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# Experimental Study of Eccentrically Loaded Columns Strengthened Using a Steel Jacketing Technique

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***Abstract*—**An experimental study of Reinforced Concrete, RC, columns strengthened using a steel jacketing technique was conducted. The jacketing technique consisted of four steel vertical angles installed at the corners of the column joined by horizontal steel straps confining the column externally. The effectiveness of the technique was evaluated by testing the RC column specimens under eccentric monotonic loading until failure occurred. Strain gauges were installed to monitor the strains in the internal reinforcement as well as the external jacketing system. The effectiveness of the jacketing technique was demonstrated, and the parameters affecting the technique were studied.

***Keywords*—**Reinforced Concrete Columns, Steel Jacketing, Strengthening, Eccentric Load.

## I. Introduction

COLUMNS are basically vertical compression members that transfer axial loads to the foundations. Although the main function of the column is to transfer axial loads, most of the time, columns are subjected to moments as well. This may be due to accidental eccentricity arising from minor misalignment during construction, or due to reduction of the column size in multistory buildings. This may also occur due to lateral drift, even in cases when the columns are not part of the structural system resisting horizontal forces.

Many researchers investigated the strengthening of columns subjected to eccentric loads. The basic idea in most of the research conducted was to increase the concrete confinement in order to achieve increased strength. This was done most of the time by wrapping the concrete column using Fiber Reinforced Polymer, FRP, carbon or glass sheets. Li et al. [1], Parvin et al. [2], Bahaa et al. [3], Yuan et al. [4] and Benzaid [5] are some examples of recent studies conducted using FRP as a wrapping material for strengthening columns subjected to eccentric loading. Some researchers used steel as a confinement material by completely wrapping the column with steel sheets, e.g. Ramirez et al. [6] and Sakino et al. [7]. Others used partial confining by using steel cages [8]-[11]. Some researchers used only steel collars for the confinement e.g. Chapman et al. [12]. It is observed that more research is needed to determine the factors that affect the efficiency of the material used versus the requirements in both strength and ductility.

In this paper an experimental program for testing square Reinforced Concrete, RC, columns subjected to eccentric loads is presented. The program was intended to examine the effect of eccentricity on the carrying capacity of the column and to study the effect of column strengthening using steel jacketing. The jacketing technique consisted of four steel vertical angles installed at the corners of the column joined by horizontal steel straps as shown in Fig. 1. The steel jacket was fully bonded to the original RC column using epoxy mortar.

The columns where loaded monotonically until failure occurred using different values of eccentricity, and different parameters of the strengthening mechanism. A comprehensive study of the behavior of the column was conducted in each case to assess the effectiveness of the strengthening mechanism.

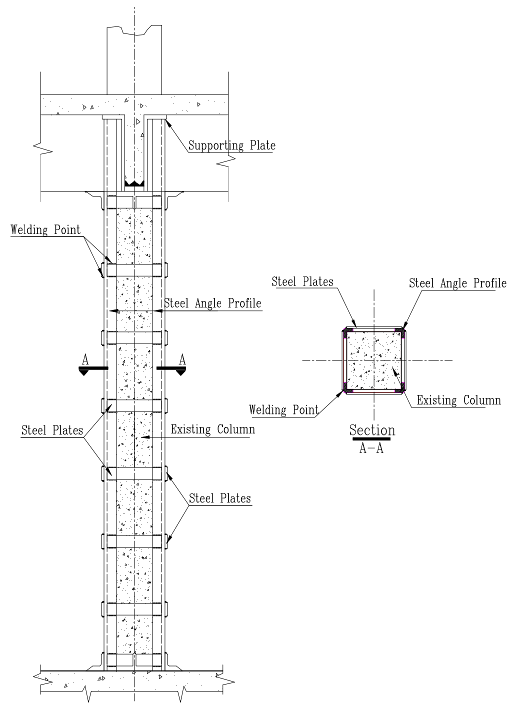


Fig. 1 Strengthening using steel jacketing technique

## II. Experimental Program

### *A. Experimental Specimen*

The experimental specimen consisted of an RC column of a square cross section 120x120mm and a length of 1000mm. The specimen was provided with a column head at the top and bottom 260x260mm as shown in Fig. 2. The RC column was reinforced using four longitudinal bars 8mm diameter and

