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Effects of trapezoidal cross-section dimensions on the behaviours of CFRP SCC beams

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Abstract. This study investigates the behaviour of trapezoidal cross-sections self-compacting reinforced concrete beams under flexural failure, with and without strengthening with carbon fibre reinforced polymer CFRP. The studied beams were divided into two groups according to their cross-sections; each group included five beams. and the first group (T50) were those with trapezoidal cross-sections with dimensions length 1,600 × height 260 × width of 160 mm at the bottom and 200 mm at the top, while second group (T30) consisted of those with trapezoidal cross-sections with dimensions length 1,600 × height 260 × width of 160 mm at the bottom and 240 mm at the top. The experimental programme included studying the effects of top width on the flexural behaviour of beams with trapezoidal cross-sections, in addition to studying the effect of reinforcing those beams with varying numbers, locations, and methods of placement of CFRP strips. The experimental results showed that trapezoidal cross-sections with 240 mm top width gave higher ultimate load capacity by 4 to 11.54%, as well as offering lower deflection, compared to trapezoidal cross-sections with 200 mm top width. In addition, strengthening beams with CFRP strips leads to an increase in the ultimate load capacity by 4 to 24% in trapezoidal cross-section beams, reducing their deflection and delaying the appearance of the first crack in the concrete. It was found that applying CFRP strips to the maximum moment region increased the ultimate load capacity by an average of 4.17 to 7.7 % in comparison to beams strengthened with strips applied along the beam.

Key words: Self-compacting reinforced concrete, flexural failure, trapezoidal cross-sections, carbon fibre reinforced polymer, simply supported span, two-point load.

1. Introduction

Self-compacting concrete (SCC) mixes fill formwork with full compacting without any need for vibration under their own weight, even in narrow places such as congested steel reinforcement. Generally, SCC is made from common materials, as used in normal concrete, with a higher ratio of powder material and a low water/powder ratio achieved by using super-plasticizer. [1] Beams are used as links in the transfer of loads from slabs to columns or walls, and as such, there are several types of cross-sections of beams to meet their required functions, taking into account the requirements of construction and architecture. The most common cross-sections are rectangular and T-section, but other cross-sections can be used, such as trapezoidal, tapered, and haunch beams. The concept of reinforced beams resisting loads is that they resist compressive stress by using a concrete compression zone and the steel bars carry tension stress in the tension zone. [2] Concrete structural elements may require strengthening for several reasons, including the aging of a building, the emergence of cracks, changes in the function of building which may lead to increased service loads, or the occurrence of mistakes in the initial implementation of casting and construction. In certain situations, it may be not possible to replace existing elements that do not satisfy structural requirements with new ones; in particular, replacing an element may not be economically feasible. The problem faced by structural engineers thus becomes the need to find new methods to strengthen the structural elements to resist increments in service load without exceeding their limits of deflection. [3]
There are several different methods used to strengthen reinforcement concrete elements. One of the most important of these methods is using fibre reinforced polymer (FRP) materials to upgrade those elements. [4]

In this study, the beams were strengthened with carbon fibre reinforced polymer (CFRP) strips to help them resist flexural failure, taking ultimate load capacity and deflection as priority goals.

2. Experimental programme
The experimental programme included constructing and testing ten beams with trapezoidal cross-sections. SCC designed with an $f'_c$ of 35 MPa was used for casting the beams. All beams were tested as simply supported beams with symmetrical two-point loading.

Depending on the top width of their cross-sections, the beams were divided into two groups: $T_{20}$ and $T_{24}$. All beams had trapezoidal cross-sections with dimensions of length $\ell=1,600$ mm × height $h=260$ mm × width in the bottom $b=160$ mm; width in the top $b'=200$ mm in group $T_{20}$, while $b'=240$ mm in group $T_{24}$. The beams were designed to fail in flexure mode. Figures (1) and (2) show the details of the reinforcement consisting of two deformed steel bars of 10 mm diameter placed in the bottom as longitudinal tensile reinforcement and two deformed steel bars with 6 mm diameter placed in the top as longitudinal compressive reinforcement. In addition, deformed steel bars with 6 mm diameter were used as shear reinforcement, placed at 100 mm centre to centre.

