Paper No. 590. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

NEW CONNECTION METHOD FOR PRECAST SHEAR WALL

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ABSTRACT

Results of four series of tests on a newly developed connection are presented. Factors influencing the maximum tensile load and the bond resistance are discussed. The seismic performance of jointed main bar is compared to that of continuous one. Actual contributions of spiral steel and concrete confinement to the maximum tensile load and to the pipe bond resistance are obtained. Based on the values of tensile loads and strains on main bar, lapped bar and spiral steel, the failure processes are categorized into whether the concrete is cracked or uncracked.

KEYWORDS

winding pipe, grout, spiral steel, precast shear wall, lapped bar, tensile load, bond stress, concrete confinement, pipe bond failure, direct pullout.

INTRODUCTION

Conventionally, joints for concrete and connections for vertical reinforcements are located at wall ends where large seismic stresses occur. An innovative method is being developed in order to connect main bars at any portion along the wall height where stresses due to lateral loads are relatively smaller. This method grew out from the general idea of *post-insertion* (Imai, 1993) where main bars can be inserted after the precast shear walls have been installed at the construction site. The connection uses locally available thin winding pipes, small diameter spiral steel, and high strength grout in addition to ordinary reinforced concrete materials. As shown in Fig. 1, two main bars are inserted at both ends of a tubular steel sheath, and the void between them is filled with high strength grout. Around the sheath are four lapped splice bars which are confined to spiral steel. During the fabrication of precast walls, main vertical bars are not included. Instead, ribbed winding pipe which is also called herein as ribbed tubular sheath is placed at the position of each vertical bar. Lapped bar

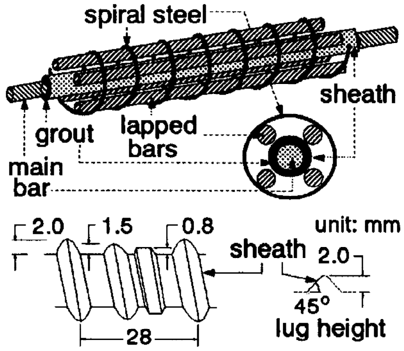


Fig. 1. Details of connection

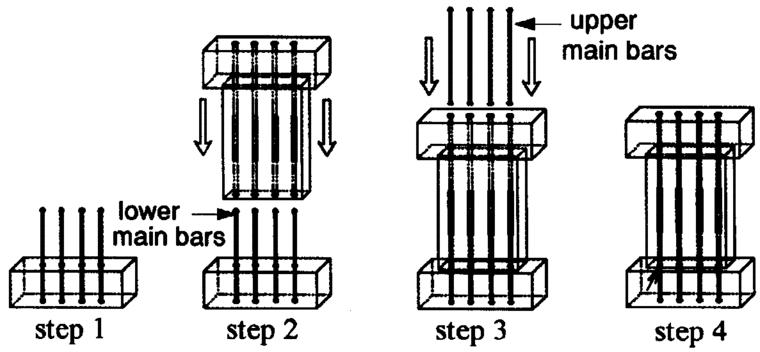


Fig. 2. Construction process

splices confined to spiral steel are put at the desired location of the joint. At the construction site, main bars are inserted from both ends of the wall into the sheaths and the unoccupied space inside the sheath is filled with high strength grout (see Fig. 2).

A shear wall, because of its shape, is the most suitable structural member for this type of connection. Greater spacing of main bar can allow such configuration of splices. In other structural members such as beams and columns, this method may not be suitable because of spacing limitations. Congested lapped splices may not allow proper compaction of the concrete.

Objectives and Significance of the Study

This paper is intended to provide the basic knowledge on the tensile capacity, bond stresses, seismic performance and tensile failure behavior of the connection. Results of intensive investigation through experimental research can gain the confidence of using such connection method in actual practice. Design guidelines can be established based on the results. This connector can be a potential supplement to the commercially available couplers, sleeves, welded plate connectors and the like.

PROGRAMME OF STUDY

The pioneering study was an investigation of the tensile capacity of the connection under direct pullout tests using 45 specimens with 200-mm thickness. Results of this exploratory test led to conducting the second pullout test with 48 specimens which aimed to investigate the tensile capacity at reduced thicknesses of 180 mm and 150 mm. The third series was member testing of seven shear walls subjected to cyclic antisymmetrical bending moments. Two of these walls were monolithic while the other five were precast which incorporated the bar connections. Pullout tests of ninety more specimens were conducted to study the failure behavior of the connection and to explain some unknown phenomena in the previous experiments. In all experiments, the specified strengths of concrete and grout were 300 and 600 kgf/cm^2, respectively.

