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Seismic resistance of vertical joints in precast shear walls

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Introduction

A research project is underway, under the auspices of the USA-Japan coordinated PREcast Seismic Structural Systems (PRESSS) program, to investigate the seismic performance of joints between panels in precast concrete shear walls. This study is a component of a larger PRESSS research project at the University of Nebraska-Lincoln which seeks to study the behavior of a six-storey precast concrete office building exposed to moderate seismic risk [1,2]. Although the focus of the larger study is on structural systems for regions of moderate seismicity, precast shear wall connections for a wider range of seismic applications are targeted here.

The objective of the present study is to develop, by means of carefully calibrated experiments, accurate behavioral models and design rules for connections in precast shear walls. The connections being studied are intended to improve seismic resistance of precast shear walls by enhancing the transfer of lateral forces between connected panels, and by increasing overall system toughness through energy dissipation. To this end, an experimental effort encompassing cyclic, lateral load tests of twelve 2/3 scale specimens of precast shear wall connections is underway at the National Institute of Standards and Technology.

A compendium of twelve connection details for precast shear walls, six for vertical joints and six for horizontal joints, have been selected for study. The selected details were either modified from existing precast construction practice in the USA, adapted from previously proposed details that have not been used, or developed as part of this study. Criteria used in the selection process included potential for improved structural behavior, ease of erection, and overall cost. This paper summarizes the design and expected behavior of the six vertical joint connections.

Although the proposed test set-up is outlined in the next session, no experimental results are given in this paper.

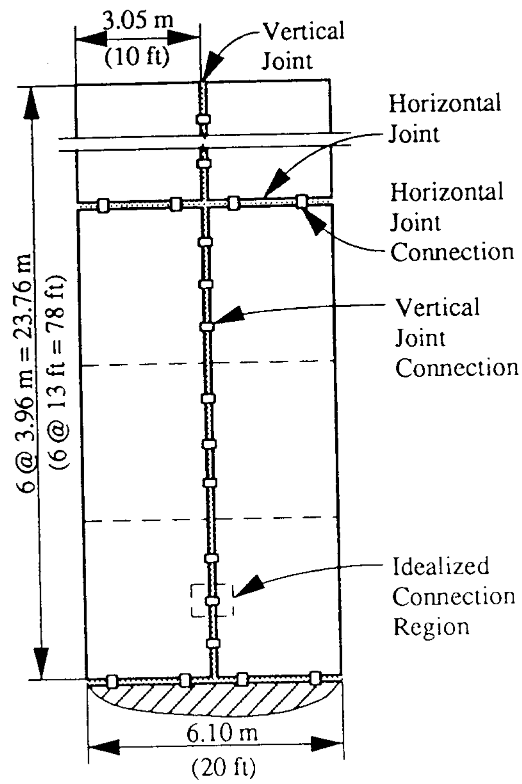


Fig. 1 Configuration of prototype precast shear wall

Specimen design and test setup

The vertical joint specimens are models of localized regions in the precast shear wall which contain the vertical joint connections (Fig. 1). Vertical interface shear force demand for the specimens was inferred from the structural analysis results that were used to design the six-storey precast office building in the University of Nebraska-Lincoln. Lateral loads were determined assuming that the building is exposed to UBC seismic zone 2B [3]. Details of that building design, which comprises separate vertical and lateral load-resisting systems, are discussed elsewhere [1,2]. The precast shear walls (Fig. 1) resist a significant portion of the design lateral loads for the entire building, and they serve as prototypes for the connection details and test specimens in this study.

The prototype shear walls are part of the stairwells in the six-storey precast office building, and they comprise four panels which are stacked two wide and two high, as shown in Fig. 1. Each panel is three stories tall and 3.05 m long. Connections are provided along horizontal and vertical joints between the panels, and the vertical joint connections are designed to transfer vertical interface shear stresses between adjacent panels.

Interface shear force demand for the vertical joint connections was determined assuming that the precast panels remain elastic during a design-magnitude earthquake. The connection elements which span the joint, on the other hand, were proportioned to yield, or otherwise mobilize energy dissipation, during such an event. The shear wall was assumed to be a vertical cantilever beam, and elastic analysis procedures for shear stresses in beams were used to determine first-storey vertical shear force given the design base shear force for the wall. A target vertical shear force capacity equal to 98 kN (22 kips) was determined for the vertical joint connections in this manner, after proper consideration had been given to the 1:2/3 length scale, as well as the difference in model and prototype panel thicknesses. In calculating the shear force, it was assumed that three vertical connections are provided at each storey.

