminary results indicate that the first two connection details, one which uses hot-rolled deformed reinfocing bars spliced with grouted splice sleeves, and another which utilizes unbonded (ungrouted) prestressing bars and mechanical couplers, responded favorably to the imposed drift history. The observed characteristics, including strength, stiffness, ductility and energy dissipation capacity, make these connections suitable for earthquake-resistant design of precast concrete shear wall buildings.

The experiments indicate that the use of grouted splice sleeves can lead to tough connections which can be used with yielding reinforcing bars. Large deformation capacities can be ensured if suitable details are used to mitigate compression damage of the concrete in the jambs and concentrated tensile strains in vertical reinforcement in the anchorage zone. Also, post-tensioned connections appear to be well-suited for lateral load resistance as long as energy dissipation capacity is not essential, and, if premature failure of post-tensioning hardware is precluded.

It is clear from these preliminary results that techniques which do not represent dramatic departures from current construction practice can be utilized to advantage for earthquake-resistant construction of precast concrete shear walls. By addressing key aspects of expected behavior, two connection details for horizontal joints are presented that appear to satisfy typical construction constraints, as well as structural performance requirements for seismic resistance. Moreover, materials and connection hardware used for these details are commonly available in the U.S.

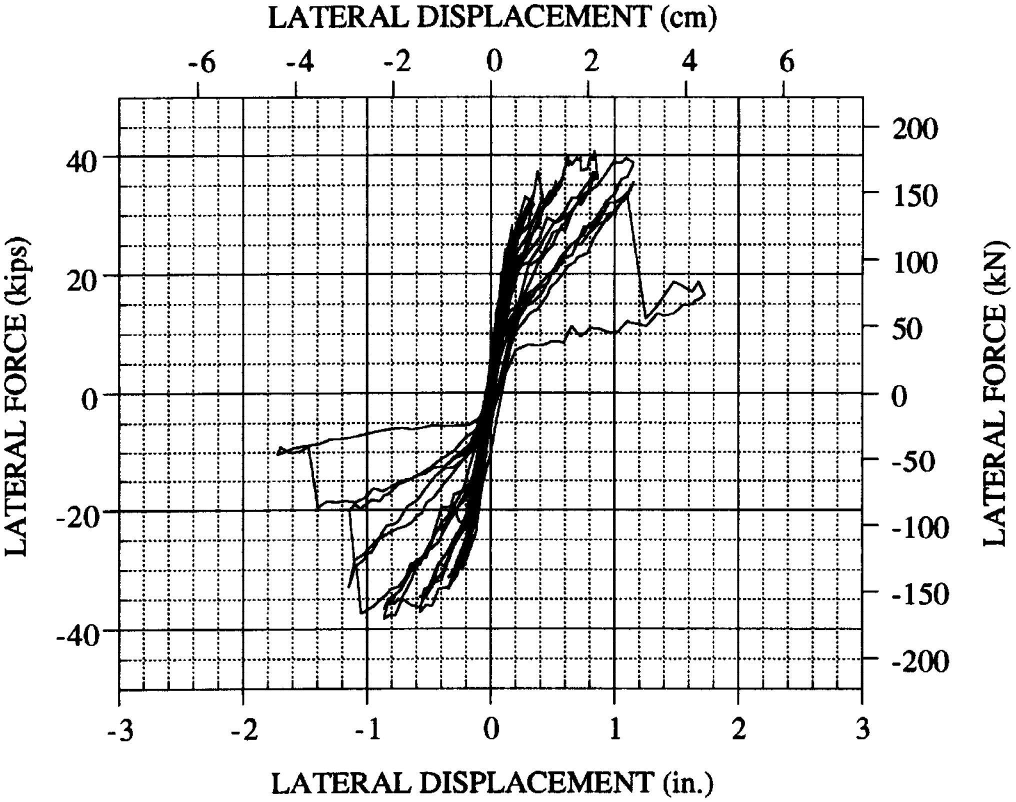

Fig. 6. Force-displacement response for specimen PTT

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