TEST RESULTS

Tensile Capacity at 200-mm Thick Wall

Forty five specimens (see Fig. 3 for the sketch) were subjected to pullout tests. Fifteen variations at three specimens per variation were done. The first variation was set to be the reference specimens which have 4-13mm splice bars, 200-mm main bar spacing, lapped length of 20d (20 times the lapped bar diameter), 2.0-mm winding pipe lug height, 60-mm spacing of spiral steel and subjected to monotonic loading. The average maximum tensile capacity of reference specimens was 23.5 tonf which was 1.07Fy (25-mm main bar: Fy = 22.0 tonf, σ_y = 4.33 tonf/cm^2) and the failure was in bond on the pipe when the bond stress was 69 kgf/cm^2.

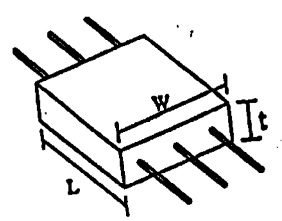
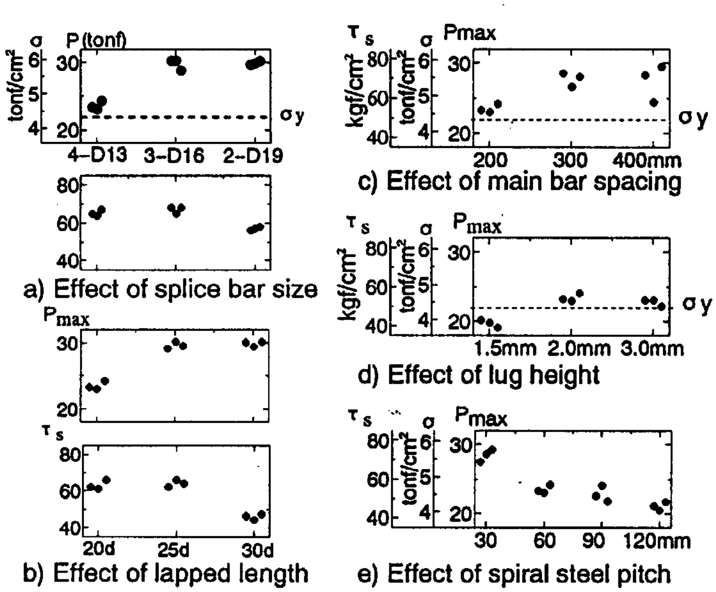


Fig. 3. Sketch of specimen



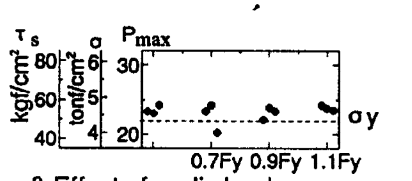


Fig. 4. Maximum tensile loads and pipe bond stresses at 200 mm thickness

Each of the above parameters was varied. The results are shown in Fig. 4. The three specimens of each variation incur similar failure modes. In this test, two types of failure occur: bond failure on the surface of the winding pipe which is termed herein as ***pipe bond failure,*** and direct pullout of main bar from the grout inside the winding pipe called herein as ***direct pullout***. Direct pullout happened only in longer specimens with lapped lengths of 25d and 30d and those with lapped bars of 3-16mm and 2-19mm when the tensile load reached the ultimate strength of the bar .

Tensile Capacity at 150 and 180-mm Thick Wall

In the pioneering experiment, the connection was concluded to be structurally adequate as it provided tensile resistance more than the main bar yield strength when the wall thickness was 200 mm. This conclusion led to the idea of further investigating the tensile resistance of the connection at reduced wall thicknesses of 150 mm and 180 mm and to confirm further the effects of other varied parameters. The main bar was changed from 25mm(390MPa) to 22mm(490MPa) and the winding pipe diameter from 42 mm to 38 mm inner diameter. The steel strength was varied because in the previous experiment, almost all connection failures occurred after yielding of main bar. In this test, collapse before main bar yielding was expected. Forty eight specimens (see Fig. 5 for the sketch), twenty four each for 150 and 180 mm thickness, were tested. For each thickness, there were eight variations at three specimens per variation. The reference specimens had a length of 600 mm, width of 400 mm, main bar spacing of 200 mm, splice length of 20d, pipe diameter of 38 mm, lug height of 2.0 mm, spiral pitch of 60 mm with 75 mm inner diameter, and 4-13 mm(780MPa) lapped bars. The results of varying the parameters are plotted in Fig. 6.