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stirrups 6mm diameter spaced at 120mm. All reinforcing bars were mild steel bars with a rated yield stress of 240 N/mm$^2$. Strain gauges were used to measure the strains of the reinforcing steel as well as the external steel jacket.

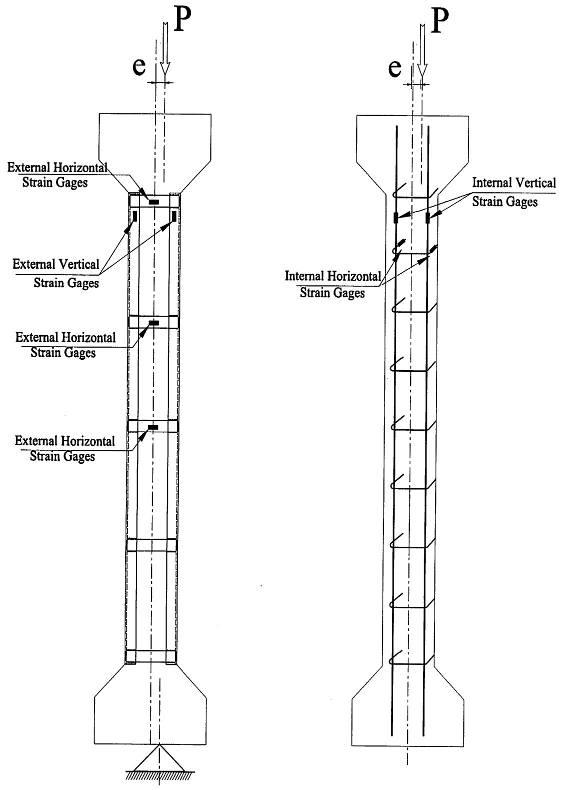


Fig. 2 Details of experimental column specimen

*B. Test Layout*

Column specimens were mounted on a steel frame in the RC laboratory of Al-Azhar University and tested under static eccentric monotonic load applied using a hydraulic jack. Load eccentricities were controlled using a column head steel device to accurately control the value of the eccentricity. The load was applied in regular increments from zero up to the failure load. At the end of each load increment, readings from the load cell and strain gauges were recorded through the data acquisition system. Test setup is shown in Fig. 3.

*C. Experimental Schedule*

A total of 27 specimens were cast and tested. 19 specimens with a target cube concrete strength, $F_{cu}$, of 15 N/mm$^2$ and 8 specimens with a target cube concrete strength of 30 N/mm$^2$.

The first group of 19 specimens ($F_{cu}$ =15 N/mm$^2$) were tested as follows. Five non-strengthened specimens were initially tested under eccentricities 0, 1, 2, 3 and 4cm representing an eccentricity to depth ratio, e/t = 0, 8.3%, 16.6%, 25% and 33.3%. The other fourteen specimens in the group were strengthened using 4 vertical angles (20 x 20 x 2 mm) and a varying number of horizontal straps (20 X 2 mm) tested under the same eccentricities. Four specimens used 3 equally distributed horizontal straps, four used 5 equally distributed horizontal straps, four used 7 equally distributed horizontal straps, and the last two used unequally distributed straps to investigate the effect of decreasing the strap spacing near the top and bottom of the column.

