Influence of CFRP Strand Sheet on Flexural Strengthening of Reinforced Concrete Beam

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Abstract

Fiber Reinforced Polymer (FRP) composites in the form of laminates and fabrics are installed on reinforced concrete members, using externally bonded (EB) techniques for strengthening. However, the utilisation of capacity of FRP composites is limited due to debonding observed in the strengthening system, due to FRP and concrete interfacial shear stress. Carbon fiber reinforced polymer (CFRP), in a new form of strand sheets were recently developed and have not been adequately investigated upon. These strands are less than 1.0 mm in diameter is woven with thread to obtain the desired width of the sheet. Such strand sheets are likely to have enhanced bond strengths due to the gaps between the strands that increase the surface available for bonding with the adhesive compared to laminates. This paper presents details of an experimental investigation of the influence of CFRP strand sheets on the flexural performance of CFRP strengthened reinforced concrete (RC) beams. In the experimental study, RC beams strengthened with CFRP strand sheets and laminates, were tested under four-point bending and compared with an un-strengthened specimen. The main parameter varied was the elastic modulus of the CFRP strand sheet and width ratio \( \frac{w_f}{b} \) of high strength CFRP strand sheets. The relative contribution of the CFRP strand sheets to the bending moment capacity was observed to be significantly higher than that in the case of the CFRP laminate. The failure mode was observed to change from debonding to concrete cover separation with an increase in width ratio. The rupture was observed as the failure mode in the specimens strengthened with high modulus CFRP strand sheets. As a result, an increase in the bending-moment capacity and ductility of the beams was also observed. Based on the observed failure modes, models for predicting the mechanical behaviour of various systems were assessed.

1. Introduction

Infrastructure has played a significant role in the development of any country. As the loads and demands on structures increase, the need for strengthening and repair of the structures increases. A large proportion of infrastructure, especially bridges, requires rehabilitation or modification during their lifetime (Al-Mahmoud et al. 2009; Jawdhari et al. 2018a, 2018b; Sharma et al. 2008). The life of a bridge may reduce due to many reasons such as moving traffic load, seismic forces in the lateral direction, chemical attack, corrosion of the steel rebars, faulty design, bad construction, etc. In 2017, The American Road and Transportation Builders Association (ARTBA), reported 9.1% of bridges to be structurally deficient, estimating a budget of 50 billion US dollars for urgent repairs. In India, out of the 172 000 road bridges, 6 500 bridges are in a “distressed” condition and 123 bridges that are over 100 years old were reported to require immediate attention (MoRTH 2019). Additionally, a large number of railway bridges are also deficient and require immediate repairs (IRB 2015). Their repairs require restrictions on traffic load or reduced speed that cause significant economy losses (Aravind et al. 2013). It is, therefore, important to develop efficient and effective repair techniques, especially in the context of developing countries like India.

FRP composites have been widely used in the last few decades as an alternative to steel reinforcement and found to be more economical as compared to conventional repair systems like steel plates etc. (Attari et al. 2012; Bonacci and Maalej 2001; Vasudevan and Kothandaraman 2014). FRP can be used for: (i) new construction, e.g., bridge decks, (ii) replacement of steel rebars in reinforced concrete members, and (iii) for strengthening to enhance the capacity of deficient structures (Hota and Vijay 2010). Since four decades, significant improvement in FRP has been seen as new ideas have emerged in terms of material properties and strengthening techniques to overcome the weaknesses and drawbacks that were found during the early stage of the development of this system. One of the important limitations of using FRP is the high risk of debonding (Motavalli et al. 2011; Peng et al. 2014). The current study is anticipated to provide an insight on the behaviour of strand sheets, which are a newly developed form of FRP strengthening and have a significant potential for the strengthening of concrete and steel structures (Kobayashi et al. 2015; Nagai et al. 2012; Peiris and Harik...
The diameter of the CFRP strands is usually less than 1.0 mm. These strands are woven with thread, leaving a gap that allows the epoxy adhesive to cover around the surface area of each strand, resulting in a better bond mechanism as compared to laminates, which are attached to the concrete surface on one face only. Furthermore, strand sheets offer the advantage that they can be used for the retrofitting of long-span structural members like bridge girders by overlapping small lengths of strand sheets using finger joints in the gaps available between the strands (Jawdhari et al. 2017, 2018b). This allows continuity of the FRP and reduces the cost of labour and equipment. Strand sheets, therefore, offer many advantages with respect to more traditional types of FRP composites like laminates and fabrics. Many studies have reported experimental and numerical investigations to study the structural behaviour of concrete and steel members strengthening with strand sheets (Hidekuma et al. 2010, 2011; Jiao et al. 2013; Kobayashi et al. 2015, 2009; Komori et al. 2012; Nagai et al. 2012; Tabrizi et al. 2015). This study is an attempt to improve the knowledge base with regard to the mechanical performance of various types of fiber composites-based strengthening techniques for reinforced concrete (RC) beams in order to improve the efficiency of repair and strengthening.

