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SHEAR STRENGTH OF CONCRETE COLUMNS WITH STEEL JACKETS

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SUMMARY

Tests of reinforced concrete columns strengthened with steel jackets were carried out. The jackets consisted of longitudinal angles and transversal plates welded to the angles. This has been a usual method to retrofit buildings in Mexico City after the 1985 earthquakes. Several procedures were used to fix the jacket to the columns, including the use of epoxy resin, pressing the angles to the concrete, heating the plates and welding them to the angles while hot, and combinations of these procedures. Two sizes of angles and plates were used to build the jackets. The columns were subjected to axial and lateral, alternating loads, and were design to fail in shear. Jacketing improved both the strength and the ductility of the columns. The experimental strengths were at least equal to the theoretical strength calculated with the methods included in the Mexico City and ACI Building Codes, when small angles were used in the jackets. With large angles, it was necessary to stick the angles to the concrete with epoxy resin or to heat the plates before welding them, in order to reach the theoretical strength. However, some slipping of the jacket over the concrete was observed in some specimens, depending on the method used to fix the jacket.

INTRODUCTION

After the 1985 Mexico City earthquakes, many damaged buildings had to be repaired and many others, although not damaged, had to be strengthened due to more demanding Building Code specifications. A usual method of repairing or strengthening reinforced concrete columns was with steel jackets consisting of angles and plates (Gonzalez-Cuevas and Iglesias, 1995) The angles are put along the heigth of the columns, and the plates are put perpendicular or diagonally. This method is more economical than the use of a steel box with solid walls or collars, common in other countries. Several tests have been conducted in columns strengthened with solid steel jackets (Aboutaha et al, 1999; Priestley, et al, 1994). However, there is a lack of experimental evidence of the behavior of concrete columns with steel jackets consisting of angles and plates. Several construction methods are used in practice and an evaluation of these methods seems to be necessary.

OBJECTIVES

To study the behavior of reinforced concrete columns with steel jackets, to compare the experimental strength of these columns with the theoretical strength calculated with the Mexico City (1995) and the ACI (1995) Building Codes, to estimate the ductility of the columns and to compare different methods of putting the steel jackets over the columns. The tests reported in this paper were carried out in columns designed to fail in shear and were conducted in columns without any damage. Tests in previously damaged columns and in columns failing in compression and flexure are in progress.