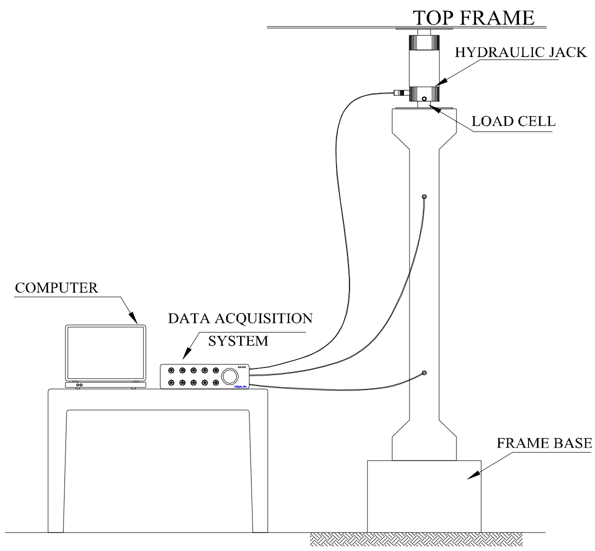


Fig. 3 Experimental setup

The second group of 8 specimens ($F_{cu}$ =30 N/mm$^2$) were tested under the same eccentricities. The same strengthening mechanism was employed except that the vertical angles had varying width ranging from 10mm to 40mm. The complete details of the experimental schedule are shown in Table I. For more information about the experimental program see [13].

## III. Experimental Results

*A. Failure Load*

Fig. 4 shows the failure load of the non-strengthened (*control*) columns under different eccentricities. The column capacity decreased from 270 KN for the axially loaded column to a value of about 100 KN for the column loaded with an eccentricity ratio e/t of 33.3%.

Fig. 5 shows the ultimate capacity of the strengthened columns. An increase ranging from 37.5% to 85% compared to the control column tested under the same eccentricity was observed. It can also be shown from the figure that the columns strengthened using 3 straps showed a slight enhancement in capacity than the columns strengthened with 5 and 7 straps. This observation, however, seems illogical since it was expected that by adding more straps, more confinement would be applied which would lead in turn in an enhancement in the column capacity. A finite element study of the columns which will be presented in a future paper showed that the capacities of the columns strengthened with 3, 5 and 7 straps were practically the same. The failure in both the experimental and finite element models always occurred in the unconfined part between the straps, and therefore it could be concluded that the number of straps didn't have an impact on the ultimate capacity of the strengthened column. In order to further investigate the effect of the strap distribution, two specimens with five and seven unequally distributed straps were tested. In these specimens one strap was located in the middle, and the rest of the straps were placed closely spaced at the top and bottom of the columns. In these specimens the failure didn't occur between the closely spaced straps but was shifted between the widely spaced straps as shown in Fig. 6. The column capacity was only increased by about 3%. Therefore it is believed that if the column was strengthened using closely spaced straps along the total length of the column, this would have greatly enhanced the load capacity of the column, but with a considerable increase in cost. In the authors' opinion, a future study involving closely spaced straps and investigating the effect of the strap spacing on the ultimate capacity of the column would be of great benefit.