Specimen configuration and test set-up for the vertical joint connection experiments are shown in Fig. 2. The connection and localized region of the panels are cast with monolithic top/base girders that serve to attach the specimens to the testing apparatus. These girders also serve to apply the shear force to the panel with a uniform stress distribution. The vertical joint has been rotated to a horizontal position, and a load/displacement history which captures the important features of seismic loading is applied to the top panel.

Details of the connections

The six vertical joint connections have been subdivided into two groups. The first group (Fig. 3) includes those connections which are joined using field welding only, whereas connections in the second group (Fig. 4) rely on bolting, or a combination of bolting and welding. In addition, the connections in the second group are easily replaceable in the event

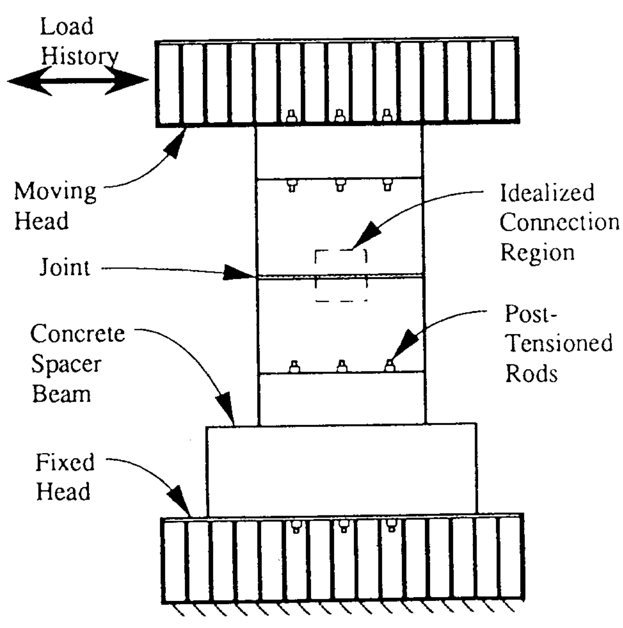


Fig. 2 Test specimen for vertical joint connections

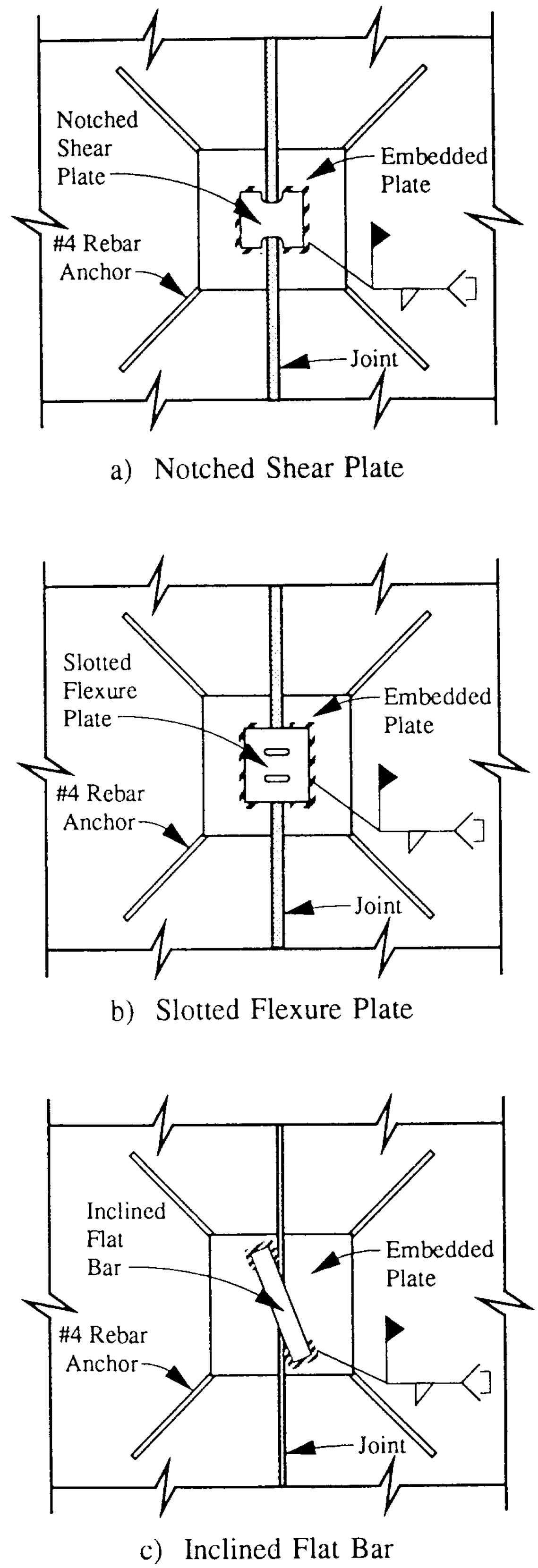


Fig. 3 Welded details for vertical joint connections

of a damaging earthquake. This last feature is a direct outcome of bolting as the method of joining, and it increases the overall value of the connection for seismic applications.

