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# CFRP strips for enhancing flexural performance of RC beams by SNSM strengthening technique

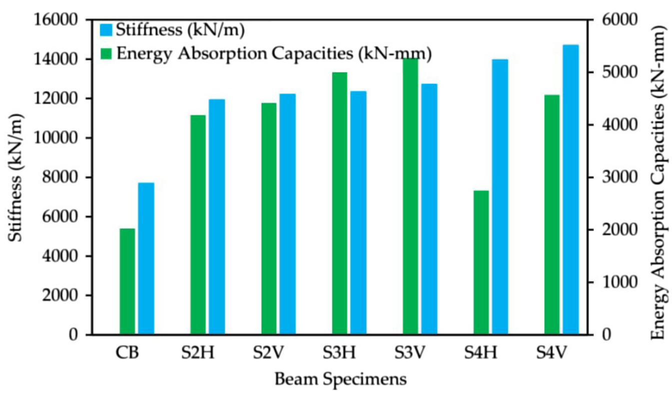
Md. Akter Hosen [a,b], Mohd Zamin Jumaat [a,*], U. Johnson Alengaram [a], N.H. Ramli Sulong [a]

[a] Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Department of Civil Engineering, Dhaka University of Engineering & Technology (DUET), Bangladesh

## HIGHLIGHTS

- New Side Near Surface Mounted (SNSM) strengthening technique for RC beams.
- SNSM technique using CFRP strips significantly improved flexural performance.
- SNSM technique also notably enhanced stiffness and energy absorption capacities.
- SNSM with CFRP-strips found to be improve the service performance of RC beams.
- Predicted and experimental results were in excellent agreement.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Side Near Surface Mounted (SNSM) strengthening technique is among the latest technique introduced recently. In this paper, SNSM carbon fiber reinforced polymer (CFRP) strips strengthening technique is proposed for enhancing the flexural performance of reinforced concrete (RC) beams. A total of seven RC beam specimens were tested: one un-strengthened control specimen, and six specimens strengthened by SNSM-CFRP strips. All beam specimens were tested under four-point bending. Analytical prediction methods were used to verify the experimental results. The load, mid-span, deflection, and strains data were recorded until failure of the specimens. The ductility, stiffness, and energy absorption capacity of the strengthened specimens by CFRP strips were enhanced due to SNSM technique. The results also showed that the SNSM-CFRP strips strengthening technique significantly enhanced the first cracking, yield, and ultimate load capacities up to 153%, 108%, and 147% respectively, compared with that of the control beam. Further, the comparison between the experimental and predicted values shows good agreement.



## 1. Introduction

Strengthening of reinforced concrete (RC) structures is essential for increasing its load carrying capacity and serviceability requirements. Currently, many research works are ongoing on strengthening RC structural elements. Carbon fiber-reinforced polymer (CFRP) reinforcements are of high tensile strength, high stiffness, low weight, durable, resistance to creep and fatigue compared to current construction materials, and have been used extensively. However, CFRP reinforcements reported weakness due to its brittle failure mode [1]. Numerous techniques have been developed and

* Corresponding author.
*E-mail address:* zamin@um.edu.my (M.Z. Jumaat).

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used to strengthened existing structural elements. The most popular strengthening techniques are external bonded reinforcement (EBR) [2] and near surface mounted (NSM) [3]. In EBR technique, strengthening reinforcements are bonded at the tension face of the flexural member using epoxy resin or adhesive; while NSM technique involves insertion of strengthening reinforcement with adhesive on the grooves prepared on the surface of the RC members. However, the EBR-strengthened specimens predominantly fail by debonding and concrete cover delamination [4–6]. Also, EBR plates are highly vulnerable to weather effect and have low fire resistance [7,8].

Costa and Barros [9] performed experimental, analytical, and numerical studies on the flexural strength of RC beams strengthened using NSM CFRP strips. NSM grooves were cut into the bottom arm of the steel stirrups and to avoid shear failure U-wrap with CFRP sheets was used. The failure modes of the strengthened specimens were premature shear and concrete cover separation. Jung et al. [10] investigated the experimental applicability of NSM technique for strengthening of RC beams using CFRP rods and strips. A mechanical interlocking grooves were used to prevent debonding failure of the NSM strengthened specimens. Sena-Cruz et al. [11] studied the efficiency of EBR, NSM, and mechanically-fastened EBR technique for flexural strengthening of RC beams under static and fatigue loading. However, the NSM-strips strengthened specimen failed by premature rip-off of the FRP strips.

The NSM technique also have some limitations: (i) needed adequate concrete cover, (ii) sufficient width of beam, (iii) necessary edge clearance, and (iv) clear spacing between the grooves [3]. Akter et al. [12] proposed the side near surface mounted (SNSM) strengthening technique to overcome the limitations of the NSM technique using steel and CFRP bars. The SNSM technique involves preparation of the grooves within the concrete cover at both sides (near the tension face) of the beam specimen using a special concrete saw and insertion of the CFRP bars with the application of the epoxy adhesive. Based on the experimental results, the SNSM strengthening technique significantly increased the first cracking, yield, and ultimate load carrying capacities of the beams by about 3.17, 2, and 2.38 times, respectively, compared with the control specimen, and notably improved the failure modes of the specimens. Shukri et al. [13] studied the flexural responses of pre-cracked RC beam specimens strengthened with the SNSM technique using CFRP bars, and the experimental results were verified using analytical models. The pre-cracked specimens revealed similar failure modes and greater stiffness compared with the non-pre-cracked specimens.

There is rarely any literature available on the flexural performance of RC beam strengthened with SNSM technique using CFRP strips. Hence, this study focusses on the assessment of the structural performance of RC beam specimens strengthened with SNSM technique using CFRP strips. Four-point bending tests were conducted up to failure of the beam specimens under static condition. The effect of the number and orientation of the CFRP strips, and the amount of strengthening reinforcement on the SNSM strengthening technique was investigated. The flexural load carrying capacity, deflection, failure modes, and cracking behaviors are discussed based on the experimental results of the tested beams. The other important features such as stiffness, energy absorption values, and ductility of the specimens were also evaluated. The theoretical analysis using the relevant theories and code of practice was used to predict the deflection; and spacing and width of cracks of the tested specimens.

## 2. Experimental procedure

### 2.1. Test matrix

A total of seven RC beam specimens was divided into three groups based on its strengthening reinforcements. In the first group, one beam specimen was kept as an un-strengthened control beam. The beam specimens (S2H, S3H and S4H) in the second group were strengthened with SNSM technique using different number of (2, 3 and 4) horizontally oriented CFRP-strips. In the last group, the beam specimens (S2V, S3V and S4V) were strengthened with different number of (2, 3 and 4) vertically oriented CFRP-strips. Table 1 shows the configuration of the beam specimens.

### 2.2. Beam specimen configurations

The beam specimen has a dimension of 125 mm (width) and 250 mm (depth). The total length of the beam specimens was kept at 2300 mm; the effective and shear spans were maintained at 2000 mm and 750 mm, respectively. All the beam specimens were reinforced with equal amount of reinforcement in order to ensure that the beams are under reinforced. The tension reinforcement ($\rho = As/(b \times d)) = 0.0085$) comprised of 2-T12 mm $\phi$ deformed steel bars and 2–10 mm $\phi$ deformed steel bars were used as holding bars, as shown in Fig. 1. Mild steel bars of 6 mm $\phi$ were used as shear reinforcement throughout the shear span. A clear cover of 25 mm for the tension face was used; while slightly higher cover of 30 mm was used for sides in order to utilize the cover for SNSM technique. The dimensions and details of the all beam specimens are shown in Fig. 1.

### 2.3. Material properties

#### 2.3.1. Concrete

All of the beam specimens were cast using ready mixed concrete. The compressive, flexural and splitting tensile strength tests were performed in accordance with BS EN 12,390-3 [14], BS EN 12,390-5 [15], and BS EN 12,390-6 [16], respectively using 100 mm cube specimens, 100 mm $\times$ 100 mm $\times$ 500 mm prism and 100 mm $\phi \times$ 200 mm height cylinder specimens. The average test results of three specimens of compressive, flexural and splitting tensile strength were found as 60 MPA, 5.78 MPa and 4.52 MPa, respectively. The modulus of elasticity tests were carried out based on ASTM C469/C469M-14 [16] using 150 mm $\phi \times$ 300 mm height cylinders, and the average modulus of elasticity was found as 36.55 GPa.

#### 2.3.2. Steel bars

Two types of steel reinforcing bars, as main and link reinforcement were used to prepare the beam cage. The high yield strength deformed reinforcing bars of 12 mm $\phi$ which had a yield strength of 550 MPa were used as a tension reinforcement. The plain mild steel bars of 6 mm $\phi$ with yield strength of 300 MPa were used as a stirrup. The modulus of elasticity (MOE) of all steel reinforcing bars was 200 GPa.

**Table 1**
Configuration of the beam specimens.

| Beam ID | Description | Scheme of strengthening | | | | |
|---|---|---|---|---|---|---|
| | | Materials | Strips size (mm) | Number of strips | Orientation of strips | Grooves size (mm) |
| CB | | | | | | |
| S2H | Beams strengthening with SNSM technique | CFRP Plates | 1.2 × 15 | 2 | Horizontal | 25 × 25 |
| S3H | | | | 3 | | |
| S4H | | | | 4 | | |
| S2V | | | | 2 | Vertical | |
| S3V | | | | 3 | | |
| S4V | | | | 4 | | |

Note: S – Side near surface mounted technique, 2, 3, 4- number of strips, H-horizontally oriented strips and V-vertically oriented strips.