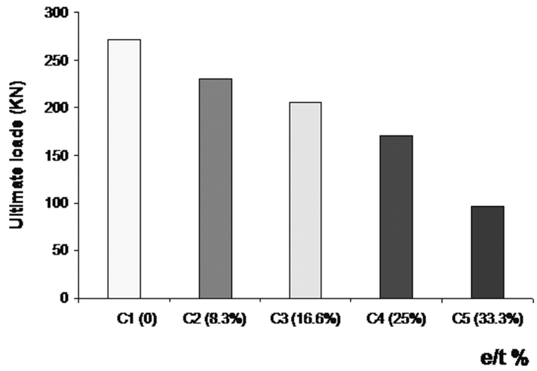


Fig. 4 Failure load of non-strengthened columns

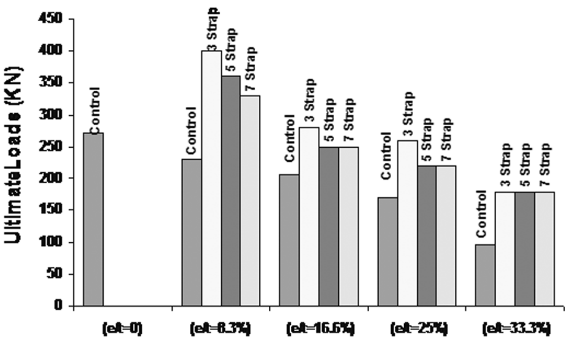


Fig. 5 Failure load of strengthened columns

Fig. 7 shows the effect of the width of the vertical angle on the capacity of the column. The ultimate capacity increased by 18% and 34% when strengthened by 1cm wide angles in the case of e/t of 25 and 33%, respectively. The ultimate capacity of the columns increased considerably by increasing the width of the vertical angles reaching a value of 78% in the case of e/t = 33% with a vertical angle of 4cm in width.

TABLE I
DETAILS OF THE EXPERIMENTAL SCHEDULE

| Code | $F_{cu}$ N/mm$^2$ | (e/t) | Conversion from Gaussian and CGS EMU to SI [a] |
|---|---|---|---|
| C1 | 15 | 0 | No Strengthening |
| C2 | 15 | 8.3 % | No Strengthening |
| C3 | 15 | 16.6 % | No Strengthening |
| C4 | 15 | 25 % | No Strengthening |
| C5 | 15 | 33.3 % | No Strengthening |
| C1 T3 | 15 | 8.3 % | 4 angles (20x20) & 3 uniformly distributed straps |
| C2 T5 | 15 | 8.3 % | 4 angles (20x20) & 5 uniformly distributed straps |
| C3 T7 | 15 | 8.3 % | 4 angles (20x20) & 7 uniformly distributed straps |
| C4 T3 | 15 | 16.6 % | 4 angles (20x20) & 3 uniformly distributed straps |
| C5 T5 | 15 | 16.6 % | 4 angles (20x20) & 5 uniformly distributed straps |
| C6 T7 | 15 | 16.6 % | 4 angles (20x20) & 7 uniformly distributed straps |
| C7 T3 | 15 | 25 % | 4 angles (20x20) & 3 uniformly distributed straps |
| C8 T5 | 15 | 25 % | 4 angles (20x20) & 5 uniformly distributed straps |
| C9 T7 | 15 | 25 % | 4 angles (20x20) & 7 uniformly distributed straps |
| C10T3 | 15 | 33.3 % | 4 angles (20x20) & 3 uniformly distributed straps |
| C11 T5 | 15 | 33.3 % | 4 angles (20x20) & 5 uniformly distributed straps |
| C12 T7 | 15 | 33.3 % | 4 angles (20x20) & 7 uniformly distributed straps |
| C13 T5 | 15 | 33.3 % | 4 angles (20x20) & 5 non-uniformly distributed straps |
| C14 T7 | 15 | 33.3 % | 4 angles (20x20) & 7 non-uniformly distributed straps |
| C15 | 30 | 33.3 % | No Strengthening |
| C17A1 X1 | 30 | 33.3 % | 4 angles (10x10) & 3 uniformly distributed straps |
| C18A2 X2 | 30 | 33.3 % | 4 angles (20x20) & 3 uniformly distributed straps |
| C19A4 X4 | 30 | 33.3 % | 4 angles (40x40) & 3 uniformly distributed straps |
| C16 | 30 | 25 % | No Strengthening |
| C20A1 X1 | 30 | 25 % | 4 angles (10x10) & 3 uniformly distributed straps |
| C21A2 X2 | 30 | 25 % | 4 angles (20x20) & 3 uniformly distributed straps |
| C21A4 X4 | 30 | 25 % | 4 angles (40x40) & 3 uniformly distributed straps |

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Fig. 6 Failure of columns strengthened with unequally distributed straps