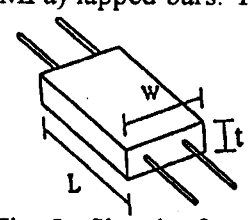


Fig. 5. Sketch of specimen

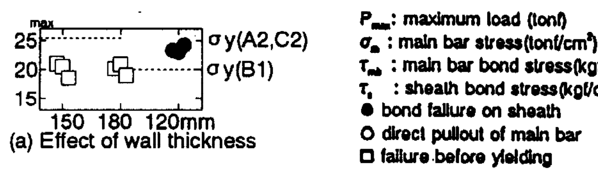
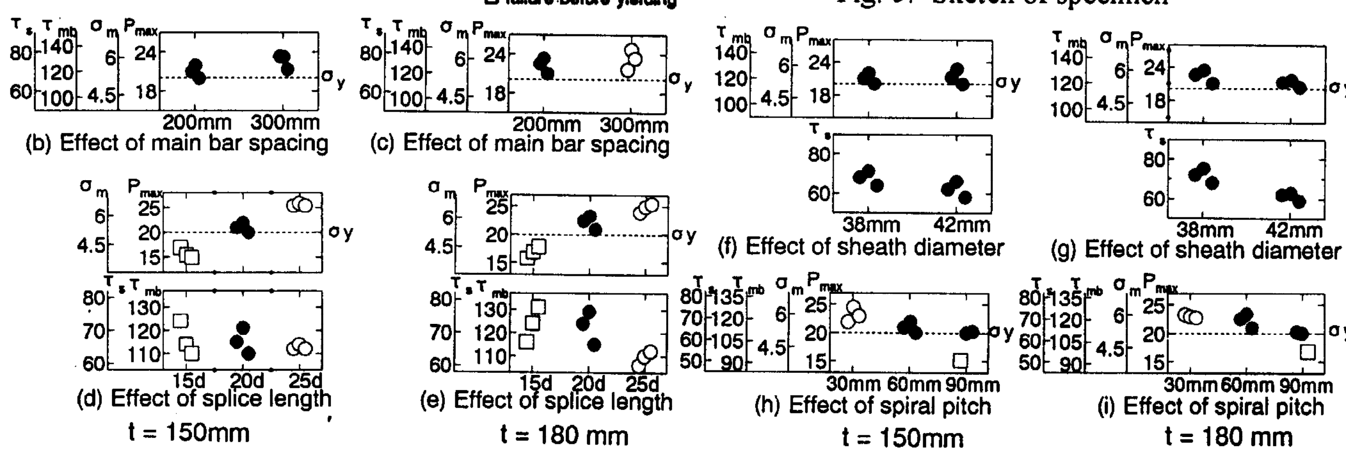



Fig. 6. Maximum tensile loads and bond stresses at 150 and 180 mm thicknesses

Seismic Behavior at 30d Lapped Length

The connection was subjected to cyclic antisymmetrical bending moments and a constant axial load (see Fig. 7) through member tests of precast walls which incorporate such connection. One precast shear wall with 4-25mm (Fy = 345 MPa) vertical bars (see Fig. 8) designed for flexural failure was compared to its monolithic

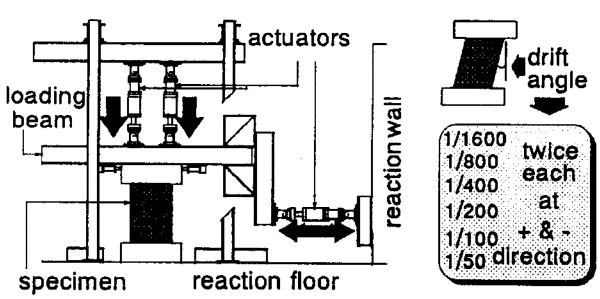


Fig. 7. Loading apparatus and loading history

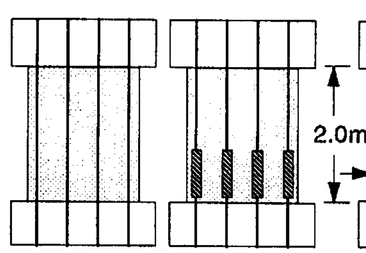


Fig. 8 Flexural type

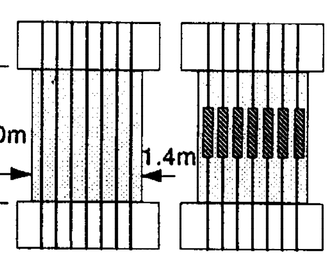


Fig. 9. Shear type

counterpart. Four other precast walls and a similar monolithic wall with 7-25mm (Fy = 390 MPa) (see Fig. 9) were designed to fail in shear. As a preliminary member test and conforming to design code requirements, only 30d (30 times the lapped bar diamater) lap splice length was used. Only the strain diagrams for the outermost main bars of flexural-failure type walls and shear-failure type walls are shown in Figs. 10 and 11. The values at peak load of the first positive cycle of every drift angle are plotted.

