REHABILITATION OF MASONRY COLUMNS USING CARBON FIBRE WRAPS

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Abstract

The use of carbon fibre reinforced polymer (CFRP) wrapping to strengthen existing masonry columns was investigated experimentally. The study was aimed at quantifying the increase in strength that can be achieved and assessing the effect of column size on the strength increase.

18 columns were tested, of three different cross sectional sizes and two different types of masonry unit. Strengthening was achieved bywrapping the square section columns directly with CFRP sheets, or by wrapping the columns after first casting a circular concrete jacket around the column. Significant strength increases were achieved, particularly in the latter case.

These preliminary tests indicate that the use of CFRP wrapping is effective as a technique for rehabilitating damaged masonry columns.

Keywords: Masonry, columns, rehabilitation, strengthening, CFRP

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INTRODUCTION

On occasion, an existing structure will reach a state where it is no longer able to resist the loads acting upon it safely. This may be a result of deterioration of the structural components, an increase in the loads or the introduction of more stringent design code requirements. For economic or heritage reasons it is often desirable to strengthen or restore the existing structure rather than replace it with a new structure.

We therefore carried out an experimental study into the use of carbon fibre reinforced polymer (CFRP) wrapping to strengthen existing masonry columns. The study was aimed at quantifying the increase in strength that can be achieved and assessing the effect of column size on the strength increase.

The present study follows from a similar study in which the strengthening effects of CFRP wrapping applied to reinforced and prestressed concrete columns was quantified (Azarnejad et al. 2000).

EXPERIMENTAL PROGRAM

The purpose of the experimental program was to assess the strength gain achieved by wrapping an existing damaged masonry column with carbon fibre reinforced polymer (CFRP) sheet. The study focused on the rehabilitation of damaged columns but the results obtained may also be applicable to strengthening of undamaged columns.

18 columns were tested. Each column was initially loaded axially until cracking was observed in the masonry. The columns were then wrapped with CFRP sheet over their full height and retested under axial compression until failure occurred.

The experimental program was conducted as two separate series of tests. Initially, three columns were constructed and tested. This served as a means of drawing preliminary conclusions as well as identifying any problems with the testing procedure. In the second series, the remaining 15 columns were tested.

Column Construction

All columns were constructed in the Civil Engineering Laboratory at the University of Calgary by a skilled mason. Type S (structural) mortar was used throughout. The columns were constructed in three different cross sectional sizes using two different types of masonry unit. All columns were the same overall height of 1.2 metres (Figure 1). The cavity formed at the centre of the column in each case was filled with grout. No reinforcement was placed in the cavity. The columns were cured for a minimum of 28 days prior to the first test.

For the Series 1 tests, one column in each cross section size was constructed (3 columns total). Bullnose shaped units were used at the column edges. The philosophy behind using this unit type was to attempt to distribute the confining forces provided by the CFRP wrap