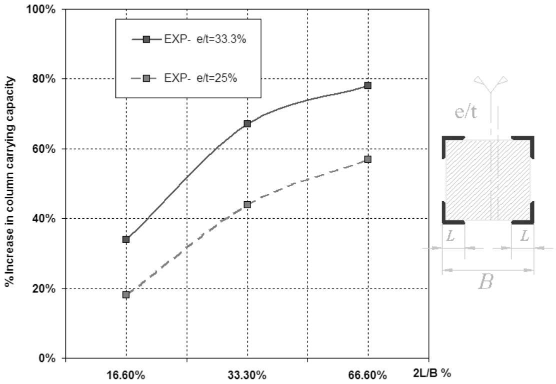


Fig. 7 Effect of vertical angle width on ultimate capacity of the columns

### B. Strain in Longitudinal Bars

Fig. 8 shows the strain in the vertical reinforcing bars for the case of the control non-strengthened column subjected to e/t=8.3%. *Bar I* is on the side of eccentricity and *bar II* on the opposite side. It is clear that *bar I* had a slightly increased compressive strain due to the strain gradient caused by the eccentricity. As the eccentricity increased the compressive strain in *bar I* increased and the strain in *bar II* decreased until it was reversed and started increasing in tension. This can be shown clearly in Fig. 9 showing the strains in the vertical bars for the control column subjected to e/t=33.3%.

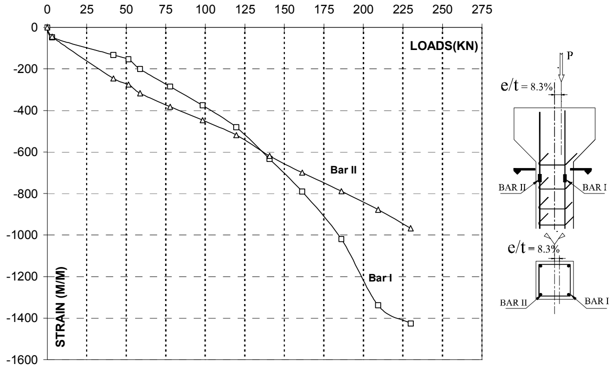


Fig. 8 Strain in bar i and ii – control column – e/t=8.3%

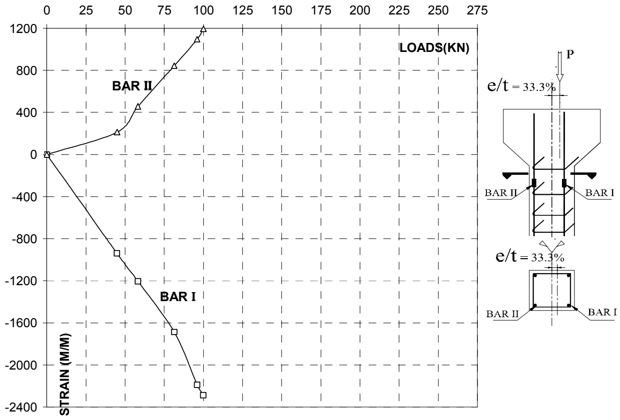


Fig. 9 Strain in bar I and II – control column – e/t=33.3%

Fig. 10 shows the strain in the vertical reinforcing *bar I* (on the same side of the eccentricity) for the cases C1T3, C2T5 and C3T7 strengthened by 3,5 and 7 straps respectively, subjected to e/t=8.3%. It can be shown that the compressive strain increased slightly as the number of straps increased. Higher compressive strains in *bar I* indicates a higher compressive force and in turn more confinement as the number of straps increased. However, this was not reflected by a similar increase in the ultimate load. This might be due to the fact that the strain was measured very close to the location of the upper strap were the confinement was high, while the failure occurred further down where effect of the strap confinement have diminished. As the eccentricity (e/t) increased, however, the increase in confinement with the increase of the number of straps was not very clear especially as the failure load was approached as can be seen in Fig. 11.