![Figure (1): Longitudinal section of specimens (all dimensions in mm).](image1)

![Figure (2): Cross-sections of specimens (all dimensions in mm).](image2)
3. Strengthening scheme and details

According to the top width of their cross-section shape, the samples were divided into two groups, T20 and group T24, with each group including five beams. Each group had a control beam without any strengthening, and four beams strengthened using a differing number and location plan of CFRP strips. All strips had a width of 40 mm and were placed on the base of their respective beams and bonded onto the concrete using sikadur-330 [5], which is a "two-part solvent free thixotropic epoxy based impregnating resin/adhesive". To prevent de-bonding between the longitudinal CFRP strips and the concrete, a U-shape of CFRP strips with 40 mm width was used at end of each CFRP longitudinal strip and bonded to the concrete using epoxy. The number of strips and spacing between them were designed according to ACI 440.2R-08 [6]. Generally, two methods were used to strengthen all beams in this study:

First method: beams were strengthened by CFRP strips placed along the beam.
Second method: beams were strengthened with CFRP strips placed on the maximum and high moment regions of the beam.

All details of strengthening for all beams are shown in Table (1) and Figure (3).

| Beam Symbol | No of strips | Width of strips (mm) | Length of strips (mm) | Thickness of strips (mm) | Spacing between strips (mm) | Width of U-shape strips (mm) |
|-------------|--------------|----------------------|-----------------------|--------------------------|----------------------------|-----------------------------|
| T20-0, T24-0 | -            | -                    | -                     | -                        | -                          | -                           |
| T20-1, T24-1 | 1            | 40                   | 1400                  | 0.166                    | -                          | -                           |
| T20-2, T24-2 | 2            | 40                   | 1400                  | 0.166                    | 30                         | 40                          |
| T20-3, T24-3 | 3            | 40                   | 933                   | 0.166                    | 10                         | 40                          |
| T20-4, T24-4 | 2            | 40                   | 700                   | 0.166                    | 30                         | 40                          |

4. CONCRETE MIX DESIGN

The concrete mixture was chosen after many trials to satisfy the fresh properties requirements of EFNARC [7] for SCC and to achieve the required compressive strength of 35 MPa at 28 days age. The proportions are shown in Table (2).

| Cement (kg/m³) | Limestone powder (kg/m³) | Water (kg/m³) | W/P ratio By weight | Corse aggregate (kg/m³) | Fine aggregate (kg/m³) | Super plasticizer (L/m³) |
|----------------|--------------------------|---------------|---------------------|-------------------------|------------------------|-------------------------|
| 350            | 175                      | 180           | 0.34                | 767                     | 797                    | 4.9 a                   |

a (1.4 Litre)/(100 kg cement)

5. Hardened properties of SCC

Table (3) shows the results of the hardened properties of the chosen SCC mix used in this research, according to ASTM C39 [8], C496 [9], C469 [10], and C78 [11] for compressive strength, splitting tensile strength, static modulus of elasticity, and flexural strength, respectively.

| Age | Compressive strength fc' (MPa) | Splitting tensile strength fct (MPa) | Static modulus of elasticity Ec (GPa) | Flexural strength fr (MPa) |
|-----|--------------------------------|-------------------------------------|--------------------------------------|---------------------------|
| 7 days | 24.62                         | 2.75                                | -                                    | 3.78                      |
| 28 days | 34.23                         | 3.54                                | 26.73                                | 4.35                      |
| 56 days | 38.74                         | -                                   | 28.14                                | -                         |
a) Control beams (T_{20}-0, T_{24}-0)

b) Beams strengthened with one strip (T_{20}-1, T_{24}-1)

c) Beams strengthened with two strips (T_{20}-2, T_{24}-2)

d) Beams strengthened with three strips (T_{20}-3, T_{24}-3)

e) Beams strengthened with two opposing strips (T_{20,-4}, T_{24,-4})

**Figure (3):** Bottom view of beams with strengthening details (x=20 for group T_{20}, while x=40 for group T_{24}; all dimensions in mm.)
6. Testing procedure
In order to prepare the beams for testing, several steps were taken before the first day of testing. These steps included cleaning each beam and painting the surface of the specimen white except for the CFRP strips, in order to help observers recognise the location and direction of the first cracks and to sketch crack patterns during the test. Each beam was left for a full day to dry. A compression testing machine, the AVERY, with a capacity of 150 tons was used to test all beams at age 56 days. Before performing the test, several further steps were taken. These steps included marking the beams with obvious labels that highlighted the location of supports and loading, as well as locating two scaling dial gauges under the beam, touching the bottom surface. One of these dial gauges was placed at mid span and the other placed under one of load locations. The beams were tested as simply supported, with two concentrated loads applied at 550 mm from edges of the beam. Initially, a small load of about 5 kN was applied then released to seat the support and the loading system, as well as to make sure that the dial gauge touched the bottom face of the beam. After that, regular incremental loading of 5 kN was applied. The deflection was recorded for each stage of loading.