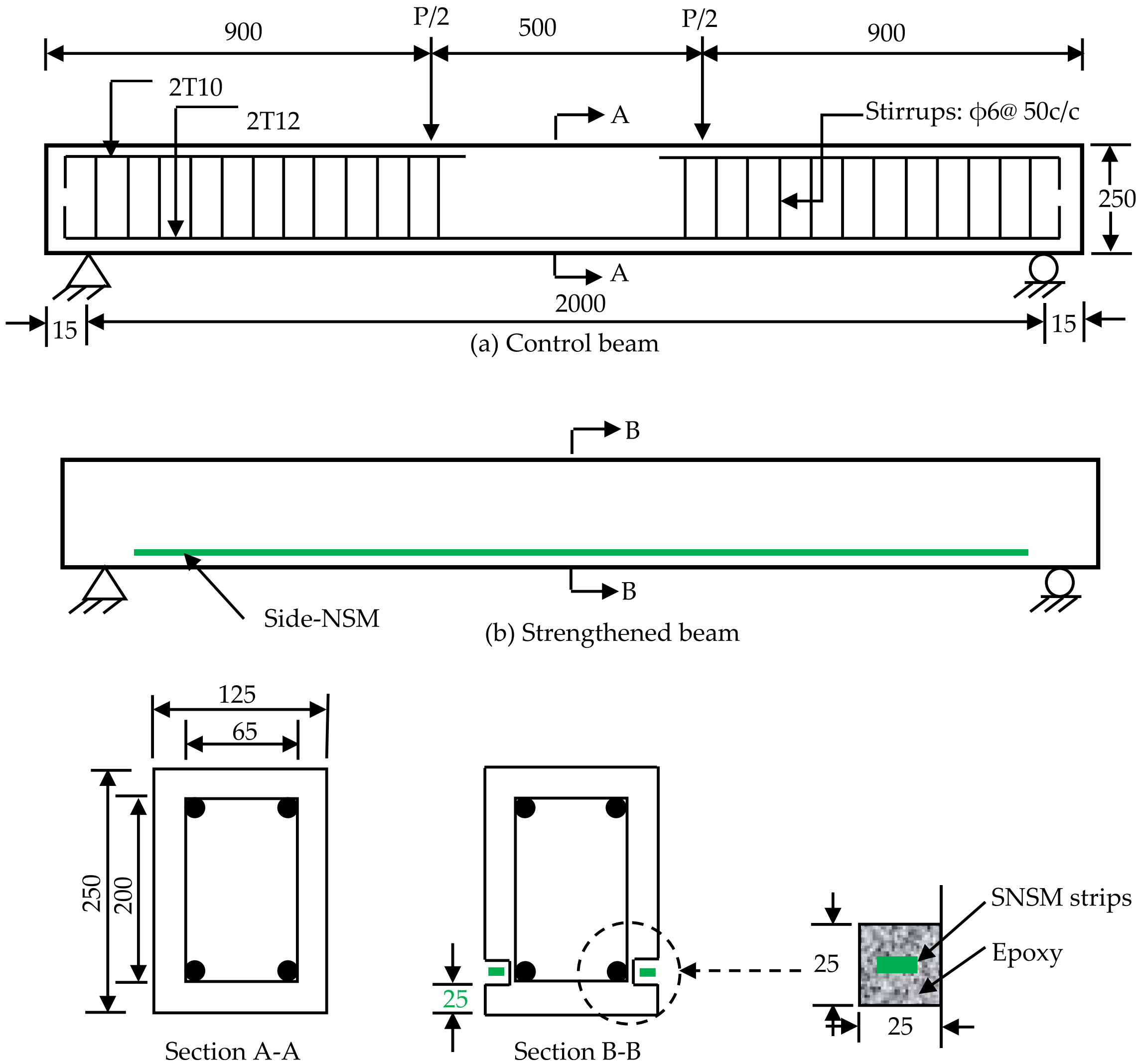



**Fig. 1.** Geometry and details of the beam specimens (all dimensions in mm).

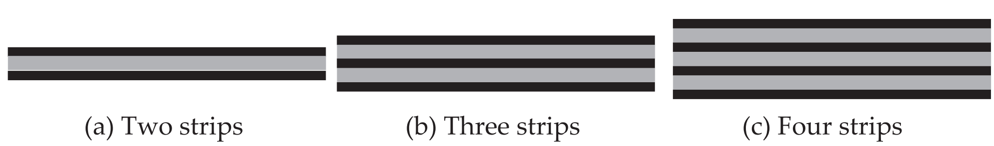



**Fig. 2.** CFRP strips configuration.

*2.3.3. Adhesive*

Thixotropic Sikadur® 30 epoxy was used as a bonding material between the strengthening reinforcement (strips) and concrete substrate of the beam specimens. The epoxy components were mixed at a ratio of 3(A):1(B) to achieve a uniform light grey color. The values compressive, shear, tensile and bond strength, and the tensile modulus of elasticity of the epoxy adhesive as provided by the manufacturer were 95 MPa, 19 MPa, 31 MPa, 21 MPa, and 11.2 GPa, respectively [17].

*2.3.4. CFRP laminate*

Pultruded CFRP laminate with a thickness of 1.2 mm, width of 100 mm and 100 m in length was used for strengthening the RC beam specimens. The values of average tensile strength, modulus of elasticity, and strain at break of the CFRP laminate as given by the manufacturer are 3100 MPa, 165 GPa, and 1.7%, respectively.

*2.4. Beam specimens fabrication*

Steel molds were used for casting the RC beam specimens. Prior to the placement of the steel cages in the steel molds, it was cleaned and greased. Before pouring the concrete, the desired clear cover was maintained using concrete blocks. The specimens were cast in three layers, and each layer was compacted using a poke vibrator to ensure adequate compaction and remove the presence of air voids. All beam specimens were cured by covering the beams with wet hessian cloths for four weeks prior to making the grooves for strengthening.

*2.5. Strengthening procedure*

The beam specimens were strengthened with side near surface mounted (SNSM) technique using different numbers and orientation (horizontal and vertical) of carbon fiber reinforced polymer (CFRP) strips. The dimensions of the grooves are shown in Fig. 1. The grooves were formed on the side the specimens in the longitudinal direction, 25 mm above the tension face via the formation of circular concrete saw cuts. Manual hammer and chisel were used for finishing off the grooves, which was then cleaned with acetone and a high-pressure air jet.

The dimensions of a single CFRP strip was 1.2 mm × 15 mm × 1900 mm, and its configuration is shown in Fig. 2. First, the CFRP strips surface was cleaned using acetone to remove any remaining dirt. Two, three, and four strips were made by CFRP laminate and requisite epoxy adhesive. Initially, the grooves were half-filled with epoxy adhesive and then CFRP-strips pressed into the center of the groove until the epoxy flowed around the strips. The remaining space in the groove was filled with the epoxy and its surface flattened using a triangular spatula. Finally, the strengthened specimens were kept in secular place without any movements for at least seven days in order for epoxy adhesive to set in.

### 2.6. Test set-up and instrumentation

The beam specimens (control and strengthened) were simply supported and tested up to failure under static condition of four-point bending. A Universal Instron machine of 250 kN capacity was used to apply the load using a steel spreader beam, as shown in Fig. 3. Linear variable differential transformer (LVDT) was used to measure the deflection of all tested beam specimens placed at the mid-span of the specimen. Strain gauge of 30 mm gauge length were affixed at the center of the upper face of specimens to measure the compressive stain of concrete. The entire test was carried out by using displacement control mode, with the rate of the actuator was set at 1.5 mm/min. The deflections and strains were recorded at 10 s intervals by the TML TDS530 data logger. At every 5 kN load increment, the crack width of the specimens was measured by a Dino-Lite digital microscope (Fig. 4). Also, the propagation of cracks was carefully observed and marked at every load increment.


**Fig. 4.** Dino-Lite digital microscope.

## 3. Experimental results and evaluations

The summary of flexural test results in terms of (i) ultimate load capacity, (ii) increments of ultimate load, (iii) maximum deflection at mid-span, and (iv) mode of failure all beam specimens are detailed in Table 2.

### 3.1. Flexural load carrying capacity

The flexural capacities of the un-strengthened control and strengthened beam specimens in terms of first cracking and ultimate load are shown in Fig. 5. The beam specimens strengthened with the SNSM technique using CFRP strips has significant influence on the stiffness of the un-cracked section. The SNSM-CFRP-strips significantly improved the first cracking and ultimate load carrying capacities by up to 2.53 times and 2.47 times, respectively, compared with the control specimens. The comparison of the first cracking and ultimate loads between the horizontally (S2H, S3H and S4H) and vertically (S2V, S3V and S4V) oriented strips strengthened specimens shows that the latter results in a higher enhancement from 8% to 24% and 4% to 18%, respectively; and it should be noted that the amount of strengthening CFRP-strips used in both the cases was same and the higher load carrying