2. Experimental programme

2.1 Specimen details

In the experimental program, five reinforced concrete (RC) beams were tested under four-point bending to failure. One specimen, which was without strengthening, was tested as the reference specimen. Four specimens were EB strengthened with high strength CFRP strand sheets, high strength CFRP laminates, and high modulus CFRP strand sheet. All specimens were cast in one batch of concrete and Fig. 1 shows the specimen configurations. Each RC beam had 150 mm width, 250 mm depth and 2000 mm length; the effective span between the supports was 1800 mm. In all specimens, two tension steel rebars of 12 mm diameter were placed at the bottom of the section, and two other compressive steel rebars of 8 mm diameter were placed at the top of the section. Rectangular steel stirrups of 8 mm diameter placed at intervals of 100 mm were used as shear reinforcement in the entire span. Two equal loads were applied at 1/3rd and 2/3rd of the effective span using a 2-point loading setup as shown in Fig. 1.

| Table 1 Material properties. |
|-----------------------------|
| Properties                  | Concrete | Steel | CFRP strand sheet | CFRP laminates | Adhesive |
| Fiber type                  | N. A.    | N. A. | High tensile strength | High modulus | N. A. |
| Fiber weight (g/m³) (wₙ₁)  | N. A.    | N. A. | 600                | 600           | 400    |
| Density (g/cm³) (ρ₀)        | N. A.    | N. A. | 1.8                | 2.1           | 1.6    |
| Design thickness (mm) (wₙ₁/ρ₀) | N. A.  | N. A. | 0.33³  | 0.28³       | 1.2    |
| Diameter of one strand (mm) | N. A.³  | 8  | 12³     | 0.83³  | 0.72³  | N. A. |
| Cross-sectional area of one strand (mm²) | N. A.  | N. A. | 0.54³  | 0.41³   | N. A. |
| Diameter of one strand including cross section resin measured (mm) | N. A.  | N. A. | 1.15  | 1.10   | N. A. |
| Numbers of strands per 500 mm width | N. A. | N. A. | 308  | 356   | N. A. |
| Yield strength (N/mm²)      | N. A.  | 545.6 | 548.1 | N. A. | N. A. |
| Ultimate strength (N/mm²)³  | 45.10  | 624.2 | 627.2 | 3400  | 1900   | 2900   |
| Young modulus strength (kN/mm²) | N. A. | 200 | 200 | 245 | 640 | 165 | 3.227 |
| Ultimate strain (µε)⁵       | N. A. | 2750⁵ | 13878 | 2969 | 17576 |
| Poisson ratio (ν)           | N. A. | N. A. | 0.32  | 0.34   | 0.3    |
| Bond stress between concrete and FRP (N/mm²)³ | N. A. | N. A. | 4.25³  | 4.17³   | 3.78³   |

a: Diameter for steel rebar, design thickness for CFRP strand sheet and laminate.
b: Tensile strength for steel rebar, FRP laminate and adhesive, and compressive strength for concrete.
c: Bond stress obtained from double lap shear test between CFRP and concrete (Kumar 2020).
d: N. A.: Not available.
e: Yield strain.
f: Excludes cross-section of resin.

