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# Experimental Study on The Behavior of Slender Rectangular Columns Under Eccentric Loading

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Abstract

This paper includes an extensive experimental program consisted of twenty seven specimens to investigate the behavior of reinforced concrete, RC, slender columns with rectangular sections under the effect of eccentric loads. The program contains three groups each has 9 specimens. The first group (A) is considered as a control group tested without strengthening and the second group (B) is strengthened using near surface mounted (NSM) longitudinal steel bars while the third group (C) is strengthened using NSM longitudinal steel bars partially wrapped with one ply of carbon fibers reinforced polymers (CFRP) sheets. In addition to the strengthening schemes, the test parameters included the investigation on the change in the ratio of the internal longitudinal steel bars as well as the stirrups' volumetric ratio. All specimens are tested eccentric loading with eccentricity-to-section height e/h equals 0.25. The research revealed that the strength gain in specimens in group (C) is higher than in group (B). The proposed strengthening schemes increased the ultimate capacity as well as the ductility of the eccentrically loaded columns.

*Keywords: Strengthening; FRP; RC Slender Columns; Eccentric Loads; Confinement.*

## 1. Introduction

A major part of the civil engineering reinforced concrete (RC) infrastructure all over the world including bridges, municipal buildings, transportation systems, and parking facilities are facing problems of deficient design and/or construction practices, space, functionality or loading alterations, overuse, seismic upgrading and of course inadequate maintenance.

Reinforced concrete columns as a major supporting element for any structure may, for numerous reasons, need strengthening. Traditional conventional methods like concrete or steel jacketing were used for repair, strengthening, or providing a lateral confinement for the RC columns [1-3]. Although both methods are effective in increasing the structural capacity, they are labor consuming and mostly results in a substantial increase in the cross section of the strengthened column.

For these reasons and to replace outdated techniques, the innovative rehabilitation and strengthening methods for reinforced concrete structures, especially with composite materials, have taken a large portion of the research and application work in the field of repair and restoration of structural elements. Fiber reinforced polymers (FRP) sheets can be used to wrap column's cross

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section with a high-strength adhesive providing confinement with composite enclosure resulting in increasing the load carrying capacity of the strengthened columns.

FRP have emerged as a promising alternative strengthening materials for upgrading deficient RC infrastructure. There is a vast available database on Fiber Reinforced Polymer-Reinforced Concrete, (FRP-RC), beams and slabs; however, literature on FRP-RC columns is infrequent and limited. Many research works were conducted in the field of repair and strengthening of reinforced concrete circular columns. However, columns with cross section like square or rectangular did not take enough attention. Confining of circular or non-circular reinforced concrete to enhance or regain strength and ductility of concentrically loaded RC short columns using CFRP sheets has been reported by numerous studies [4-9]. In reality, columns are never exposed to concentric load but always exposed to eccentric load (combined axial load and bending moment). RC columns under the effect of eccentric loads still need thorough investigations.

The main FRP-based strengthening techniques used for the rehabilitation of RC structures are the externally bonded reinforcement (EBR) and NSM reinforcement. In the case of columns, the EBR technique is used to increase the concrete confinement and the column shear resistance, [10-12]. The results showed that that full wrapping of the concrete column provided higher load carrying and energy absorption capacities than partial confinement. However, partial wrapping with the existence of internal stirrups can still be significant in terms of load carrying and energy dissipation requirements, and in terms of economy of FRP materials [13].

The NSM technique is based on installing laminates into precut grooves executed on the concrete cover of the elements. The NSM has been investigated for the strengthening of reinforced concrete beams in flexure and in shear, [14-20].

For columns, NSM proved to be very effective in terms of increasing their flexural resistance, as long as the NSM bars can be effectively anchored in the adjacent elements. Combining NSM laminates for the flexural resistance, with strips of wet lay-up FRP sheets located in between existing steel hoops would result in a high effective technique [21].

The available literature on the strengthening of eccentrically loaded slender rectangular RC columns is still limited. The use of ordinary steel reinforcement for the use as NSM is almost incited although it has a vital importance for its cheap price compared to the FRP.

This paper presents the results of comprehensive experimental investigation on the behavior of eccentrically loaded slender RC columns with rectangular cross section strengthened with two strengthening scheme combining NSM longitudinal reinforcement and transversal CFRP partial wraps.

## 2. Experimental Program

### *2.1 Test matrix*

Test matrix is given in Table 1. A total of 27 slender column specimens were tested in the present study. Test parameters included two different strengthening schemes using either near surface mounted (NSM) steel reinforcing bars or NSM steel bars confined with carbon fiber reinforced polymer (CFRP) sheets in addition to the change in the longitudinal reinforcement ratio “$\mu$” and volumetric ratio of stirrups “$\rho_v$”. The specimens were divided into three main groups, (A), (B), and (C), each having nine specimens. Specimens of Group (A) were tested without strengthening as control specimens. However, specimens of other groups (B) and (C) were strengthened, respectively, with NSM steel reinforcing bars (scheme 1) and NSM steel bars confined with one layer of CFRP sheets (scheme 2).

### *2.2 Material properties*

The used steel was of grade 240/350. One of the types of CFRP sheets available in the Egyptian market was used for the wrapping in scheme 2. The properties of the used materials as extracted from the manufacturer data sheet are given in Table 2.

TABLE 1: SPECIMENS' MATRIX

| group | Specimen notation | Longitudinal reinforcement | | shear reinforcement | | strengthening scheme |
|---|---|---|---|---|---|---|
| | | steel details | Ratio "μ" | details | "$\rho_v$" | |
| A | G1C1 | 4Ø8 | *μ=1%* | Ø6@100mm | 0.73% | N/A |
| | G1C2 | | | Ø6@150mm | 0.49% | |
| | G1C3 | | | Ø6@200mm | 0.37%, | |
| | G2C1 | 4Ø10 | *μ=1.57%* | Ø6@100mm | 0.73% | |
| | G2C2 | | | Ø6@150mm | 0.49% | |
| | G2C3 | | | Ø6@200mm | 0.37%, | |
| | G3C1 | 4Ø12 | *μ=2.26%* | Ø6@100mm | 0.73% | |
| | G3C2 | | | Ø6@150mm | 0.49% | |
| | G3C3 | | | Ø6@200mm | 0.37%, | |
| B | G4C1 | 4Ø8 | *μ=1%* | Ø6@100mm | 0.73% | (Scheme 1)<br>4×2Ø6 Longitudinal NSM bars |
| | G4C2 | | | Ø6@150mm | 0.49% | |
| | G4C3 | | | Ø6@200mm | 0.37%, | |
| | G5C1 | 4Ø10 | *μ=1.57%* | Ø6@100mm | 0.73% | |
| | G5C2 | | | Ø6@150mm | 0.49% | |
| | G5C3 | | | Ø6@200mm | 0.37%, | |
| | G6C1 | 4Ø12 | *μ=2.26%* | Ø6@100mm | 0.73% | |
| | G6C2 | | | Ø6@150mm | 0.49% | |
| | G6C3 | | | Ø6@200mm | 0.37%, | |
| C | G7C1 | 4Ø8 | *μ=1%* | Ø6@100mm | 0.73% | (Scheme 2)<br>4×2Ø6 Longitudinal NSM bars<br>+<br>CFRP sheet strips 100mmwidth spaced @250mm |
| | G7C2 | | | Ø6@150mm | 0.49% | |
| | G7C3 | | | Ø6@200mm | 0.37%, | |
| | G8C1 | 4Ø10 | *μ=1.57%* | Ø6@100mm | 0.73% | |
| | G8C2 | | | Ø6@150mm | 0.49% | |
| | G8C3 | | | Ø6@200mm | 0.37%, | |
| | G9C1 | 4Ø12 | *μ=2.26%* | Ø6@100mm | 0.73% | |
| | G9C2 | | | Ø6@150mm | 0.49% | |
| | G9C3 | | | Ø6@200mm | 0.37%, | |

