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IMPROVING the PERFORMANCE of PRECAST SEISMIC STRUCTURAL SYSTEMS

An OVERVIEW of the PRESSS FIVE-STORY PRECAST TEST BUILDING

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INTRODUCTION

The Precast Seismic Structural Systems (PRESSS) Program has been on going for over ten years now, with the final phase well underway. PRESSS, sponsored by the National Science Foundation, PCI and PCMAC, has coordinated the efforts of over a dozen different research teams across the country to improve the seismic performance of precast buildings. Since the very beginning of the program, all of the research teams involved in PRESSS have had their eyes on two primary objectives:

- To develop comprehensive and rational design recommendations needed for a broader acceptance of precast concrete construction in different seismic zones.
- To develop new materials, concepts and technologies for precast concrete construction in different seismic zones.

The first and second phases of PRESSS are described in a previous PCI Journal article [Priestley, 1996.] The third phase consists of the seismic design and testing of a 60% scale five-story precast building. In this paper, an overview of the test building, as well as a description of the expected research results are presented.

PRESSS III OBJECTIVES

Academic research is often focused solely on improved performance. While history confirms that this is a worthy goal, the reality of the construction marketplace is that improved performance will generally not be accepted unless it also results in a lower cost. Even if the precast concrete industry decides that improved performance is important, most developers will not pay more for an improved product if there are other, cheaper, products available using other building materials. Thus, the PRESSS III research team, comprising researchers and industry advisory group members, has kept in mind that in addition to improving performance cost control is crucial.

The PRESSS III test building is based on the design of two prototype five-story precast office buildings, 100' x 200' in plan, with 12'-6" story heights. Both buildings use frames to resist lateral loads in the longitudinal direction, and shear walls to resist lateral loads in the transverse direction. The first building, shown in Figure 1, uses pretopped double tees to span between a central gridline and the perimeter of the building. The second prototype building is identical, but uses a topped hollowcore floor system

The final product of the research, however, is not the test itself, but the design recommendations that will result. While the test building (the details of which are described further on in this paper) is not the most economical way to implement these new systems, the final design recommendations are the key to obtaining improved performance at a competitive cost in real buildings.

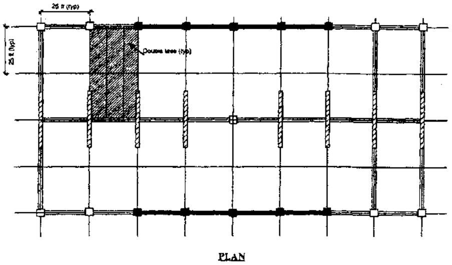

Figure 1: **Prototype Building with Pretopped Double Tees (Hollowcore Building is similar)**

EXISTING DESIGN CODES (Force Based Design)

While jointed construction is allowed by code, the focus of the prescriptive code provisions has been on emulation of monolithic concrete, largely because a consistent set of design recommendations for jointed precast systems was not available. Jointed systems can only be used if they are justified by test data on a case by case basis. On the contrary, PRESSS has focused almost exclusively on systems that rely on and take advantage of the unique properties of precast concrete. The intention is then to develop a consistent set of design recommendations for jointed precast systems that can be used to update the code.

Seismic design in current codes is exclusively force based. That is, a designer uses elastic properties to determine an elastic base shear, which is then converted to a design base shear by dividing by a force-reduction factor, R. The value of R depends largely on the ductility capacity of the system chosen, but its value is somewhat arbitrary and varies from code to code. While maximum structural displacements must satisfy certain limits, they are in most cases based on elastic structural properties and are amplified by factors intended to approximate the post elastic response. This approach has some significant drawbacks [Priestley, 1998], especially for precast concrete, but despite them it is still the legal design procedure for at least the foreseeable future.

While the systems included in the test building are expected to be cost effective even using force based design, the PRESSS III Test building adopts an alternative design procedure that more thoroughly incorporates the advantages of well-designed precast systems. As will be discussed below, a further reduction to design base shear is achieved, providing substantial cost savings for precast buildings in seismic zones.