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EXPERIMENTAL PROGRAM

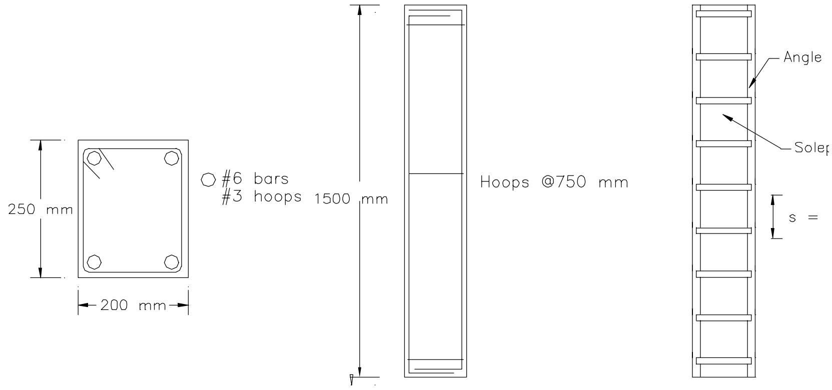

Figure 1: Test specimen

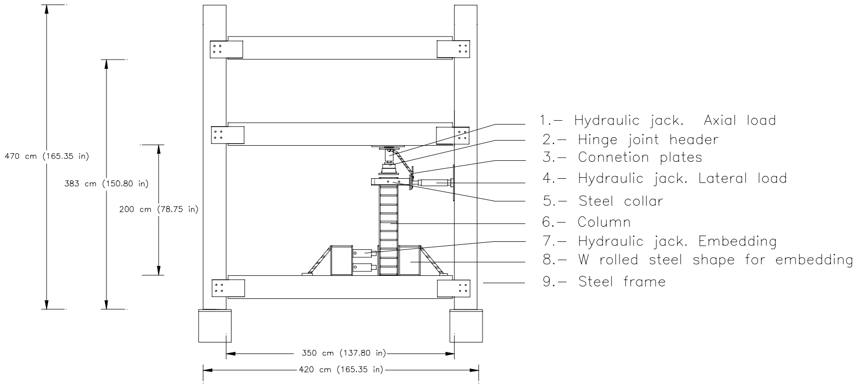

Figure 2: Test rig

Figure 1 shows the specimen used in this series of tests. It is a rectangular section column, with b = 200 mm, h = 250 mm and l = 1500 mm. Longitudinal steel consisted of 4 No. 6 bars, and transversal steel consisted of the jacket plates, that was a variable in the study. The pilot specimens, without jacket, have only three No. 3 stirrups for construction purposes, one at each end and another one in the middle. Concrete compression strength was f_c' = 24.5 N/mm^2 and longitudinal steel yield point was f_y = 412 N/mm^2. The jackets steel had a yield point f_y = 248 N/mm^2 (A36 steel).

The columns were fixed at one end and the loads were applied at the other end. This was a free end, so the specimen represents a part of a column between a joint and an inflection point. At the beginning of the tests, a constant axial load of P = 1470 N was applied to the columns, then an horizontal, alternate load was applied. During the first load cycles, the horizontal load was a fraction of the calculated shear strength. After the yielding of the longitudinal steel, a lateral displacement was imposed to the column and this displacement was increased in each load cycle up to the column failure. Figure 2 shows the test rig and figure 3 shows a specimen being tested.

Figure 3: Testing a specimen

The variables in the study were the size of the angles and plates forming the jackets, and the construction method for fixing them to the concrete columns. Two sizes of angles were employed, both of equal legs. Small angles were 32 mm in width and 3.175 mm in thickness (1 ¼" X 1/8") and large angles were 64 mm in width and 6.35 mm in thickness (2 ½" x ¼"). The cross section of the four small angles in a column is equivalent to the area of the longitudinal steel in a column corresponding to the minimum ratio specified in the Mexico City Building Code (0.04) and that of four large angles is equivalent to the maximum ratio in the Building Code (0.08). With small angles, plates 25.4 mm in width and 3.175 mm in thickness (1"x1/8") were used, and with large angles, plates 25.4 mm in width and 6.35 mm in thickness (1"X1/4"). In both cases, plates were welded to the angles at 150 mm (6") center to center.

With regard to the construction methods, the jacket was fixed to the column according to the following procedures:

a) Pressing the angles to the concrete with a special devise controlling the pressing force, and welding the plates while the angles were pressed (Method A),
b) The same procedure but additionally sticking the angles to the concrete with an epoxy resin (Method B),
c) Sticking the angles to the concrete with epoxy, without pressing (Method C),
d) Just putting the angles in the columns without pressing or sticking (Method D),
e) Heating the plates to 90°C, and welding them to the plates while hot so that pressing is got by shortening of the plates as they cool (Method E),
f) The same procedure but heating the plates to 70°C (Method F), and
g) The same procedure but heating the plates to 50°C (Method G).

Methods E, F and G represent the most common practice in Mexico. Heating of the plates is made usually with a welding blowpipe and a thermal chalk. However, in this research project, the plates were heated in an electric oven for better control of the temperature.

Methods A, B, C, and D were used in combination with small angles and large angles. Methods E, F and G were used only with small angles, since it was evident in the first tests that behavior of the columns with small angles was good enough. Two specimens for each combination of variables were tested with methods A to D, and five specimens with methods E to G. 34 specimens in total were tested, including three control specimens without jackets. Hereafter a notation is used consisting of the words *small* or *large*, referring to the angles of the jacket, followed by a capital letter, *A* to *G* referring to the method of fixing the jacket.

