論文 Local Structural Behavior of Precast Structural Walls with Spirally Confined Lap Splices under Seismic Loads

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ABSTRACT: The results of member tests using nine precast structural walls with spirally confined lap splices of different lengths (5d, 10d, 15d, 20d, 25d and 30d) are presented. The effects of varying the lapped length and the location of splices in four flexural type walls and in five shear type walls are studied by investigating the external deformations and strain distributions on steel reinforcements. A lap splice length of at least 20d at the bottom of a flexural type wall and at least 10d at midheight of a shear type wall is capable of resisting internal forces when there are vertical mesh reinforcements and the wall is subjected to antisymmetrical bending moments combined with axial load.
KEYWORDS: seismic behavior, winding sheath, grout, spiral steel, lap splice, precast structural wall, lapping bar, main bar, internal force, strain distribution, load - displacement relation.

1. INTRODUCTION

The spirally confined lap splice as shown in Fig. 1 has been developed from the idea of ***main bar post-insertion method*** [1]. Previous results [2] of structural wall member tests showed that a lapped length of 30d (d = lapping bar diameter) is more than adequate for the lap splice to perform like a continuous bar inside a precast wall under antisymmetric bending moments and axial load. Precast walls with such lap splices had similar or better seismic behavior than their monolithic counterparts. A horizontal concrete joint for precast walls called ***laid mortar method*** slipped 4.0 mm along a 1.4 m wide wall. In other methods such as ***mortar seal*** and ***all-grout***, the slippage was controlled to within 1.0 mm. This study presents the results of a further investigation on the seismic behavior of walls with varied lapped lengths. Nine precast walls, as shown in Fig. 2, were tested. Four are bending failure type and the other five are shear failure type. The aim is to investigate the local structural behavior of precast walls with different lapped lengths under seismic loads and determine the minimum splice length.

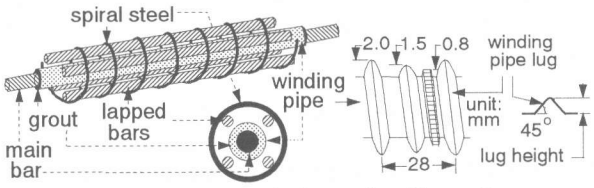

Fig. 1 Details of spirally confined lap splice.

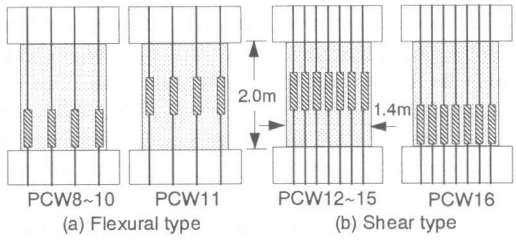

Fig. 2 Features of precast structural wall specimens.

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2. EXPERIMENTAL METHOD

The features of wall specimens are shown in Figs. 2(a) and (b) and the properties are specified in Table 1. Each wall measures 2.0 m high, 1.4 m wide and 15 cm thick. In all specimens except PCW10, ***mortar seal and grout method for internal wall*** is used for the horizontal concrete joint. ***Laid mortar method*** is utilized in PCW10. The specified strengths of concrete and grout are 300 kgf/cm^2 and 600 kgf/cm^2, respectively. The actual compressive strengths of concrete, grout, and mortar during the tests are 350~390 kgf/cm^2, 770 kgf/cm^2 and 570 kgf/cm^2, respectively. The actual yield strengths of main bars D25 (SD390), D25 (SD345), lapping bars D13 (SD345), mesh reinforcements D10 (SD390A) and ϕ6 spiral steel are 4.40 tonf /cm^2, 3.90 tonf /cm^2, 3.80 tonf /cm^2, 3.80 tonf /cm^2, 5.51 tonf /cm^2, respectively.

Table 1 Design specifications of specimens.