DESIGN OF THE PRESSS III TEST BUILDING

The Phase III test building is not intended to create new design concepts, but rather to examine the suitability of design concepts created in earlier phases of PRESSS or other precast concrete research. One criterion used in determining which systems would be included in the test building was that the concept had to have been experimentally validated through a component test. The complete building test is important because it raises many questions of design and constructability, which do not arise in component tests. Also, the behavior of a complete, statically indeterminate system involves many features, including verification of seismic design methods that do not occur in statically determinate component tests.

The specific objectives of the test can be summarized as:

- Validate a rational design procedure for precast seismic structural systems;
- Provide acceptance of prestressing/post-tensioning of precast seismic systems;
- Provide experimental proof of overall building performance under seismic excitation;
- Establish a consistent set of design recommendations for precast seismic structural systems.

The PRESSS III Test Building consists of frames in one direction and a shear wall in the other, as shown in

Figure 2. The floor system used in the first three levels is pre-topped double tees, and the top two levels consist of topped hollowcore. Those choices were made in order to include the two major structural framing systems used in precast construction today. The building will be tested in the frame and wall directions independently under simulated seismic loads that represent earthquakes up to 50% stronger than zone 4 design level earthquakes recognized in codes. During the loading in each direction, two independently controlled actuators at each floor level will prevent torsion.

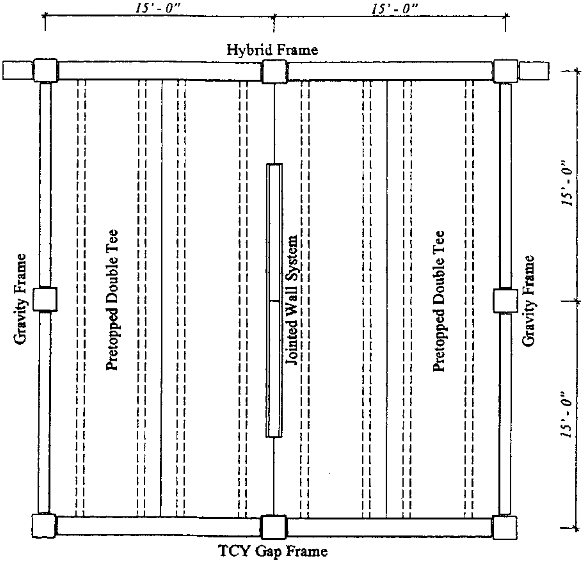

Figure 2: Test Building Levels 1, 2 & 3 with Pretopped Double Tees (Topped Hollowcore Levels 4 & 5 are similar)

Frame Connection Systems

Four different types of ductile connection systems are used in the PRESSS III Test Building Frames, all of which are non-proprietary. They are:

- Tension-Compression Yielding (TCY) Gap Connection
- TCY Connection
- Hybrid Connection
- PreTensioned Connection

The first three of these systems consist of multi-story columns, and single-bay beams, and are appropriate for floor-by-floor construction. The PreTensioned Connection uses multi-bay beams and single-story columns and is appropriate for "up-and-out" construction. The Hybrid Connection and PreTensioned Connection are used in one seismic frame and the remaining two connections are adopted in the other seismic frame. The amounts of energy dissipation and residual displacement vary between the four connections, allowing a designer to control seismic behavior of the structure with an appropriate choice of connection system.

Hybrid Frame

The Hybrid Connection was developed during the last phase of a multi-year project at the National Institute of Standards and Technology [Stanton, et. al., 1997]. The Hybrid Frame interior joint is shown in Figure 3. The beams are connected to multi-story columns by unbonded post-tensioning strands that run through a duct in the center of the beam and through the columns. Mild steel reinforcing is placed in ducts at the top and bottom of the beam, through the column, and is grouted. It yields alternately in tension and compression and provides energy dissipation.