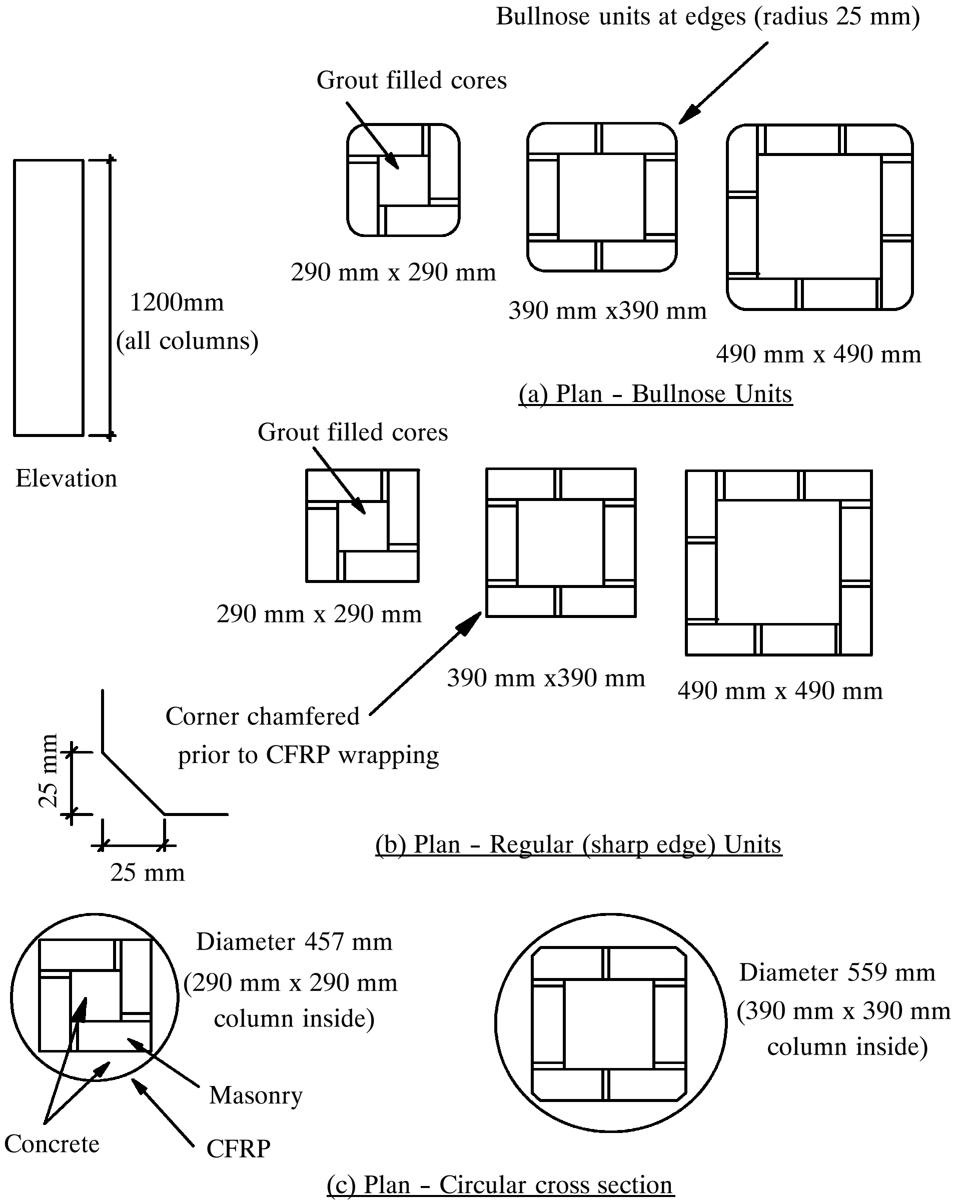

Figure 1. Column Details

over a larger area at the corners of the columns than would be achieved from using regular sharp edged units. The sharp edged units used along the flat sides for the intermediate and large size columns were from the same clay material and production process. For the second series of tests, again one of each size of column was constructed using the bullnose shaped units and accompanying sharp edge units. A further four columns were constructed of each size with a different unit. This second unit type was not available in the bullnose shape and so the corner edges of these latter 12 columns were sharp.

Testing of Unwrapped Columns

Each of the 18 columns (3 for Series 1 and 15 for Series 2) was loaded axially in compression until cracking was first observed (Figure 2). The aim was to damage the columns to a stage that would be considered in need of repair but not replacement. The columns were instrumented with displacement transducers, one at each corner, over a gauge length approximating one third of the column height and centred about midheight. The use of four transducers allowed checking that the loading was concentric. The vertical deflection at each transducer as well as the axial load were recorded at one second intervals during testing. The four transducer readings were averaged to allow plotting of column load versus axial deflection.