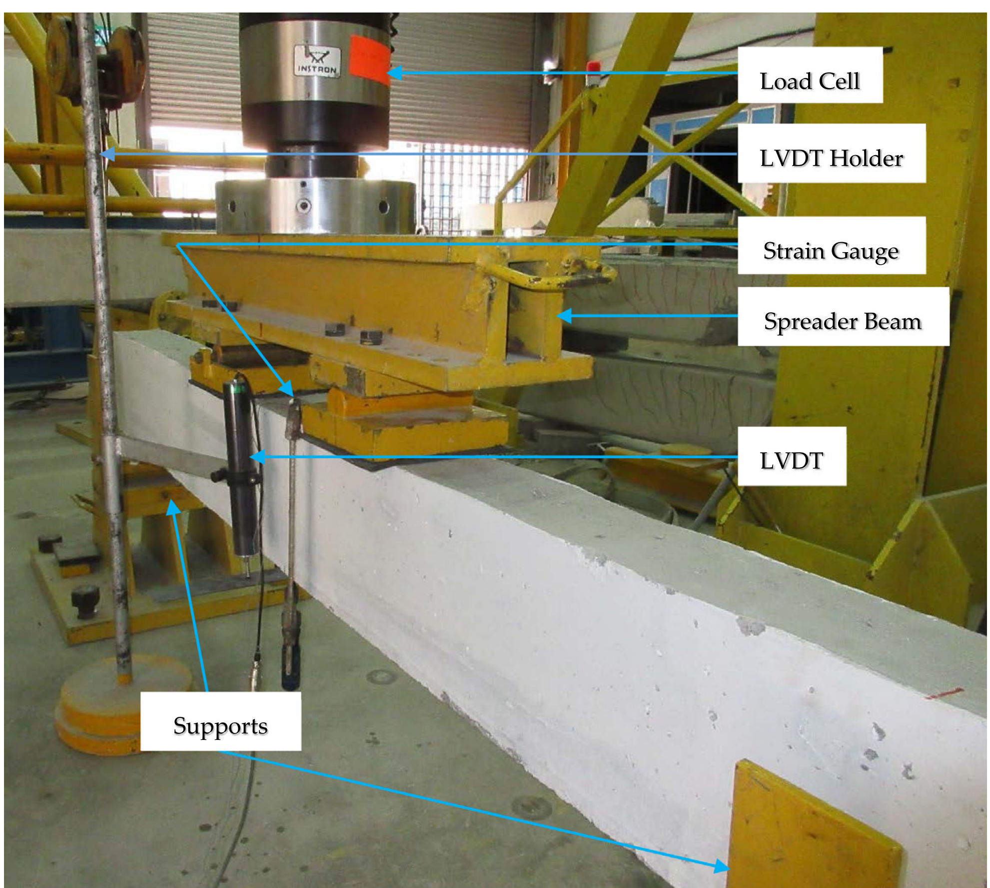



**Fig. 3.** Experimental test set-up and instrumentation.

**Table 2**
Summary of the flexural test results.

| Beam ID | Ultimate load capacity (kN) | Increment of ultimate load (kN) | Increment of ultimate load (in times) | Maximum deflection (mm) | Failure modes |
|---|---|---|---|---|---|
| CB | 68 | – | – | 35.33 | Flexural failure |
| S2H | 135 | 67 | 1.98 | 47.60 | Flexural failure |
| S2V | 138 | 70 | 2.03 | 46.85 | Flexural failure |
| S3H | 154 | 86 | 2.26 | 48.23 | Flexural failure |
| S3V | 160 | 92 | 2.35 | 48.06 | Flexural failure |
| S4H | 156 | 88 | 2.29 | 27.03 | End cover separation |
| S4V | 168 | 100 | 2.47 | 42.63 | Flexural failure |

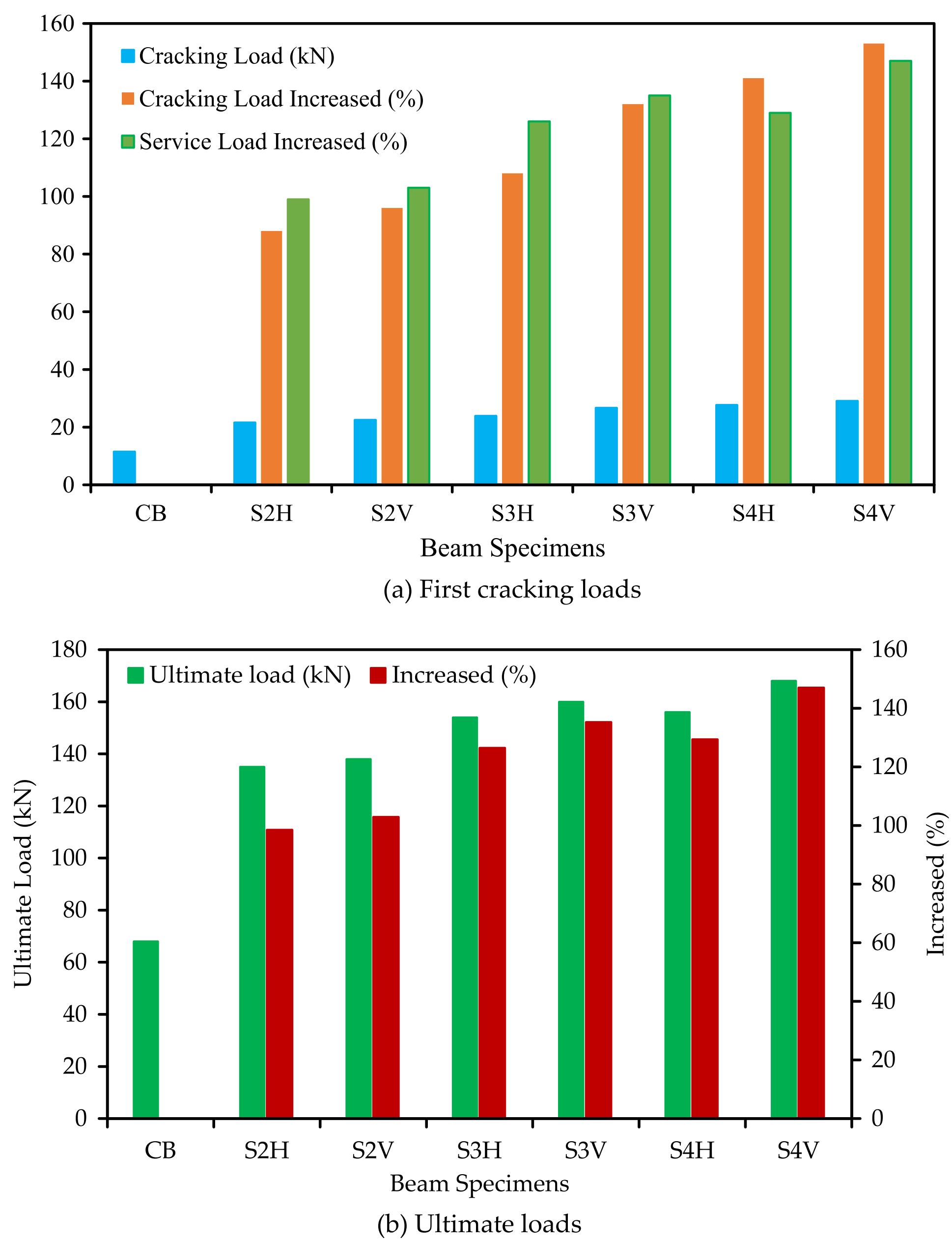



**Fig. 5.** First cracking and ultimate load carrying capacity of the specimens.

capacity of the vertically oriented CFRP strips could be attributed to higher flexural rigidity. Thus, SNSM technique with vertical oriented CFRP-strips can be considered for practical strengthening it site for the rehabilitation of the RC structural elements.

The strengthening of the RC beam specimens using CFRP bars as a strengthening reinforcement in SNSM technique increased the first cracking and ultimate loads up to 100% and 102%, respectively compared to control beam specimen [12]. In contrast, the NSM technique with CFRP strips strengthened the RC beam specimens and improved its flexural capacity up to 66% compared with the reference specimen [18]. The NSM-CFRP bars enhanced the ultimate capacity by up to 98% of the RC beam specimens [19].

The service load is defined as the 60% of its ultimate load carrying capacity of the specimen [20]. The comparison between the control and the horizontally and vertically oriented SNSM-CFRP strips strengthened beam specimens show an increase in the service load carrying capacity up to 126% and 129% respectively, for the latter.

### 3.2. Load-deflection curves

The load versus deflection relationship curves for the RC beam specimens strengthened with SNSM technique using CFRP strips are shown in Fig. 6. In this study, the load-deflection curves show trilinear distinct phases. The first phase comprises of un-cracked section and linear elastic behavior of the beam specimens. The curves in this phase for control and strengthened beams are linear which represents the full composite behavior of the beams. The first cracking load of the control specimen was 11.5 kN, with a deflection of 1.1 mm. In contrast, the SNSM-CFRP strips strengthened specimen shows enhanced cracking load with lower deflection. The second phase contains the first cracking to yielding of internal reinforcing steel of the specimens. The tensile strength of concrete in the beam specimens exceeded the modulus of rupture of the concrete, while the flexural rigidity of the specimens gradually decreased in this phase. The control specimen had a deflection of 9.01 mm at the yield load of 60 kN. However, the specimens strengthened with horizontally oriented CFRP-strips sustained almost double the load as that of the control beam. An increase in the yield load of about 8% was obtained for the vertically strengthened beam compared to horizontally strengthened beam. The final phase is considered as the period between yielding of internal reinforcing steel and the failure of the beam specimens. As shown in the Fig. 6, the increasing rate of deflection exceeded that of the previous phase of the strengthened specimens due to the yielding of steel and low modulus of elasticity of CFRP strips. Thus, the stiffness of the beam specimens in this phase reduced rapidly. The SNSM-CFRP strips control the number and width of