2018a, 2018b). The diameter of the CFRP strands is usually less than 1.0 mm. These strands are woven with thread, leaving a gap that allows the epoxy adhesive to cover around the surface area of each strand, resulting in a better bond mechanism as compared to laminates, which are attached to the concrete surface on one face only. Furthermore, strand sheets offer the advantage that they can be used for the retrofitting of long-span structural members like bridge girders by overlapping small lengths of strand sheets using finger joints in the gaps available between the strands (Jawdhari et al. 2017, 2018b). This allows continuity of the FRP and reduces the cost of labour and equipment. Strand sheets, therefore, offer many advantages with respect to more traditional types of FRP composites like laminates and fabrics. Many studies have reported experimental and numerical studies to investigate the structural behaviour of concrete and steel members strengthening with strand sheets (Hidekuma et al. 2010, 2011; Jiao et al. 2013; Kobayashi et al. 2015, 2009; Komori et al. 2012; Nagai et al. 2012; Tabrizi et al. 2015). This study is an attempt to improve the knowledge base with regard to the mechanical performance of various types of fiber composites-based strengthening techniques for reinforced concrete (RC) beams in order to improve the efficiency of repair and strengthening.
Table 2 shows the strengthening details (thickness and type of CFRP) of the specimens. The specimens were named based on the type and the width of CFRP used. Two different widths of CFRP strand sheets were used to evaluate the effect of width ratio of the strand sheets. One CFRP high modulus strand sheet was also used to investigate the influence of the elastic modulus. One of the specimens was strengthened using a CFRP laminate for comparison.

Table 2 Strengthening detail of specimens.

| Reference       | CFRP fiber type | Strand sheet / Laminates | Width (mm) | Width ratio (w_f/b) | Area of CFRP (mm²) |
|-----------------|-----------------|--------------------------|------------|---------------------|-------------------|
| STR-HT600-125  | High strength   | Strand sheet             | 125        | 0.83                | 125×0.333 = 41.625|
| STR-HT600-50   | High strength   |                          | 50         | 0.33                | 50×0.333 = 16.65   |
| STR-HM600-50   | High modulus    | Strand sheet             | 50         | 0.33                | 50×0.286 = 14.3    |
| STR-S512-50    | High strength   | Laminate                 | 50         | 1.2                 | 50×1.2 = 60.0      |

w_f: Width of FRP; b: Width of RCC beams.

2.2 Application of CFRP and instrumentation

The test setup and the specimens were instrumented to measure loads, deformations and strains. Two load-cells were used to measure the applied load and three linear variable differential transformers (LVDTs) were used to measure the deflection. Electrical strain gauges were installed inside the specimens to measure the strains of concrete, steel reinforcement and the CFRP. Figure 2(a) shows the layout of strain gauges affixed on the reinforcement. Three LVDTs were placed at the quarter spans and mid-span, to measure the vertical deflections. Strain gauges were also installed on the surface of CFRP strand sheets and laminate, as shown in Fig. 2(b), to measure the distribution of the tensile strain. Figure 3 shows the experimental setup and the data acquisition system used in this study.

The bond between the concrete substrate and the CFRP composite material plays an important role in the performance of a strengthened beam. An adequate bond allows for a proper transfer and distribution of forces between the two adhered materials and a sound surface preparation is a part of the process to achieve this. During the strengthening procedure, special attention was paid to ensure the bond between the reinforced concrete beam and CFRP. The beam’s tensile face where the strengthening material was applied, was ground using an electric grinder to remove any dust, laitance, foreign particles and to attain an aggregate rich layer that provides a rough surface profile for CFRP bonding. The steps for the preparation of the concrete surface and the application of the CFRP strand sheets have been shown in Fig. 4.

![Fig. 1 Details of RC beams used in the experiments: (a) and (b) Dimensions, reinforcement details and loading setup; (c) High strength CFRP strand sheet; (d) High modulus CFRP strand sheet.](image-url)
Fig. 2 Instrumentation of (a) reinforcement cage (b) CFRP strand sheets.

Fig. 3 Experimental setup: (a) RC beam specimen; (b) DEWETRON data acquisition system.

Fig. 4 Systematic procedure of application of strand sheets.


3. Discussion of test results

3.1 Failure mode and crack pattern
Various failure modes, as seen in Fig. 5, were observed during the tests. The reference specimen failed due to yielding of steel rebars followed by crushing of concrete (YS-CC) as shown in Fig. 5(a). Three distinct failure modes were observed in the strengthened specimens: debonding of CFRP (FD), concrete cover separation (CCS) and the rupture of CFRP (FR). In the strengthened specimens (STR-HT600-50, STR-S512-50), debonding was initiated with the flexural cracks starting within the pure bending span and then propagating towards the ends of CFRP strand sheet and laminate. As the stress at the interface between the CFRP and the concrete reached the bond strength, a slip occurred at this interface, as reported in study by Chen et al. (2019). Finally, the CFRP strand sheet and laminate debonded from the rest of the specimen (FD) and at some location along with 2 to 4 mm of its concrete substrate, as shown in Figs. 5(b) and 5(d). The specimen STR-HT600-125, which was strengthened throughout the width of the beam excluding

(a) Failure mode of yielding of steel followed by crushing of concrete (YS-CC) reference.