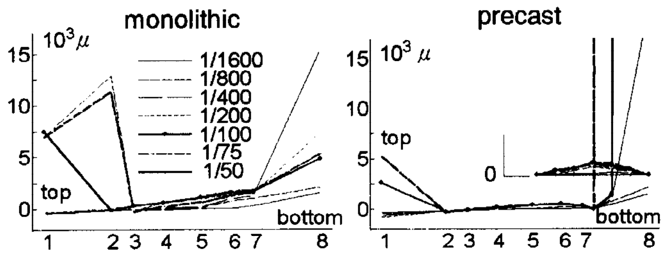


Fig. 10. Flexural-failure type bar strain distribution

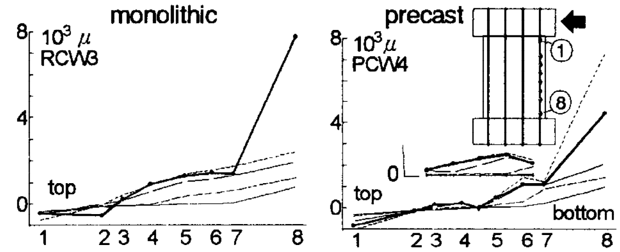


Fig. 11. Shear failure type bar strain distribtion

Effect of Type of Bar, Spiral Steel and Concrete Thickness on Tensile Capacity and Bond Stress

As a reinvestigation, 90 specimens (see Fig. 12) were subjected to pullout tests. These specimens were divided into six groups at 15 specimens per group. In each group, five variations on the lapped length at three specimens per variation were done: 10d, 15d, 20d, 25d and 30d. The first group which was considered to be the reference group had 200 x 200 mm concrete section, 60-mm spiral steel spacing, 25 mm (σ_y=390MPa) main bar with bamboo-type lugs, 4-13 mm (σ_y=680MPa) lapped bars, and 42-mm winding pipe inner diameter with 2.0 mm lug height. The changes done in the other five groups were: main bars with screw-type lugs, without spiral steel, with 30 mm spiral steel spacing, 400 x 400 mm concrete section, and 400 x 400 mm concrete section without spiral steel. A general idea of differences in the tensile capacity and in bond stress on the winding pipe can be visualized using the graphs in Fig. 13 and 14, respectively. Typical load - displacement diagrams are shown in Fig. 15. The diagrams resemble that of a continuous main bar.

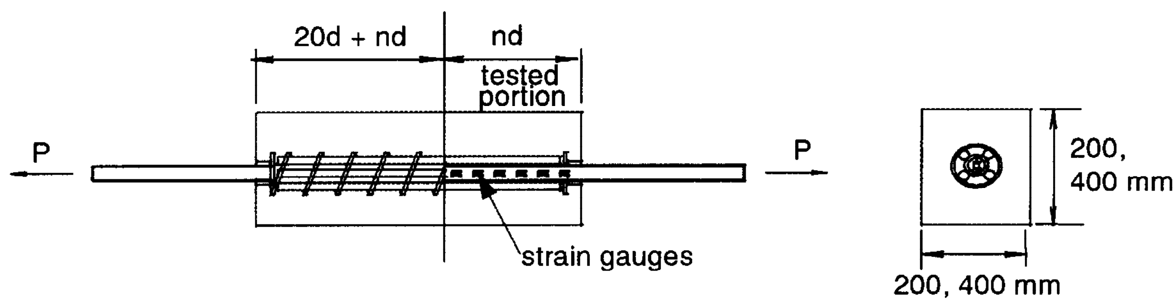
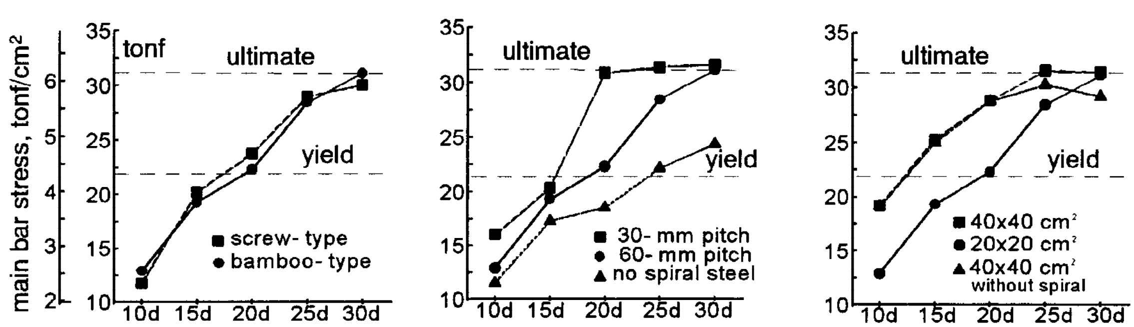