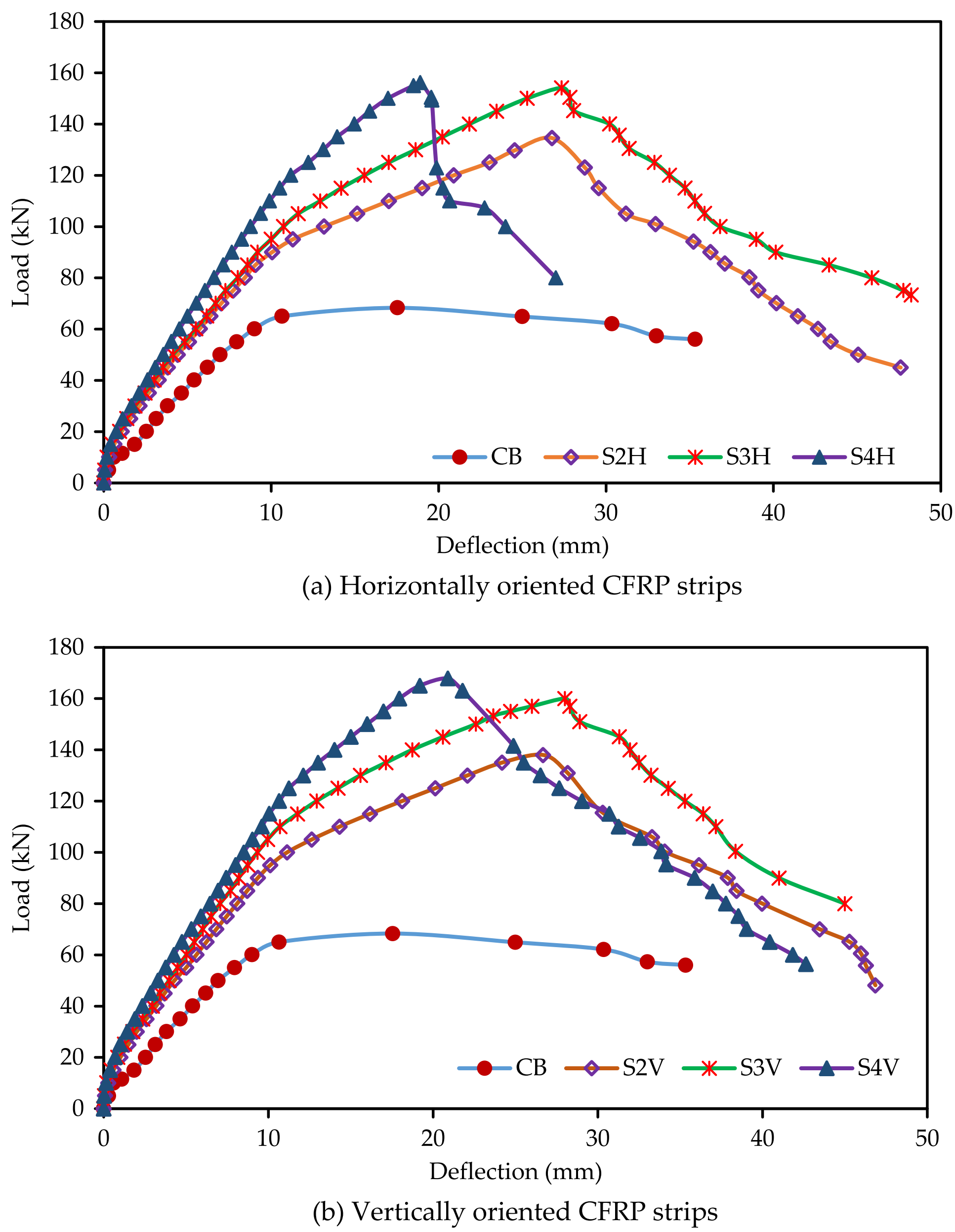


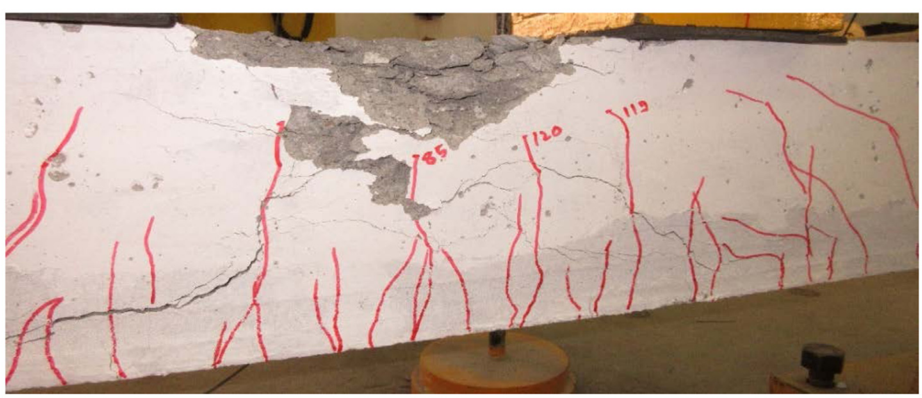

**Fig. 6.** Load versus mid-span deflection curves of the tested beam specimens.

the cracks until the failure of the specimens. Hence, the strengthened specimens could carry higher ultimate load compared to that of the control specimen.

### 3.3. Failure modes of the specimens

The typical failure modes of the beam specimens are shown in Fig. 7. The failure of control beam specimen occurred through concrete crushing in the compression zone after the yielding of steel reinforcement. In the constant moment region, the flexural cracks were initiated near the mid-span and propagated up to the full depth of the section, which accounts for the ultimate failure. The initial crack was obtained at a load of 11.5 kN. Then, several flexural cracks opened up to a load of 60 kN, which was very close to the yield load of the steel reinforcement. Finally, the cracks were extended into full depth of the beam section at a load of 68 kN, which resulted in failure of the specimens. All of the SNSM-CFRP strips strengthened beam specimens' mode of failure was flexure, which is similar to the control specimen, except for the S4H specimen. However, the first cracking, yield, and ultimate load capacities of the specimens differed. Numerous flexural cracks occurred and propagated along the depth of the section. A few shear cracks were initiated between the loading point and support, but were not responsible for the final failure of the specimens. For the S4H beam specimen, flexural cracks were initiated and propagated up to the point of failure. However, from the end of the CFRP strips, 45° inclined cracks developed at the yielding load of 120 kN, and gradually propagated to the loading point. After a load of 150 kN, the crack width increases rapidly, leading the failure mode of the specimen. Finally, the end concrete cover separation occurred at a load of 156.21 kN. This failure modes could have occurred due to inadequate groove depth for placing four strips horizontally.

(a) CB




(b) Strengthened beam failed by flexure

(c) S4H beam failed by end concrete cover separation

**Fig. 7.** Failure modes of the beam specimens.

The end concrete cover separation of the strengthened beam specimen can be eliminated to provide the U-wrap end anchorage using the CFRP sheet [21]. In contrast, the NSM-CFRP or NSM-steel bars strengthened specimens failed by debonding [22,23].

### 3.4. Efficiency of the SNSM technique

Fig. 8 shows the reduction of deflection and compressive strain of the concrete due to strengthening with SNSM technique using CFRP strips. The deflection of the strengthened beam specimen decreased by about 73%, 56%, and 53% at applied loads of 20 kN, 40 kN, and 60 kN, respectively, compared with the control specimen. Also, the extreme fiber concrete compressive strain of the strengthened beam specimens reduced by about 56%, 51%, and 54% at the same applied loads of 20 kN, 40 kN and 60 kN, respectively. This reduction could be due to the increased flexural rigidity of the strengthened beam specimens by the SNSM-CFRP strips. On the other hand, vertically oriented CFRP strips decreased the deflection and concrete compressive strain over the horizontally oriented strips maximal of about 3%, 4%, and 5%, and 11%, 9%, and 12%, respectively, at the applied loads of 20 kN, 40 kN, and 60 kN respectively.

It was reported that the NSM-steel bars strengthened RC beam specimens' deflection and concrete compressive strain decreased by about 57%, 48% and 51%; 54%, 35% and 38% at 30 kN, 50 kN and 70 kN, respectively, compared to the control beam [24].

### 3.5. Cracking behaviors

Cracks in the reinforced concrete structures should not be severe or wide, as this could led to durability problems [25]. In the tested beams, the first crack was visible at a load of 11.5 kN in the control specimen; however, in the strengthened beams, as expected the first crack loads were found at higher loads of 21.6

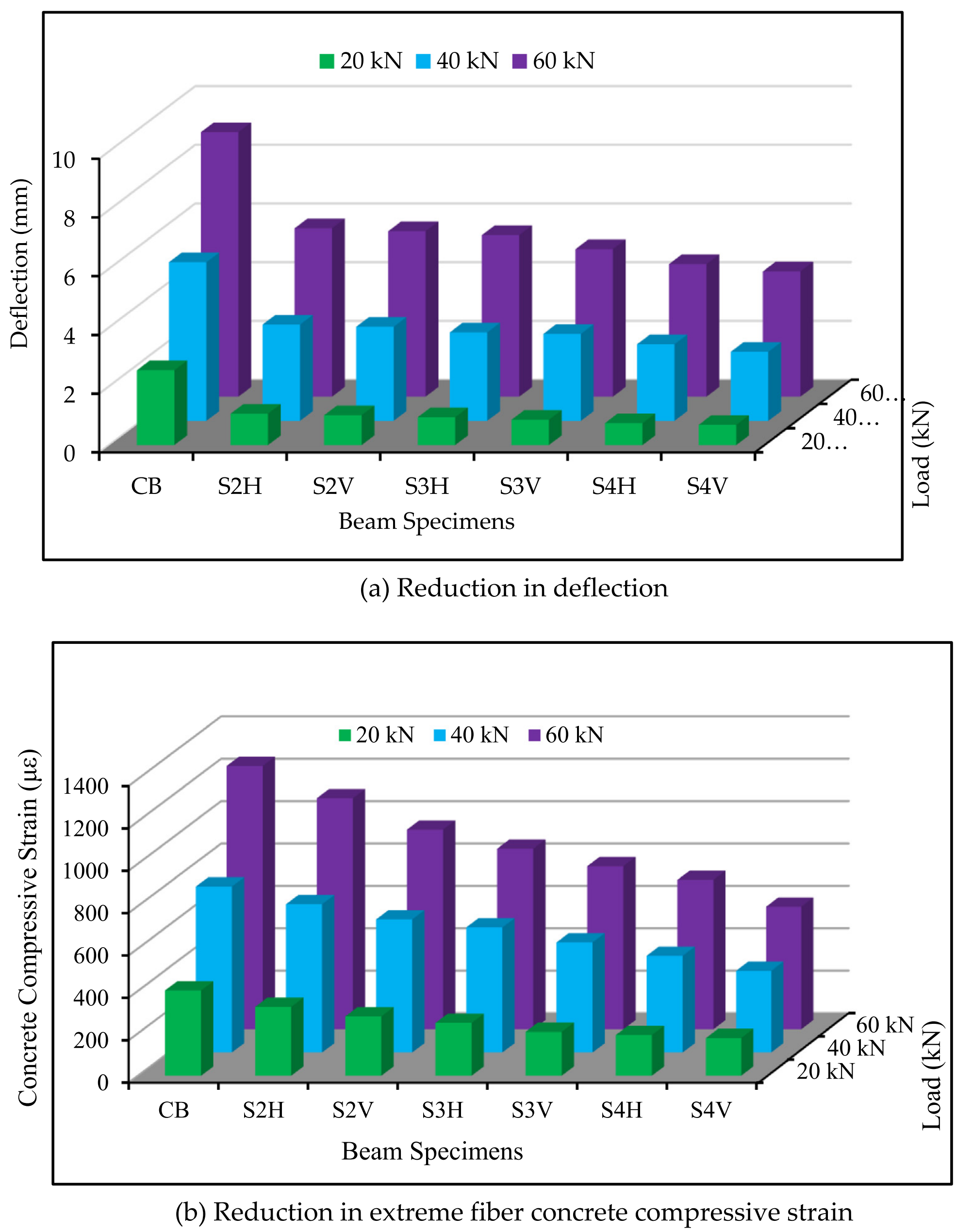



**Fig. 8.** Deflection and strain reduced due to strengthening by SNSM-CFRP strips.

kN, 22.5 kN, 23.9 kN, 26.7 kN, 27.7 kN, and 29.1 kN in the specimens S2H, S2V, S3H, S3V, S4H, and S4V, respectively. This shows that the SNSM technique significantly enhanced the first cracking load of the specimens due to the CFRP strips at the side grooves on the tension face (Fig. 1). The SNSM-CFRP strips delay the commencement of cracks in the tension face of the specimens, and subsequently restrained the propagation of the cracks. The delay of the first crack occurrence is important for the serviceability of the structures. The SNSM technique preserved the uncracked section, preventing the intrusion of water and carbon dioxide from the adverse environmental conditions which could corrode the steel reinforcement in the concrete [26].