(b) Failure mode of debonding of FRP (FD) of STR-S512-50.

(c) Failure mode of concrete cover separation (CCS) of STR-HT600-125.

(d) Failure mode of debonding of FRP (FD) of STR-HT600-50.

(e) Failure mode of rupture of FRP (FR) of STR-HM600-50.

Fig. 5 Failure mode for specimens.
the side cover, the failure mode was seen to be concrete cover separation (CCS) [Fig. 5(c)]. A rupture of the CFRP was observed in the case of the high modulus CFRP strand sheet [Fig. 5(e)].

The crack patterns for cover separation [Fig. 5(c)], CFRP debonding [Figs. 5(b) and 5(d)] and CFRP rupture [Fig. 5(e)] were highly similar. Most cracks were vertical and distributed within the pure bending span. A few inclined shear cracks were found within the shear span. In debonding failure, most cracks occurred under the loading point [Figs. 5(b) and 5(d)], while in concrete cover separation mode more inclined shear cracks were observed along with cracks occurred under the loading points [Fig. 5(e)].

The crack pattern i.e., average ($S_{av}$) and maximum crack spacing ($S_{max}$) have been reproduced graphically for better understanding and shown in Fig. 6 and the crack characteristics are given in Table 3. The average ($S_{av}$) and maximum crack spacing ($S_{max}$) of strengthened specimens were estimated by three methods (Ceroni and Pecce 2008; Eurocode 2004; fib 2001) and the experimentally measured values were found to be the

| Beam specimens        | Experimental values | Theoretical values |
|-----------------------|---------------------|--------------------|
|                       | $S_{av}$ | $S_{max}$ | $S_{av}$ | $S_{max}$ | $S_{av}$ | $S_{max}$ |
| Reference             | 97       | 143        | 120      | 192        | 92      | 143        |
| STR-HT600-125         | 70       | 121        | 108      | 91         | 75      | 116        |
| STR-HT600-50          | 79       | 129        | 115      | 133        | 82      | 128        |
| STR-HM600-50          | 80       | 135        | 109      | 133        | 76      | 129        |
| STR-S512-50           | 78       | 135        | 108      | 133        | 75      | 118        |

$S_{av}$: Average crack spacing, $S_{max}$: Maximum crack spacing, all values in mm.

Table 3 Experimental and theoretical crack spacing.

![Fig. 6 Crack patterns: (a) Reference; (b) STR-HT600-125; (c) STR-HT600-50; (d) STR-HM600-50; (e) STR-S512-50.](image-url)
closest to the estimates using the methods in fib Bulletin 14 (fib 2001) and those of Ceroni and Pecce (2008). As the strengthened beams were observed to have a larger number of finer cracks, the average ($S_{ave}$) and maximum crack spacing ($S_{max}$) of the strengthened specimens were found to be lower in the range of 16% to 27% and 6% to 15%, respectively, as compared to the reference specimen. This is in agreement with the results reported by Wight et al. (2001). This also led to a higher energy absorption in the strengthened specimens (Darain et al. 2016). In the case of debonding failure, most cracks occurred under the loading point but in the reference specimen cracks almost spread evenly.

3.2 Comparison of experimental and analytical cracking and ultimate bending moments

The theoretical cracking bending moment for specimens (STR-HT600-125, STR-HT600-50, STR-HM600-50 and STR-S512-50) were determined by methods proposed by Daugevičius et al. (2019) and Deng et al. (2017). A comparison of the experimental and theoretical values is shown in Fig. 7(a). The experimental values were found to match closely with the method proposed by Deng et al. (2017).

The theoretical ultimate bending moment for specimens (STR-HT600-125, STR-HT600-50, STR-HM600-50 and STR-S512-50) were estimated using six methods and provisions given in various published guides, reports and literatures (ACI 2017; fib 2001; ISIS 2001; Lee and Moy 2007; Li et al. 2013; NCHRP 2010). For calculation of theoretical bending moment (BM), the strengthening scheme was assumed to be externally bonded (EB) based on the bonded of strand sheet on the bottom face of RCC beam. A comparison of the experimental and theoretical values is shown in Fig. 7(b). The main observations from this comparison are listed below:

i) In the case of CCS failure mode (STR-HT600-125), the experimental ultimate BM was found to have a good agreement with ACI (2017).

ii) In the case of FD failure mode (STR-HT600-50 and STR-S512-50), the measured ultimate BM of strand sheets and laminate strengthened specimens were

![Experimental values](Fig. 7)
found to have a good agreement with fib Bulletin 14 (fib 2001) and NCHRP Report 655 (NCHRP 2010), respectively.

iii) In the case of FR failure mode (STR-HM600-50), the experimental ultimate BM had a good agreement with ISIS Module No. 4 (ISIS 2001).