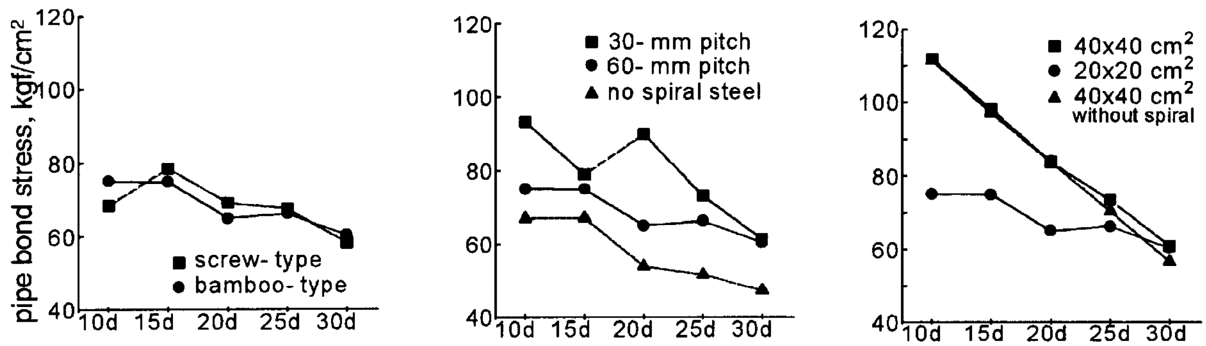
Fig. 12. Sketch of third pullout test specimen



a) bar type varied b) amount of spiral steel varied c) concrete thicknes varied
Fig. 13. Comparison of maximum tensile loads

Strain Distributions on Main Bar, Lapped Bar and Spiral Steel

The actual strain distributions on the component materials of the connection with different parameters are shown in Fig. 16. The strain distribution on the main bar was obtained using the technique of Nilson, (1972), where the bar was sawed longitudinally on a diametral plane and slots were milled along the center line Only the strain distributions of specimens with 30d lapped length were plotted because they are similar to those in specimens with lower lengths at the same load level. Clear differences can be observed especially on the strains of lapped bars and of spiral steel. The implications of such distributions are discussed in the following section.



a) bar type varied b)amount of spiral steel varied c) concrete thickness varied

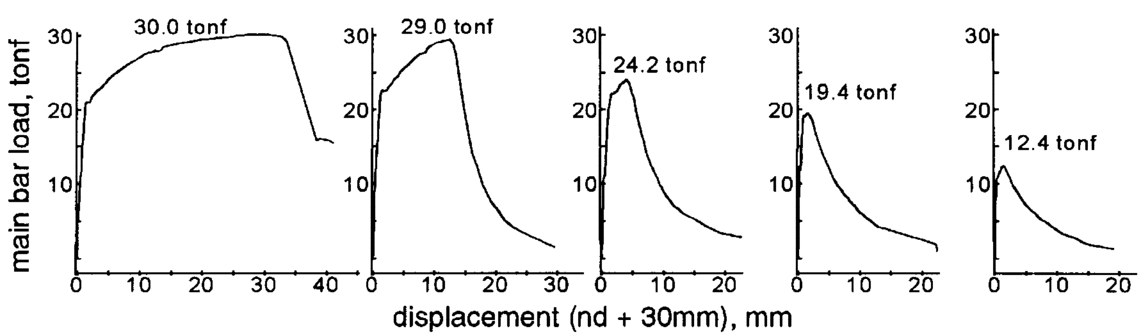
Fig. 14. Comparison of pipe bond stresses at maximum load

DISCUSSION AND ANALYSIS OF TEST RESULTS

Quantitative facts furnished in the foregoing test results, which will be the sole basis of the following discussions and analyses, provide the basic knowledge and foundation of information on the tensile resistance, bond strength, seismic performance, and mode of failure of the connection.

Tensile Capacity

From the results of the first and second pullout tests shown in Figs. 4 and 6, the factors that mainly affect the maximum tensile resistance of the connection can be enumerated. These are: lapped length, size of splice bars, concrete thickness, spacing of main bars, amount of confining reinforcements such as shear reinforcements and spiral steel, splitting strength of concrete, and winding pipe lug height. The factors which are considered to have slight effects on the tensile capacity are: cyclic loads below the yield strength of the bar when the lapped length is 20d or more, and winding pipe diameter. When factors such as size of lapped bars and spacing of main bars are varied, there is a change in lapped length and in concrete confinement, respectively. The maximum load increases or decreases not because of the change in size of lapped bar or spacing of main bar but because of the change in lapped length and in concrete confinement, respectively (Adajar et al, 1993, 1994). Therefore, it may be generalized that there are only three major factors which greatly influence the tensile strength of the joint. These are: lapped length, concrete confinement, and amount of confining reinforcement particularly the spiral steel.



a) 30d b) 25d c) 20d d) 15d e) 10d

Fig. 15. Load - displacement relations and ductility

In the third pullout test, where only these three major factors were varied, the actual contributions of spiral steel and concrete confinement on the tensile capacity at a wider range of lapped length (10d, 15d, 20d, 25d, and 30d) were obtained. Figure 13 (a) indicates that tensile loads obtained using screw-type or bamboo-type main bars are the same. The only difference between these two types of main bars is that when the load reaches the ultimate strength of main bar, the screw-type fails by direct pullout because the spacing of its lugs is smaller at 10 mm compared to 15 mm in bamboo type. Specimens with bamboo-type bars and also those with screw-type bars which do not reach the ultimate load of the bar collapse in bond on the pipe. As shown in Fig. 13(b), when lapped bars are confined to spiral steel with 60 mm pitch, the maximum tensile load increases by approximately 12.0 percent of that without spiral when lapped lengths are 10d and 15d. From 20d to 30d lapped length, the additional load due to spiral steel confinement is about 20 to 30 percent.