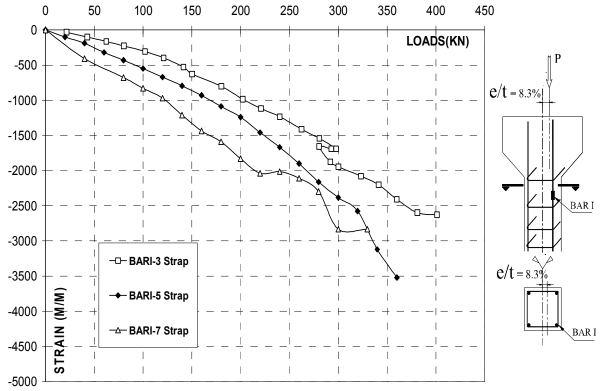


Fig. 10 Strain in bar I for various strengthened columns (e/t=8.3%)

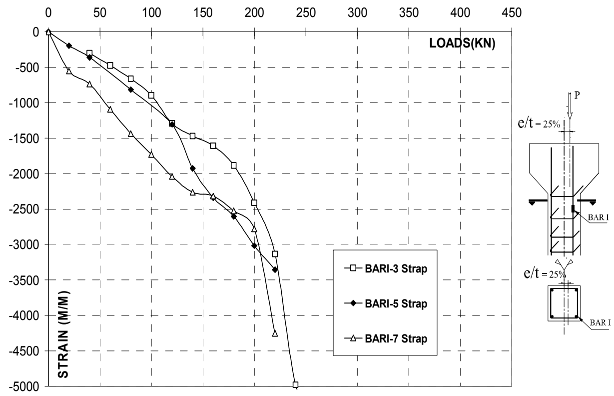


Fig. 11 Strain in bar I for various strengthened columns (e/t=25%)

*C. Strain in Stirrups*

Fig. 12 shows the strain in the second stirrup from the top on the side of the eccentricity (*stirrup I)* and on the opposite side (*stirrup II)* for the case of the control non-strengthened column subjected to e/t=8.3%. *Stirrup I* showed a slight increase in tension strain than *stirrup II*, indicating a slight increase in vertical compression strain on the side of eccentricity as expected. As the eccentricity increased the difference in tension strain between the two points on the stirrup increased as the stress gradient increased with the increase of eccentricity. This could be clearly observed in Fig. 13 for e/t =25%.

Fig. 14 shows the strain in *stirrup I* on the same side of the eccentricity for the columns C4T3, C5T5 and C6T7, strengthened using 3, 5 and 7 straps, respectively, and subjected to eccentricity e/t=16.6%. No clear relationship can be drawn from the figure that relates the number of strengthening straps to the strain in the stirrups. This might be logical, because in the case of the increased confinement, the compressive vertical stress in the concrete will increase without any notable increase in the tensile strain in the transverse direction.

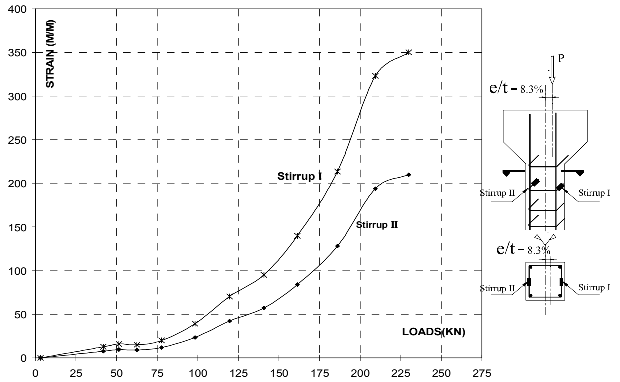


Fig. 12 Strain in stirrup for control column (e/t =8.3%)