3.3 Critical load and deflection

**Table 4 Test results.**

| Specimen          | Concrete cracking | Rebar yielding | Peak load | Failure mode |
|-------------------|-------------------|----------------|-----------|--------------|
|                   | Applied load (kN) | Mid-span deflection (mm) | Energy absorption (kN.mm) | Applied load (kN) | Mid-span deflection (mm) | Energy absorption (kN.mm) |                  |
| $P_{cr,exp}$, $\Delta_{cr,exp}$, $E_{cr,exp}$ | $P_{y,exp}$, $\Delta_{y,exp}$, $E_{y,exp}$ | $P_{u,exp}$, $\Delta_{u,exp}$, $E_{u,exp}$ |
| Reference         | 29.1              | 1.52           | 23        | 114.4        | 6.3            | 493                     | 132.0             | 14.2            | 1131           | YS-CC          |
| STR-HT600-125     | 38.2              | 2.11           | 47        | 145.8        | 10.9           | 879                     | 176.1             | 17.6            | 2204           | CCS            |
| STR-HT600-50      | 36.3              | 1.89           | 39        | 131.0        | 10.3           | 823                     | 153.1             | 18.3            | 2053           | FD             |
| STR-HM600-50      | 37.3              | 1.93           | 32        | 134.1        | 6.9            | 457                     | 174.7             | 14.5            | 1621           | FR             |
| STR-S512-50       | 36.1              | 1.66           | 28        | 147.8        | 9.0            | 659                     | 170.5             | 13.8            | 1589           | FD             |

**Table 5 Bending moment (BM) contribution per unit (kN) axial stiffness of CFRP applied.**

| Critical Stages | Beam specimen | BM of strengthened specimen (kNm) | BM of reference specimen (kNm) | Percentage increase in BM as compared to reference | BM contributed by CFRP (kNm) | Elastic modulus (kN/mm²) | Area of CFRP ($w_f t_f$) (mm²) | Axial stiffness of FRP (kN) | Normalised BM ($M_{FRP,exp}$) (kNm/kN) | Percentage variation as compared to laminate |
|-----------------|---------------|-----------------------------------|--------------------------------|---------------------------------------------------|-----------------------------|--------------------------|-------------------------------|-------------------------------|--------------------------------------|-----------------------------------|
| (i)             | (ii)          | (iii)                             | (iv)                          | (v) = (iii)/(iv)                                   | (vi) = (iii) - (iv)         | (vii)                    | (viii)                        | (ix)                          | (x) = (vii) x (viii)               | (xi) = (vii) / (ix)                |
| STR-S512-50     | 10.8          | 8.7                               | 24%                            | 2.1                                                | 165                         | 60                       | 9900                         | 0.03                          | 0%                                   |
| STR-HT600-125   | 11.5          | 8.7                               | 31%                            | 2.7                                                | 245                         | 41.625                   | 10198                        | 0.07                          | 29%                                 |
| STR-HT600-50    | 10.9          | 8.7                               | 24%                            | 2.1                                                | 245                         | 16.65                    | 4079                         | 0.13                          | 148%                                |
| STR-HM600-50    | 11.2          | 8.7                               | 28%                            | 2.5                                                | 640                         | 14.3                     | 9152                         | 0.17                          | 29%                                 |
| STR-S512-50     | 44.3          | 34.3                              | 29%                            | 10.0                                               | 165                         | 60                       | 3374                         | 0.17                          | 0%                                   |
| STR-HT600-125   | 43.7          | 34.3                              | 27%                            | 9.4                                                | 245                         | 41.625                   | 9900                         | 0.23                          | -9%                                 |
| STR-HT600-50    | 39.3          | 34.3                              | 14%                            | 5.0                                                | 245                         | 16.65                    | 10198                        | 0.3                           | 20%                                 |
| STR-HM600-50    | 40.2          | 34.3                              | 17%                            | 5.9                                                | 640                         | 14.3                     | 4079                         | 0.41                          | -36%                                |
| STR-S512-50     | 51.2          | 39.6                              | 29%                            | 11.5                                               | 165                         | 60                       | 9152                         | 0.19                          | 0%                                   |
| STR-HT600-125   | 52.8          | 39.6                              | 33%                            | 13.2                                               | 245                         | 41.625                   | 3374                         | 0.32                          | 10%                                 |
| STR-HT600-50    | 45.9          | 39.6                              | 16%                            | 6.3                                                | 245                         | 16.65                    | 9900                         | 0.38                          | 32%                                 |
| STR-HM600-50    | 52.4          | 39.6                              | 32%                            | 12.8                                               | 640                         | 14.3                     | 10198                        | 0.9                           | 20%                                 |