Confining to 30-mm pitch spiral steel, gives 20 to 40 percent increase on the tensile load when the lapped lengths are 10d and 15d. When the lapped length is 20d, the contribution reaches around 60 percent of the connection without spiral. At 25d and 30d, the maximum load can not be obtained because the main bar collapsed.

Figure 13(c) shows that when the concrete section of specimens with 60 mm spiral pitch is changed from 200x200 mm^2 to 400x400 mm^2, the maximum tensile capacity increased to about 30 to 50 percent when the lapped length is within 10d and 20d. In higher lapped lengths the actual contribution of the concrete confinement can not be evaluated because the resistance provided is more than the ultimate load of the bar. At 400x400 mm^2 concrete section, whether the connection is confined to spiral steel or not does not make any big difference on its maximum tensile capacity.

At 200 mm wall thickness, the maximum tensile load slightly exceeds the yield strength σ_y of main bar when the lapped length is around 17d and the spiral pitch is 30 mm, when the lapped length is 20d and the pitch is 60 mm, and when there is no spiral steel but the lapped length is 25d (see Fig. 13(b)). The maximum load provided by a 400x400mm^2 concrete section is more than σ_y when the lapped length is at least 15d with or without spiral steel (see Fig. 13(c)). The conditions when the maximum load exceeds the ultimate strength σ_u of the main bar can be easily identified in using Fig. 13(b) and (c).

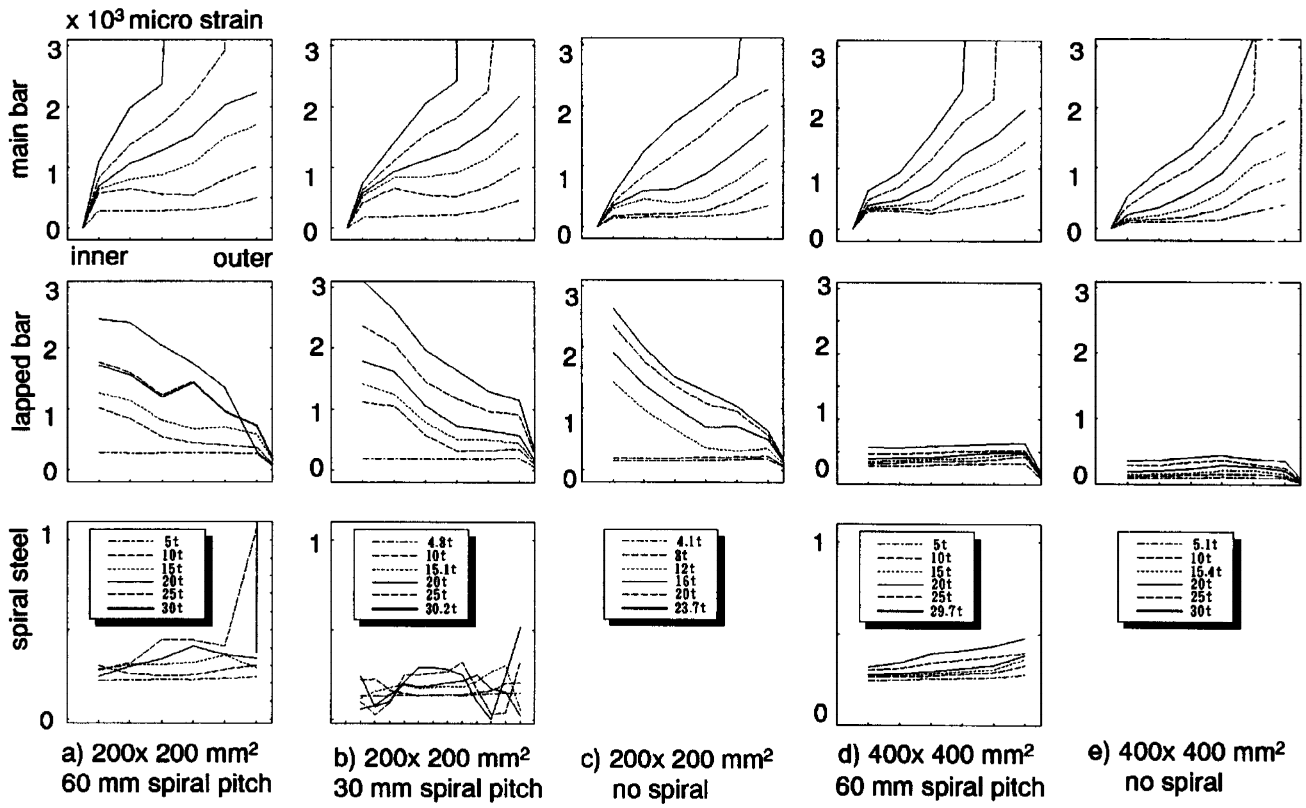


Fig. 16. Strain distributions on main bar, lapped bar and spiral steel at 30d lapped length