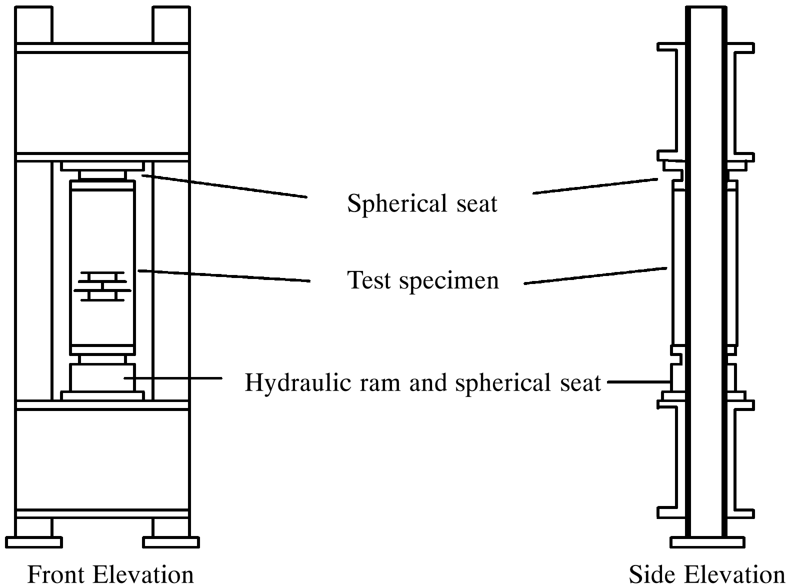

Figure 2. Schematic of Test Frame

The plot of load versus deflection was used to identify a reduction in column stiffness. This coincided with the appearance of first cracking and enabled the loading to be stopped before excessive column damage occurred. The small load increment observed between first cracking and ultimate column capacity was discovered during one of the Series 2 tests in which the column was completely destroyed with an explosive type failure at a load only slightly larger than that required to cause first cracking (see results below). This indicates that the load recorded to cause first cracking provides an *approximate* measure of the strength of the column prior to CFRP wrapping for later comparison with the wrapped strength.

CFRP Wrapping

All but one of the 18 columns were transported to be wrapped with CFRP sheets to industry standards by a coating contractor. The remaining column was destroyed by accident during the initial stage of testing as noted above. Before transporting to be wrapped some of the columns required prior treatment:

- The columns constructed using bullnose units required no treatment.

- All but two of the columns constructed using sharp edged units at the corners were saw cut along each edge to produce a 45° chamfer of 25mm (Figure 1b). The idea behind this was to approximate the effect of the bullnose thereby distributing the confining pressure provided by the wrap over a larger area at the corners of the column and also helping to avoid cutting the CFRP at the sharp column edge. This treatment was applied to all of the intermediate and large columns, and 2 of the small columns constructed from the second type of units (sharp edges).
- The remaining 2 small sized columns and 2 of the intermediate sized columns constructed from the second type of units (sharp edges) were surrounded with cylindrical cardboard column formwork. Concrete was then cast to form a concrete surround to the masonry column (Figure 1c). The cylindrical shape utilises the confining pressure provided by the CFRP wrap around the complete perimeter of the column. By contrast, the square column cross sections experience confinement in the vicinity of the column corners only.

Following the various above preparations all of the columns were sandblasted, coated with epoxy primer and bonding resin, then wrapped with the CFRP sheets. The CFRP sheets were in the form of a single layer of unidirectional reinforcement placed with the strong direction horizontally over the full column height. The design philosophy relies on the wrap to carry tensile forces around the perimeter of the columns as a result of lateral expansion of the underlying column under axial compressive load. Constraining the lateral expansion of the column confines the masonry and thereby increases its compressive capacity. For the Series 1 tests, a lap length of only 50 mm was used along the vertical join in the CFRP sheet. This was found to result in premature failure of the CFRP wrap at the join (see results below). For the Series 2 tests, the lap join was increased to 150 mm to ensure that separation failure did not occur at the join.

<u>Testing of CFRP Wrapped Columns</u>

The 17 wrapped columns were each loaded axially until ultimate failure occurred. The same instrumentation was used as for the initial cracking tests but linear potentiometers were used in place of the displacement transducers to avoid damage to the latter more expensive instruments should explosive type failures occur. The ultimate load and failure mode were recorded.

<u>Material Properties</u>

Tests were conducted to assess the compressive strength of the masonry and concrete used to construct the columns. Five high masonry prism stacks and diameter 100 mm x 200 mm high concrete cylinders were tested. For the Series 1 tests, the average compressive strength for the bullnose masonry was 18.5 MPa, and for the grout, was 30.3 MPa. For Series 2, the average compressive strengths were 26.7 MPa for the bullnose masonry, 25.5 MPa for the regular sharp edged masonry, 37.8 MPa for the grout used to fill the column cores, and 39.3 MPa for the concrete used for the circular concrete jackets.

