Shear Strengthening of T-Section RC Beams Using Double-Side Externally Bonded CFRP

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Abstract. This paper aims at investigating the effect of S-wrap EB-CFRP to shear-strengthen RC T-beams. The experimental program included seven 3.3m-span T-beams that were tested under three-point loading. The specimens were divided into two major groups, including four specimens with no steel stirrups (Group 1), and three specimens with steel stirrups at half of the effective depth (d/2) center to center spacing (Group 2). Five of the seven specimens were strengthened in shear using S-wrap EB-CFRP strips used at d/4 and d/2 spacings. The shear capacity, maximum deflection under the applied load, failure mode, and the strain development in the CFRP strips, steel stirrups, and the main tensile reinforcement were reported in this paper. The overall results show that the addition of EB-CFRP strips to T-beams is an effective method of enhancing the shear capacity of T-Beam in the absence of steel stirrups. With the presence of steel stirrups in the T-beams, the contribution of the EB-CFRP strips in enhancing the beams' shear capacity appears to be small relative to that of steel stirrups.

1. Introduction

Reinforced concrete structures are in danger of deterioration under harsh conditions such as overloading, extreme weather, chemical attacks, and many other factors that will ultimately affect the RC members' structural integrity. Hence, the retrofitting and structural rehabilitation of concrete structures have increasingly become a necessity. One of the widely-used recent technologies in structural enhancements involves the use of externally bonded Fiber Reinforced Polymer (EB-FRP) sheets/strips [1-5]. These technologies have been introduced as alternatives to conventional methods, which come with many limitations, such as being time-consuming, labor-intensive, and costly. The recent technologies, on the other hand, offer significant advantages such as the ease of installation, high durability, high strength to weight ratio, and non-magnetic nature of the FRP [1, 4, 6-9]. The uses of EB-FRP reinforcement may generally be classified as flexural strengthening, shear strengthening, and improving the confinement and ductility of compression members [3, 4, 6, 7]. However, this technique is still relatively new, with limited research that started only less than 25 years ago [3, 5, 8]. This is particularly true for the shear strengthening of T-beams [5], where the presence of the flange in such beams can limit the development of sufficient tensile stress in the EB-FRP to effectively contribute to the shear strength of the member. Moreover, the reported experimental results in the literature showed large scatter when compared to the prediction of the existing design guidelines such as the ACI 440.R2-17.
When strengthening an RC beam in shear, there are various ways in which the EB-FRP systems can be applied. For instance, it can be applied as discrete strips at certain spacing, or as one large continuous band along the member. Moreover, the EB-FRP wrapping scheme could consist of completely wrapping the beam section, using U-shaped wraps, or using double-sided S-wraps, as shown in figure 1.

![Figure 1. EB-FRP shear strengthening schemes: S-wrap, U-wrap, and Fully Wrapped (left to right).](image)

Typical failure modes reported in the literature [9-11] for RC beams, strengthened in shear with EB-FRP, include predominantly FRP de-bonding, which usually occurs for FRP U-wrap and S-wrap schemes. This typically happens at a relatively low level of strain in the FRP due to interfacial bond fracture that happens along the FRP-concrete interface, which significantly limits the retrofitting and strengthening performance of these schemes.

The present research focuses on the shear resistance of FRP-strengthened T-beams as they present the closest representation to the real condition of RC beams in practice. As such, fully wrapping the beam would be impractical, and the member shall be strengthened using either U-wraps or S-wraps. In this paper, S-wraps were chosen considering the faster and friendlier installation procedure of this scheme besides the relatively few available researches compared to U-wraps. The research aims to assess the efficiency of the S-wrap scheme in strengthening the T-beams in shear. The shear capacity, maximum deflection under the applied load, failure mode, and the strain development in the CFRP strips, steel stirrups, and the main tensile reinforcement, are used to assess the said efficiency. Furthermore, the interaction between the existing different types of reinforcement (EB-CFRP strips and the steel stirrups) was being under investigation.