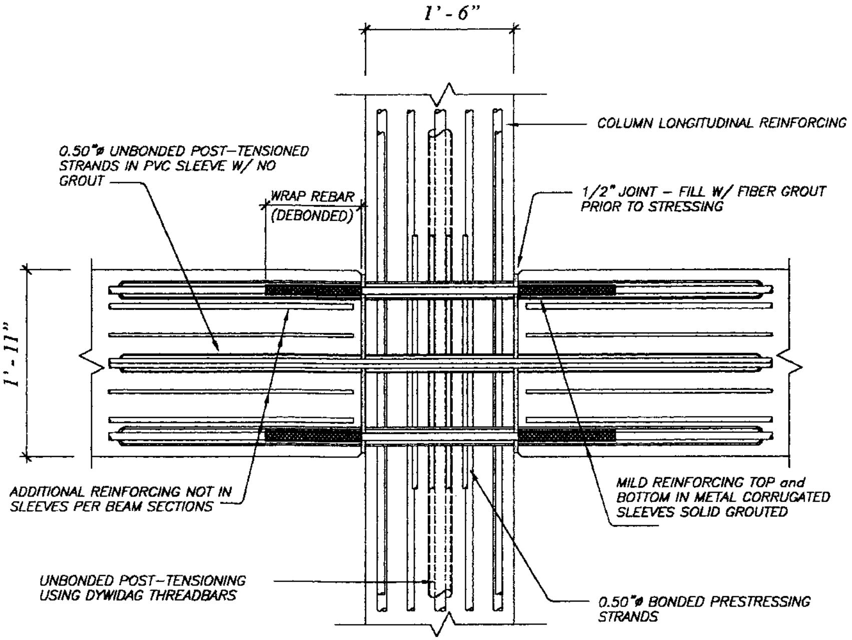

Figure 3: Hybrid Frame Interior Joint

PreTensioned Frame

The PreTensioned Frame is intended to be used for construction where the most economical method consists of using one-story columns with multi-span beams. Long, multi-span beams are cast in normal pretensioned beam beds, with specified lengths of the pretensioning strand debonded. These beams are then set on one-story columns with the column reinforcing extending through sleeves in the beams. Rebar splices ensure the continuity of the column above the beam, as shown in Figure 4. As the frame displaces laterally, the debonded strand remains elastic. While the system dissipates relatively less energy compared to other systems, it does self-right after a major seismic event.