The crack width of the beam specimens was measured using the Dino-Lite digital microscope across the tension steel reinforcing bars position in the constant moment zone at varying load levels. The crack width of the tested specimens was recorded using a laptop, up to the yielding of the tension steel reinforcement. The relationship between the load and crack width of all the tested RC beam specimens is shown in Fig. 9. When the applied load increased, the width of the flexural cracks started to spread and propagate from the soffit to the top of the specimens. The flexural crack width of all the tested beam specimens was compared at a load of 60 kN-the yielding load of the tension steel of control specimen. At this load of 60 kN the formation of crack width was wider at about 0.91 mm in the control specimen. The corresponding crack widths were 0.48 mm, 0.39 mm, 0.36 mm, 0.27 mm, 0.22 mm, and 0.13 mm for specimens S2H, S2V, S3H, S3V, S4H and S4V, respectively. The SNSM-CFRP strips strengthened specimens showed lower crack widths at all load levels compared with the control specimen. The trend of the crack width can also be classified by this technique. The vertically oriented strips strengthened specimens showed lower crack width compared with the horizontally oriented strips strengthened specimens.

The total number of cracks and average crack spacing of the CB, S2H, S2V, S3H, S3V, S4H, and S4V specimens were 16, 34, 36, 37, 38, 28 and 40, respectively, and 92 mm, 59 mm, 56 mm, 44 mm, 43 mm, 69 mm, and 41 mm, respectively. Only the S4H specimen exhibited different characteristic of the number and average spacing of the cracks due to the debonding failure mode. The degree of cracks spacing changed throughout the span length of the specimen, depending on the deflection and stresses. The cracks spacing of the specimens was closer at constant moment region, and increased gradually near the support.

On the other hand, SNSM technique with CFRP bars for flexurally strengthened RC beam specimens had the maximum number of cracks of 19 with average crack spacing of about 96 mm [27]. However, the NSM-steel bars strengthened RC beam specimens showed the maximum number and average spacing of cracks as 20 and 95 mm, respectively [23].

### 3.6. Stiffness

Stiffness is one of the prevalent properties of reinforced concrete structures, and is defined as the capability to resist load/displacement. Stiffness is a key factor in serviceability of RC structures, such as crack characteristics and displacement. The stiffness of RC strengthened beam specimens predominantly depends on the applied load, cracks, and the strengthening reinforcements and bonding materials, namely epoxy adhesive [28].

In this study, the stiffness of the beam specimens is estimated from the gradient of the load versus deflection curve at the service load level. The service load is defined as the ratio of first crack load to the load corresponding to the point of deflection that is equal to *L/480* (where, *L* = span length of the beam specimens) [29]. The SNSM technique with CFRP strips significantly enhanced the stiffness of the RC beam specimens, as shown in Fig. 10. In the unstrengthened RC beam specimen, the internal reinforcing steel control the stiffness, which is affected by the propagation of the cracks [30]. However, the SNSM-CFRP strips restricted the initiation and propagation of the cracks. The beam specimens strengthened with horizontally oriented (S2H, S3H and S4H) strips increased stiffness from 55% to 82% compared to the control specimen, as opposed to the vertically oriented (S2V, S3V and S4V) strips increased, which reported an increase from 59% to 91%. The vertically oriented CFRP strips is regarded as effective in the context of stiffness of the specimens.

It can be seen from the flexurally strengthened RC beams with SNSM technique using GFRP bars [31] that the stiffness of the beam increased up to 114%; whereas the prestressed RC beams strengthened by NSM technique using prestressed steel tendon increased stiffness of about 96% compared with the reference beam specimens [28].

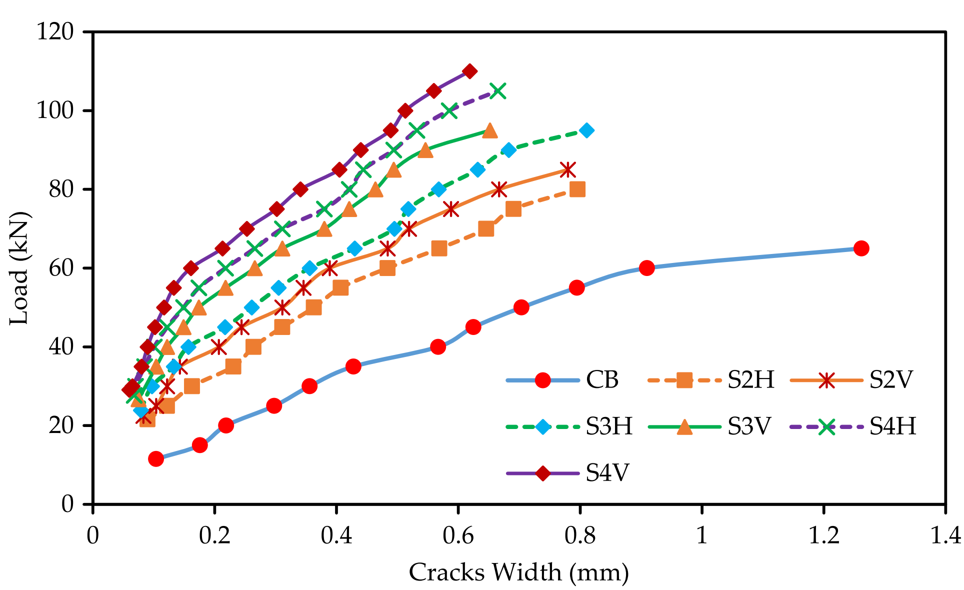



**Fig. 9.** Load versus crack width of beam specimens.

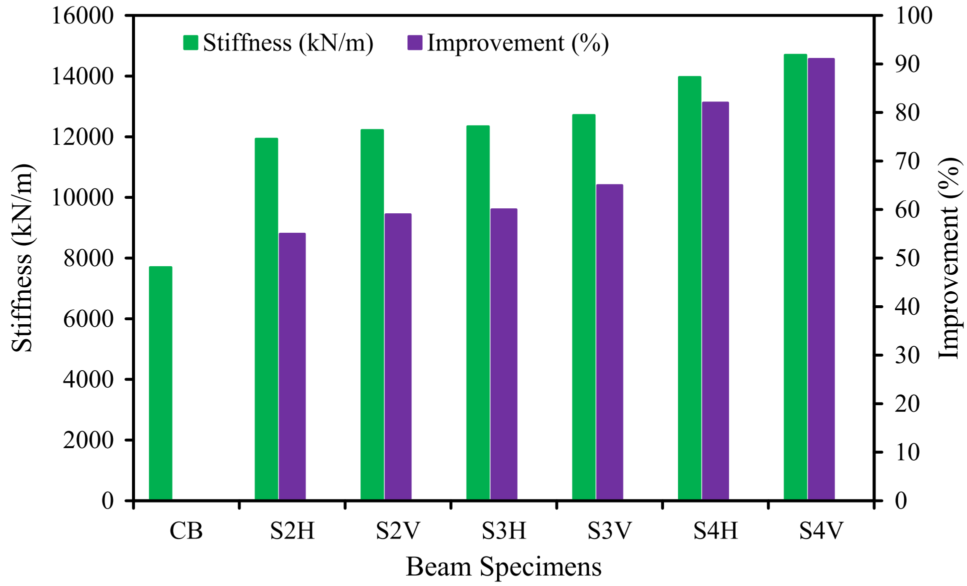



**Fig. 10.** Improved stiffness of the strengthened specimens by SNSM-CFRP strips.

### *3.7. Energy absorption capacities*

The energy absorption capacity of structural members is a dominant behavior for the assessment of the toughness or fracture work [32]. The energy absorption capacity per unit area of the cross-section of the beam specimens is determined by the area of the load-deflection diagram. The energy absorption capacities for all beam specimens and enhancement are graphically shown in Fig. 11. The beam specimens strengthened with the SNSM technique using CFRP-strips significantly enhanced the energy absorption capacity compared with the control specimen. This is due to significant delay in the occurrence of first crack and the enhancement of the yield and ultimate loads by the RC beam specimens strengthened with SNSM-CFRP-strips. The beam specimens strengthened with vertically oriented CFRP-strips showed an increase in energy absorption capacity of about 118–161%. On the other hand, the horizontally oriented CFRP-strips increased energy absorption of about 36–147%. However, the S4H specimen showed a small enhancement in the energy absorption capability compared with the other strengthened specimens due to the rapid failure by debonding of the CFRP-strips together with end concrete cover after yielding and before the rupture of the CFRP strips. It can therefore be concluded that the vertically oriented CFRP-strips showed higher enhancement of energy absorption capacity compared with horizontal oriented CFRP-strips strengthened beam specimens. This significant enhancement of energy absorption capacity relies on the large improvement of load carrying capacity and stiffness and higher deflection at post-cracking stage. The RC beam specimens strengthened by NSM technique using CFRP bars had reduction in the energy absorption capacity up to 49% [22]. The flexurally strengthened with NSM-CFRP strips RC beams showed a decrease in the energy absorption capacity of about 38% [33].