TABLE 2: PROPERTIES OF THE USED MATERIALS

| Material | Dimension, mm | Tensile strength, MPa | Modulus of elasticity E, MPa | Elongation at break% |
|---|---|---|---|---|
| Steel | ϕ = 6, 8, 10, 12 | 240 | $2.0\times10^5$ | ≥16.0 |
| CFRP Sheets | virtual thickness $t_f$= 0.13 | 3450 | $2.3\times10^5$ | 1.50 |
| Epoxy resin | ≈ 1.0mm | 30 | $3.8\times10^3$ | 0.9 |

The sheet was unidirectional with nonstructural weaves in the secondary direction to hold the fabrics together. The sheet was glued using epoxy resin. A cured CFRP composite sheet (CFRP including resin) has a thickness of about 1.0mm, an average tensile strength of 894 MPa, and an ultimate elongation of 1.33%. Concrete with an average characteristic compressive strength of 22±2 MPa was used for the casting of the tested columns.

### *2.3 Test specimen*

The test specimen was a rectangular reinforced concrete slender column. The Egyptian code of Practice, ECCS-203, limits the upper slenderness ratio "$\lambda_b$" for the un-braced rectangular short columns to $\lambda_b$=10.0. In this work, the slenderness ratio was taken equals 20 which exceeded the code limits by 100% for all columns. The overall height of the test specimen was 2000 mm. All specimens were subjected to eccentric loading in which the eccentricity ratio "*e*/*t*" value was kept constant (0.25) for all specimens in which "*e*" represents the offset between the load and the specimen centre. To apply the eccentric loading, rigid lower and upper steel plates with eccentric rolling bar were used. The specimen's cross section was 100×200 mm. The longitudinal steel reinforcement consisted of four normal mild steel bars either 4Ø8, 4Ø10 or 4Ø12 to account for the test variable of the ratio of the longitudinal steel bars "μ" which corresponded to steel reinforcement ratios of about 1%, 1.57% and 2.26%, respectively.

$$\mu = \frac{A_s}{b \times h} \times 100 \qquad (1)$$

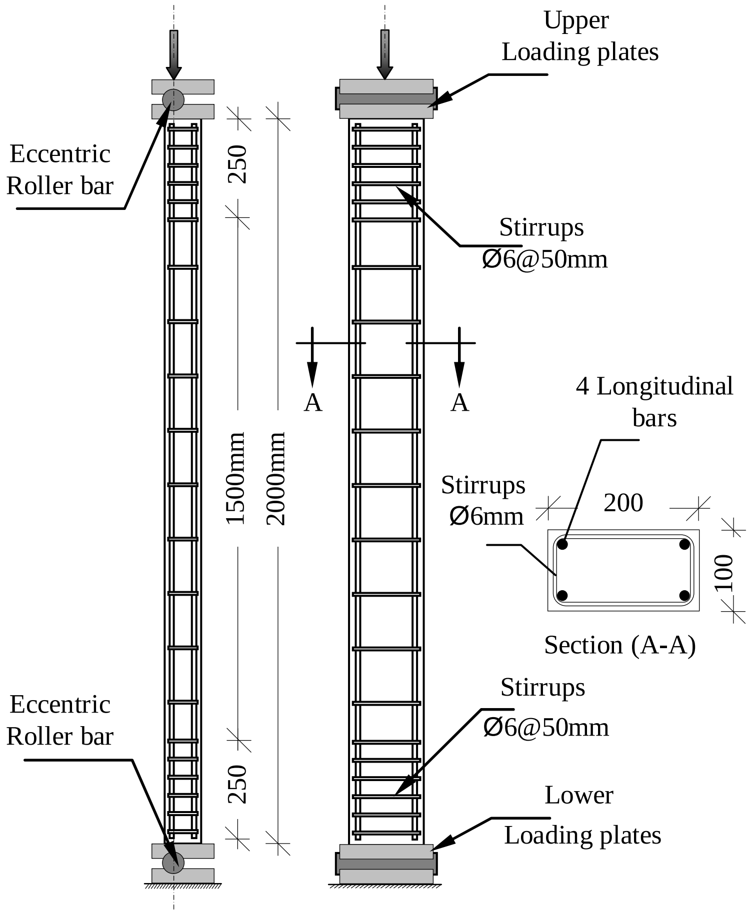


Figure 1. Specimen concrete dimensions and reinforcement details

The shear reinforcement consisted of 6mm diameter plain ties spaced at either 100mm, 150mm or 200mm to account for the change in the stirrups' volumetric ratio "$\rho_v$" which corresponded to stirrups' volumetric ratios of about 0.73%, 0.49% and 0.37%, respectively. To assure the failure would happen within the middle height of the specimen, stirrups were spaced at 50mm at both ends for 250mm distance. Details of specimens and loading plates are shown in Figure 1.

$$\rho_v = \frac{v_{st}}{v_c} \times 100, \text{ in which } v_{st} = \frac{\pi\, \phi_{st}^2}{4} \times \Sigma O \text{ and } v_c = b \times h \times s$$

### 2.4 *Installation of Strengthening Schemes*

Installation of NSM reinforcing steel was performed in the test program for groups B and C. to install the NSM steel a groove was cut in the longitudinal direction of the column using a concrete saw and a grinder. The groove width was approximately 24mm. The depth of groove was fixed at 15 mm measured from the extreme tension fiber of the column. Once groove cut was done, it was thoroughly cleaned using a compressed air then filled half depth with epoxy paste. The additional NSM reinforcements were then placed into the grooves and topped up with epoxy paste. The adhesive was smoothed, edges cleaned and left to cure for the suitable duration. For group C, the columns were partially wrapped with one ply of unidirectional CFRP sheets. Strengthening schemes are shown in Figure 2.