Specimen	Failure type	Main bar	Location of lap splice	Type of concrete joint	Lapped length	Mesh bars	Concrete strength kgf/cm^2
PCW8	flexural	4-D25 SD345	bottom	mortar seal and grout for inner wall	20d	2 - D10 @200mm horizontal and vertical	370
PCW9					25d		370
PCW10				laid mortar	30d		350
PCW11			midheight	mortar seal and grout for inner wall			350
PCW12	shear	7-D25 SD390			5d		360
PCW13					10d		360
PCW14					15d		380
PCW15					20d		380
PCW16			bottom		30d		390

d = lapped bar diameter spiral steel pitch = 60 mm axial stress = 10 kgf/cm^2
wall thickness = 150 mm winding pipe inner diameter = 42 mm
height = 2.0 m, width = 1.4 m winding pipe lug height = 2.0 mm

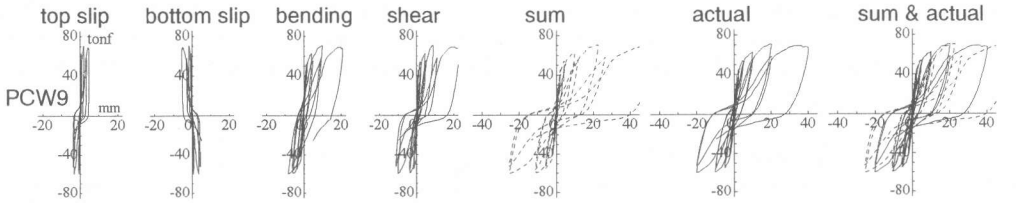
Precast members were cast in the prefabrication plant and were assembled in the laboratory following the ***main bar post-insertion method***. Each specimen was subjected to cyclic anti-symmetrical bending moments and a constant axial stress of 10.0 kgf/cm^2. The drift angle R caused by the lateral force was doubled after every two hysteretic loading cycles. Displacement transducers and strain gauges were used to measure the external deformations and strains on steel reinforcements, respectively.

3. TEST RESULTS AND DISCUSSIONS

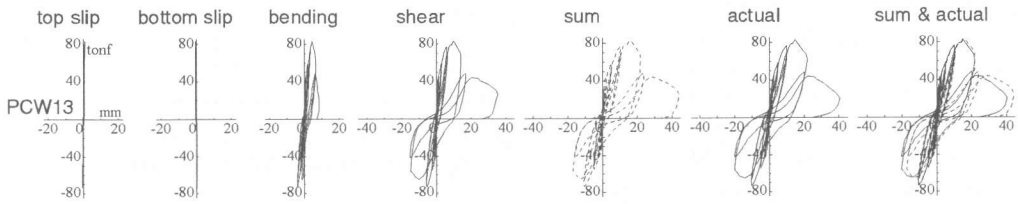
3.1 Lateral load - component deformation hysteretic relations

The hysteretic behavior of each deformation component against the lateral load is visualized in Fig. 3 where the proportion of each displacement to the total lateral movement can be seen. The actual measured total lateral displacement is compared to the summation of component deformations such as slip at the top end of the wall, slip at the bottom end, bending deformation and shear deformation. As can be observed in Fig. 3(a), each deformation component which is almost the same in all flexural type walls has a noticeable contribution on the lateral displacement but the bending deformation is slightly more prevalent than slip and shear displacement. The hysteretic relations of all deformation components against the lateral load which are the same in shear type walls are plotted in Fig. 3(b). Shear deformation is much larger than bending deformation and slip. The slip at the top and bottom of a wall, which is within 1.0 mm, is somewhat negligible. There is a good agreement between the summation of components and the measured actual displacement which shows good accuracy in the measurement of displacements.

The percentage deformation components as calculated from the values obtained by displacement transducers[3] are shown in Fig. 4. In flexural type specimens as shown in Fig 4(a), the slip is more than 10 percent of the total lateral displacement. Before R = 1/400, flexural type specimens tend to deform due to bending, but after a displacement of 5.0 mm (R = 1/400) and yielding of main bars, the displacement becomes a combination of flexure and shear with additional displacement at the top and bottom due to slip. In shear type walls, the slip is below 10 percent as



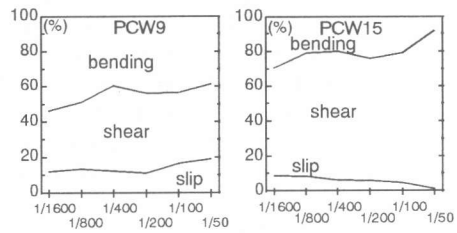
(a) flexural failure type walls.



(b) shear failure type walls.