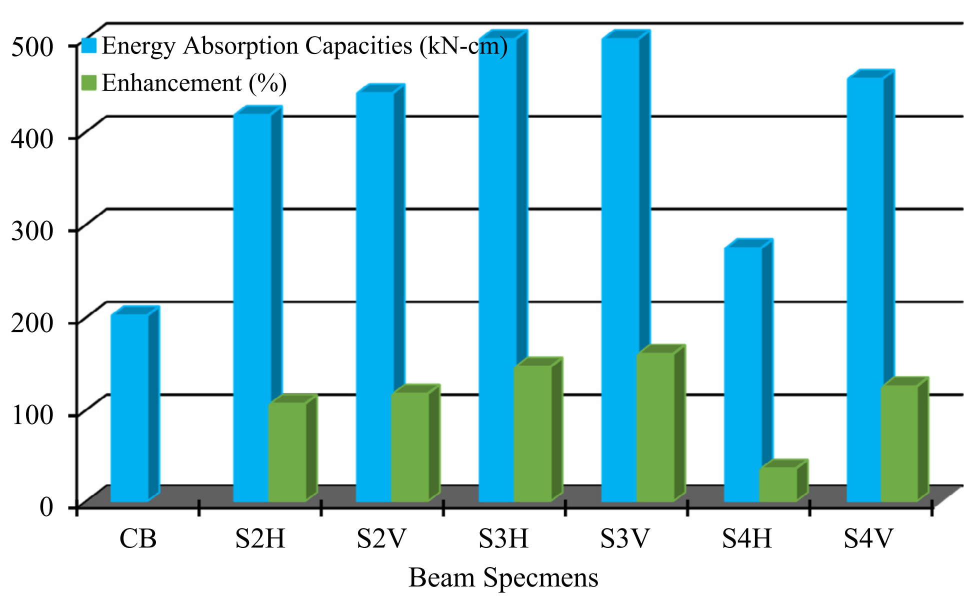



**Fig. 11.** Energy absorption capacity of SNSM-CFRP strips strengthened beam specimens.

### 3.8. Effect of number and orientation of SNSM-strips

The number of SNSM-strips significantly influence the flexural capacity of the RC strengthened beam specimens. Increasing the number of CFRP-strips enhances the flexural capacity of the specimens. However, by increasing the strengthening CFRP-strips in SNSM technique reduces the amount of epoxy adhesive, which could affect the bond performance between the CFRP-strips and concrete substrate. Hence, it is important to determine the influence of the number of CFRP-strips on strengthening performance. The correlation between the flexural capacity and number of CFRP-strips for both orientations (vertically and horizontally) is shown in Fig. 12, and represented by the following Eqs. (1) and (2). However, the vertically oriented of CFRP-strips shows steep gradient, due to its strong $R^2$ value compared with the horizontally oriented strips. The Eqs. (1) and (2) can be used for predicting flexural capacity from the number of CFRP strips.

$$F = 15N + 110.33 \quad (1)$$

$$F = 10.50N + 116.83 \quad (2)$$

where $F$ = flexural capacity (kN), and $N$ = number of CFRP-strips. The experimental flexural capacity of strengthened beam specimens in this study is compared with the predicted by Eqs. (1) and (2) as shown in Table 3. And it is found that the predicted flexural capacity calculated based on equations is very conservatives compared with the experimental values.

The effect of the orientation of CFRP-strips on the flexural capacity and ductility index is shown in Fig. 13. The vertically oriented CFRP-strips in SNSM technique shows a higher flexural capacity compared with the horizontally oriented of strips, due to the greater bending stiffness of the vertically oriented CFRP-strips.

Ductility is a crucial characteristic of the structural elements. It allows the structure to attain ultimate load carrying capacity by controlling the sectional strength. It is also very important in blast loading and earthquake. Ductility is a more complicated problem when flexural RC members are strengthened with fiber reinforced polymer (FRP) plates [34]. Deflection ductility is defined by the ratio of mid-span deflection at ultimate load ($\Delta_u$) to yielding of tension reinforcement ($\Delta_y$) [35].

**Table 3**
Comparison of experimental and predicted flexural capacities.

| Beam specimens | No. of equation | Flexural capacities of the specimens (kN) | |
|---|---|---|---|
| | | Experimental | Predicted |
| S2V | 1 | 138 | 140 |
| S3V | | 160 | 155 |
| S4V | | 168 | 170 |
| S2H | 2 | 135 | 138 |
| S3H | | 154 | 148 |
| S4H | | 156 | 159 |

The values of flexural capacity and deflection ductility versus orientation of the CFRP strips are shown in Fig. 13. The SNSM strengthening technique using the CFRP strips shows that an increase in the number of CFRP strips significantly enhances the deflection ductility, expect for the S4H specimen, due to the end concrete cover separation failure mode. The increased ductility was found 36% and 46%, respectively for horizontally and vertically oriented CFRP-strips, compared with the control specimen. The lesser number of strips strengthened beam specimens showed higher ductility, due to its lower stiffness. Once four strips were used as a horizontal (S4H) and vertical (S4V) oriented strengthened reinforcement, the ductility of the horizontally oriented strengthened specimen decreased of about 13%, while the ductility of the vertically oriented specimen increased by 5%, due to its higher stiffness. Hence, the vertically oriented CFRP-strips in the SNSM strengthening technique significantly enhanced the flexural capacity and ductility.

### 3.9. Effect of strengthening reinforcements

The efficiency of the experimental programme of the SNSM-CFRP-strips technique is controlled by the amount of strengthened reinforcements. Increasing the area of SNSM-CFRP strips significantly enhances the flexural performance up to 147% of the RC beam specimens. The flexural performance of beam specimens strengthened with SNSM-CFRP vertically oriented strips exceeded that of the specimens strengthened with SNSM-CFRP horizontally oriented strips with the same area of strengthening reinforcement,

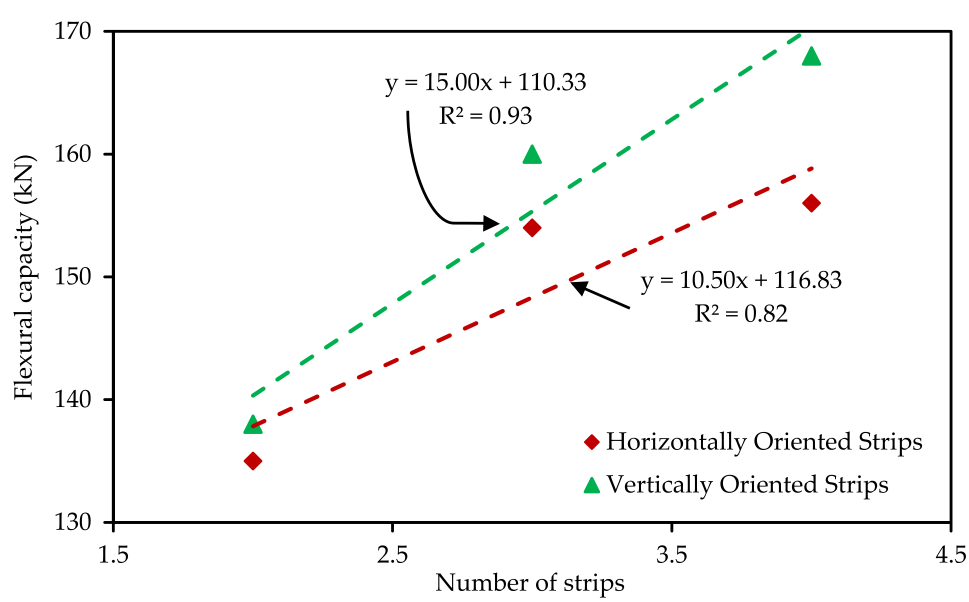



**Fig. 12.** Influence the number of CFRP strips on the flexural capacity.

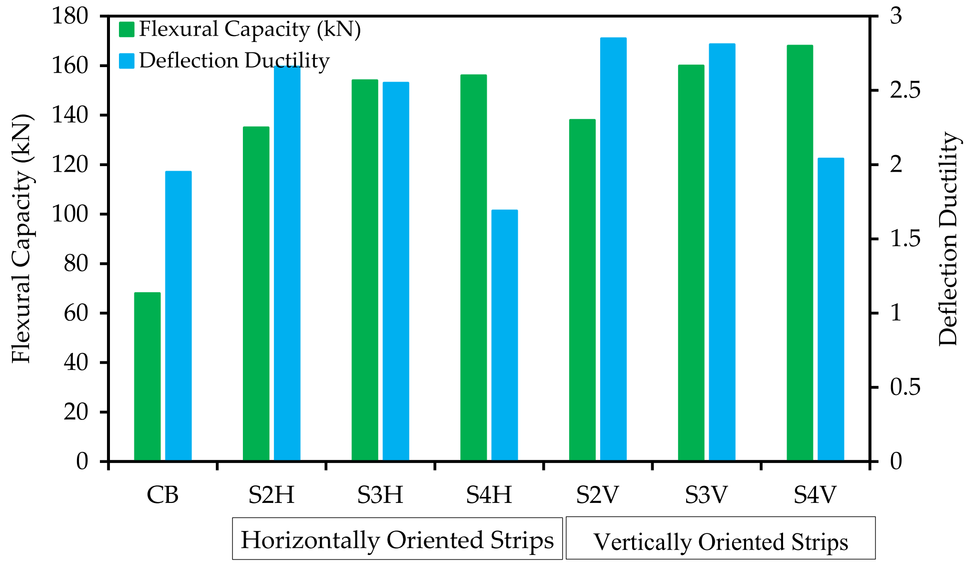



**Fig. 13.** Influence of the orientation of CFRP-strips on the flexural capacity.

at 4% to 18%. The relationship between the flexural performance and area of strengthening reinforcement for SNSM-CFRP strips strengthened beam specimens is illustrated in Fig. 14, and the following equations are proposed for the correlation ($R^2 = 0.94$ for vertical and $R^2 = 0.82$ for horizontal strips):

$$P = 0.61A_s + 62.33 \quad (3)$$

$$P = 0.42A_s + 73 \quad (4)$$

where $P$ = flexural performance (%) and $A_s$ = area of strengthened reinforcement ($mm^2$). The comparison between the experimental and predicted flexural performance of the SNSM-strips strengthened beam specimens based on the equations is shown in Table 4. When the strengthening reinforcement (CFRP) area is used in Eqs. (3) and (4), it was found that the variance between the experimental and predicted flexural performance of the strips strengthened specimens much closer.