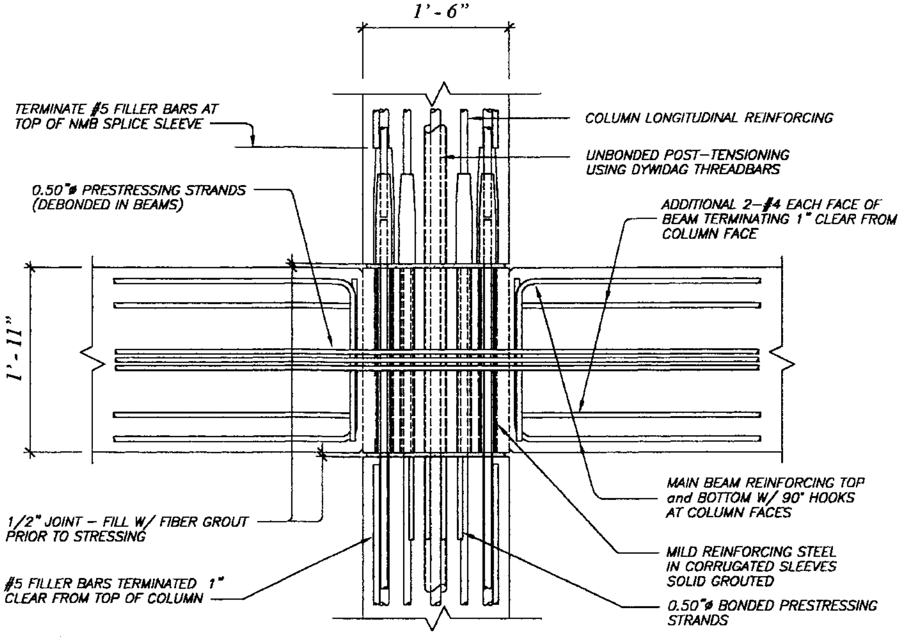

Figure 4: **PreTensioned Frame Interior Joint**

TCY Gap Frame

The TCY Gap Frame addresses the problem of frame beam elongation in an innovative way. The beams are erected between columns leaving a small gap between the end of the beam and the face of the column. Only the bottom portion of this gap is grouted to provide contact between the beam and column (Figure 5.) Centered on this bottom grout region, post-tensioning bars clamp the frame together. At the top of the beam, mild steel reinforcing is grouted into sleeves that extend the length of the beam and through the column. The reinforcing is carefully debonded for a specified length at the gap so that it can yield alternately in tension and compression without fracture. Since the gap opens on one side of the column as it closes on the other side by almost an equal amount, the length of the frame does not change, even as the connection yields.

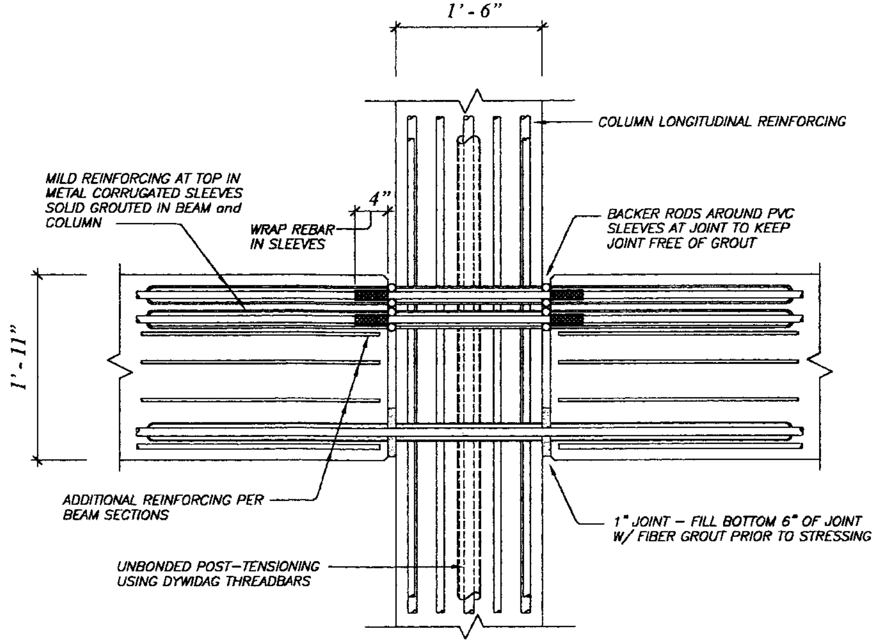

Figure 5: **TCY Gap Frame Interior Joint**

TCY Frame

The TCY Connection attempts to model a traditional tension/compression yielding connection, similar to what is used in cast-in-place construction. However, rather than distributed yielding along a hinge length of the beam, yielding is concentrated at the connection. To ensure that the beam reinforcing that provides moment strength and energy dissipation does not fracture prematurely at this concentrated yielding location, it is debonded over a short length at the beam/column interface (Figure 6).