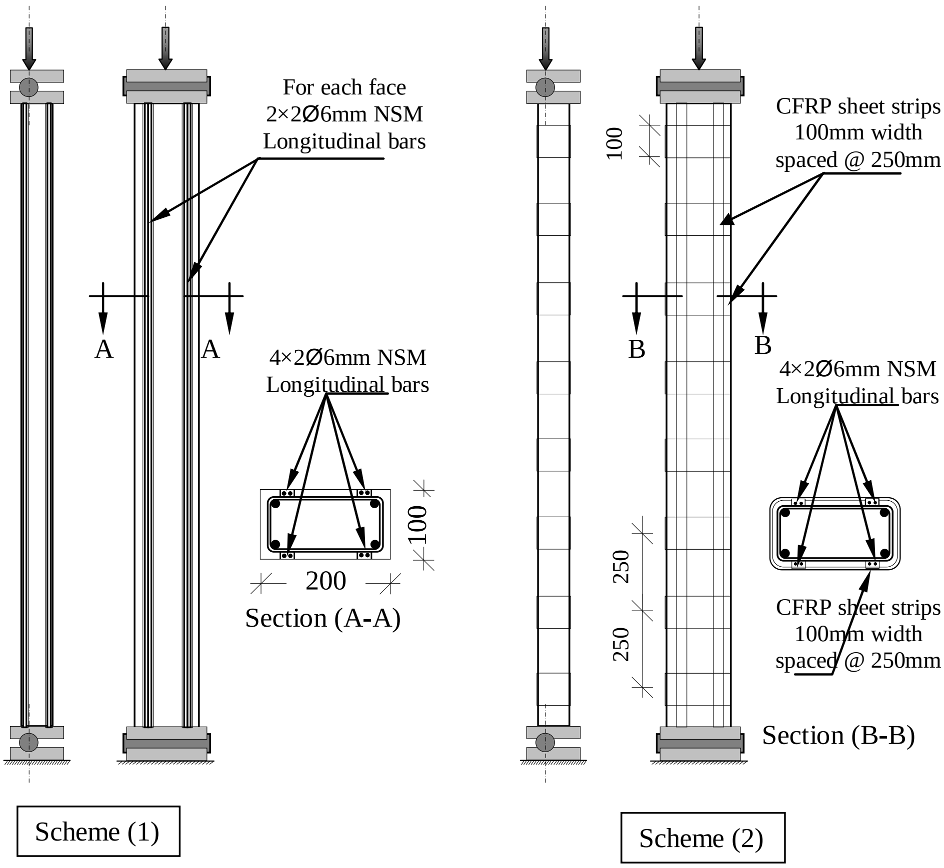


Figure 2. Schematic drawing of strengthening schemes

## 3.0 Test results and discussion

### *3.1 Effect of strengthening*

Two main strengthening schemes were used in this research program. The first scheme was using external NSM longitudinal steel bars partially wrapped with one ply of CFRP Sheet. The second scheme was exactly as the first one without wrapping by the CFRP sheet. In the following paragraphs, the effect of strengthening on the behavior of the eccentrically loaded columns will be presented.

#### *3.1.1 Effect of strengthening on lateral buckling of the slender columns.*

Figure 3 shows the relationship between the load and lateral buckling for tested columns having reinforcement ratio $\mu$ = 1%, at different stirrups' volumetric ratios $\rho_v$ = 0.73%, 0.49% and 0.37%. For any specific ratio of $\rho_v$, it is clear that the two external strengthening schemes increased the flexural stiffness of the tested columns as a result of the reduced lateral buckling.

The flexural stiffness is expressed by the slope of the load-lateral buckling curve. For columns with $\rho_v$= 0.73%, the load required to reach a 10mm of lateral buckling, (this value is taken to guarantee the representation of all specimens including the control ones), for specimens G4C1 and G7C1 increased by 23% and 61%, respectively, than the reference specimen G1C1. Same trend was dominating when $\rho_v$= 0.49%, as the required load to deliver the same lateral buckling (10mm) exhibited increases of 19% and 58% for specimen G4C2 and G7C2, respectively, over the reference column G1C2. For the last group when $\rho_v$=0.37%, the specimen G4C3 and G7C3 showed 89% and 131% higher load than their reference column G1C3.

It may be said that the strengthening scheme (2) showed better improvement in load capacity at the same value of lateral buckling than columns strengthened by Scheme (1) for any value of $\rho_v$.

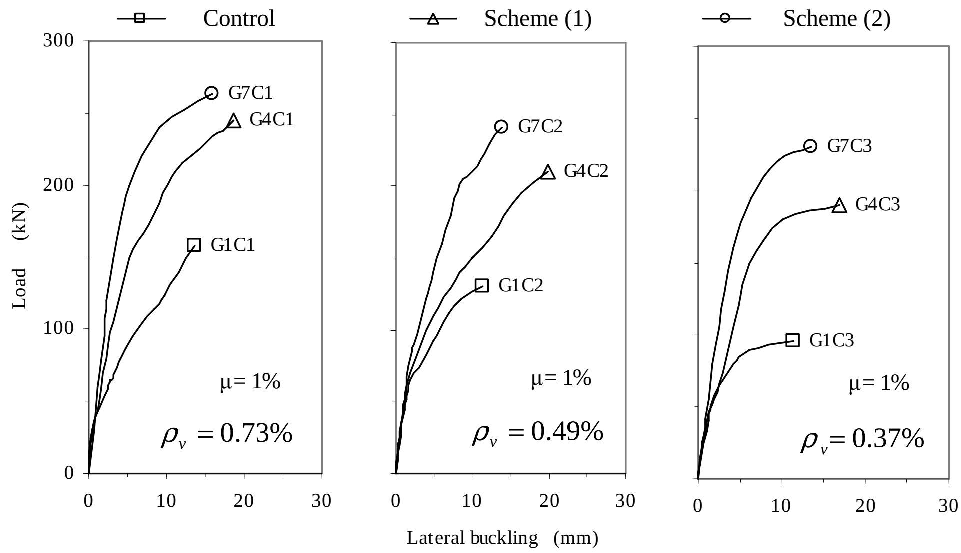


Figure 3. Effect of strengthening scheme on the lateral buckling for longitudinal reinforcement ration μ=1%

For specimens with internal reinforcement μ = 1.57% and 2.26% the same trend and conclusion is reassured. The relations are shown in Figures 4 and 5 respectively.