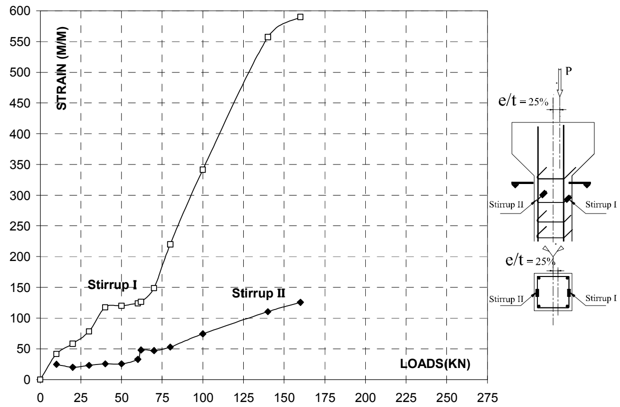


Fig. 13 Strain in stirrup for control column (e/t =25%)

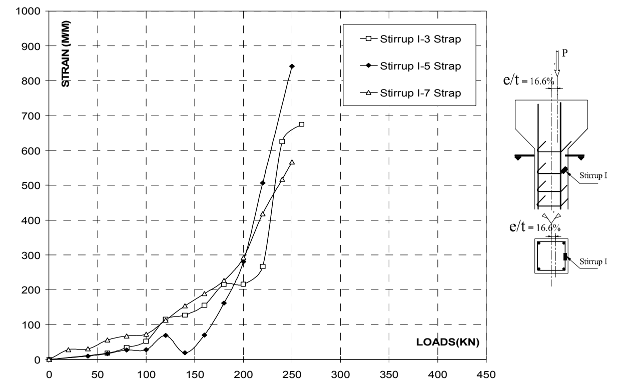


Fig.14 Strain in stirrup I for various strengthened columns (e/t=16.6%)

*D. Strain in Vertical Angles*

Fig. 15 shows the strain in the strengthening vertical angles for column C4T3 strengthened using 3 straps and subjected to eccentricity e/t=16.6%. *Angle I* on the eccentricity side showed higher compressive strains than *angle II* on the opposite side as shown in the figure. This of course is attributed to the stress gradient caused by eccentricity. Similar observations were noticed for the other specimens subjected to different values of eccentricities. The number of straps used for strengthening didn't have a noticeable effect on the strain in angles I or II. It was also noticed that the percentage of the load carried by the strengthening angle compared to the ultimate load decreased as the eccentricity increased. This is shown in Fig. 16 for the columns strengthened with 3 straps (C1T3, C4T3 and C7T3 and C11T3) as an example.

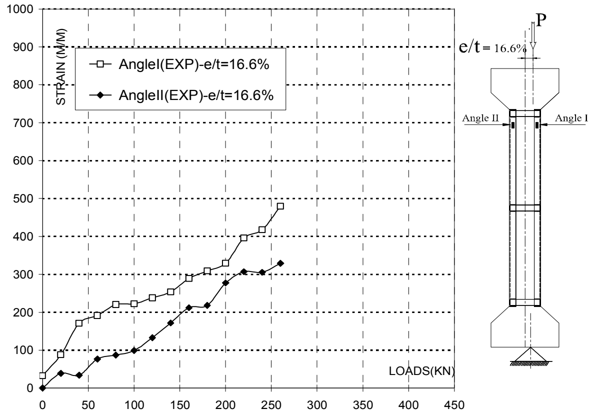


Fig. 15 Strain in vertical steel angles (e/t =16.6%)

### *E. Strain in Horizontal Strengthening Straps*

Fig. 17 shows the strain in the middle strap for column specimens strengthened using 5 straps for different values of e/t. It is noticed from the figure that no relation can be deducted between the eccentricity ratio and the strain in the horizontal middle strap. This behavior was typical for the upper strap for the same specimens and for the other tested column specimens as well. This observation reinforces the conclusion concerning the effect of the number of straps on the behavior of the strengthened columns.