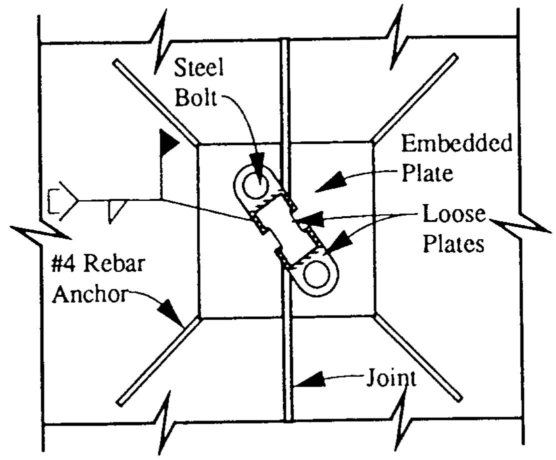
Reinforcement in the panels is identical for all six vertical joint specimens, as are the anchor plates in the welded connection details (Fig. 3). For the first two bolted connections (Fig. 4a and 4b), the anchor plates have been modified slightly, while the anchor plate in the last bolted detail (Fig. 4c) has been reoriented so that it is normal to the panel. To allow for the use of bolts, steel hex nuts are welded to the reverse side of the anchor plates.

In all six connection details, the connector plates are treated as the weak link, while the welds, bolts and anchorages are proportioned to resist, without yielding or failing, the stresses associated with the connector plates attaining their strength. For each anchor plate, four 13 mm (0.5 in.) diameter headed anchor studs have been selected to resist the vertical force associated with connector plate strength, while the #4 (13 mm, 0.5 in. diameter) reinforcing bar anchors were proportioned such that the horizontal component of force resists the torque generated by the maximum vertical force in the connection. It is noted that the anchor studs, being on the reverse side of the anchor plate, are not shown in Figs. 3 and 4.

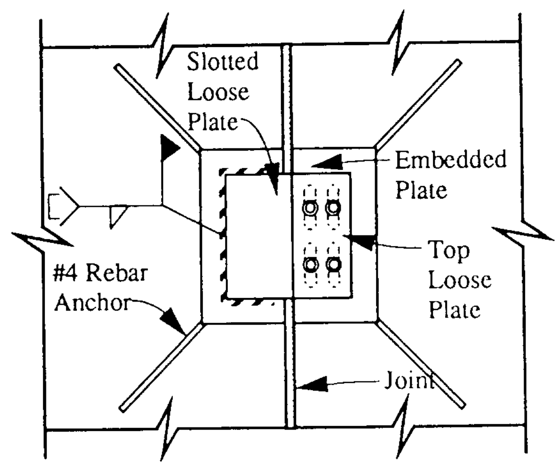
The welded details (Fig. 3) are modifications of one of the most common connections in precast practice in the USA for vertical joints. However, the shape and/or orientation of the 9.5 mm (0.375 in.) thick rectangular loose plate, which is normally welded to the anchor plates in a horizontal position, have been modified. In the first welded connection (Fig. 3a), the loose plate has been notched, and dimensions have been selected so that the 70 mm (2.75 in) notched depth of the plate resists in direct shear the targetted connection force at first yielding. The enlarged ends of the plate enable the use of sufficiently large fillet welds so that weld design strength exceeds the strength of the loose plate.

In the second welded connection detail, the 133 mm (5.25 in) total depth of the three slender beams between slots in the loose plate have been proportioned such that they resist in flexure the targetted connection force at first yielding. The third welded detail is an attempt to load the 44 mm (1.75 in.) wide loose plate axially, for which purpose it has been rotated so that it makes a 20-degree angle with the vertical joint. This connection has been tested in monotonic tension, and it has been found to be as good as, if not better than, shear plates [4].