7. Experimental results
During the testing of each beam, the first crack was observed and marked in pen; its propagation was followed, then other crack patterns were sketched and the load for major cracks written on in tons. Most cracks that appeared during the test were flexural cracks, as all tested beams were designed to fail by flexure.

7.1. Behaviours and strength of beams in group T20
This group contained five beams of trapezoidal cross-section with dimensions of length 1,600 × height 260 × width 160 mm in the bottom and 200 mm in the top. One of these beams was without any strengthening CFRP to act as a control beam, while other four beams were strengthened by different numbers and locations of CFRP strips. Details of this strengthening were mentioned in Table (1) and Figure (3). Tables (4) and (5) list the test results for this group, and Figure (4) shows the failure modes of the beams. In the control beam, T20-0, when the applied load was increased, it was observed that some small flexural cracks appeared along the beam in the tension area at the bottom of the beam, and the first crack occurred in the middle of the beam. As the load increased, the quantity of cracks increased and they became wider and began to propagate up to the compression zone at the top of beam until failure occurred. In beams T20-1 and T20-2, the first cracks occurred in the middle of the beams, and small flexure cracks appeared along the beams in the tension areas at the bottom of the beams before propagating up to the compression area at the top of beam until the strengthening strips broke up at the middle of the beam where maximum moment was present; failure occurred after that point. In beams T20-3 and T20-4, the first cracks and small flexure cracks appeared in the edge of the CFRP strips in the tension area at the bottom of the beam, perhaps due to the CFRP strips making the middle region of the beam stronger in terms of resisting the maximum moment, causing the region adjacent to the CFRP strips to become weaker. Therefore, the cracks propagated in this region up to the compression area at the top of the beam, where the strips remained without breaking off; failure occurred through the peeling up of the cover of the concrete in the region adjacent to the CFRP strips.

| Beam  | Pcr (kN) | Δε20'centre (mm) | Δε20'(under load) (mm) | Pu (kN) | Δu20'centre (mm) | Δu20'(under load) (mm) |
|-------|----------|------------------|----------------------|--------|-----------------|-----------------------|
| T20-0 | 50       | 2.33             | 1.97                 | 115    | 11.15           | 8.54                  |
| T20-1 | 55       | 2.51             | 2.29                 | 120    | 10.63           | 9.12                  |
| T20-2 | 60       | 2.44             | 2.05                 | 130    | 10.56           | 9.45                  |
| T20-3 | 65       | 2.07             | 1.91                 | 140    | 9.45            | 9.05                  |
| T20-4 | 65       | 3                | 2.65                 | 125    | 10.78           | 9.89                  |

Pcr: Visible first crack load (kN).

Table (4): Test results of group T20.
Pu: Ultimate Load (kN).
Δcr/centre, Acr (under load): deflection measured in conjunction with visible first crack at mid span and under load respectively.
Δu/centre, Δu (under load): deflection measured in conjunction with ultimate load at mid span and under load respectively.

**Table (5): Increase of cracking, ultimate load, and decrease of deflection at load by percent for group T20.**

| Beam  | Δcr/50/centre (mm) | Δu/115/centre (mm) | (+) % deflection at centre Acr | Δu | % Pcr | % Pu | Pu_0/cont % |
|-------|--------------------|-------------------|---------------------------------|----|------|------|-------------|
| T20-0 | 2.33               | 11.15             | 0                               | 0  | 0    | 0    | 1           |
| T20-1 | 2.06               | 9.45              | 11.59                           | 15.25 | 10  | 4.35 | 1.043       |
| T20-2 | 1.78               | 7.21              | 23.61                           | 35.34 | 20  | 13.04 | 1.130       |
| T20-3 | 1.37               | 5.95              | 41.2                            | 46.64 | 30  | 21.74 | 1.217       |
| T20-4 | 1.89               | 8.62              | 18.88                           | 22.69 | 30  | 8.7   | 1.087       |