Note: Values of $w_f$ and $t_f$ are given in Table 1.
absolute values of the flexural parameter i.e., applied BM of strengthened specimens. Thus, the flexural parameter was normalised with respect to the axial stiffness of CFRP used at three critical stages, viz., (i) first crack, (ii) yielding of steel and (iii) ultimate failure of the specimens and is also given in Table 5.

From Table 5 the normalised BM at the first crack stage of high strength CFRP strand sheets strengthened specimens (STR-HT600-125, STR-HT600-50 and STR-HM600-50) were observed to be increase by 29%, 148% and 29%, respectively, in comparison with CFRP laminate strengthened specimen. Similarly, at the ultimate stage, the normalised BM was seen to be enhanced by 10%, 32% and 20%, respectively. The increase in the width ratio of high strength CFRP strand sheets in the specimen (STR-HT600-125) by a factor of around 2.5 was seen to shift the failure mode from FD to CCS. It can be inferred that the application of CFRP strand sheet/laminates effectively increased the sectional moment of inertia, thereby increasing the cracking load (Chen et al. 2019).

The load-deflection behaviour of the specimens is presented in Fig. 8. From Fig. 8, the reduction in deflection was observed to be 44%, 34%, 21% and 52% in the specimens STR-S512-50, STR-HT600-125, STR-HT600-50 and STR-HM600-50, respectively, as compared to ultimate deflection of the reference specimen. These observations are in line with the study conducted by Chen et al. (2019) and Darain et al. (2016).

From Table 5, it was observed that the ultimate load carrying capacity of strengthened specimens (i.e., STR-S512-50, STR-HT600-125, STR-HT600-50 and STR-HM600-50) increased by 29%, 33%, 16% and 32%, respectively, as compared to reference specimen.

### 3.4 Ductility

The ductility index was measured by two methods, (i) displacement ductility index (Al-Deen Bsisu et al. 2015; Almusallam et al. 2015; Ashour et al. 2004; El-Gamal et al. 2016; Hashemi et al. 2008; Kim and Shin 2011; Tan et al. 2009), and (ii) energy absorption ductility index $\mu_E = 0.5\times(\frac{E_A_{\text{ext}}}{E_A_{\text{tot}}} + 1)$ (Alsayed and Alhozaimy 1999; Grace et al. 1998; Hashemi et al. 2008; Kim and Shin 2011; Orozco and Maji 2004; Oudah and El-Hacha 2012; Wang and Belarbi 2011; El Zareef and El Madawy 2018; Zou 2003) and is given in Table 6. It was observed that the displacement ductility index of CFRP strengthened specimens reduced by 9% to 35% as compared to the reference (unstrengthened) specimen. It can also be seen that the displacement ductility index improved by 7%, 20% and 40% in the strengthened specimens (STR-HT600-125, STR-HT600-50 and STR-HM600-50), respectively, as compared to the strengthened specimen with CFRP laminate (STR-S512-50). Similarly, the energy absorption ductility index was seen to be higher than 6%, 0% and 35%, respectively, as compared to the CFRP laminate strengthened specimen (STR-S512-50). It was also observed that the energy absorption after yielding stage improved by 42%, 32% and 25%, respectively, in the strengthened specimens (STR-HT600-125, STR-HT600-50 and STR-HM600-50) as compared to the strengthened specimen with CFRP laminate (STR-S512-50).