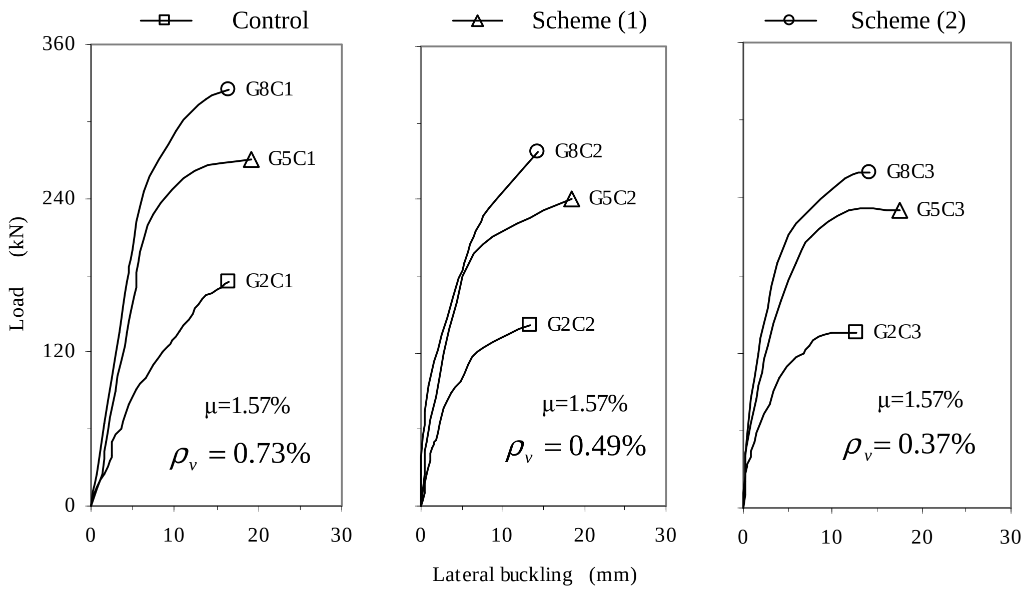


Figure 4. Effect of strengthening scheme on the lateral buckling for longitudinal reinforcement ration μ=1.57%

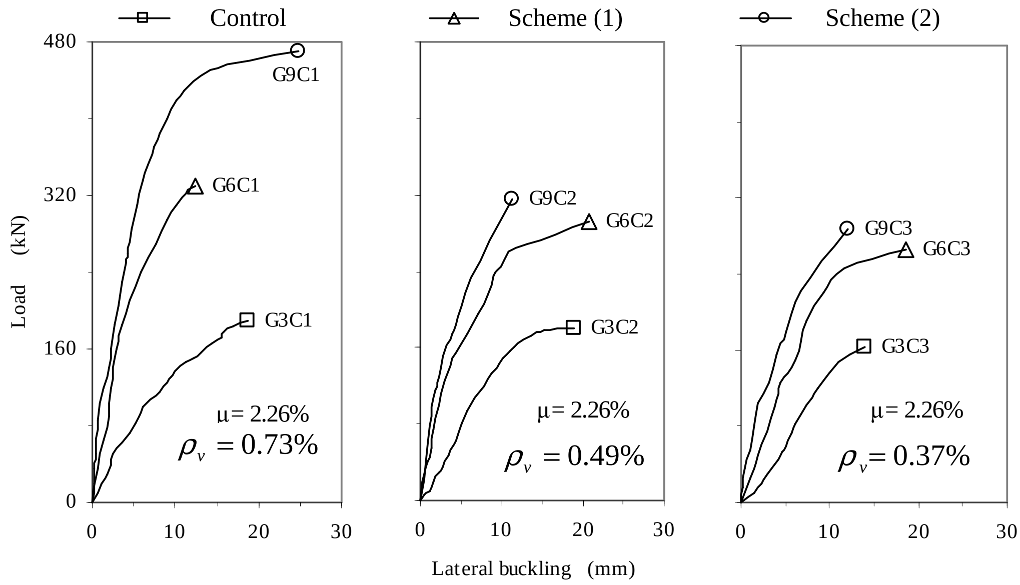


Figure 5. Effect of strengthening scheme on the lateral buckling for longitudinal reinforcement ration μ=2.26%

### *3.1.2 Effect of strengthening on strain*

The relationships between load and longitudinal steel strain for all specimens are shown in Figures 6, 7 and 8. Curves for specimen G1C1 were not reported due to unpredicted faults in the out put of the strain gauges before testing. From the Figures, it is easily noted that strengthened slender columns specimens of either group B strengthened with scheme 1 or group C strengthened with scheme 2, exhibited higher stiffness manifested in lower strain values at any load level than group A (control specimens). It is also depicted that most of the strengthened specimens showed superior ultimate strains relative to those of the control specimens of group (A). The load required delivering steel compression or tension strain of 0.002 for strengthened specimens was much higher than that required for the control specimen for any ratio of either internal longitudinal or transversal reinforcement.

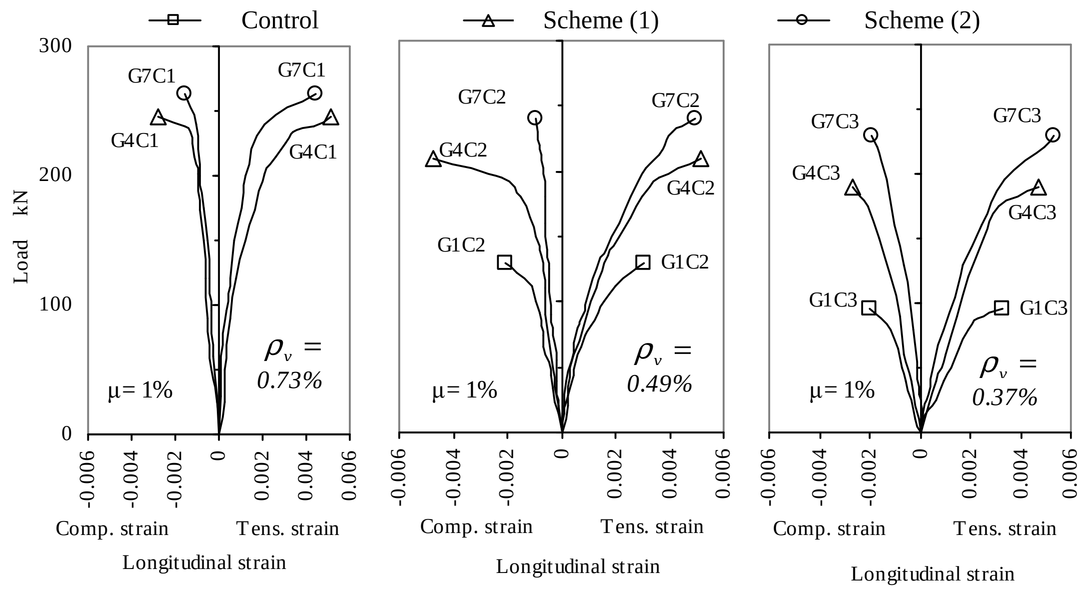


Figure 6. Effect of strengthening scheme on the strain behavior and stiffness for specimens with longitudinal reinforcement ration μ=1.0%