2. Experimental investigation

2.1. Material properties

The concrete used to cast the T-beams was a normal weight Ordinary Portland Cement (OPC) concrete with a compressive strength of 47 MPa according to ASTM C39[12]. The details of the steel reinforcements used in the test specimens were as follows:

- 4 #12 mm rebars for the beam flange
- 4 #25 mm rebars for the beam web
- 8 mm rebar for the stirrups

The properties of the reinforcement steel rebars are shown in table 1. Externally-bonded carbon fiber reinforced polymer (EB-CFRP) composites with properties summarized in table 2 are used to strengthen the specimens and were installed according to ACI 440.R2-17 guidelines [13].

| Bar Diameter | Yield Strength | Yield Strain \( \mu \varepsilon \) |
|--------------|----------------|---------------------------------|
| mm           | MPa            |                                 |
| 8            | 592            | 2960                            |
| 12           | 575.4          | 2877                            |
| 25           | 558.6          | 2793                            |

*Yield strain computed considering a modulus of elasticity (\( E_s \)) of 200,000 MPa for all bars.*
2.2. Test specimens and configuration

The experimental program in the present research included a total of 7 full-scale T- beams that were designed to fail in shear. All beams have similar geometrical properties and longitudinal main reinforcing rebars ($\rho_s = 0.0385$). The geometric details for the beam section were as follows:

- effective span length ($L_e$): 3300 mm
- effective depth ($d$): 340 mm
- shear span to effective depth ratio ($a/d$): 3.2

Further other details are shown in figure 2.

| Properties                  | Unit    | Grade |
|-----------------------------|---------|-------|
| Fiber Weight                | g/cm³   | 300   |
| Fiber Density               | g/cm³   | 1.8   |
| Fiber Thickness             | mm/ply  | 0.168 |
| Tensile Strength of CFRP    | MPa     | 4,000 |
| Fiber Elasticity Modulus    | MPa     | 230,000 |
| Rupture Strain              | $\mu \varepsilon$ | 17,391 |

Table 2. CFRP properties.

To investigate the effect of different variables on the shear behavior of the beams, the specimens were categorized into two main groups, as shown in table 3 and table 4. In these tables, the specimens are named in a way to indicate whether or not they incorporate steel stirrups, EB-CFRP, and the spacing of the steel stirrups and/or EB-CFRP strips. Specimens that are duplicates of other specimens have the letter "D" at the end. As shown in the previous tables, the S-wrap EB-CFRP strips were spaced at 90 mm and 170 mm, these values of spacing have been selected as a quarter and half of the specimens’ effective depth ($d = 340$ mm) following the same spacing which was followed in the steel stirrups along the beams of Group 2 (i.e. at 170 mm), in this manner, it will be easier to understand the targeted interaction between the steel stirrups and EB-CFRP strips.

2.2.1. Group 1. Specimens in this group have no steel stirrups and consist of 4 beams labeled as follows:

- **a)** NS-0FC is a control beam without EB-CFRP
- **b)** NS-1F90 is a strengthened beam that incorporates a single layer of EB-CFRP spaced at 90 mm center to center (c/c)
- **c)** NS-1F90D is a duplicate of specimen NS-1F90
- **d)** NS-1F170 is a strengthened beam that incorporates a single layer of EB-CFRP spaced at 170 mm (c/c)
2.2.2. **Group 2.** Specimens in this group have steel stirrups that are spaced at 170 mm (c/c) and consist of 3 beams labeled as follows:

a) S170-0FC is a control beam without EB-CFRP

b) S170-1F170 is a strengthened beam that incorporates a single layer of EB-CFRP spaced at 170 mm (c/c)

c) S170-1F170D is a duplicate of specimen S170-1F170

### Table 3. Specimen reinforcement details.

| Beam Name   | $\rho_v$ | $d_f$ (mm) | $t_{frp}$ (mm) | $w_{frp}$ (mm) | $S_{frp}$ (mm) | $\rho_f$ |
|-------------|----------|------------|----------------|----------------|----------------|----------|
| NS-0FC      | 0        | 0          | 0              | 0              | 0              | 0        |
| NS-1F90     | 0        | 240        | 0.166          | 50             | 90             | 0.0012   |
| NS-1F90D    | 0        | 240        | 0.166          | 50             | 90             | 0.0012   |
| NS-2F90D    | 0        | 240        | 0.332          | 50             | 90             | 0.0025   |
| NS-1F170    | 0        | 240        | 0.166          | 50             | 170            | 0.0007   |
| S170-0FC    | 0.0039   | 0          | 0              | 0              | 0              | 0        |
| S170-1F170  | 0.0039   | 240        | 0.166          | 50             | 170            | 0.0007   |
| S170-1F170D | 0.0039   | 240        | 0.166          | 50             | 170            | 0.0007   |
| S170-1F170D ON | 0.0039 | 240        | 0.166          | 50             | 170            | 0.0007   |