Fig. 3 Typical load - component deformation hysteretic relations.

shown in Fig. 4(b). The component due to shear is about 40 ~ 60 percent in the beginning and becomes more than 90 percent at R = 1/50 when failure occurs in PCW12 ~ 15. In these specimens, lap splices are located at midheight. In PCW16 where lap splices are at the bottom, the initial shear deformation is only approximately 20 percent and increases to more than 90 percent just before the wall fails. The percentage deformations in shear type specimens differ depending on the location of lap splices. Walls with lap splices at midheight have larger shear deformation in the beginning than walls with splices at the bottom. Also, as the lap splice length increases from 5d in PCW12 to 20d in PCW15, the initial shear deformation increases from about 40 ~ 60 percent.

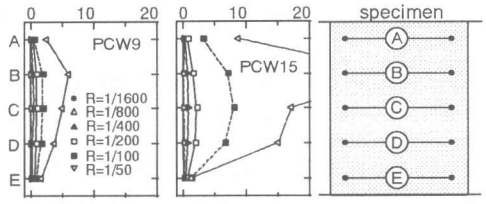


(a) flexural type (b) shear type

Fig. 4 Percentage deformation components.

3.2 Lateral expansion

In flexural type specimens, the maximum expansion when R = 1/100 is less than 3.0 mm as shown in Fig. 5(a). Compared to the expansion of a monolithic wall [2], precast members prevent lateral expansion better because of the additional stiffness provided by the lapping bars and confined grout. Shear type walls expand at the middle up to 10 mm when R = 1/100 and more than 20 mm when R = 1/50 as shown in Fig. 5(b). The lateral expansions of the top and bottom ends remain less than 3.0 mm while those at midheight portion increase to more than 20 mm. Widening at the ends is prevented by the anchorage of main bars in the reaction beams. Shear type specimens have greater expansion than flexural type walls because there are more diagonal cracks.



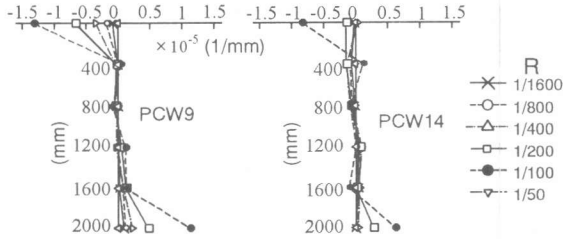
(a) flexural type (b) shear type

Fig. 5 Typical lateral expansions.

3.3 Curvature distribution

Figure 6(a) shows that the curvature distribution in a flexural type specimen is almost symmetrical with large curvatures at the ends. It resembles the bending moment distribution. The

curvatures at the top and bottom ends become large because of main bar yielding. This yielding allows excessive deformation which facilitates rotation at both ends of a wall. On the other hand, since the middle portions of main bars do not yield because the seismic stresses are less, the curvatures remain small.



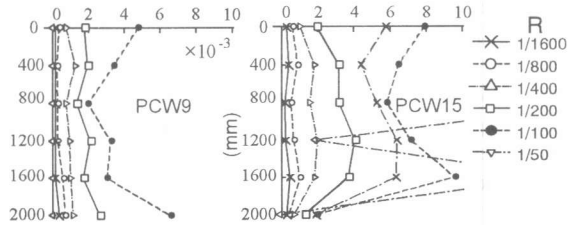
(a) flexural type (b) Shear type

Fig. 6 Typical curvature distributions.

Curvartures in shear type walls as shown in Fig. 6(b) are smaller compared to those of flexural type walls. In PCW12, where the lapped length is 5d located at midheight, the curvature at midheight becomes large when R = 1/200 and 1/100. At this stage, excessive cracking has occurred and the splices, without the tensile contribution of concrete, are subjected to tensile stresses produced by combined bending and shear. A lapped length of 5d can not resist large tensile internal forces but because of the support of vertical mesh reinforcements, the splices are not pulled out. Although the splices are not pulled out, large deformations occur at midheight which enhance the curvatures at midheight. In other shear type specimens, the splices at midheight are adequate to resist internal tensile forces, that is why no much curvature due to splice deformation occur at that portion. Before the maximum lateral load at R = 1/100, the curvature distributions resemble the bending moment diagrams of the walls. At maximum load, the shape of the curvature diagrams become irregular. It can be caused by unnecessary measurements of displacement transducers which may have been affected by large movements of cracked concrete or irregular response of failing wall.