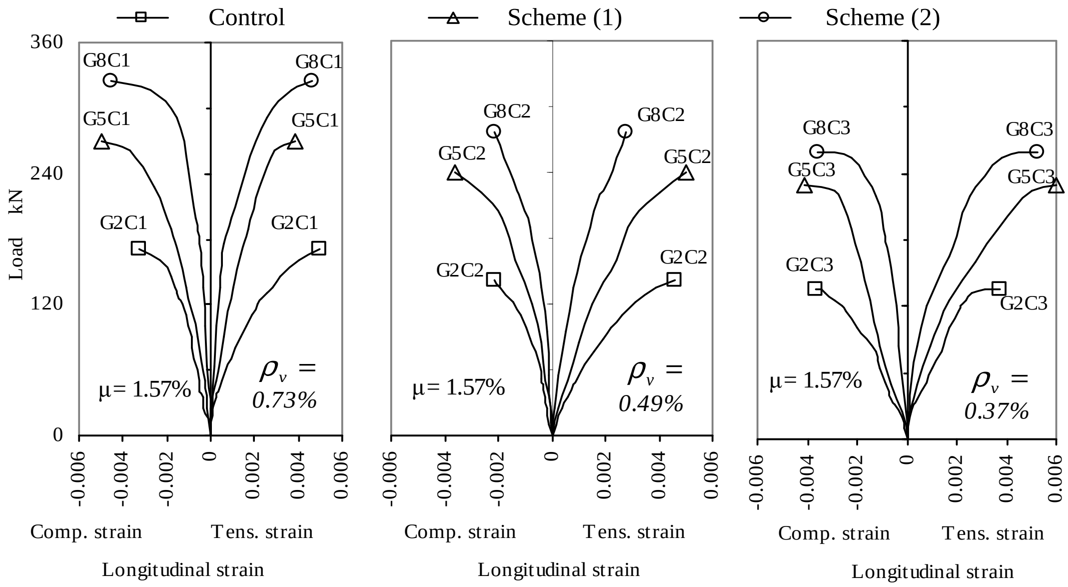


Figure 7. Effect of strengthening scheme on the strain behavior and stiffness for specimens with longitudinal reinforcement ration μ=1.57%

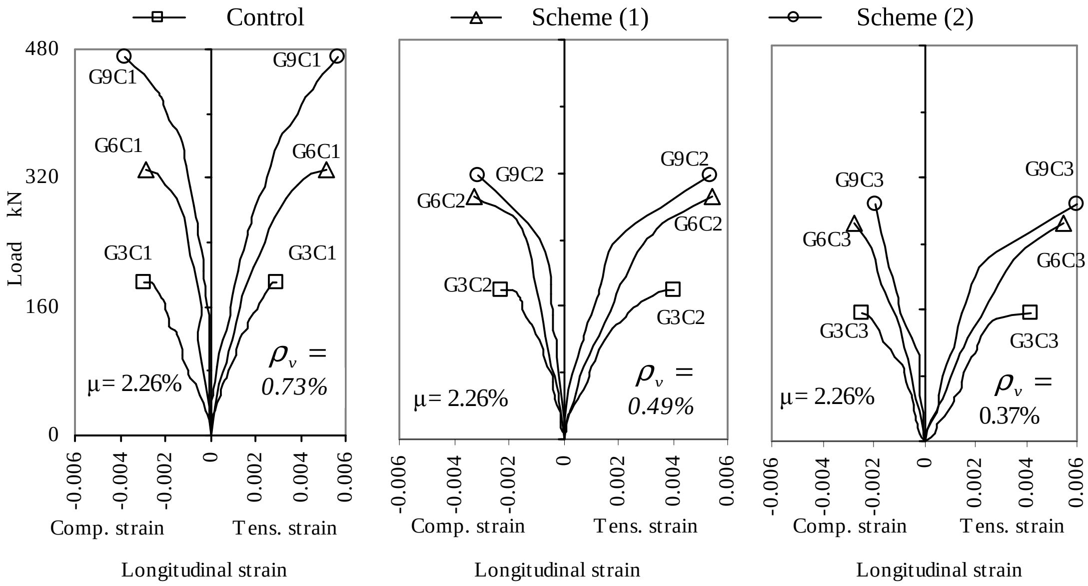


Figure 8. Effect of strengthening scheme on the strain behavior and stiffness for specimens with longitudinal reinforcement ration μ=2.26%

The highest increase in that load was 86% for G9C3 compared with its reference G3C3 and the lowest was 45% higher than its reference specimen G1C2. The enhancement in the tensile ultimate strain was a maximum 91% for G9C3 while the minimal enhancement was 29% for G7C3 compared to their reference specimens. It should be said that specimen G8C3 exhibited 7% lower ultimate strain than its reference G2C3.

### *3.1.3 Effect of strengthening on Failure loads*

Figure 9 shows the ultimate failure load for the different volumetric ratios of internal stirrups.

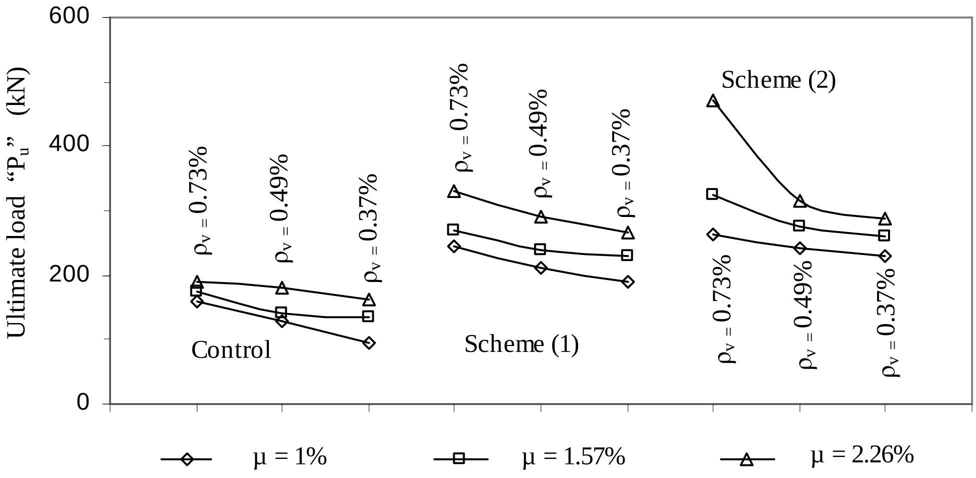


Figure 9. Effect of stirrups volumetric ratio "$\rho_v$" on the ultimate failure loads

It is easily noted that the increase in "$\rho_v$" helped in maintaining higher ultimate load for either the control or strengthened specimens. When μ=1%, control specimens exhibited failure load 158kN when $\rho_v$=0.73% compared with 95kN for specimen with $\rho_v$=0.37%. For slender column specimens strengthened with NSM longitudinal reinforcement (scheme 1), specimens with $\rho_v$=0.73% showed 245kN ultimate load compared with 190 kN for specimens containing internal stirrups with $\rho_v$=0.37%. Strengthening using NSM partially wrapped with CFRP (scheme 2), demonstrated ultimate load of 263kN and 230 kN for $\rho_v$=0.73% and $\rho_v$=0.37%, respectively. The same trend is noticeable for the internal longitudinal reinforcement μ=1.57% or μ=2.26%. It may be concluded that the increase in internal transversal reinforcement ratio "$\rho_v$" increases the ultimate load for slender column specimens whether control or strengthened.