### Table 4. Test variables under study.

| Beam Name            | variables under study                                      |
|----------------------|-----------------------------------------------------------|
| NS-0FC               | • Effect of adding one / two layer of FRP strips at 90 mm on shear behavior |
| NS-1F90              |                                                          |
| NS-1F90D             | • Effect of FRP strips spacing on shear behavior           |
| NS-1F170             |                                                          |
| S170-0FC             | • Effect of adding one layer of FRP strips at 170 mm on shear behavior |
| S170-1F170           |                                                          |
| S170-1F170D          |                                                          |

2.3. **Test setup and instrumentation**

Testing of the beam specimens was conducted under displacement control using a three-point loading configuration. The load was applied gradually at a rate of 0.60 mm/minute until beam failure using a 500 kN capacity actuator. The displacement of the beam at three points, including the loading point, was measured using three linear variable differential transducers (LVDTs), as shown in figure 3.

3. **Results and discussion**

3.1. **Failure modes**

When loaded, the maximum shear in the beam is expected to develop in the short shear span, which is the subject area of our investigation. As such, most of the shear cracks will develop in this area. For all beams in Group 1, sudden brittle failure was observed. The failure was associated with the development of a major diagonal crack extending from the loading point at the flange and passing...
through the entire web. This crack was the main reason for the debonding of all EB-CFRP strips. It is worth mentioning that specimen NS-1F90D had an additional crack that started from the loading point and continued horizontally through the flange, although it did not affect the shear capacity of this beam compared to its duplicate counterpart NS-1F90. The failure patterns for all specimens of Group 1 are shown in figure 4.

On the other hand, the failure mechanism of strengthened beams in Group 2 was predominantly ductile with the gradual development of shear cracks as well as the debonding of the EB-CFRP strips. Final failure was accompanied by the development of a nearly-horizontal crack in the flange that started from the loading point and extended beyond the center of the short shear span, in addition to one major diagonal crack, as shown in figure 5. Visually, the beam curvature and the cracking patterns gave sufficient warning about the onset of failure of the beams.

In general, the failure of the EB-CFRP system was by partial debonding, indicating that the EB-CFRP system was not fully utilized up to its maximum capacity. Strain measurements in the CFRP showed that failure took place at CFRP strains well below the CFRP rupture strains shown in table 2.

3.2. Load deflection curves

The load-deflection curves of the control and strengthened beams are plotted in figure 6 and figure 7 for Group 1 and 2, respectively. As shown in these figures, the strengthened beams in both groups exhibited an increase in their shear capacities, which was associated with a reduction in the maximum deflection values. For Group 1 beams, one can easily observe from the load-deflection curves the sudden brittle failure. It is worth noting as well that specimen NS-1F90 and its duplicate counterpart (NS-1F90D) showed almost the same load-deflection response. For both specimens, the use of one layer of EB-CFRP increased the beam's shear strength by 41% and reduced its maximum deflection by about 20%, as shown in table 5. For specimen NS-1F170, where the spacing of the EB-CFRP strips was increased from 90 mm to 170 mm, the beam's shear strength increased by only 21%, and its maximum deflection reduced by 17% relative to the control.

For Group 2 beams, which incorporated steel stirrups at 170 mm spacing, the load-deflection responses showed increased ductility in comparison to those of Group 1 specimens. For the former beams (Group 2), the use of one layer of EB-CFRP increased the beam's shear strength by only 9% and reduced its maximum deflection by about 18%. It is worth noting here for specimen S170-1F170(D) that the reduction in the maximum deflection was 34% relative to the control due to
premature concrete crashing at the loading point. This result was not considered to be reliable to compute an average reduction in maximum deflection for Group 2 beams. The above results demonstrate that the use of EB-CFRP in the shear strengthening of T-beams is more effective in the absence of steel stirrups. These results are consistent with findings reported in the literature [14].