The CFRP fabric had a tensile strength of 958 MPa and an Elastic Modulus of 73 GPa (properties of the cured laminate). This information was obtained from the CFRP manufacturer (Sikawrap 103C).

RESULTS AND DISCUSSION

Series 1 Tests

Unwrapped Columns. The three columns were each loaded axially in compression as described above. In each case vertical cracks developed in the masonry on all four faces of the square section columns. For the small and intermediate sized columns, the cracks initiated at the base of the column in each case and propagated vertically through the units and perpend joints for several courses. For the large column, cracking initiated near midheight and propagated vertically through the units and perpend joints towards the top and bottom of the column.

The loads to cause cracking in each case are summarised in Table 1. The load increased with increasing cross sectional area of the columns. However the ratio of cracking loads between columns of different cross sectional area is poorly correlated to the ratio of the load bearing areas. This is partly due to different ratios of grout to masonry area in each case but perhaps more strongly influenced by the inherent material variability as well as the differing degrees to which each of the columns was damaged. The latter was difficult to control.

Plots of Axial Load versus Deflection for each of the columns indicated that the response is essentially elastic up until cracking. There was only slight loss of stiffness with loading. The displacement recovery upon unloading was of the order of 80 - 90%. A typical load versus deflection plot for an unwrapped column is shown in Figure 3.

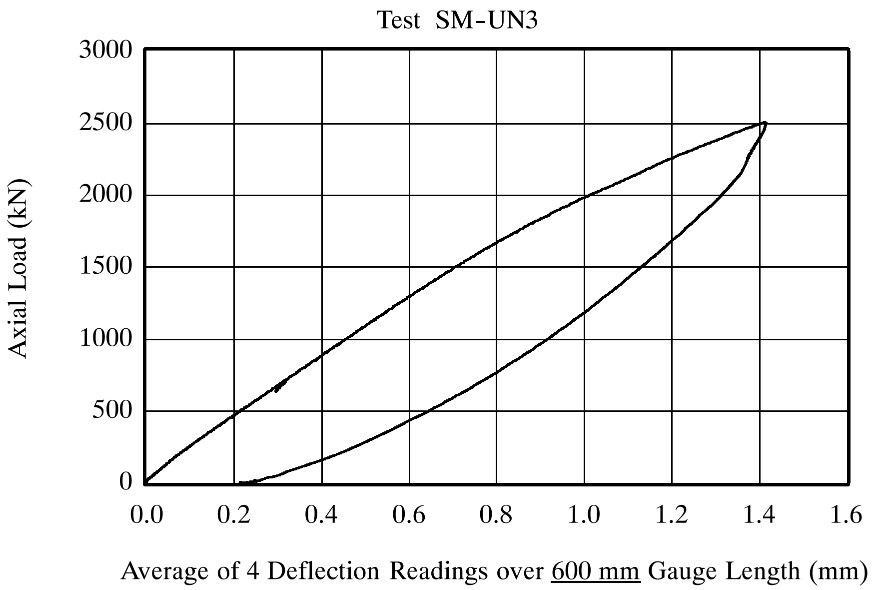

Figure 3. Typical load versus deflection plot for the unwrapped columns

Table 1. Test Results

Test	Section size (mm x mm)	Unwrapped I.D.	Unwrapped Cracking Load (MN)	CFRP Wrapped I.D.	CFRP Wrapped Peak Load (MN)	Load Increase (%)
Series 1						
Bullnose	290 x 290	SM-UN	2.5	SM-WP	2.6	2.5
	390 x 390	MD-UN	2.6	MD-WP	3.7	43
	490 x 490	LG-UN	4.2	LG-WP	6.0	43
Series 2						
Bullnose	290 x 290	R-S-N	2.1	R-S-W	2.7	26
	390 x 390	R-M-N	4.1	-	-	-
	490 x 490	R-L-N	3.4	R-L-W	5.8	73
Sharp						
(Square after wrap)						
	290 x 290	S-S-N3	2.0	S-S-W3	2.5	27
	290 x 290	S-S-N4	2.2	S-S-W4	2.5	14
	390 x 390	S-M-N1	3.3	S-M-W1	4.7	44
	390 x 390	S-M-N4	3.2	S-M-W4	4.6	45
	490 x 490	S-L-N1	4.0	S-L-W1	5.2	30
	490 x 490	S-L-N2	4.3	S-L-W2	5.7	34
	490 x 490	S-L-N3	5.0	S-L-W3	6.1	21
	490 x 490	S-L-N4	4.1	S-L-W4	5.1	25
(Circular after wrap)						
	290 x 290 (dia 457)	S-S-N1	2.2	S-S-CW1	6.0	180
	290 x 290 (dia 457)	S-S-N2	2.1	S-S-CW2	6.6	216
	390 x 390 (dia 559)	S-M-N2	3.5	S-M-CW 2	8.7	148
	390 x 390 (dia 559)	S-M-N3	3.4	S-M-CW 3	8.7	157