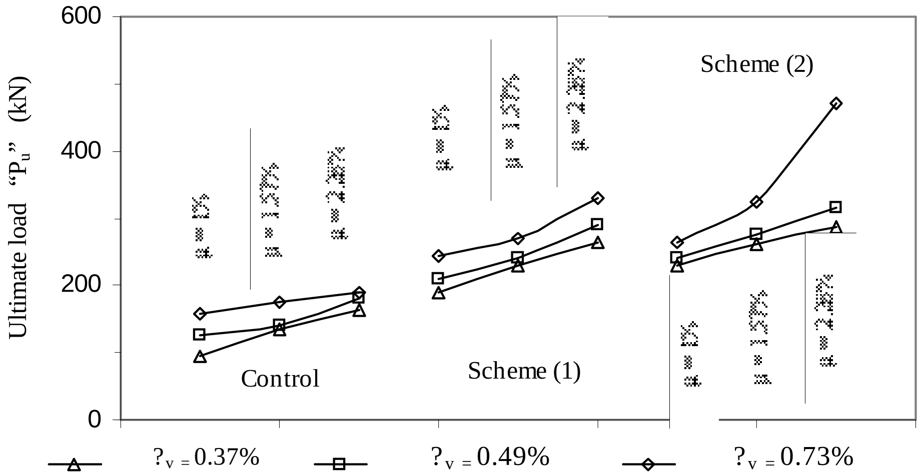


Figure 10. Effect of internal vertical reinforcement on ultimate failure load

Of course, the increase in longitudinal internal reinforcement μ for columns will result in increase in the ultimate load. However, for any ratio of "$\rho_v$", it should be mentioned that, while the maximum increase in ultimate load ranged between 21% and 70% for control columns, it showed between 34% to 39% and 24% to 31% for specimens strengthen with scheme 1 and 2 respectively, it may be said that the increase in μ did not show the same load gain percentage as in reference columns. It is also noted that the use of strengthening scheme 2 showed more efficiency in maintaining higher failure load than strengthening with scheme 1, this is clearly depicted in Figure 10. Investigation of the increase in ultimate load due to strengthening is shown in Figure 11. A summary of the ultimate loads and the ratios of increases are shown in Table 5.

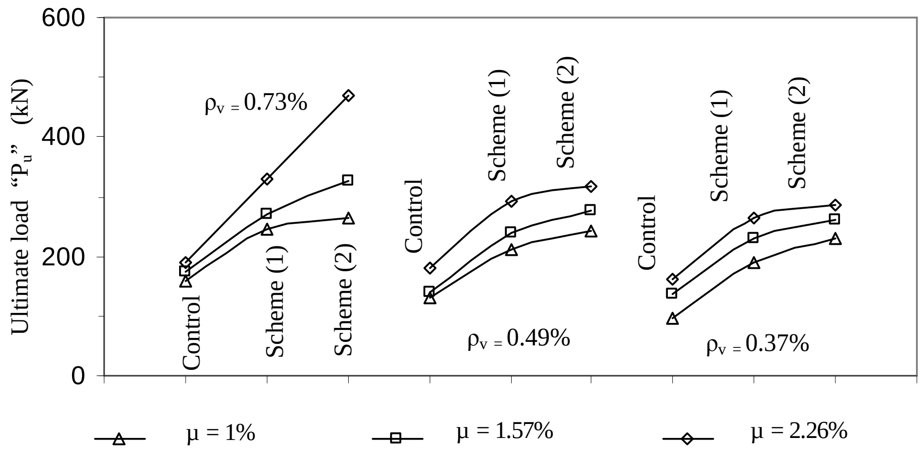


Figure 11. Effect of external strengthening on ultimate failure load

TABLE 5: ULTIMATE LOADS AND THE RATIOS OF INCREASE

| Specimen notation | Transversal reinforcement "$\rho_v$" | Longitudinal reinforcement Ratio "μ" | Ultimate load $P_u$ (kN) | % increase in ultimate load $P_u$ | Specimen configuration |
|---|---|---|---|---|---|
| G1C1 | 0.73% | *μ=1%* | 158 | --- | reference |
| G4C1 | | *μ=1%* | 245 | 55 | Strengthened with (Scheme 1) |
| G7C1 | | *μ=1%* | 263 | 66 | Strengthened with (Scheme 2) |
| G2C1 | | *μ=1.57%* | 174.5 | --- | reference |
| G5C1 | | *μ=1.57%* | 270 | 55 | Strengthened with (Scheme 1) |
| G8C1 | | *μ=1.57%* | 325 | 86 | Strengthened with (Scheme 2) |
| G3C1 | | *μ=2.26%* | 190 | --- | reference |
| G6C1 | | *μ=2.26%* | 330 | 74 | Strengthened with (Scheme 1) |
| G9C1 | | *μ=2.26%* | 470 | 174 | Strengthened with (Scheme 2) |
| G1C2 | 0.49% | *μ=1%* | 130 | --- | reference |
| G4C2 | | *μ=1%* | 210 | 61 | Strengthened with (Scheme 1) |
| G7C2 | | *μ=1%* | 241 | 85 | Strengthened with (Scheme 2) |
| G2C2 | | *μ=1.57%* | 141 | --- | reference |
| G5C2 | | *μ=1.57%* | 240 | 70 | Strengthened with (Scheme 1) |
| G8C2 | | *μ=1.57%* | 277 | 96 | Strengthened with (Scheme 2) |
| G3C2 | | *μ=2.26%* | 180 | --- | reference |
| G6C2 | | *μ=2.26%* | 291 | 62 | Strengthened with (Scheme 1) |
| G9C2 | | *μ=2.26%* | 316 | 75 | Strengthened with (Scheme 2) |
| G1C3 | 0.37% | *μ=1%* | 95 | --- | reference |
| G4C3 | | *μ=1%* | 190 | 100 | Strengthened with (Scheme 1) |
| G7C3 | | *μ=1%* | 230 | 142 | Strengthened with (Scheme 2) |
| G2C3 | | *μ=1.57%* | 135.5 | --- | reference |
| G5C3 | | *μ=1.57%* | 230 | 70 | Strengthened with (Scheme 1) |
| G8C3 | | *μ=1.57%* | 260 | 92 | Strengthened with (Scheme 2) |
| G3C3 | | *μ=2.26%* | 163 | --- | reference |
| G6C3 | | *μ=2.26%* | 265 | 63 | Strengthened with (Scheme 1) |
| G9C3 | | *μ=2.26%* | 287 | 77 | Strengthened with (Scheme 2) |

Form the figure and table it may be said that the strengthening schemes succeeded to increase the ultimate capacity of the slender columns. It should be stated that strengthening with NSM wrapped partially with CFRP (Scheme 2) exhibited higher increase in ultimate load than specimens strengthened with NSM only in scheme 1.