![Figure 4. Group 1 beams after failure.](image)

![Figure 5. Group 2 beams after failure.](image)

![Figure 6. Load-deflection curves of group 1 beams (without steel stirrups).](image)

![Figure 7. Load-deflection curves of group 2 beams (with steel stirrups).](image)

3.3. Strain response

In an attempt to reach a comprehensive understanding of the interaction between the different types of reinforcement in the T-beams, including the EB-CFRP strips, the steel stirrups, and the main tensile
steel rebars, strain gauges were installed in various locations along the short shear span in each type of reinforcement, and the strain measurements were recorded.

Table 5. Summary of load-deflection test results.

| Beam Name | Max Load (KN) | Load Ratio [LR] | Deflection at Max load (mm) | Deflection Ratio [DR] |
|-----------|--------------|----------------|-----------------------------|-----------------------|
| Group 1   |              |                |                             |                       |
| NS-0FC    | 164.31       | 1.00           | 15.52                       | 1.00                  |
| NS-1F90   | 231.11       | 1.41           | 12.32                       | 0.79                  |
| NS-1F90D  | 231.21       | 1.41           | 12.66                       | 0.82                  |
| NS-1F170  | 198.59       | 1.21           | 12.83                       | 0.83                  |
| Group 2   |              |                |                             |                       |
| S170-0FC  | 389.26       | 1.00           | 42.98                       | 1.00                  |
| S170-1F170| 421.36       | 1.08           | 35.27                       | 0.82                  |
| S170-1F170D| 428.08      | 1.10           | 28.25                       | 0.66                  |

For the EB-CFRP strips, strain gauges were numbered as “FRP1” for the strip that lies directly under the applied load, and the number increased until reaching the nearest support, as shown earlier in figure 4 and figure 5. The same procedure was also followed for numbering the strain gauges in the steel stirrups for specimens in Group 2. The maximum measured strain values of all CFRP strips and steel stirrups are shown in table 6, where the strain gauge, which recorded the highest strain for a given specimen, is written between brackets while the missing values during testing are shown in the table as "missing".

For the main tensile steel rebars, only one strain gauge was attached on the reinforcement Rebars. The maximum measured strains in the main tensile steel ranged from about 900 to 1200 με among the 4 specimens in Group 1, as shown in table 7 and figure 8. Although the use of EB-CFRP strips has contributed to shear strength enhancements of the T-beams, it did not quite shift the failure mode from shear to flexure, which would have been associated with yielding of the main tensile steel. Furthermore, the maximum measured strains in the EB-CFRP strips ranged from 3700 to 5100 με among the 3 strengthened specimens, as can be seen from table 7 and figure 9.

On the other hand, there was clear yielding of the main tensile steel in Group 2 specimens, which incorporated steel stirrups. The maximum measured strains in the main tensile steel ranged from about 3800 to 4700 με among the 3 specimens, as shown in table 7 and figure 8. Strain measurements in the steel stirrups indicate that the latter had also yielded with maximum stirrup strains ranging between 5800 to 7600 με among the 3 specimens, as shown in table 7 and figure 10. As for strain measurements in the EB-CFRP strips, they ranged from 2500 to 5800 με among the two strengthened specimens, as shown in table 7 and figure 9.

3.4. Comparison of test results with ACI440.2R-17 guidelines

In this section, the contribution of the EB-CFRP (V_f) to the total beam shear strength is calculated from both the experimental results and the ACI440.2R-17 guidelines [13]. From the experimental results, V_f was computed as the difference in shear capacity between the strengthened beams and their control counterparts. For each beam, the shear capacity was computed based on the ultimate load of the beams. The calculated values of V_f from ACI440.2R-17 guidelines did not incorporate any environmental or material strength reduction factors. For each beam, two V_f values were calculated, one based on effective CFRP strain ε_{ef} from the guidelines (Method 1) and another based on experimentally measured ε_{ef} (Method 2) as shown in table 8. A comparison between the experimentally-measured and the predicted V_f values are shown in table 8 for each specimen. Results for duplicate beams are shown in this table as average values.

The results in table 9 indicate that the ACI440.2R-17 guidelines underestimate the EB-CFRP contribution (V_f) to the beam shear strength by about 15 to 20% (Method 1). This seems to be due to the underestimated effective CFRP strain (3565 με) by the guidelines in comparison to the experimentally-measured values. When the latter is used in computing V_f using the guidelines
equations, a nearly-perfect match is observed between the experimentally-measured and the predicted $V_f$ values (Method 2). It is also interesting to note that the experimentally-measured CFRP strain at failure was slightly above the maximum limit (4000 µε) allowed by the ACI440.2R-17 guidelines to guard against the loss of aggregate interlock at failure.