![Fig. 8 Load-deflection curve up to peak load also showing cracking load and deflection.](image-url)
125, STR-HT600-50 and STR-HM600-50) as compared to the CFRP laminate strengthened specimen (STR-S512-50). It is inferred that CFRP strand sheets have 10 to 12% higher limit bond stress between FRP-concrete interface as compared to CFRP laminates resulting in an improvement in the displacement and the energy absorption ductility index as compared with CFRP laminates. The CFRP strand sheet strengthened specimens were also seen to exhibit higher values of post-yield energy absorption compared to the CFRP laminate strengthened specimen. Based on the above results, it can be concluded that the ductility index derived from the energy absorption method is a better way to measure the ductility when high tensile strength materials are used for strengthening of RC beams.

### 3.5 Strains in steel, CFRP and shear stress at FRP-concrete interface

The experimentally measured strain values at mid-span with increasing applied load until the ultimate failure for strengthened specimens are presented in Table 7. From Fig. 9, it is observed that the compressive strain at extreme compression fiber in CFRP strand sheets strengthened specimens (STR-HT600-125 and STR-HT600-50) was increased by 16% and 17%, respectively, at yielding stage and 28% and 18%, respectively, at the ultimate stage as compared to specimen STR-S512-50. While comparing the increased width ratio 0.33 to 0.83 of high strength CFRP strand sheets specimen, the compressive strain further increased by 8%.

Figure 10 illustrates the CFRP strain distribution for all strengthened specimens. The lines in this graph are drawn at intervals of 20 kN of applied load and at the stage of rebar yielding. The percentage of the total strain capacity of the CFRP strand sheets and the increase in this strain with reference to the laminate are shown in Fig. 11. From Fig. 11, it is observed in the specimen STR-HM600-50, the high modulus of the sheet led to an increase in the strain in the sheet until its capacity leading to its rupture. The specimens strengthened with high strength CFRP strand sheet (STR-HT600-50) and the CFRP laminate (STR-S512-50) experienced debonding failure mode (FD) and the strand sheet specimen exhibit-
An enhancement of 28% was observed for the specimen STR-HT600-125 as compared to STR-S512-50 due to the concrete cover separation failure mode. The increase in the width ratio of the strand sheet was led to an increase in the strain capacity utilisation by another 6%.

While the prestressing of high strength CFRP (Badawi and Soudki 2009; Hajighashemi et al. 2011; Huang et al. 2005, 2000; Peng et al. 2014; Şakar and Tanarslan 2014; Wight et al. 2001; Ye et al. 2014) and anchoring of sheets (Adhikary and Mutsuyoshi 2002; Al-Deen Bsisu et al. 2015; Alagusundaramoorthy et al. 2003; Ali et al. 2014; Almusallam et al. 2015; Aravind et al. 2013; Bahn and Harichandran 2008; Chahrour and Soudki 2005; Chen et al. 2000).

Table 7 Test results of strains in concrete, steel and CFRP.

| Beam specimen       | Experimental applied load (kNm) | Strain at mid-span (µε) |
|---------------------|---------------------------------|-------------------------|
|                     | At first crack                  | SGc                      |
| STR-S512-50         | 37.3                            | -311                     |
|                     | At yielding                     | SGc,SG,ST,SGT            |
|                     | 147.8                           | -1056                    |
|                     | At failure                      | +847                     |
|                     |                                  | +2750                    |
|                     |                                  | +3596                    |
| STR-HT600-125       | 38.2                            | -316                     |
|                     | At first crack                  | +117                     |
|                     |                                  | +483                     |
|                     | At yielding                     | +867                     |
|                     |                                  | +250                     |
|                     | At failure                      | +867                     |
|                     |                                  | +6267                    |
| STR-HT600-50        | 36.2                            | -468                     |
|                     | At first crack                  | +84                     |
|                     |                                  | +551                     |
|                     |                                  | +930                     |
|                     | At yielding                     | +738                     |
|                     |                                  | +2750                    |
|                     |                                  | +5617                    |
|                     | At failure                      | +3439                    |
|                     |                                  | +8028                    |
| STR-HM600-50        | 38.5                            | -348                     |
|                     | At first crack                  | -238                     |
|                     |                                  | +366                     |
|                     |                                  | +970                     |
|                     | At yielding                     | +945                     |
|                     |                                  | +2750                    |
|                     |                                  | +2824                    |
|                     | At failure                      | -1021                    |
|                     |                                  | +988                     |
|                     |                                  | +2997                    |
|                     |                                  | +3012                    |