### *3.2 Ductility response*

The modulus of toughness defined as the area under the load-deflection curve is considered in this research to represent the ductility of the tested slender columns. It was always thought that the gain in the ductility of the columns would increase with the addition of horizontal confinement. Although this might be true for partially confined circular slender columns it is not the case for rectangular partially confined eccentrically loaded slender columns.

Figure 12 represents the percentage of the gain in ductility for different column specimens relative to their control one. It is clear that the two strengthening schemes exhibited noticeable gain in ductility compared to the control specimens. It is also clear that the gain in ductility of eccentrically loaded slender columns strengthened with NSM reinforcement (Scheme 1) exhibited higher gain in ductility than slender columns strengthened with NSM reinforcement partially wrapped with CFRP as in scheme 2. The gain in ductility for specimens strengthened with scheme 1 having internal reinforcement ratio μ=1.57% ranged between 125% and 150% for ρv=0.73% and ρv=0.37%, respectively. When μ=1.0% the ductility increase ranged between 140% and 170%. Except specimen G4C2, when μ=2.26% the increase in ductility was almost 165% for either ρv=0.49% and ρv=0.37%. Same trend was noted for specimens strengthened with scheme 2. It may be said that the increase in internal transversal reinforcement "ρv" reduces the gain inductility. Comparing gain in ductility for specimens strengthened with scheme 1 with those with scheme 2 revealed that: when μ=1.0% and 1.57% and ρv=0.73% scheme 1 showed 125% and 140% gain in ductility relative to 115% and 130% for specimens strengthened with scheme 2 respectively. Of course this was not the case when μ=2.26% as specimen G4C2 failed at a very high exceptional load. The same trend may be easily extracted from curves for ρv=0.49% and ρv=0.37%. It could be said that the improvement in ductility of eccentrically loaded slender columns was much higher for columns with Scheme 1 than those with scheme 2.

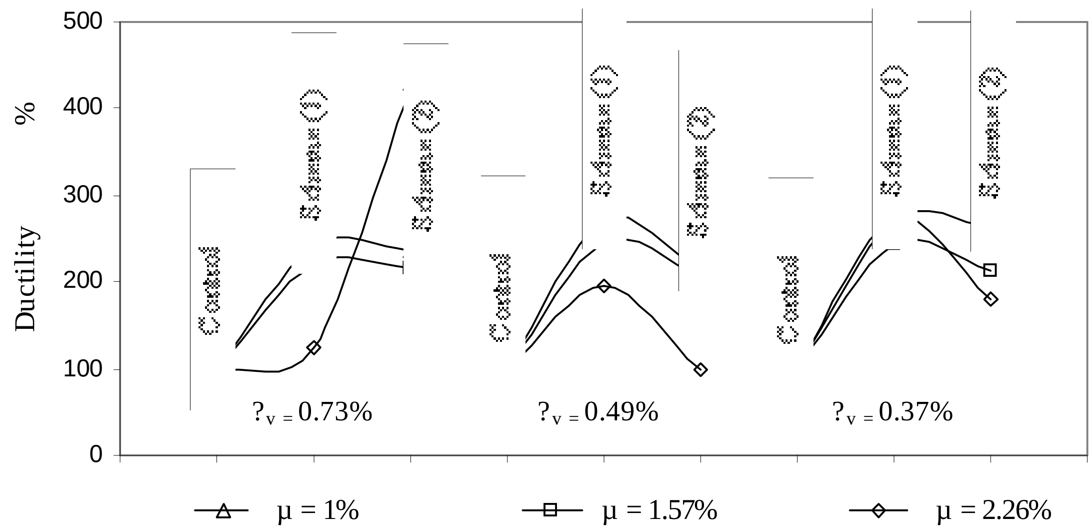


Figure 12. ductility of different specimens

### *3.3 Modes of failure:*

Through the investigation conducted in this research program, three modes of failure were distinguished. The modes of failure observed for the un-strengthened and strengthened slender rectangular columns under the effect of eccentric loading are reported herein.

#### *3.3.1 Failure mode of control specimens*

Figure 13 presents the main characteristics of the modes of failure for the control un-strengthened rectangular slender columns. Generally, the failure was sudden and brittle. There was only one major crack that appeared near mid-height of the specimen near failure. Lateral buckling of specimens was noticeable however it was much higher with the lesser longitudinal reinforcement ratio μ and wider transversal stirrups spacing manifested in lower ρv.

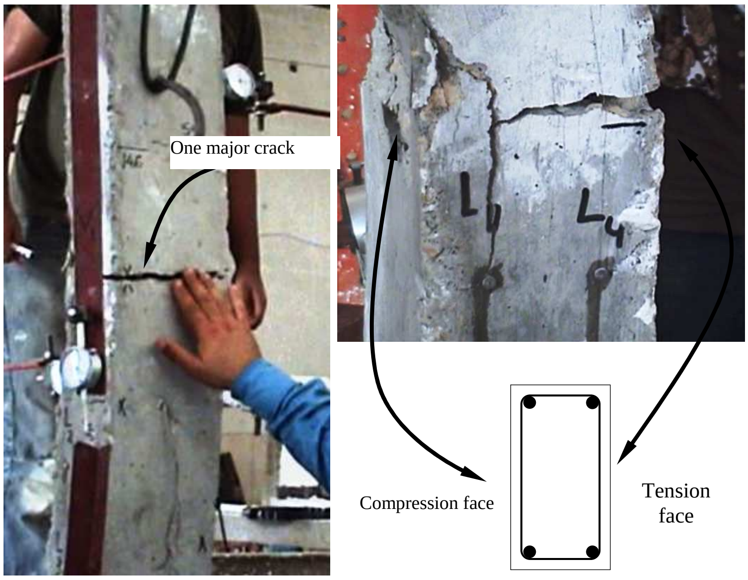


Figure 13. Failure of control un-strengthened slender columns

#### *3.3.2. Failure modes for Strengthened columns*

The strengthening of columns with either NSM longitudinal reinforcement as in scheme 1 or with NSM longitudinal reinforcement partially wrapped with CFRP wraps as in scheme 2 affected the modes of failure of these columns.