The above comparison provides further evidence for the effectiveness of the S-wrap scheme in the shear strengthening of T-beams. The presence of the flange did not seem to negatively affect the capacity of the EB-CFRP strip to develop the necessary tensile strain to contribute to the shear strength of the T-beam.

4. Summary and conclusions

This paper focused on studying the effect of using double-sided (S-wrap) EB-CFRP in the shear strengthening of RC T-beams. Two variables were taken into consideration in the study: the effect of adding one layer of EB-CFRP strips with and without the presence of steel stirrups, and the effect of spacing of the EB-CFRP strips. The experimental program consisted of two groups of specimens, which included seven T-Beams. Two of the specimens were used as control, and five were strengthened with one layer of EB-CFRP. Four of the specimens did not incorporate any steel stirrups (Group 1), and three of the specimens included steel stirrups spaced at d/2 (c/c) (Group 2). The following is a summary of the main findings from the study:

• In the absence of steel stirrups, the addition of one layer of EB-CFRP strips spaced at 90 mm (c/c) resulted in a 41% increase in the shear strength of the T-beams relative to the control. However, this strength increase was associated with about 20% reduction in the deflection capacity. Furthermore, the strength increase was not sufficient to shift the failure mode from shear to flexure. The strengthened specimens failed in a brittle manner without prior warning of impending failure. Strain measurements revealed no yielding of the main tensile reinforcement at failure. By increasing the EB-CFRP strips spacing from 90 mm to 170 mm (c/c), the achieved strength increase was only 21% relative to the control specimen. This strengthening increase was associated with about 17% reduction in maximum deflection.

• In the presence of steel stirrups, the use of EB-CFRP has resulted in about a 9% increase in the beam shear capacity and an 18% decrease in the beams’ maximum deflection. The load-displacement response of the specimens showed noticeable ductility in comparison to specimens without steel stirrups. Both the steel stirrups and the main tensile steel showed yielding prior to failure. The latter occurred progressively with an increasing number of shear cracks forming in the web and gradual debonding of the EB-CFRP as the specimen approached the onset of failure.

• According to the above mentioned findings, there was a clear interaction between the steel stirrups and the EB-CFRP strips, as the existence of the steel stirrups spaced at a distance equal to d/2 has inhibited the efficiency of EB-CFRP strips, as they made only a 10% gain in shear strength compared to 41% without the presence of the steel stirrups.

• The predominant mode of failure for all strengthened specimens was debonding of the EB-CFRP strips, triggered by diagonal shear cracks. Final failure was associated with the development of a major diagonal crack extending from the loading point at the flange and passing through the entire web. In some specimens, a nearly-horizontal crack starting from the loading point and extending past the center of the short shear span had also progressively formed together with the diagonal shear cracks.

• The strain measurements in the EB-CFRP strips indicated the effectiveness of the S-wrap scheme in contributing to the shear strength of the T-beams. The presence of the flange did not seem to negatively affect the required development length for the EB-CFRP to effectively contribute to the shear strength of the member. Most of the EB-CFRP strips recorded tensile strains at failure that were greater than the maximum limit (4000 µε) allowed by published design guidelines (e.g., ACI 440.2R-17) to guard against the loss of aggregate interlock at failure.

• A comparison between the measured shear strength enhancements ($V_f$) and those computed as per ACI440.2R-17 guidelines indicated that the latter underestimated the contribution of EB-CFRP to the beam’s shear strength by about 15 to 20% among the tested specimens. When the experimentally-measured maximum strain values in the EB-CFRP are used in the ACI440.2R-17 guidelines equation
for \( V_i \), a nearly-perfect match is observed between the experimentally-measured and the predicted strength enhancements.