The magnitude of pressing, applied directly with the device or through the cooling of the transversal plates, was calculated for not exceeding the allowable bearing stresses in the concrete. This was done with a finite element model.

OBSERVED BEHAVIOR

In each cycle, the lateral load and the lateral deflection at the free end of the columns were recorded, and the pattern of cracks was registered. Axial load remained constant at 1470 N, as mentioned above. Figure 4 shows a typical load – deflection graph and figure 5, a typical pattern of cracks.

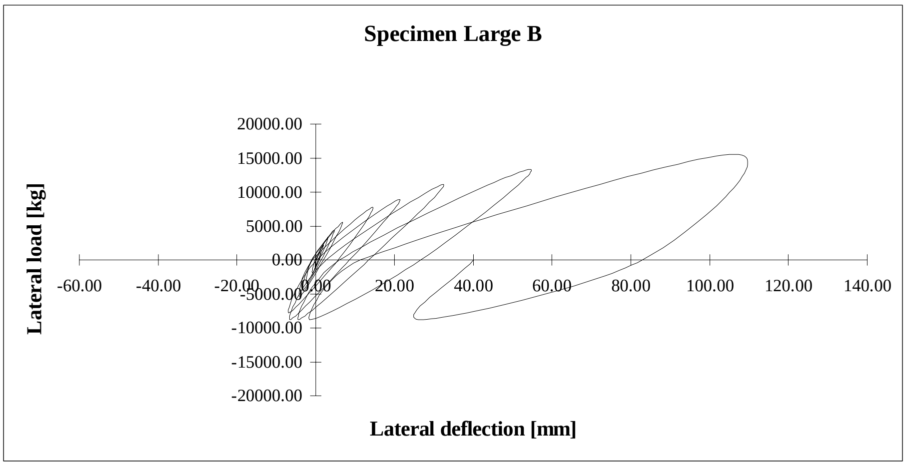

Figure 4: Typical load-deflection graph

Figure 5: Pattern of cracks

Failure occurred by shear in all the specimens, except Large B specimens that did not fail because the load capacity of the system was reached before failure and the test was interrupted. The patterns of cracks corresponded to shear failure in all the specimens, including those that did not fail. However, behaviors were rather ductile, as specimens resisted several cycles of load, and lateral deflections at failure were several times the deflection at yielding of the longitudinal steel. It was possible to determine a diagonal crack of 3 mm in width as that corresponding to severe damage in the specimens and identify the corresponding load to the so called visual diagonal cracking load. The previously damaged specimens that are being tested in the continuation of this program are loaded until a 3 mm diagonal crack is detected and then they are jacketed and tested again. No damages were observed in the angles, in the transversal plates or in the welding of the plates to the angles.

As it can be seen in table 1, the theoretical strength was greater than the experimental strength in most of the specimens. However, a slipping of the angles over the concrete was detected in some specimens that reached a good strength. Specimens corresponding to methods A, D, F, and G showed this behavior. It can be seen that epoxy prevents slipping of the angles and so it does a high temperature in heating the plates.

The control specimens, without jackets and without lateral stirrups, had a brittle shear failure as expected, with diagonal cracks wider than 3 mm and small lateral deflections.

THEORETICAL AND EXPERIMENTAL STRENGTHS

The theoretical shear strength of the specimens was calculated with the following equations included in the Mexico City Building Code, similar to the ACI Building Code equations, although the axial load effect, second bracket of second member of equation 2, is taken in a different but equivalent way.

$$V = V_C + V_S \tag{1}$$

$$V_C = \left[0.16\sqrt{f'_c}\,bd\right]\left[1 + 0.007\left(P_u / A_g\right)\right] \tag{2}$$

$$V_S = A_v f_y d / s \tag{3}$$

where
V = total shear strength
V_C = shear strength of concrete
V_S = shear strength of transversal steel
P_u = axial force
A_g = gross transversal area of the column
A_V = area of transversal stirrups
s = distance between stirrups

Equation 2 is in the SI system, with f_c' in N/mm^2, and A_v in equation 3 is taken as the area of two transversal plates of the jacket, since this area is equivalent to the area of the stirrups in a beam or column. Reduction factors were not taken into account, nor reduced stresses specified in the Mexico City Building Code. The term V_S was equal to cero for the control specimens.