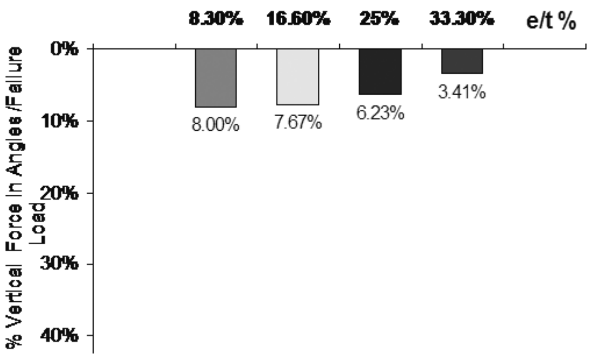


Fig. 16 Force in vertical angle / failure load versus e/t for specimens strengthened using 3 straps

### *F. Failure Modes*

The failure mode of the un-strengthened column subjected to axial load was a typical shear failure as shown in Fig. 18. For un-strengthened specimens subjected to eccentric loads failure started by separation of the concrete cover on the same side of eccentricity. This was followed by partial loss of confinement, buckling of the reinforcing bars, and crushing of the concrete in the compression part as shown in Fig. 19. Failure occurred most of the time in the upper one third of the column. Occasionally, however, the failure occurred in the lower portion.

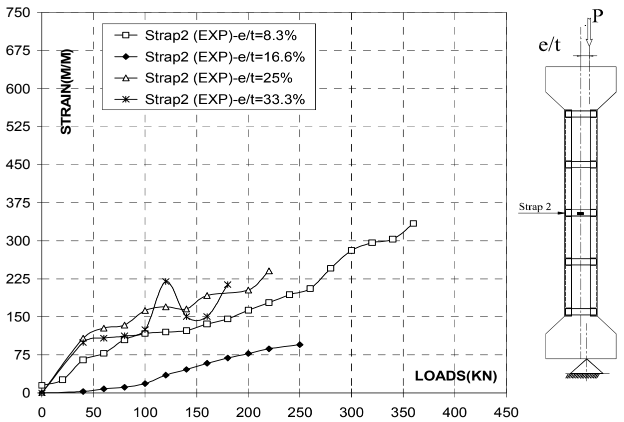


Fig. 17 Strain in middle strap for various e/t for specimens strengthened using 5 straps

For columns strengthened with vertical steel angles and horizontal straps, the mode of failure was also identical to that shown in Fig. 19 but occurred at a location away from the straps as shown in Fig. 20. In the case when the wider (40mm X 40mm) angles were used for strengthening the failure mode was also similar but the crushing of concrete and loss of concrete cover was considerably less due to more confinement caused by the wider angles. This can be shown in Fig. 21.

Fig. 18 Failure mode of axially loaded column

## IV. CONCLUSION

Columns strengthened using a steel jacketing technique formed of 4 vertical angles and a number of horizontal straps were experimentally tested under eccentric monotonic load. It was observed that the ultimate load carrying capacity of columns decreased up to 85% as the eccentricity increased to a value of e/t of 33.3%.


Fig. 19 Failure mode of eccentrically loaded column

Fig. 20 Failure mode of eccentrically loaded strengthened column

Fig. 21 Failure Mode of Eccentrically Loaded Column Strengthened using 40mm Angles

The steel jacketing techniques used in the strengthening of columns increased the column ultimate capacity to a value ranging from 21% to 87%. It was observed that the number of horizontal straps didn't have a noticeable effect on the ultimate capacity of the columns. This was probably attributed to the wide spacing between the horizontal straps in all cases tested in this study. Due to the wide spacing, the confinement didn't affect the entire column, and failure occurred in the space between the horizontal straps. Therefore, a future study is recommended to evaluate the maximum permissible spacing between horizontal straps so as to benefit from the confining effect of the straps and to prevent failure from occurring between the straps. It was also shown that the width of the vertical angles had a considerable effect on the ultimate capacity of the strengthened column.

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