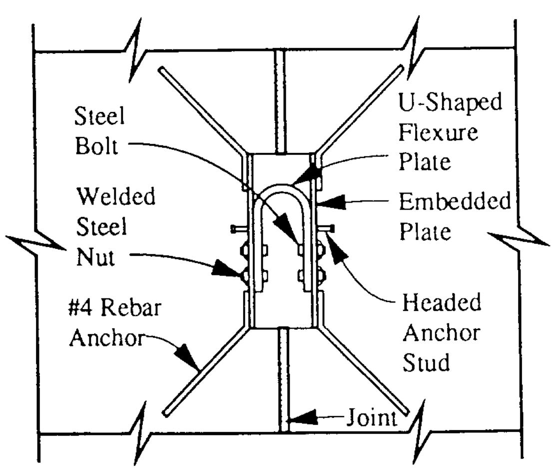
The Pinned Tension Strut (Fig. 4a) is an attempt to improve the Inclined Flat Bar connection (Fig. 3c). There is evidence indicating that sizable flexural stresses are induced in this bar during loading, and that these stresses limit the amount of plastic deformation before the bar fractures [4]. The flat bar is replaced by three loose plates, of which two are bolted. The third plate, which is notched, is welded to the other two and has an effective width of 51 mm (2 in.). The



a) Pinned Tension Strut



b) Brass Friction Device



c) U-Shaped Flexure Plate

Fig. 4 Bolted details for vertical joint connections

Table. 1 Comparison of vertical joint connection details

Vertical Joint Connection	Mode of Response	Calculated Initial Stiffness	Calculated Yield Force[1]	Calculated Ultimate Strength[2]
Notched Shear Plate	Shear	1,300 (7,440)	99.1 (22.3)	160 (35.9)
Slotted Flexure Plate	Flexure	1,290 (7,380)	98.0 (22.0)	237 (53.3)
Inclined Flat Bar	Axial	455 (2,600)	98.7 (22.2)	159 (35.8)
Pinned Tension Strut	Axial	588 (3,360)	98.4 (22.1)	158 (35.6)
Brass Friction Device	Friction	2,580 (14,750)	102 (23.0)[3]	120 (23.0)[3]
U-Shaped Flexure Plate	Flexure	43 (240)	39.1 (8.8)	63 (14.2)

[1] F_y = 248 kN/mm^2 (36 ksi)
[2] F_u = 400 kN/mm^2 (58 ksi)
[3] At slip

notches serve to control the location of yielding and plastic deformation in the 9.5 mm (0.375 in.) thick plate, as well as to limit plate strength so that it does not exceed weld strength. The bolted ends eliminate the potential for flexural stresses, and the three-plate arrangement provides the connection with sufficient tolerance to accommodate the usual variation in actual width of vertical joints. To accomodate a larger width, the strut is placed such that it intersects the vertical joint at a 35-degree angle.

The Brass Friction Device (Fig. 4b) is an adaptation of the Slotted Bolted Connection developed by Popov for steel structures [5]. The key elements of this connection are the 3 mm (0.125 in.) thick half-hard cartridge brass plates placed between the anchor plate and the slotted plate, and between the slotted plate and the top loose plate. These plates serve to provide a reliable friction force over many load cycles [5], and the required 38 kN (8.6 kip) normal force is generated and calibrated by steel disc springs (Belleville Washers) placed below the bolt heads (Fig. 4b).

Inelastic flexural deformations, which are mobilized by the rolling action of the u-shaped plate as it bends and unbends, is the source of resistance and hysteretic energy dissipation in the last bolted connection (Fig. 4c). This device was developed by Kelly as an energy dissipating connector for precast shear walls [6], and it is used in the present study with essentially no change. The central portion of a 16 mm (0.625 in.) thick plate that is 127 mm (5 in.) wide is bent into a semicircle with an inside radius of 43 mm (1.69 in.). Tolerance to accommodate variable-thickness joints can be provided by fabricating the u-shaped plate such that it fits in the pocket even when the vertical joint width is equal to zero. Shim plates can be used as needed to properly install the u-shaped plate.

Summary of connection details

Table 1 provides a summary of the six connection details for vertical joints in this program. With their large initial elastic stiffnesses, the Notched Shear Plate and Slotted Flexure Plate connections are well-suited for strong coupling of shear wall panels, i.e. the panel assemblage acts as a monolithic unit. The Brass Friction Device and U-Shaped Flexure Plate details are better suited for applications in which a more reliable capacity to dissipate energy is desired, especially when repairability is also sought.

Because of its shallow depth, in relation to that of other connector plates, the U-Shaped Flexure Plate detail possesses smaller stiffness and strength. Unlike the other five connection details, it was not possible to proportion the u-shaped plate to resist the target vertical shear force for the connection and still retain realistic dimensions for the connection. This feature, as well as the relatively small stiffness to horizontal in-plane forces in the shear wall, make this connection well-suited for control joints which also serve as dampers.

Acknowledgements

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