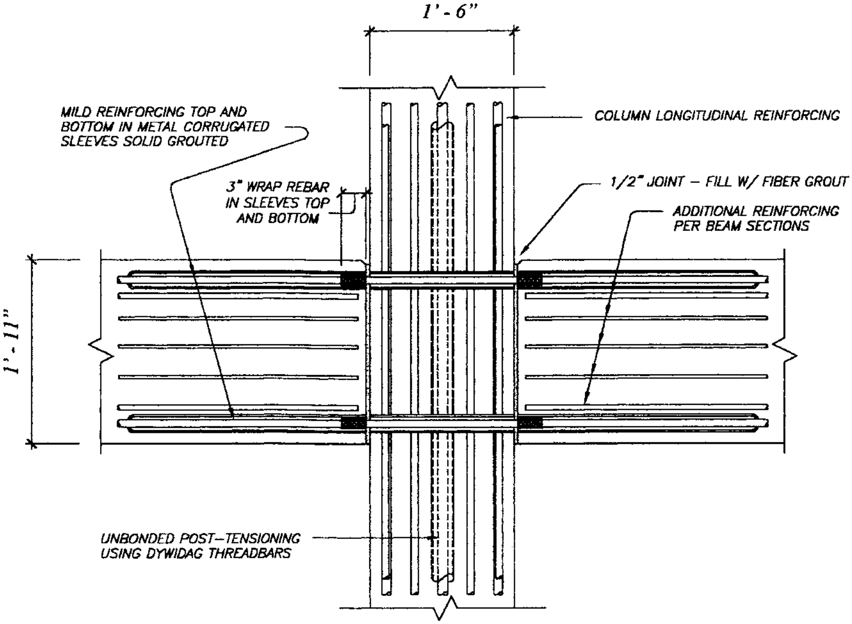

Figure 6: **TCY Frame Interior Joint**

Frame Columns

The frame columns used for all systems contain both mild steel reinforcing and post-tensioning bars. While the post-tensioning bars are intended to represent the equivalent dead loads based on the prototype structure, their inclusion in the test will validate that this method of adding vertical load to a precast column is an effective way to influence system performance. In addition, the columns in the Prestressed Frame are prestressed up to the fourth level. This bonded prestressing economically adds strength to the columns, which are prevented from yielding using capacity based design. These details will validate the performance of prestressed frame columns.

Building Frame Choices

While it was never intended that multiple connection types would be used on different floors or in different frames of the same building, the PRESSS research team and industry advisors felt strongly that several different frame systems should be included in the test building. The objective was to provide designers with several alternatives using precast concrete.

In addition, by validating several different frame types, it is hoped that future innovations can fit into the framework developed by PRESSS, through component testing rather than requiring additional large-scale building tests.

Wall System

For the past several years, the PCI Ad Hoc Committee on Precast Walls has been promoting precast shear walls as seismic systems for all seismic zones [PCI Ad Hoc Committee, 1997.] This work has focused on "tuning" jointed walls to lengthen the structural period and reduce the design base shear forces. The focus was on evaluation of elastic stiffness, without explicit consideration of ductility. Elastic forces were distributed so that sufficient resistance to overturning was provided by the gravity loads on the system. The PRESSS building takes this concept one step further by considering the behavior of the jointed shear wall system when the wall lifts off and rocks, and its effect on design forces. An appropriate level of hysteretic damping is added to the wall system through the connection devices located at the vertical joint between wall panels.

Due to limitations on the building size, imposed by the dimensions of the testing laboratory, only one jointed wall system is incorporated in the test building. Instead of limiting the lateral loads to those that could be resisted by the inherent gravity loads in the system, vertical unbonded post-tensioning is used to resist overturning in this wall system. U-shaped flexure plates (UFP), as tested in PRESSS Phase II [Schultz and Magana, 1996], are used for vertical joint connection devices where damping is achieved by means of flexural yielding of the plates. The unbonded post-tensioning is designed to re-center the wall system when the load is removed so there will be no residual drift after a design-level earthquake. Re-centering is ensured by relating the elastic capacity of the post-tensioning to the yield strength of the panel-to-panel connections.