Table 1 shows the theoretical and experimental strengths of the specimens. The figures are the average of two specimens for methods A to D, five specimens for methods E to G, and three control specimens. Some tests were interrupted when a lateral load of 109.2 kN was reached because the load system could not provide a larger load. But the specimens had a severe damage and total collapse was near to occur.

Table 1. Theoretical and Experimental Strengths

Specimen	Theoretical Strength (kN)	Experimental Strength (kN)
Small A	90.6	87.3
Small B	90.6	109.2
Small C	90.6	98.2
Small D	90.6	103.7
Large A	148.1	109.2
Large B	148.1	152.8
Large C	148.1	141.9
Large D	148.1	98.2
Small E	94.3	109.2
Small F	94.3	109.2
Small G	94.3	109.2
Control	58.3	60.8

ANALYSIS OF RESULTS

a) Jacketing of columns with longitudinal angles and transversal plates improves the strength and the ductility of reinforced concrete columns failing in shear. The strength of jacketed members was 43 percent greater than control specimens as a minimum and 150 percent as a maximum.
b) All the methods for fixing the jacket to the column were suitable for retrofitting concrete columns. Strength improvements were similar for the various methods, although method A, consisting in just pressing the angles against the concrete, was a little less efficient. However, slipping of the angles over the concrete was observed in some specimens. This behavior may be undesirable, since lateral deformations of buildings with columns strengthened with methods in which slipping may occur, can be excessive, and cumulative damage might develop.
c) When the angles were fixed with epoxy resin to the columns, no slipping was observed even when no pressing of the angles against the column was applied. This behavior was observed with small and large angles. So, this suggests that it is unnecessary to apply both pressing and epoxy simultaneously (Method C).
d) Pressing alone does not work better than just putting the angles over the column and welding the plates. It seems that early lateral deformation of the columns by Poisson effect develops pressing of the jacket against the column.
e) The usual method of heating the transversal plates, and welding them to the angles while they are hot, worked very well. However, slipping of the angles were observed when the heating temperature was 50°C (Method G). Displacements up to 5 mm occurred. With temperatures of 70°C, displacements were very small, approximately 1 mm, and with 90°C no slipping was detected.
f) The experimental shear strengths of jacketed columns with small angles were greater or almost equal than those calculated with the usual method presented in ACI and Mexico City Building Codes, equations 1 to 3. The difference in specimens Small A is negligible for practical purposes. However, in the specimens with large angles, the theoretical strength was not reached when the angles were not stuck to the concrete with epoxy or when the transversal plates were not heated before welding them to the angles. Slipping of the angles over the concrete was also greater in those specimens. It must be observed that in equations 1 to 3, the area of stirrups, A_v, must be substituted by the area of the transversal plates.
g) It seems unnecessary to use heavy jackets. Small angles with an area equivalent to the minimum longitudinal steel in columns, $\rho = 0.04$, provide enough strength improvement and it is easier to fix them to the column.

CONCLUSIONS

Jacketing of reinforced concrete columns with steel longitudinal angles and transversal plates is a suitable method for retrofitting columns. Strength and ductility are substantially improved whichever the method for fixing the jacket to the concrete. However, a recommendation is made to use epoxy resin to stick the angles to the concrete in order to avoid slipping of them. Slipping can be also avoided by heating the transversal plates before welding them to the angles to a minimum temperature of 70°C.

When small angles are used in the jackets, whichever the method to put the jacket, the shear strength of the columns can be calculated with the equations of ACI or Mexico City Building Codes, using the area of transversal plates instead of the area of transversal stirrups. With large angles in the jackets, the equations can be used if they are stuck with epoxy resin or if the plates are heated before welding them to the angles. Otherwise, the equations may overestimate the strength of jacketed columns.

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