3.4 Shear distortion

The shear distortions in a flexural type wall shown in Fig. 7(a) are almost constant along the wall height until R = 1/200. The values are within 0.002. Higher distortions at the top and bottom may have been enhanced by yielding of main bars.



(a) flexural type (b) Shear type

Fig. 7 Typical shear distortions.

On the other hand, shear distortions in a shear type wall are more than twice those of a flexural type wall. As can be seen in Fig 7(b), the values reach more than 0.01 in all specimens at maximum lateral load. Varying the lapped length from 5d in PCW12 to 30d in PCW15 does not have distinct effect on shear distortions of the walls if the splices are located at midheight. However, changing the location of splices from midheight in PCW15 to bottom in PCW16, has a recognizable effect on the distortion. The lapping bars which are restrained to move at the lower end provide additional stiffness which makes the lower portion of PCW16 more rigid than those of other specimens.

3.5 Analytical approximation of strains on steel reinforcements

Assuming that shear reinforcements (also called herein as lateral mesh reinforcements) yield and the compressive stress in concrete reaches the yield point of concrete, the strains on steel reinforcements of shear type precast walls may be determined by superposition of the actions of truss and arch mechanisms presented by AIJ [4] and the effect of axial load. Since no bond failure occurred in any specimen, the shear strength provided by the truss mechanism is regarded to be governed by yielding of shear reinforcements. In walls subjected to antisymmetrical bending moments and axial

load, strains on steel reinforcements induced by the actions of truss and arch mechanisms and axial load can be illustrated in Fig. 8. In the truss mechanism, assuming that only the two outermost bars act, point C, where the main bar internal stress is zero, may be located by a line passing through midpoint M inclined at an angle ϕ. The intersection of the line and the main bar axis is the approximate location point C. Different from a line with a very small thickness, the inflection in a wide wall is not only a point but an area (horizontal projection of diagonal line C-C) which acts as one element. Because the area becomes a compressive field, the point of inflection C of the line along the outermost main bar is not at midheight but somewhere at the corner of the area of inflection shown in Fig. 8(a). The internal force along a resisting main bar in the truss mechanism is $\boldsymbol{P_{truss} = p_w \sigma_{wy} bL(x)}$ where p_w, σ_{wy}, and b is the shear reinforcement ratio, shear reinforcement yield strength and thickness, respectively. In the arch mechanism shown in Fig. 8(b), the internal force $\boldsymbol{P_{arch}}$ on a vertical steel reinforcement is the corresponding component of the arch action along the vertical direction equivalent to $\boldsymbol{V_a \cos\theta / number\ of\ bars}$ where V_a equals the second term of the shear strength equation for Method A of AIJ. Additional resistance $\boldsymbol{P_{axial}}$ (axial load/number of bars) is exerted by each vertical reinforcement against axial load as illustrated in Fig. 8(c). From the superimposed loads, the strains on each vertical reinforcement can be obtained as

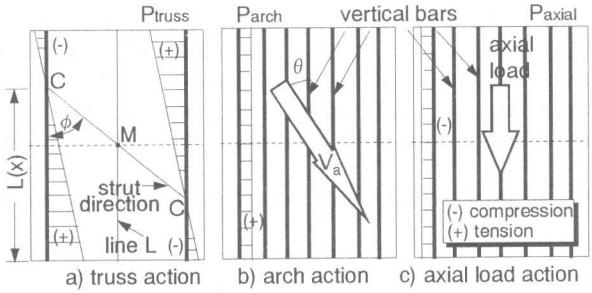


Fig. 8 Superimposed loads.

$$\varepsilon(x) = \frac{P_{truss}}{AE} + \frac{P_{arch} + P_{axial}}{\Sigma AE} \tag{1}$$

3.6 Strain distributions on main bars, lapping bars and spiral steel

Typical strain distributions on main bars, lapping bars and spiral steel of typical flexural type (PCW9) and shear type (PCW15) walls can be seen in Figs. 9 and 10, respectively. Other specimens of the corresponding type have similar strain distributions. It can be noticed that only the end portions of outer main bars are subjected to compression during the action of seismic loads. All other bars are in tension. Even if a symmetrical bending moment is applied on the wall, the strain distributions on outer main bars are not symmetrical. Strains obtained using superposition of the axial load and the actions of arch and truss mechanisms agree well with the experimental results. This implies that in the truss mechanism, the outermost main bar and four outermost vertical mesh bars contribute in