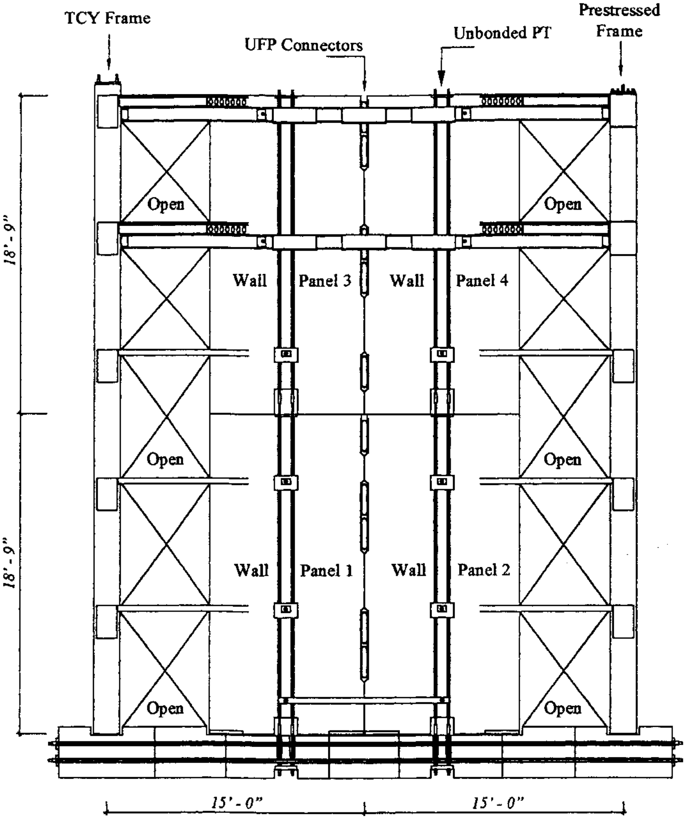

Figure 7: Shear Wall Elevation

Figure 7 shows the shear wall elevation, with unbonded PT located at the center of each panel. The shear wall is expected to displace laterally to approximately 2% story drift under a design level earthquake. This is consistent with the drift limits in both NERHP [NEHRP, 1997] and the UBC [ICBO, 1997]. This lateral displacement requires a vertical panel-to-panel displacement on the order of 2 inches for the 9-foot panel. Thus, the UFP connection shown in Figure 8 was chosen for its ability to retain its force capacity through this large displacement. The post-tensioning was designed to be just at the point of yielding at 2% drift. Should the designer desire a smaller design story drift, or less energy dissipation, simpler panel connections could be used.

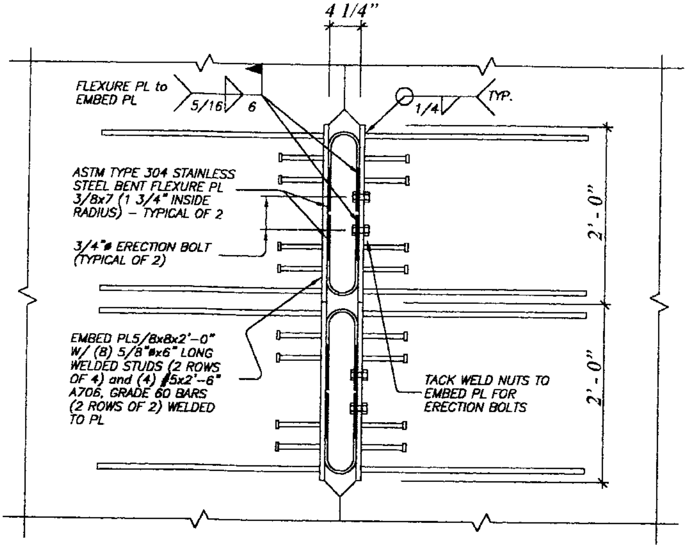

Figure 8: **U-Shaped Flexure Plate Detail**

DIRECT DISPLACEMENT BASED DESIGN

As noted previously, Force Based Design represents the behavior of jointed precast systems poorly. It relies on an initial elastic period, which is not only difficult to compute in a system whose flexibility resides largely in the connections, but also has little influence on the post-elastic behavior of the structure. The R factors included in design codes are also not intended to be applied to systems, such as some of those used here, which do not emulate monolithic concrete structures. Thus, the results obtained by representing the seismic performance of precast systems using a force based design approach are questionable.

For this reason, the test building was designed using a more consistent Direct Displacement Based Design (DBD) procedure [Priestley, 1998], in which the design is based directly on an inelastic target displacement and effective stiffness. The target structural displacement is determined from an allowable inter-story drift permitted by design codes while the effective stiffness is approximated to the secant stiffness of the building corresponding to its expected fundamental mode of response. Use of both the elastic stiffness for determining inelastic structural displacements and arbitrary reduction factors, as in Force Based Design, are completely eliminated in this design approach.