**Table 4**
Predicted flexural performance based on the area of CFRP-strips.

| Beam specimens | No. of equation | Flexural performance (%) | |
|---|---|---|---|
| | | Experimental | Predicted |
| S2V | 3 | 103 | 106 |
| S3V | | 135 | 128 |
| S4V | | 147 | 150 |
| S2H | 4 | 99 | 103 |
| S3H | | 126 | 118 |
| S4H | | 129 | 133 |

In contrast, the amount of NSM-CFRP strips was 42 $mm^2$ and increased the flexural capacity up to 47% [18], while strips made using the NSM technique using 56 $mm^2$ of CFRP increased the ultimate load up to 44% [36].

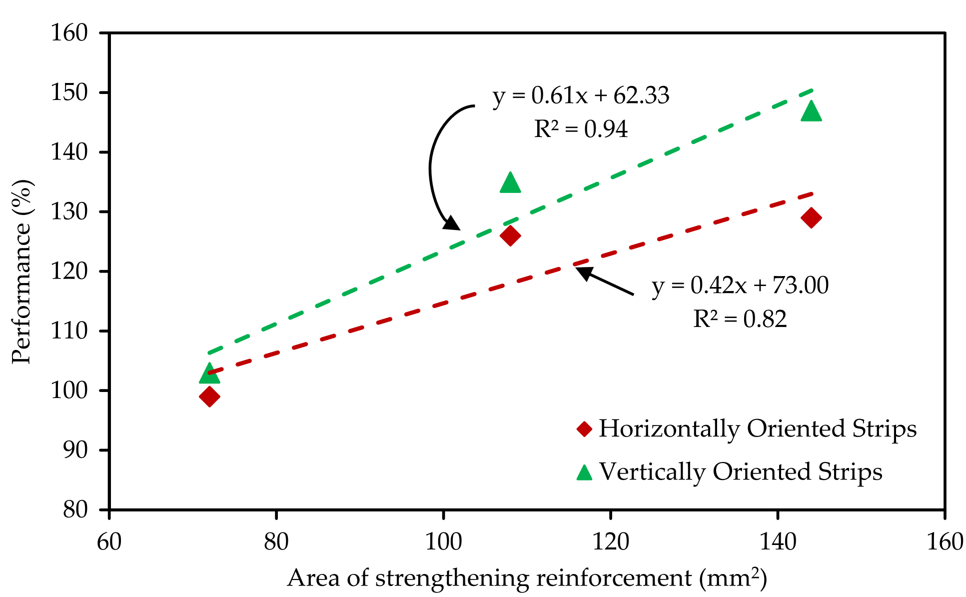



**Fig. 14.** Influence of strengthening reinforcement on the performance of SNSM technique.

## 4. Predictive models

### 4.1. Model of load-deflection curves

The load vs. mid-span deflection for control and strengthened RC beams with SNSM CFRP strips is predicted based on the deflection model reported by Said [37]. The load-deflection curves can be divided into three distinct linear phases, which are (Fig. 15):

(a) Pre-cracking phase ($P < P_{cr}$)
(b) Cracking phase ($P_{cr} \leq P \leq P_y$)
(c) Post-cracking phase ($P_y < P < P_u$)

(*a*) *Pre-cracking phase*: This phase is distinguished by its elastic behavior, as there are no cracks initiated on the concrete section of the beam specimen. Hence, the effective moment of inertia ($I_e$) of the section is considered to be equivalent to the transformed moment of inertia of the un-cracked section ($I_{unc}$), comprising the contribution of the SNSM CFRP strips.

$$I_e = I_{unc} \tag{5}$$

$$I_{unc} = \frac{by^3}{3} + \frac{b(h-y)^3}{3} + nA_s(d-y)^2 + n_{SNSM}A_{SNSM}(d_{SNSM}-y)^2 \tag{6}$$

$$\Delta_{cr} = \frac{(P/2)L_a}{24E_cI_{unc}}(3L^2 - 4L_a^2) \tag{7}$$

(*b*) *Cracking phase*: The behavior of this phase is inelastic due to the cracks being initiated and spread in the concrete section. Hence, the moment of inertia of the concrete section is degraded, but its value is even higher than a fully cracked moment of inertia, due to the influence of tension stiffening. The effect of tension stiffening is maximum at the first cracking load, which is then reduced as the applied load increases until it nearly vanishes at the yielding of specimens, as shown in Fig. 14. Consequently, the un-cracked moment of inertia ($I_{unc}$) is regarded as the upper bound in the phase, while the cracking moment of inertia ($I_{cr}$) is almost at the lower bound of that section. Therefore, the effective moment of inertia ($I_e$) is used is this phase.

$$I_{cr} = \frac{by^3}{3} + nA_s(d-y)^2 + n_{SNSM}A_{SNSM}(d_{SNSM}-y)^2 \tag{8}$$

In accordance with Bischoff [38], the effective moment of inertia in this phase is expressed as:

$$I_e = I_{cr}/\left[1 - (1 - I_{cr}/I_{unc})(M_{cr}/M)^2\right] \tag{9}$$

$$\Delta_y = \frac{(P/2)L_a}{24E_cI_e}\left(3L^2 - 4L_a^2\right) \tag{10}$$

(*c*) *Post-cracking phase*: In this phase, assumed the beam specimen yielded and the concrete section was fully cracked. Hence, the strain hardening effect of steel reinforcement is regarded in this phase, to enhance the accuracy of the model. Thus, the effective moment of inertia (Ie) can be calculated using the curvature of the beam. The curvature in the phase can be evaluated by linear interpolation between the curvature at first yielding of tension steel $\phi_y$ and the ultimate curvature $\phi_u$.

$$\varepsilon_y = \frac{f_y}{E_s} \tag{11}$$

$$\phi_y = \frac{\varepsilon_y}{d-y} \tag{12}$$

$$\phi_u = \frac{\varepsilon_{cu}}{y} \tag{13}$$

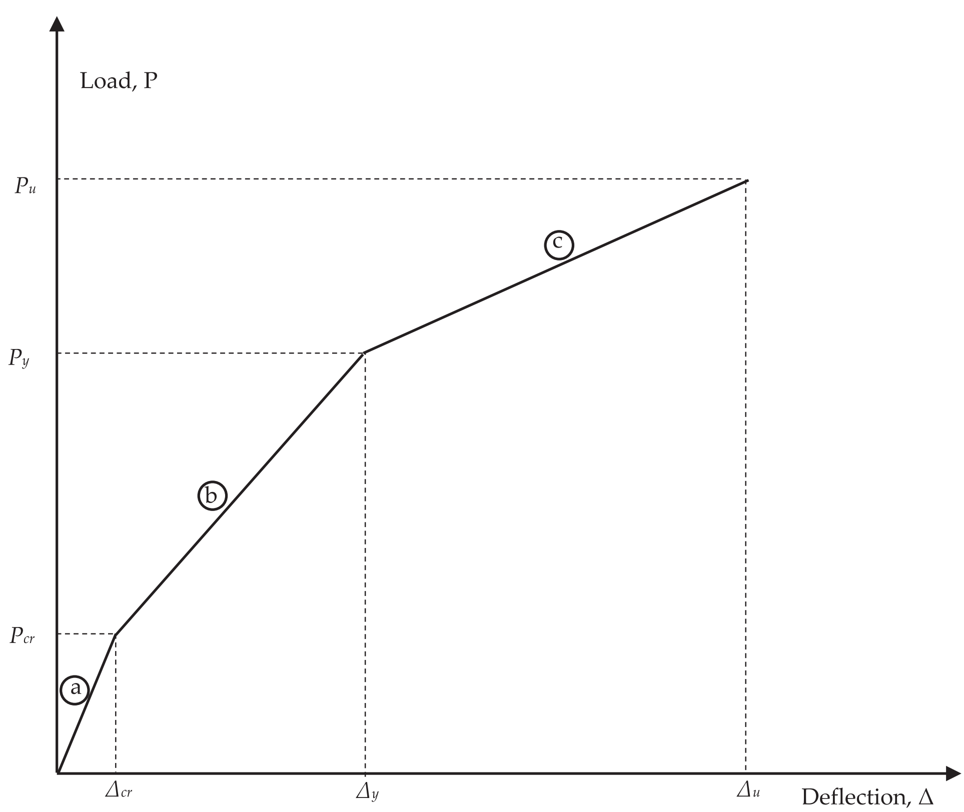



**Fig. 15.** Schematic load-deflection curve of a strengthened beams specimen.

$$\phi = \phi_y + \frac{M - M_y}{M_u - M_y}(\phi_u - \phi_y) \quad (14)$$

$$I_e = \frac{M}{E_c \phi} \quad (15)$$

The deflection of the post-cracking phase can be calculated from Eq. (10), where $A_s$ is cross-sectional area of tension steel, $A_{snsm}$ is cross-sectional area of CFRP-strips, $b$ is the width of the beam, $d$ is the effective depth of the beam section, $E_c$ is the modulus of elasticity of the concrete, $E_s$ is the modulus of elasticity of the tension steel, $E_{snsm}$ is the modulus of elasticity of the SNSM-CFRP strips, $f_y$ is the yield tensile strength of steel, $h$ is the depth of the beam section, $I_{cr}$ is the cracked transformed moment of inertia, $I_e$ is the effective moment of inertia, $I_{unc}$ is the un-cracked transformed moment of inertia, $L$ is the clear span length of the beam, $L_a$ is the shear span length of the beam, $M$ is the applied bending moment, $M_{cr}$ is the cracking bending moment, $M_y$ is the yield bending moment, $M_u$ is the ultimate bending moment, $n$ is the modular ratio, $n_{snsm}$ is the modular ratio of the SNSM-CFRP strips, $P$ is the applied load, $P_{cr}$ is the cracking load, $P_y$ is the yielding load, $P_u$ is the ultimate load, $y$ is the depth of neutral axis, $\epsilon_s$ is the yield strain of tensile steel reinforcement, $\epsilon_{cu}$ is the ultimate compressive strain of concrete, $\phi$ is the curvature, $\phi_y$ is the curvature at yield, and $\phi_u$ is the curvature at ultimate.