Fig. 10 CFRP tensile strain distribution along their length for specimens: (a) STR-HT600-125; (b) STR-HT600-50; (c) STR-HM600-50; (d) STR-S512-50.
al. 2019; Garden et al. 1998; Garden and Hollaway 1998; Hussain et al. 1995; Jawdhari et al. 2018b; Jumaat and Alam 2009; Nguyen-Minh et al. 2018; Rabinovitch and Frostig 2003; Rasheed et al. 2010; Siddiqui 2009; Swamy and Mukhopadhyaya 1999; Xiong et al. 2007; Zhang et al. 2012, 2017; Zhou et al. 2013; Zhuang et al. 2018) have been recommended to allow greater utilisation of the capacity of the FRP composites, it can be seen from the results here that even without these measures 50% of the capacity of the high strength CFRP strand sheets and 100% of the capacity of the high modulus sheets is utilised. This increase in capacity can be attributed to an increase in the bond stress by 10% to 12% in the strand sheets as compared to CFRP laminates (Kumar 2020).

Based on the force equilibrium and linear elasticity of CFRP strand sheet/laminates, the following relationship can be derived (Ceroni 2017; Ceroni et al. 2016; Chen et al. 2019; Chen and Cheng 2016; Foraboschi 2016; Jawdhari et al. 2018b; Sui et al. 2018) to calculate the interfacial bond stress between any two adjacent strain gauges:

\[
\tau = \frac{E_f (x_i) - E_f (x_{i+1})}{f_t (x_i - x_{i+1})} \cdot E_f f_t
\]

where \(x_i, x_{i+1}\) are the locations of any two consecutive gauges, measured from the reference point, \(E_f\) is the CFRP tensile modulus, N/mm², \(E_f (x_i) - E_f (x_{i+1})\) are strains at locations \(x_i, x_{i+1}\) respectively, \(f_t\) is the diameter/thickness of the CFRP strand sheet/laminate. The distribution of adhesive shear stress was derived from the measured CFRP tensile strain by using the above equation in the strengthened specimens and shown in Fig. 12. Bond stress values of 3.21 N/mm², 3.70 N/mm², 1.97 N/mm² and 3.37 N/mm² were obtained for the specimens STR-HT600-125, STR-HT600-50, STR-HM600-50 and STR-S512-50, respectively, as compared to the limit bond stress value of 4.25, 4.25, 4.16 and 3.78 N/mm², respectively, obtained from the double lap shear test (Table 1). It was seen that debonding in the specimens STR-HT600-50 and STR-S512-50 occurred at 87% and 89%, respectively, of bond stress as compared to the value obtained from the double lap shear test. The specimens where the failure occurred due to concrete cover separation and CFRP...
rupture were found to attain 75% and 47% of the limit bond stress obtained from the double lap shear test. Therefore, the limit bond stress between concrete-FRP interface achieved and shows good agreement with the model in the case of the failure mode of debonding for strengthening specimens STR-HT600-50 and STR-S512-50. This study establish that the value of the limit bond stress measured using the double-lap shear test proves to be useful to understand the possible mode of failure of strengthened RC beams.

4. Conclusions

The main conclusions drawn from this study are listed below.

1. The improved bond in the case of strand sheets was seen to increase the failure moments and change the failure modes.
2. Different models available in the literature were found to be suitable for different situations and different calculations. For example, while in the case of CCS failure mode the ultimate BM was found to have a good agreement with ACI (2017). In the case of FD failure, the ultimate BM of the specimens were found to have a good agreement with the for the design requirements and NCHRP Report 655 (NCHRP 2010) and in the case of FR failure mode, the ultimate BM was seen to have good agreement with ISIS Module No. 4 (ISIS 2001).
3. In all cases, the cracking moments were found to match closely with the method proposed by Deng et al. (2017).
4. The mid-span deflections of all the strengthened specimens were seen to reduce significantly in comparison to the reference specimen. A reduction in average and maximum crack spacing was seen to occur leading to higher energy absorption in the strengthened specimens.
5. The normalised BM of CFRP strand sheets at three critical stages of loading was significantly higher than the specimen with laminates.
6. The compressive strain at extreme compression fiber increased in CFRP strand sheet strengthens specimens as compared to CFRP laminate strengthened specimen at the yielding and ultimate stage.
7. Due to the increased bond, the strand sheets were able to attain higher strain levels prior to debonding compared to the laminates.
8. CRFP strand sheets were also seen to improve the displacement and energy absorption ductility index as compared with CFRP laminates due to their better bond.

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