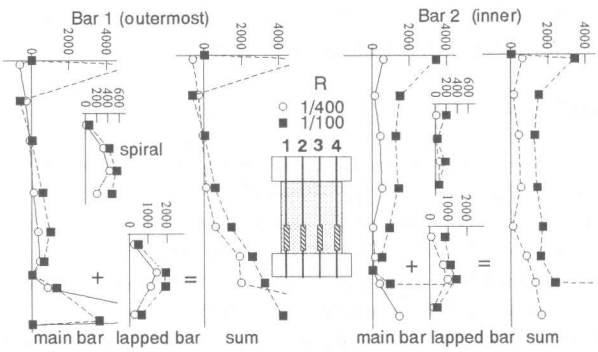


Fig. 9 Strains on main bars, lapping bars and spiral of PCW9.

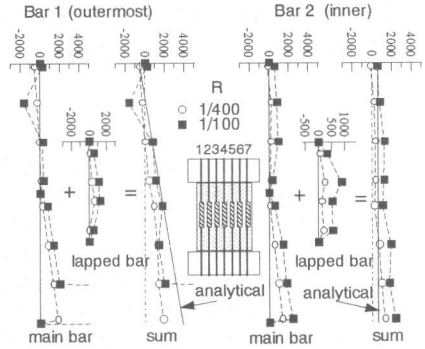


Fig. 10 Strains on main bars and lapping bars of PCW15.

resisting the shear force. The shear force provided by the arch mechanism and the axial load are distributed equally to all main bars and vertical mesh reinforcements. An effective transfer of load on the joint is testified by the summed strain distributions of lapping bars and main bars. In all specimens, the strains on the spiral steel are less than 1000 microstrain which means that the maximum stress on a spiral steel is less than half its yield strength.

3.7 Strain distributions on lateral and vertical mesh reinforcements

As shown in Fig. 11, the strain distributions on vertical mesh reinforcements are almost the same in all walls. The strain distributions on approximately four outermost main bars resemble that of the outermost main bar. This proves that vertical mesh reinforcements assist main bars in resisting seismic loads. It can be noticed in Fig. 11 that vertical mesh reinforcements do not yield.

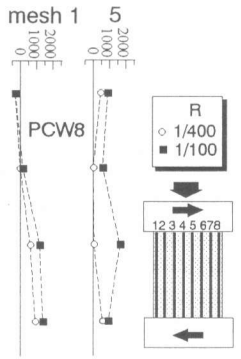


Fig. 11 Vertical mesh strains.

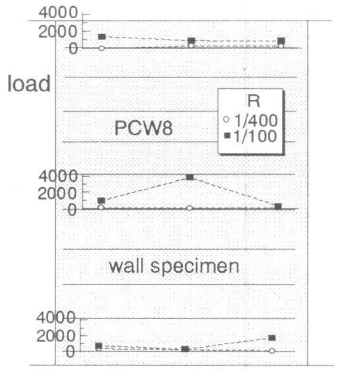


Fig. 12 Shear reinforcement strains.

The distributions of strains on lateral reinforcements of a flexural type wall as shown in Fig. 12 are similar to those of a shear type specimen. When the wall is subjected to a lateral load directed to the right as shown in Fig. 12, the strains on portions of lateral reinforcements that are close to corner-to-corner diagonal become large. The strain enlargement is mainly caused by concrete diagonal cracking. In both flexural and shear type specimens, the lateral reinforcements yield at the middle portion of the walls where there are cracks. This proves the validity of the assumption that shear reinforcements yield in using the truss and arch theory.

4. CONCLUSIONS

From the foregoing discussions of test results, the following conclusions can be drawn:

1. Lap splice length variation has a negligible effect on the seismic performance of precast walls.
2. A lap splice length of at least 20d at the bottom of a flexural type wall and at least 10d at midheight of a shear type wall is capable of resisting internal forces when the wall is subjected to antisymmetrical bending moments combined with axial load.
3. Vertical mesh reinforcements assist spliced main bars in resisting internal forces.
4. Superposition of the axial load, truss and arch actions determines well the strains on main bars.
5. The load - deformation relations, flexural deformations, lateral expansions, curvature distributions and shear distortions are similar in specimens of the same type regardless of the lapped length.

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