**Table 6.** Maximum recorded strain values in CFRP strips and steel stirrups (in \( \mu \varepsilon \)).

| Group 1 | Beam Name | NS-0FC | NS-1F90 | NS-1F90D | NS-1F170 |
|---------|-----------|--------|---------|----------|----------|
| FRP 1   | -         | 416    | 406     | 3063     |
| FRP 2   | -         | 652    | 112     | [4288]   |
| FRP 3   | -         | 1638   | 1033    | 4201     |
| FRP 4   | -         | missing| 2612    | 4269     |
| FRP 5   | -         | 4369   | 3681    | 3800     |
| FRP 6   | -         | [5101] | 3364    | 1951     |
| FRP 7   | -         | 2730   | [3703]  | -        |
| FRP 8   | -         | 2028   | 3162    | -        |
| FRP 9   | -         | 2114   | 3021    | -        |
| FRP 10  | -         | -31    | 1661    | -        |
| FRP 11  | -         | 617    | 80      | -        |
| FRP 12  | -         | missing| 50      | -        |

| Group 2 | Beam Name | S170-0FC | S170-1F170 | S170-1F170D |
|---------|-----------|----------|------------|-------------|
| Stirrup 1 | [7485] | 5618    | [7651]    |
| Stirrup 2 | 3329  | 1641    | 3751      |
| Stirrup 3 | 2609  | [5807]  | 1148      |
| Stirrup 4 | missing | 3154    | 5051      |
| Stirrup 5 | missing | 2640    | 3035      |
| Stirrup 6 | missing | 2490    | 3339      |
| FRP 1   | -       | 1620    | 1080      |
| FRP 2   | -       | 1423    | 2460      |
| FRP 3   | -       | 913     | 2967      |
| FRP 4   | -       | 2107    | 2384      |
| FRP 5   | -       | 1823    | [5760]    |
| FRP 6   | -       | [2581]  | 4102      |
Table 7. Summary of recorded maximum strains in EB-CFRP, steel stirrups, and main tensile steel (in με).

| Beam Name   | Max. FRP strain | Max. Stirrup strain | Max. longitudinal reinforcement strain |
|-------------|-----------------|---------------------|----------------------------------------|
| Group 1     |                 |                     |                                        |
| NS-0FC      | -               | N/A                 | 1022                                   |
| NS-1F90     | 5101            | N/A                 | 908                                    |
| NS-1F90D    | 3703            | N/A                 | 1219                                   |
| NS-1F170    | 4288            | N/A                 | 1152                                   |
| Group 2     |                 |                     |                                        |
| S170-0FC    | -               | 7485                | 3944                                   |
| S170-1F170  | 2581            | 5807                | 3853                                   |
| S170-1F170D | 5760            | 7651                | 4721                                   |

Figure 8. Applied load versus strain in tensile rebars.

Figure 9. Applied load versus strain in CFRP strips with highest recorded strain.

Figure 10. Applied load versus strain in steel stirrup with highest recorded strain.
Table 8. Strain values in CFRP from the ACI440.2R-17 guidelines and based on experimentally measured.

| Specimen       | Effective CFRP strains as per ACI 440 (µε) | Average CFRP strains from experiment (µε) |
|----------------|-------------------------------------------|------------------------------------------|
| NS-1F90/90D    | 3564.50                                   | 4402.00                                  |
| NS-1F170       | 3564.50                                   | 4288.00                                  |
| S170-1F170/170D| 3564.50                                   | 4171.00                                  |

Table 9. Summary of recorded maximum strains in EB-CFRP, steel stirrups, and main tensile steel (in µε).

| Specimen       | Contribution of EB-CFRP to Shear Strength: V_f (KN) | Method 1: V_f^{ACI}/V_f^{Exp} | Method 2: V_f^{ACI}/V_f^{Exp} |
|----------------|-----------------------------------------------------|------------------------------|------------------------------|
|                | Experimental Results | Method 1: using the effective CFRP strain as per ACI440 | Method 2: using average FRP strains from experiment |
| NS-1F90/90D    | 45.60 | 36.70 | 45.40 | 0.80 | 1.00 |
| NS-1F170       | 22.80 | 19.40 | 23.40 | 0.85 | 1.03 |
| S170-1F170/170D| 23.40 | 19.40 | 22.80 | 0.83 | 0.97 |

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Acknowledgment

This work was partially supported by the University of Sharjah under grant number 18020401100-P and by the Sustainable Construction Materials and Structural Systems (SCMASS) research group. Supports received from M/s FAST BUILDING CONT. CO., and CONMIX LTD during the experimental program are gratefully acknowledged and appreciated.