<u>CFRP Wrapped Columns.</u> Each of the three columns was loaded axially in compression until ultimate failure occurred. For the small column, failure occurred by separation of the CFRP wrap across the vertical lap joint at the base of the column. A strain gauge placed on the wrap to measure circumferential strain in the CFRP indicated that the stress in the

wrap was only a small percentage of its tensile strength. The wrap was thus not effectively utilised. The failure load recorded for the column was only 2.5% higher than the load required to crack the column prior to CFRP wrapping. This premature failure highlighted the need for a larger lap length for the vertical join in the CFRP.

Failure for the intermediate sized column also occurred as a result of failure in the CFRP lap joint at the base of the column. However, the failure load was 43% greater than the cracking load for the column prior to wrapping. This perhaps results from more complete bonding between the CFRP and the masonry around the perimeter of the column cross section thereby making the strength at the lap less critical until a higher load was reached. A higher circumferential strain was achieved in the CFRP prior to failure than for the small column.

The observation that failure occurred in both cases at the base of the column indicated the need for some form of end confinement to ensure failure away from the column ends. For the Series 2 tests, steel confining brackets were fabricated for both the square and cylindrical column shapes. These were used at the upper and lower ends of all columns, unwrapped and wrapped. The brackets were designed to confine the first 100 mm of column height at each end of the columns.

For the large column, the CFRP wrap did not rupture or separate at the join. The column was loaded past peak load. During loading, cracking of the masonry and grout within the wrap could be heard. In the final state, the CFRP wrap was folded along horizontal lines due to overall column shortening. The folding coincided with the underlying mortar joints which were crushed under the load. Bulging of the masonry beneath the wrap was also observed.

The results for the Series 1 wrapped column tests are summarised in Table 1.

Series 2 Tests

Unwrapped Columns. 15 columns were tested in this category. The columns were loaded until cracks appeared in the masonry. The cracks extended vertically, alternately through the perpend joints and the units. For a small number of columns the cracking initiated at the base of the column or in the midheight region but in the majority of cases the cracks initiated at the top of the column and propagated vertically downwards.

The cracks tended to appear in line with the underlying interface between the masonry and grout core. At the top of the columns, the bond between the masonry and the grout was visibly less complete than at the base of the columns as a result of greater grout shrinkage away from the masonry at the exposed top surface. This lack of bond is thought to be the cause for the masonry cracks initiating at the tops of the columns. For one of the intermediate sized columns, the column was inverted prior to testing. The result was cracking at the bottom (formerly the top) of the column, helping confirm this hypothesis.

For several of the intermediate and large sized columns, spalling of the brick unit surface occurred at the top and bottom courses of brickwork. This occurred along the top and bottom column edges between the corner confining brackets. For the small sized columns, the length of unconfined edge between the brackets was not sufficient to allow spalling.

The intermediate sized column constructed using bullnose shaped units at the edges could not be CFRP wrapped and retested as it completely failed during the unwrapped test. The column failed explosively at load and deflections readings only marginally above those observed to just cause cracking. The failure was not intentional.

The loads to cause masonry cracking in each case are shown in Table 1. For the columns constructed using the second type of masonry unit (sharp edged):

- Despite the difficulty controlling the degree of cracking in each test, the loads required to cause cracking for columns of any given size do not differ significantly.
- The loads clearly increase with increasing column cross section.
- The ratio of cracking loads between columns of different cross sectional area appears to be roughly correlated to the ratio of the load bearing areas.