### 4.2. Modeling of crack spacing and width

The flexural crack spacing and width of the beam specimens were computed in accordance to the Euro-code 2 [39], which is based on the modular ratio of the CFRP strips and steel reinforcement and the neutral axis (N.A.) location for the composite section of the beam specimens. The flexural crack spacing and width of the SNSM-CFRP strips strengthened beam specimens can be determined as follows:

$$S_m = 50 + 0.25 k_1 k_2 \frac{\phi}{\rho_{eff}} \quad (16)$$

$$\rho_{eff} = \frac{A_s + n_{SNSM} A_{SNSM}}{A_{ceff}} \quad (17)$$

$$A_{ceff} = \min \begin{Bmatrix} 2.5 \times b \times c \\ b \times (h - y)/3 \end{Bmatrix} \quad (18)$$

$$n_{SNSM} = \frac{E_{SNSM}}{E_c} \quad (19)$$

$$w_k = S_m(\varepsilon_{sm} - \varepsilon_{cm}) \quad (20)$$

$$\varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s - k_t \frac{f_{ct}}{\rho_{eff}}\left(1 + \alpha_e \rho_{eff}\right)}{E_s} \geqslant 0.6 \frac{\sigma_s}{E_s} \quad (21)$$

$$\alpha_e = \frac{E_s}{E_c} \quad (22)$$

where $S_m$ is the flexural crack spacing, $k_1$ is the bond coefficient (0.80 and 1.6 for high bond and plain steel rebar respectively), $k_2$ is the strain distribution coefficient (0.50 and 1.0 for bending and pure tension respectively) $\phi$ is the diameter of the steel rebar, $\rho_{eff}$ is the effective reinforcement ratio, $A_{ceff}$ is the effective area of concrete in tension, $w_k$ is the crack width, $\epsilon_{sm}$ is the mean strain in the reinforcement for effects of tension stiffening of the concrete, $\epsilon_{cm}$ is the mean strain in the concrete between cracks, $\rho_s$ is the stress of the tension reinforcement, $k_t$ is the factor of the duration of loading (0.4 and 0.6 for long and short term loading respectively), f_{ct}is the tensile strength of the concrete, and the remaining symbols designating its usual meanings.

## 5. Verification of the models

### 5.1. Validation of load-deflection curves

Fig. 16 depicts the comparison between the load-mid-span deflection curves achieved from the experimental test results and the analytical prediction models for all beam specimens. As seen from the graphs, the experimental and predicted load-deflection curves exhibited agreement, especially for all of the SNSM-CFRP strips strengthened beam specimens. However, the predicted deflection was found lower up to the yielding of the specimen compared with experimental results for control beam specimen.

### 5.2. Validation of crack spacing and width

The predicted flexural crack spacing's for CB, S2H, S2V, S3H, S3V, S4H, and S4V specimens were 91 mm, 65 mm, 64 mm, 61 mm, 60 mm, 59 mm, and 58 mm, respectively. The experimentally obtained values were 92 mm, 59 mm, 56 mm, 44 mm, 43 mm, 69 mm, and 41 mm, respectively, for CB, S2H, S2V, S3H, S3V, S4H, and S4V respectively, signifying a consent between these two. The comparison between the experimental and predicted crack width of the specimens is shown in Fig. 17. As seen from the figure, there is an agreement between the crack width of the predicted and experimental results obtained for all of the beam specimens.

## 6. Conclusions

The following conclusions are made based on this study:

- The SNSM technique with CFRP strips is effective in improving flexural performance. The yield and ultimate load carrying capacities significantly increased up to 108% and 147%, respectively, compared with the control specimen, mainly based on the number and orientation of the strips and failure mode of the specimens.
- The SNSM-CFRP strips significantly enhanced the first cracking and service load up to 153% and 129%, respectively over the control beam specimen, which is very important in the context of serviceability concerns.
- The CFRP strips with SNSM strengthening technique significantly improved the service performance of the RC beam specimens by decreasing deflection at various loading phases.
- The SNSM-CFRP strips strengthened specimens exhibited excellent ductile behavior due to typical flexural failure mode of the specimens (except S4H). This provides ample warning before failure, and could be regarded as a crucial advantage of the SNSM strengthening technique.
- The predicted results of the strengthened specimens showed closer values as that of the experimental results.
- The SNSM strengthening technique with CFRP-strips enhanced the stiffness and energy absorption values up to 91% and 161%, respectively, compared with the control specimen.
- The use of CFRP as a vertically oriented strips resulted in better flexural performance compared with the horizontally oriented strips, due to its higher bending stiffness.
- Further research work is required to investigate the flexural performance of RC beam specimens strengthened with SNSM technique using prestressed CFRP strips.

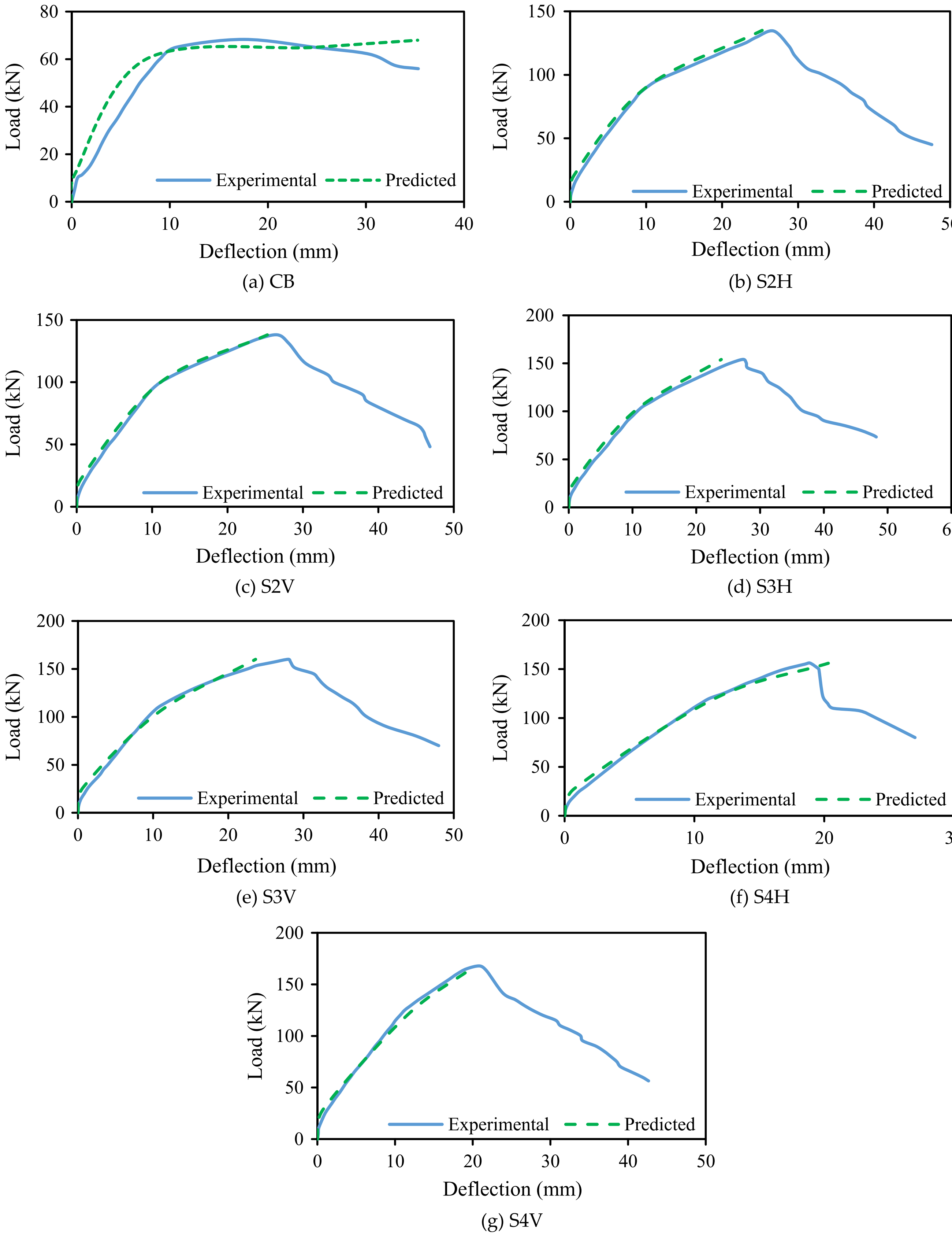



**Fig. 16.** Comparison of experimental and predicted load-deflection curves.

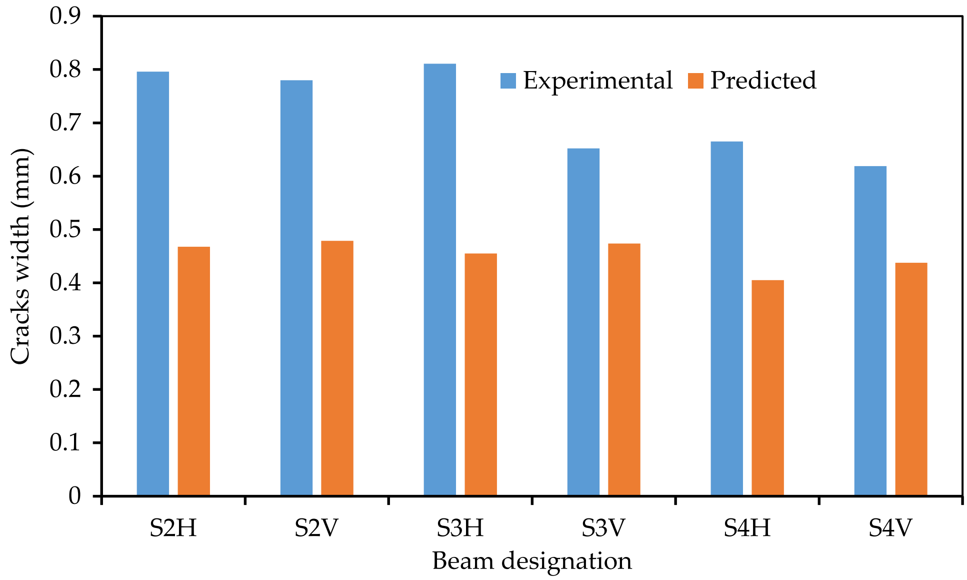



**Fig. 17.** Comparison between the experimental and predicted cracks widths.

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