Bond Stress

Only the bond stress on the surface of the winding pipe is examined because almost all specimens fail in bond on the pipe. Other types of failure are discussed in the section for mode of failure. In the first two pullout tests, where 15d to 30d lapped lengths and utmost 200 mm thickness of concrete are adopted, the average bond stress on the winding pipe at peak load ranges from 60 to 80 kgf/cm^2. Additional pullout tests confirm that the average pipe bond stress decreases to 50 kgf/cm^2 when the wall thickness is 200 mm and without spiral steel confinement (see Fig. 14(b)). This bond stress reaches almost 115 kgf/cm^2 when the concrete section is 400x400 mm^2 even without spiral steel (see Fig. 14(c)). These figures show that at 20d to 30d lapped length, the pipe bond stress is the same when confined to 30-mm pitch spiral steel at 200 mm concrete thickness and when the concrete thickness is 400 mm with or without spiral steel. The difference occurs when the lapped lengths are 10d and 15d. The bond stress in specimens with 400 mm thickness increases constantly while that in specimens with 30-mm spiral pitch becomes somewhat constant. This indicates that concrete is the main factor that affects the bond on the pipe. At 400 mm thickness, no crack was noticed when the peak load was reached. It shows that there was a nearly perfect concrete confinement of the connection. In such a case, the effect of spiral steel on the pipe bond stress is very slight which may be neglected. It can be concluded from this fact that the main cause of failure for this type of connection is the cracking of concrete. Uncracked concrete together with lapped bars and confining reinforcements act as one solid body which resists the pullout load on the main bar. This means that the component materials of this solid body have no movement relative to each other, They deform together as if each material is a part of a monolithic body. The spiral steel and other reinforcements are activated only after cracking of concrete.

At 200 mm thickness, the contribution of spiral steel with 60 mm pitch to the bond resistance is approximately 12 percent of that without spiral when lapped lengths are 10d and 15d, and 21 to 28 percent when lapped lengths are 20d, 25d and 30d (see Fig. 14(b)). When the spiral pitch is 30 mm, the bond stress increases by 39 percent of that without spiral steel when the lapped length is 10d, 18 percent when the length is 15d, and 67 percent at 20d length (see Fig. 14(c)). At lapped lengths of 25d and 30d, the actual contribution can not be determined because the main bar collapses before the bond stress at maximum possible load is reached.

Seismic Behavior

The behavior of the connection under the action of combined shear, bending moment and constant axial load is different from when it is subjected to pullout load. The difference lies on the distribution of stress along the length. In direct pullout loading, the distribution is almost uniform, while in combined moment and shear loading, it varies as shown in Figs. 10 and 11. The strain distributions on the outermost main bars and lapped bars of precast flexural-failure type and shear-failure type specimens indicate that lapped bars of 30d length transmit the stress completely to the connected main bars. These distributions resemble those of the outer main bars of monolithic specimens. The seismic performance of precast walls with such bar connections is similar or better than that of monolithic walls. The difference in their behavior is mainly caused by the additional stiffness provided by lapped bars on the wall. At the location of bar connection, the amount of steel reinforcement increases because of lapped bars which increases the stiffness of the wall on that portion. The additional stiffness has slight effect on the lateral load at peak of every cycle and on the process of concrete cracking (Adajar et al, 1995).

Failure Mode

There are two types of connection failure when subjected to pullout load. These are pipe bond failure and direct pullout of main bar. In specimens with bamboo type bars, all failures are in bond on the pipe. Direct pullout of main bar only occurred in screw type main bars when the maximum load reaches the ultimate strength of the main bar. In other specimens having screw type bars which did not reach the ultimate load, the failure was in bond on the pipe. One reason why direct pullout of main bar happens is that at ultimate load level, because of excessive elongation particularly at end portion of the specimen, the main bar shrinks. The shrinkage somehow decreases the bond between the main bar and the grout. But the main reason is that the spacing of lugs in screw-type bar is 10 mm while that in bamboo-type bar is 15 mm. The lesser the spacing of lugs, the smaller the amount of resisting concrete between lugs.