Strengthened specimens typically showed a final ductile flexural failure. Several minor cracks appeared in the early stages of loading on the tension side of the cross section. The cracks were noted to get wider with the increase in loading. The final failure was accomplished with crushing of the concrete in the compression side as well as buckling of internal and NSM reinforcement. This mode of failure is shown in Figure 14.

The failure of specimens strengthened with scheme 2 started with the occurrence of transversal fine cracks at mid height of the column. With the higher load level, cracks propagated towards the compression side of the cross section of the column. Clear lateral buckling of all columns of this group was a dominant characteristic. At failure, the longitudinal reinforcement (internal and NSM) buckled and concrete at the compression side of the specimen crushed, wide cracks were noted in tension side and finally crushing of concrete core. Views of this mode of failure are shown in Figure 15.

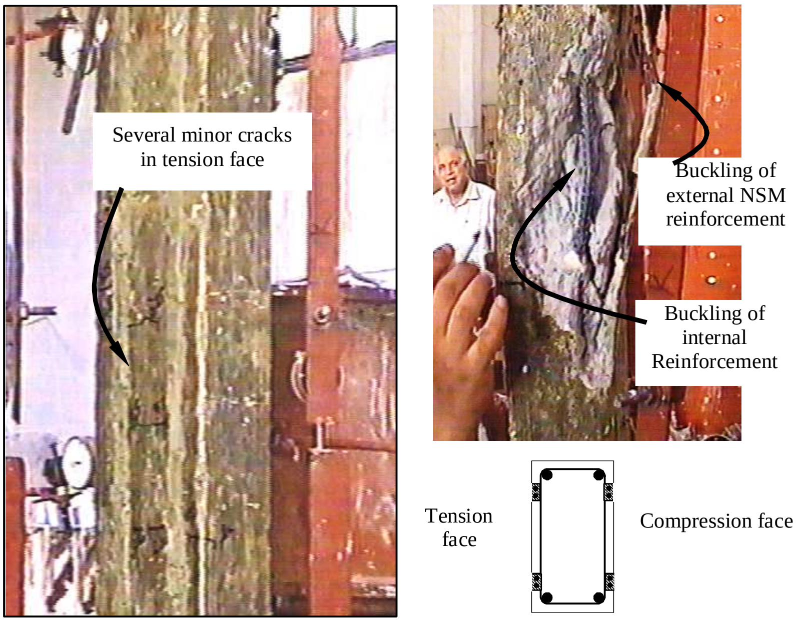


Figure 14. Failure of specimens strengthened with scheme 1

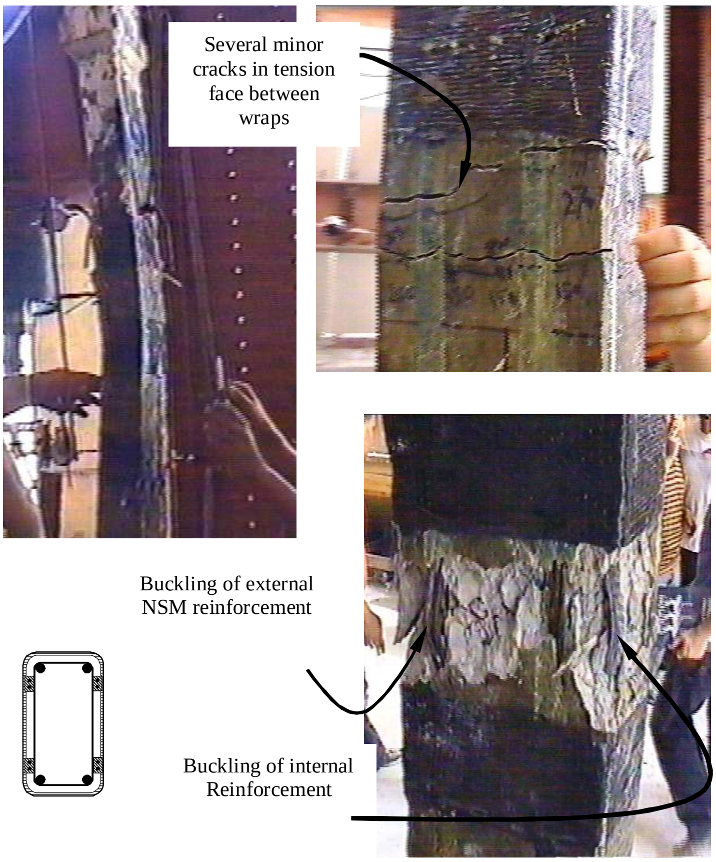


Figure 15. Failure of specimens strengthened with scheme 2

## 4.0 Conclusions

The presented extensive experimental program clarified the feasibility of using NSM techniques for the strengthening of slender columns under eccentric forces. The presented analytical model is promising and considered the ratios of μ and $\rho_v$. Results obtained are summarized as follows:

1. It may be said that the strengthening scheme (2) showed better improvement in load capacity at the same value of lateral buckling than columns strengthened by Scheme (1) for any value of $\rho_v$.
2. Strengthening increased the stiffness of the strengthened column manifested in lower strain values at any load level than the control specimens. It is also depicted that most of the strengthened specimens showed superior ultimate strains relative to those of the control specimens of group
3. The increase in internal stirrups volumetric ratio "$\rho_v$" resulted in higher ultimate load for either control or strengthened specimens. For example, (for the same μ=1%), increasing $\rho_v$ from 0.37% to 0.73%, the failure load for control specimen increased from 95kN to 158kN. However, for specimen strengthened with scheme 1, the load increased from 190kN to 245kN.
4. Increasing the longitudinal internal reinforcement μ for the strengthened columns did not show the same increase in ultimate load as in reference columns. For any ratio of "$\rho_v$", the maximum increase in ultimate load ranged between 21% and 70% for control columns, while it showed between 34% to 39% and 24% to 31% for specimens strengthen with scheme 1 and 2 respectively, it is noted that scheme 2 showed more efficiency in maintaining higher failure load than scheme 1.
5. The strengthening schemes succeeded to increase the ultimate capacity of the slender columns. Strengthening with NSM wrapped partially with CFRP (Scheme 2) exhibited higher increase in ultimate load than specimens strengthened with NSM only in scheme 1.
6. Both strengthening schemes exhibited noticeable gain in ductility compared to the control specimens. For strengthened specimens, the gain in ductility of eccentrically loaded slender columns strengthened with NSM reinforcement (Scheme 1) exhibited higher gain in ductility than slender columns strengthened with NSM reinforcement partially wrapped with CFRP as in scheme 2. It may be concluded that the increase in internal transversal reinforcement "ρv" reduces the gain inductility.

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