Direct Displacement Based Design Procedure

In Direct Displacement Based Design, first the target displacement is selected. Then the system properties are chosen to achieve that displacement under a design displacement response spectrum. In this process, the true hysteresis behavior of the system is modeled using a linearly responding elastic system with equivalent viscous damping.

The DBD design procedure, as adopted in the test building, is illustrated in Figure 9. The damping is first estimated for the building, using prior component test results. Representing the building with a SDOF system, the fundamental period corresponding to the target displacement is found from the displacement spectrum. The effective stiffness is computed from the known mass and the estimated period. The design base shear is then obtained from the effective stiffness and target displacement and member sizes and reinforcing are chosen to resist this base shear. The true physical properties of the members are used to generate a more refined, hysteretic, force-displacement curve. The effective damping is calculated from the hysteresis loop area to ensure that the assumed damping was adequate. This final step was only necessary due to lack of information on global hysteretic damping.

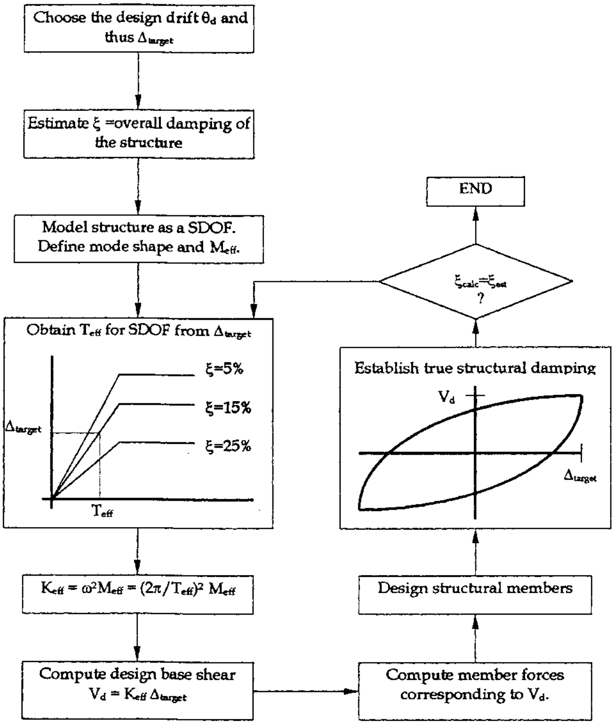

Figure 9: Direct Displacement Based Design Flowchart

Results of Direct Displacement Based Design

For the PRESSS III Prototype Building, Direct Displacement Based Design resulted in a design base shear noticeably lower than would be used for force based design. For the prototype building, the design base shears are compared in Figure 10.

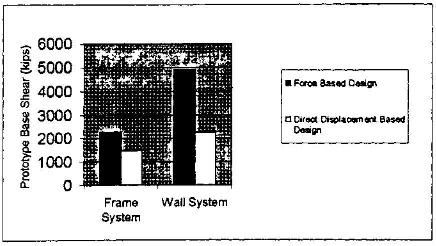

Figure 10: Design Base Shear Comparison

Clearly the improved performance these systems will bring can also result in substantial cost savings over traditional structural systems.

CONCLUSIONS

The PRESSS III Test Building and Design Recommendations will prove the performance of five different ductile precast concrete systems. These systems are economical even using Force Based Design, but will be even more so once their beneficial attributes can be directly taken into account using Direct Displacement Based Design (DBD).

As is clear in the design of the test building, the benefits of the DBD approach to precast buildings are substantial. Following validation of this design method by the PRESSS III test building, a coordinated effort can hasten the implementation of DBD into design codes. Once the Design Recommendations are published, the precast industry should be positioned to facilitate their acceptance into building codes. Recently, several codes have included sections on precast concrete seismic systems, but they apply primarily to emulative systems. These sections should be expanded to cover jointed systems and to incorporate the results of the PRESSS program if its benefits are to be fully utilized. Then precast concrete will truly be the "solution of choice" in all seismic regions.

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