Δcr/50/centre: Deflection measured in conjunction with cracking load of control beam (50 kN) at mid span
Δu/115/centre: Deflection measured in conjunction with ultimate load of control beam (115 kN) at mid span

7.2. Behaviours and strength of beams in group T24

This group included five beams of trapezoidal cross-section with dimensions of length 1,600 × height 260 × width in bottom 160 and in top 240 mm. One of the beams was without any strengthening strip of CFRP, to act as a control beam, while the other four beams were strengthened with differing numbers and locations of CFRP strips. Tables (6) and (7) list the test results for this group, and Figure (5) shows the failure modes of the beams. In control beam T24-0, when the applied load was increased, it was observed that some small flexural cracks appeared along the beam in the tension area at the bottom of the beam, and the first crack occurred in the middle of the beam. As the load increased, the number of cracks increased and these become wider, beginning to propagate up to the compression area at the top of the beam until failure occurred. In beams T24-1 and T24-2, the first cracks occurred in the middle of the beams in the tension area at the bottom of the beams, and the cracks propagated up to the compression area at the top of beams until the strengthening strips was cut off at the middle of the beams where the maximum moment was present; failure occurred after that. In beams T24-3 and T24-4, the first crack occurred at the edge of the CFRP strips, in the tension area at the bottom of the beam. This may be due to the CFRP strips making the middle region of beam stronger in terms of resisting the maximum moment, while the region adjacent to the CFRP strips becomes weaker, allowing cracks to propagate in it up to the compression area at the top of beam, where the strips remain without breaking off and failure occurs through the peeling away of the cover of the concrete in the region adjacent to the CFRP strips.

**Table (6): Test results of group (T24).**

| Beam  | Pcr (kN) | Δcr/centre (mm) | Acr (under load) (mm) | Pu (kN) | Δu/centre (mm) | Δu (under load) (mm) |
|-------|----------|-----------------|----------------------|---------|----------------|-----------------------|
| T24-0 | 50       | 2.06            | 1.62                 | 125     | 11.44          | 8.68                  |
| T24-1 | 50       | 1.86            | 1.53                 | 130     | 10.11          | 8.65                  |
| T24-2 | 60       | 2.06            | 1.82                 | 145     | 10.46          | 9.45                  |
| T24-3 | 65       | 1.89            | 1.74                 | 155     | 9.56           | 9.07                  |
| T24-4 | 65       | 2.61            | 2.36                 | 130     | 9.62           | 8.85                  |

**Table (7): Increase of cracking, ultimate loads, and decrease of deflection at loads by percent for group T24.**
| Beam  | $\Delta_{cr}/50/centre$ (mm) | $\Delta_{u}/125/centre$ (mm) | (-) % Deflection at centre | (+) % Pcr | % Pu | $P_u$ | $P_u/cont$ |
|-------|-------------------------------|-------------------------------|--------------------------|----------|-----|-------|-----------|
| T24-0 | 2.06                          | 11.44                         | 0                        | 0        | 0   | 0     | 1         |
| T24-1 | 1.86                          | 9.25                          | 9.71                     | 19.14    | 0   | 4     | 1.04      |
| T24-2 | 1.53                          | 7.56                          | 25.73                    | 33.92    | 20  | 16    | 1.16      |
| T24-3 | 1.25                          | 5.91                          | 39.32                    | 48.34    | 30  | 24    | 1.24      |
| T24-4 | 1.69                          | 8.88                          | 17.96                    | 22.34    | 30  | 4     | 1.04      |

$\Delta_{cr}/50/centre$: Deflection measured in conjunction with cracking load of control beam (50 kN) at mid span

$\Delta_{u}/125/centre$: Deflection measured in conjunction with ultimate load of control beam (125 kN) at mid span.

Figure (4): Crack patterns of group $T_{20}$. 
Figure (5): Crack patterns of group $T_{24}$
8. Effect of CFRP strip number on beam behaviours:

Figure (6) shows the effects of CFRP strengthening strips' number on beam capacity. A comparison of beams T20-1 and T20-2 in group T20, strengthened with one and two strips respectively, with control beam T20-0 makes it clear that the CFRP strengthening affects ultimate load capacity, cracking load, and deflection. Adding one strip of CFRP to beam T20-1 caused increases in ultimate load and cracking load over that of the reference beam by 4.35% and 10% respectively, while adding two strips of CFRP to beam T20-2 caused increases in ultimate load and cracking load over the reference beam of 13.04% and 20%, respectively. Moreover, the strengthening with two strips used for beam T20-2 increased the ultimate load and cracking load by 8.33% and 9.09% respectively over using only one strip. Examining the results for beams T24-1 and T24-2 of group T24, which were strengthened with one and two strips respectively, and comparing these with control beam T24-0, it was clear that the CFRP strengthening also affected the ultimate load capacity, cracking load, and deflection in this case. Adding one strip of CFRP to beam T24-1 caused an increase in ultimate load over the reference beam of 4%, while the cracking load remained constant; adding two strips of CFRP to beam T24-2 caused an increase in ultimate load and cracking load over the reference beam of 16% and 20% respectively.

Increasing strengthening from one to two strips for beam T24-2 thus increased ultimate load and cracking load by 11.54% and 20%, respectively. The deflection value decreased for the same level load in groups T20 and T24 when using one strip and became even smaller when using two strips. Figure (7) shows the effect of strengthening strip number on the deflection of beams at mid span.

Figure (6): Effect of strengthening strip number on ultimate load capacity.

Figure (7): Effect of CFRP strip number on deflection at mid span.
9. Effect of strengthening strip location on beam behaviours:
A comparison was made between the first method, used in beams $T_{20}$-1 and $T_{24}$-1, strengthened with one strip along the beam with length 1400 mm, and the second method, used in beams $T_{20}$-4 and $T_{24}$-4, strengthened with the same length of strip cut it into two pieces of length 700 mm and each placed on the maximum moment region at about 450 mm, dragging the remaining length for each strip to the near side high moment region. The results show that second method gave increments in ultimate load and cracking load of 4.17% and 18.18% in group $T_{20}$, while group $T_{24}$ showed no increment in ultimate load, but displayed a cracking load increase of 30% when compared with the first method. Another comparison was made between the method used in beams $T_{20}$-2 and $T_{24}$-2, strengthened with two strips along the beams with length 1,400 mm, and the second method, used in beams $T_{20}$-3 and $T_{24}$-3, which were strengthened using the same amount of CFRP but with three strips of length 933 mm placed on the middle distance between the supports of the beams to resist the maximum moment in mid span and the high moment in the adjacent regions. The results show that second method gives increments in ultimate load and cracking load of 7.69% and 8.33% in group $T_{20}$, and 6.9% and 8.33% in group $T_{24}$ compared with the first method. Generally, it is evident that the second method, which focused on strengthening by strips at the maximum moment region, as used in beams $T_{20}$-4, $T_{24}$-4, $T_{20}$-3, and $T_{24}$-3 gives better results compared with the first method used in beams $T_{20}$-1 and $T_{24}$-1, and $T_{20}$-2 and $T_{24}$-2, respectively. Using the second method also decreased the deflection in all cases. Moreover, when using the first method, failure occurred in the middle of beam by flexure where the steel reinforcement yielded, followed by a rupture of the CFRP strips; using the second method moved the flexure failure to the strip ends and occurred by means of peeling the cover from the concrete. Figures (8) and (9) illustrate the effects of strengthening strip locations for groups $T_{20}$ and $T_{24}$ on the ultimate load capacity and deflection of beams at mid span.

10. The effects of cross-section shape on beam behaviours:
Figures (10) and (11) show the effects of varying top width of trapezoidal cross-section beams on their strength and deflection. The results indicate that increasing the top width of trapezoidal cross-section beams from 200 mm to 240 mm increased ultimate load capacity by 4 to 11.54 %, with deflection decreasing for all cases. This may be due to the compression area in the trapezoidal cross-section becoming bigger with any increase in the top width, causing the depth of the equivalent rectangular compression zone to become smaller, which lead to an increase in the moment arm $\left(\frac{d-a}{2}\right)$. Moreover, the moment of inertia becomes bigger when the top width of the trapezoidal cross-section increases. Generally, the increase in top width of trapezoidal cross-section beams led to an increase in ultimate load capacity and decreased deflection for all cases.

![Figure (8): Effect of strengthening strip location on ultimate load capacity.](image-url)
**Figure (9):** Effect of strengthening strip location on deflection at mid span.