The abovementioned two types of failure are only after the maximum load is reached. It is also important to know the step-by-step process of failure from the beginning of loading until before the maximum load is reached. In these series of pullout tests, two different processes of failure occured. These processes differ mainly because of the thickness of concrete. In 200 mm thick specimens, the failure starts by cracking of concrete perpendicular to the main bar at portion where main bar ends meet. Just before or after that perpendicular cracking, longitudinal splitting starts at the end of the specimen and develop gradually along the length. Related studies (Tepfers, 1982; Goto, 1971; Gambarova et al, 1989; Orangun et. al, 1977; Fujii-Morita, 1983) explain the manner of occurrence of longitudinal cracks. If there is no spiral steel or reinforcement across the longitudinal cracks, the connection collapses suddenly when the splitting resistance of concrete along the length is exceeded. If there are reinforcements across the longitudinal cracks, more resistance is acquired which results to higher tensile resistance and ductile failure. However, in 400 mm thick specimens, usually there is no perpendicular or longitudinal cracking on concrete. The load increases until the maximum bond resistance (values shown in Fig. 14(c)) between the surface of winding pipe and the concrete is reached. That is when failure occurs. The resistance against tensile load of main bar is solely done by the concrete together with lapped bars and confining reinforcements which act as one solid body. Lapped bars, lateral reinforcements and spiral steel do not move separately relative to each other or to concrete. Their deformations coordinate with the necessary displacements of parts of a solid body. In other words, when the concrete is uncracked, these component materials do not act against each other, rather, they cooperate with one another by working together in resisting the pulling out load. A good proof is that the strain distribution (see Fig. 16(d) and (e)) on lapped bars remains constant from the beginning of loading until the maximum load which indicates that there is no bond stress acting on lapped bars and its strain is similar to the strain of concrete. The confinement of spiral steel has a very slight effect on bond stress if the thickness is 400 mm. An evidence is that, with and without spiral steel, the maximum tensile resistance is the same when the concrete thickness is 400 mm (see Fig. 14(c)).

The main difference in these two processes is that in uncracked concrete, the concrete, lapped bars, mesh reinforcements and spiral steel act as one monolithic body resisting the main bar together with grout and winding pipe, while in cracked concrete, each component material acts separately. An example is the case of specimens with 200x200 mm^2 concrete section. The splitting strength of concrete, which can be considered to be its tensile strength as well, is 30.28 kgf/cm^2. Multiplying this value by the area of the section transformed to concrete (417 cm^2) gives 12.6 tonf (agrees well with the test results), which is the required tensile load to cause sectional crack perpendicular to the main bars. The sectional crack usually occurs near the location of main bar ends. When this happens, the normal stress, which can be assumed to be uniformly distributed over the section of specimen perpendicular to the main bar, concentrates suddenly to lapped bars because the tensile resistance of concrete on that section is lost completely. It means that the tensile stress carried by both concrete and lapped bars before cracking becomes the load of lapped bars alone after cracking. This statement is testified by the observed sudden increase in the values of strain gauges (see Figs. 16(a), (b) and (c)) of lapped bars near the crack at that load level. Such occurrence caused major changes on the resisting mechanism against pullout load. Instead of concrete, lapped bars and spiral steel against the main bar, the mechanism becomes lapped bars against main bar through the confinement of concrete segment and spiral steel between the pulling end of lapped bar and that of main bar. In such a case, the confinement of concrete and spiral steel prevents not only the main bar from coming out of one end but also the coming out of lapped bars from the other end. This phenomenon is the reason why the strain distribution on lapped bars of 200-mm thick specimens is not constant. If perpendicular cracking does not occur as in the case of 400-mm thick specimens, then the strain distribution on lapped bars is uniform as can be seen in Fig. 16(d) and (e). Perpendicular cracking does not occur in 400-mm thick specimens because the required tensile load to produce that crack is approximately 48.0 tonf but the ultimate load of the main bar is only about 32.0 tonf.

CONCLUSIONS

From the foregoing discussions and analyses of test results, the following conclusions are drawn:

1. The three major factors which greatly influence the tensile resistance of the connection are lapped length, concrete confinement, and amount of confining reinforcement particularly the spiral steel.
2. After reaching the maximum tensile load, two types of failure occur: pipe bond failure and direct pullout of main bar from the grout. Direct pullout of main bar happens only in screw-type main bars when the tensile load reaches the ultimate strength of the bar, otherwise, the failure is in bond on the pipe.
3. The failure process can be categorized into whether the concrete is cracked or uncracked.
4. Cracking of concrete mainly causes the collapse of the connection. Uncracked concrete together with lapped bars and confining reinforcements act together as one against pullout load on main bar.
5. Spiral steel, lateral reinforcement and lapped bars are greatly activated only after cracking of concrete.
6. Ranges of maximum tensile loads and bond resistances on the winding pipe are established when lapped lengths are within 10d and 30d. Actual contributions of spiral steel and confining concrete are found.

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