Exceptions to the above occurred for the columns constructed using the bullnose units. The intermediate sized column supported an unusually large load and the large column, an unusually small load.

As for the Series 1 unwrapped tests, the load versus deflection responses were largely elastic up until cracking with displacement recovery in the order of 80 – 90% upon unloading (Figure 3).

CFRP Wrapped Columns. After wrapping with CFRP, ten columns of square cross section and four columns of circular cross section were tested.

The square section columns were each loaded past peak load until a significant decrease in the load carrying capacity was observed. In all cases the CFRP wrap remained essentially intact. In only 2 of the columns, small tears in the wrap were observed. In each case the tears occurred at a corner of the column in plan and over a height equivalent to one or two of the fibre weave bundles in the CFRP fabric (5 – 10 mm). In no case did the wrap fail at the vertical lap joint or at the column ends. This confirmed that the use a larger lap length compared to the Series 1 tests and end confining brackets were successful in preventing such failures.

During loading, and particularly as the peak load was approached, significant cracking of the masonry and grout could clearly be heard together with the sound of the CFRP wrap delaminating from the flat column sides. In the failed state the square section columns typically displayed horizontal folds in the CFRP wrap coinciding with crushed underlying mortar joints and visible bulging out of the masonry beneath the wrap.

The peak loads recorded for the square section columns are shown in Table 1. Also shown are the load increases (%) from the cracking load prior to CFRP wrapping to the peak load for the wrapped columns. The percentage increases range between 14 and 73% with a mean increase of 34%. Prior to testing it was expected that the load increase achieved would decrease with increasing column cross section. This hypothesis was based on the idea that the smaller square cross section would have the same area of confinement at the corners as a larger cross section but a shorter length of unconfined material between column corners (and thus a larger proportion of confined material). The results indicate that this is not the case with the greatest load increases observed for the intermediate sized columns and the *smallest* for the small sized columns. A greater number of tests may be necessary to make further conclusions in this regard.

A typical load versus deflection plot for the CFRP wrapped square section columns is shown in Figure 4.

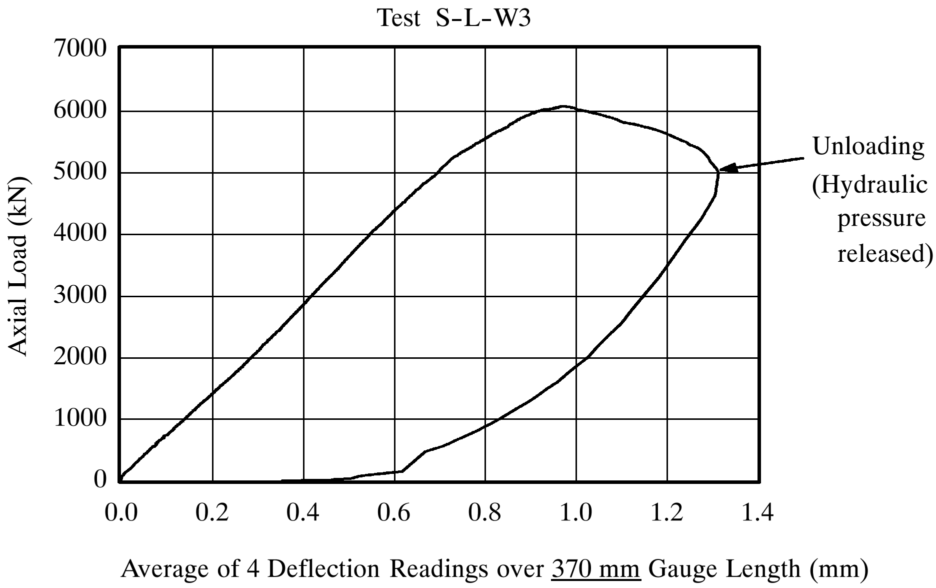

Figure 4. Typical load versus deflection plot for the CFRP wrapped SQUARE section columns

The circular section columns were each loaded until failure occurred. In each case there were very few visible or audible signs of distress prior to a very sudden and explosive failure (Figure 5). Plots of load versus deflection (Figure 6) did however provide warning of the imminent failure in each case. After an initially linear response, the column stiffness gradually reduced, followed by extended deformation at close to peak load before failure occurred. In each case the failure load was either equal to the peak load or only marginally less than the peak.