**Figure (10):** Effect of cross-section shape on ultimate load capacity.
**Figure (11)**: Effect of cross-sections shape on deflection at mid span.
11. Conclusions
By comparing the test results for ten SCC beams with two different top widths and trapezoidal cross-sections unstrengthened and strengthened with CFRP strips differing in number, location, and placement methods, it can be concluded that

1. Trapezoidal cross-sections with top widths of 240 mm give higher ultimate load capacities by 4 to 11.54%, in addition to lower deflection, compared to trapezoidal cross-sections with top widths of 200 mm in reinforced concrete beams.
2. Strengthening trapezoidal cross-section reinforcement concrete beams using one or two CFRP strips with lengths of 1,400 mm or by using three CFRP strips with lengths of 933 mm increased ultimate strength by 4.35 to 21.74% for those with a flange of 200 mm, and by 4 to 24% for those with a flange width of 240 mm.
3. When beams were unstrengthened or strengthened with one or two strips of CFRP, cracking failure modes occurred in the mid span of the beams and failure was triggered by the yielding of the steel bars, followed by CFRP rupture. In beams strengthened with two opposing strips or three strips of CFRP, cracking failure modes occurred in the weak region beside the ends of the CFRP strips and the beams failed due to the cover of concrete peeling from the end of the CFRP strips.
4. For economic purposes, this study was interested in identifying the location of CFRP strips that could achieve the best results using the least amount of CFRP by comparing between the first method, which used CFRP strips along beams (T20-1, T20-2, T24-1, T24-2), and the second method, which strengthened using CFRP strips on the maximum and high moment regions using the same total length of CFRP (T20-4, T20-3, T24-4, T24-3). The second method was seen to give higher ultimate load capacity by 4.17 to 7.7% in trapezoidal cross-sections with 200 mm top width beams, and 0 to 6.9% in trapezoidal cross-sections with 240 mm top width beams, in addition to reducing deflection more generally. The cracking position that caused failure in the first method occurred in the middle of the beams, while in the second method, this changed to the end of the CFRP strips.
5. For reinforced concrete beams with trapezoidal cross-sections with top widths of 200 mm, strengthening using CFRP strips increased the cracking load by 10 to 30%, while in trapezoidal cross-sections with top widths of 240 mm, strengthening using one strip had no effect; increments in cracking load did, however, appear clearly when using two or three CFRP strips, reaching up to a 30% improvement.
6. The addition of CFRP strips as reinforcement elements to concrete beams reduces their deflection at the same load level; deflection measured at the cracking load of the control beam was reduced by 11.19 to 41.2% in trapezoidal cross-sections with 200 mm top width beams, and 9.71 to 39.32% in trapezoidal cross-sections with 240 mm top width beams. On the other hand, deflection measured at the ultimate load of the control beams was reduced by 15.25 to 46.64% in trapezoidal cross-sections with 200 mm top width beams, and 19.14 to 48.34% in trapezoidal cross-sections with 240 mm top width beams.
7. Strengthening reinforced concrete beams with CFRP strips did not affect the failure mode, flexure, as the beams were designed for this mode.
12. References

[1] ACI 237R-07 2007 Self-consolidating concrete American Concrete Institute ACI Committee 237

[2] Howard C S 1923 Formulas tables and graphs for trapezoidal reinforced concrete beams Bachelor's thesis California Institute of Technology.

[3] Badr H A 2016 experimental study and finite element modeling for the flexural behavior of self-consolidating reinforced concrete t-beams strengthened with carbon fiber reinforced polymer M.Sc. thesis Department of Building and Construction Engineering of University of Technology 123 pp.

[4] Soudki K El-Salakawy E and Craig B 2008 Behavior of CFRP strengthened reinforced concrete beams in corrosive environment. Journal of Composites for Construction. 11 3 291-8

[5] Sika 2008 Data sheet Sikadur-330 7 pp

[6] ACI 440 2R-08 2008 Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures American Concrete Institute

[7] EFNARC 2002 Specifications and guidelines for self-compacting concrete EFNARC Association House 99 West Street Farnham Surrey GU9 7EN UK

[8] ASTM C39/C39M-03 2003 Standard test method for compressive strength of cylindrical concrete specimens ASTM International

[9] ASTM C496/C496M-04 2004 Standard test method for splitting tensile strength of cylindrical concrete specimens ASTM International

[10] ASTM C469-02 2002 Standard test method for static modulus of elasticity and poisson’s ratio of concrete in compression ASTM International

[11] ASTM C78-10 2010 Standard test method for flexural strength of concrete (using simple beam with third-point loading) ASTM International