The sequence of failure for the cirular columns is thought to be due initially to progressive damage in the concrete and masonry, resulting in the gradual loss of column stiffness. The lateral expansion of the deteriorating masonry/concrete core then results in load transfer to the CFRP wrap. This provides sustained load carrying capacity to the column as it deforms further. Finally the brittle CFRP material ruptures allowing the large amount of internal energy to release suddenly. The two largest circular section columns each supported approximately 8.7 MN. As for the square section columns, the end confining brackets prevented failure from initiating at the column ends and inspection of the column remains indicated that wrap failure did not initiate at the vertical lap joint.

Figure 5. Circular section column after failure

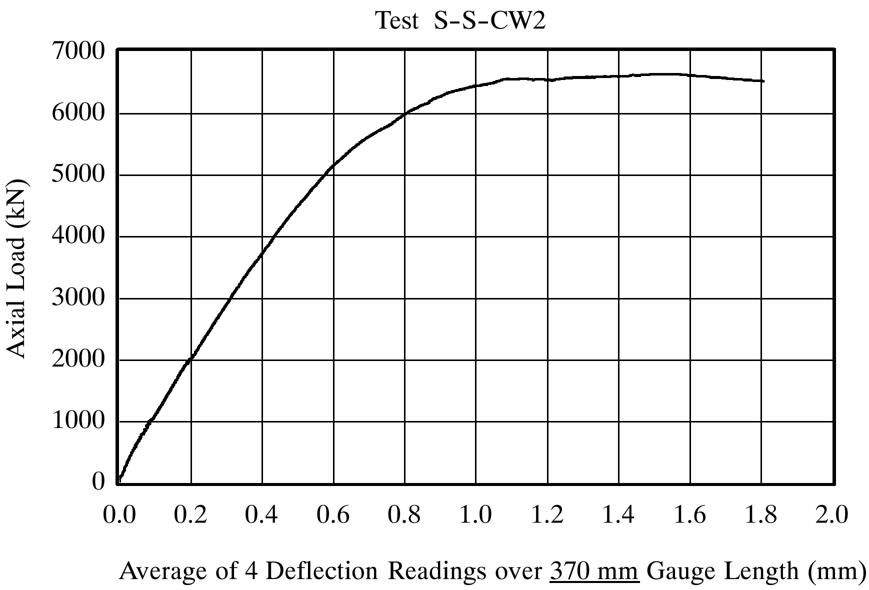

Figure 6. Typical load versus deflection plot for the CFRP wrapped CIRCULAR section columns

As shown in Table 1, load increases from the unwrapped cracking loads to the loads to fail the modified circular and CFRP wrapped columns ranged between 148% and 216% (mean 175%). Despite the additional column area, these increases clearly highlight the effectiveness of the CFRP wrap when provided with a circular cross section to confine.

CONCLUSION

The axial loads required to cause cracking in the unwrapped masonry columns are representative of the loads experienced by such columns in service where damage has been noted. After rehabilitating the columns using CFRP wraps, the additional loads required to failure the columns were determined.

In the cases where the original square section column was CFRP wrapped, the average load increase was in the order of 35%. If a circular concrete jacket is provided prior to wrapping, load increases averaging 175% were observed due to confinement by the CFRP wrap being effective around the full perimeter of the circular cross section.

For the rehabilitated columns, the masonry/grout core must experience considerable damage and associated lateral expansion before the CFRP wrap takes up any significant load. The CFRP wrap is thus of most benefit in the scenario of column overload.

The test results presented do not enable any decisive conclusions to be made regarding the effect of column size (cross sectional area) on the strength increase achieved.

These preliminary tests indicate that the use of CFRP wrapping is effective as a technique for rehabilitating damaged masonry columns. However, to maintain the aesthetics of masonry, an additional layer of finishing would be required.

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REFERENCES

Azarnejad, A., Tadros, G., Shrive, N.G., McWhinnie, K. (2000). Column Strengthening With CFRP Wraps. Proc. Canadian Society of Civil Engineers Structural Conference, London, Ontario, 2000. pp 200-207.