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Shear retrofitting with manually made NSM FRP sheets (MMFRP) of RC beams

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Abstract

This paper presents an experimental study to evaluate the effectiveness of the proposed carbon manually made fibre-reinforced polymer (MMFRP) folded sheet for shear strengthening of nine RC beams using near-surface mounted (NSM) method, in addition to an unstrengthened control beam. In the laboratory, MMFRP folded sheets were manually manufactured. MMFRP is made by folding an FRP sheet into appropriate groove widths. Carbon MMFRP folded sheets with varying strip amounts, FRP areas and development lengths increase the shear strength of rectangular-reinforced concrete (RC) beams. Double, triple and quadruple strips of FRP were intended to test the enhancement of strength capacity when the strip quantity was just increased without modifying the FRP area and development length. In addition, different FRP areas and development lengths were used to analyse the FRP area and development length of NSM-FRP strips. The advantages of beam strengthening employing different MMFRP folded sheets are explored based on experimental findings. In comparison with the control beam, beams with double, triple and quadruple strips demonstrate 68%, 59% and 74% improvements in shear load-carrying capacity, respectively. However, the study discovered that if the number of strips, FRP area or development length is raised, the member's shear strength capability is estimated to improve.

Keywords: Shear strengthening, NSM FRP strip, CFRP, MMFRP, Reinforced concrete beams

Introduction

The usage of fibre reinforcement polymer (FRP) composites for the strengthening of various reinforced concrete structural elements is widespread. Glass FRP (GFRP), carbon FRP (CFRP), aramid FRP (AFRP) and basalt FRP (BFRP) are the most commonly used types. Due to their strong tensile and ductility qualities, CFRP and GFRP are the most commonly used FRP materials for strengthening. FRP can also be manufactured by combining different materials to create a hybrid FRP composite that combines the benefits of both. Due to their advantageous features, FRP composites have recently grown in popularity in the construction industry. First and foremost, FRP may be pultruded as needed in the field. FRP can make the strengthening process more efficient, quick and effective. Plates, strips, sheets, rods and laminates are all popular forms of FRP composites. The externally bonded (EB) system and the near-surface mounted (NSM) system are two of the most popular FRP strengthening techniques.

The NSM system entails embedding additional reinforcement inside the weak structural member's concrete cover. Because it is so easy to make a considerable increase in the structural member's capacity, this technique has outperformed most of the other ways. Furthermore, this procedure requires maintaining the aesthetics of structural parts while also appropriately protecting the strengthening material from damaging environmental influences. Several studies have shown that the NSM approach may be utilised to reduce debonding between FRP and concrete. This failure scenario prevents the strengthening material from performing its maximum potential. However, with some strengthening approaches, such as EB-FRP, the debonding mode of failure appears to be the primary mode of failure.

The goal of this research is to look into using the NSM CFRP technique for shear strengthening rectangular RC beams.

(1) To study the efficacy of the NSM-FRP technology in improving the load capacity of shear-deficient rectangular RC beams
(2) To investigate the effects of various FRP configurations on specimen load capacity and deformational properties
(3) To look into the failure processes of RC beams that have been strengthened with the NSM technique

Previous research

Because of its simplicity, the EB method is the most widely utilised strengthening approach. It is typically utilised to strengthen structural parts for flexure, axial, torsion and shear. The EB approach has been used to investigate a number of shear applications. The FRP composite is commonly applied to the concrete cover of the weak structural member using epoxy resin, adhesive anchors, cementation mortar or mechanical fasteners in the EB system. The system can sometimes be employed by combining two methods: resin/mechanical fasteners or adhesive anchors/cementation mortar. However, the EB approach has certain disadvantages, including premature debonding of the FRP composite from the concrete substrate, low fire resistance, which causes bond breakdown at elevated temperatures due to complete exposure, and inability to be put on wet surfaces. The NSM-FRP strengthening technology is used to address these difficulties [1].

Shear strengthening of RC beams has been the subject of numerous investigations. Rizzo and Lorenzis [2] looked into the possibility of employing carbon fibre-reinforced polymer (CFRP) to improve the shear load-carrying capacity of beams. The effectiveness of NSM CFRP strips and round bars was investigated by the authors, as shown in Fig. 1.

Fig. 1 CFRP rods and strips

One specimen was strengthened with EB laminates for comparison purposes. When compared to the unstrengthened reference beam, utilising NSM-CFRP bars, NSM-CFRP strips and EB-CFRP laminates increased the shear strength of the beams by 44%, 41% and 16%, respectively. Furthermore, additional researchers discovered that CFRP bars applied using the NSM approach increased the shear strength of RC thin beams by 17 to 25% [3].

Badawi and Soudki [4] found that RC beams strengthened with NSM CFRP rods had a minor loss in ductility. Their findings also revealed that as the prestressing level of RC beams grew, the ductility of the NSM CFRP strengthened beams decreased. When a traditional failure mode is established, the NSM approach may have a minimal effect on the eventual elongation of RC components [5]. In cases of non-classical failures, peeling, as reported by Al Mahmoud et al. [6], De Lorenzis et al. [7] and Radfar et al. [8], or pull out of the CFRP rod, as observed by Al Mahmoud et al. [9], De Lorenzis and Nanni [10] and De Lorenzis et al. [11], can lead to a more brittle and less ductile state.

According to research conducted in Germany, the bonding qualities of NSM CFRP strips are superior than those of CFRP strips that are externally bonded [12]. According to Arduini, Gottardo and DeRiva [13], using high-strength mortar with compensating shrinkage or epoxy putty ensures that the NSM FRP strengthening system is fully used.

Beams strengthened using rectangular NSM CFRP rods with epoxy adhesive and cement grout as a bonding agent enhanced their ultimate load-carrying capability by 77 and 56%, respectively [14]. The ultimate load capacity was enhanced by 108 and 93%, respectively, when high-strength rectangular NSM FRP rods and high-modulus rectangular NSM FRP rods were used [15].

Hassan [16] studied the performance of several NSM FRP reinforcing bars and strips, as well as externally bonded FRP sheets, on small-scale concrete beams and slabs, including a cost analysis for each of the FRP strengthening approaches. The use of NSM CFRP reinforcing bars increased the strength by 36%, according to test findings. Due to strip peeling failure, employing NSM CFRP strips enhanced the strength by 43%, compared to just 11% using the axial stiffness employed as externally bonded strips. According to Hassan [16], the bond qualities of the FRP reinforcing bars, as well as the bond between the epoxy adhesive material and the surrounding concrete in the groove, determine the efficiency of utilising FRP reinforcing bars as NSM reinforcement.

This study used the NSM method to test the effectiveness of the proposed manually made FRP folded sheet (MMFRP) for shear strengthening of nine RC beams. Through an experimental and numerical investigation, the effect of the MMFRP sheet on the behaviour of strengthened beams was investigated.

Experiment

All of the specimens were made using the same materials and had the same geometry. The average compressive strength of a 28-day cube was found to be 30 1.5 ± MPa. The beam has a length of 2300 mm, a width of 150 mm and a depth of 250 mm. From all sides, a constant concrete cover of 25 mm has been maintained. With a clear span of 2000 mm between the supports, all beams were 4-point monotonically loaded. As illustrated in Fig. 2, the loading points were placed 550 mm from each support and 900 mm from the other loading point. The beam reinforcement has been constructed to make the beam shear deficient only at the crucial shear span, in order to meet the study goals efficiently. As a result, preliminary

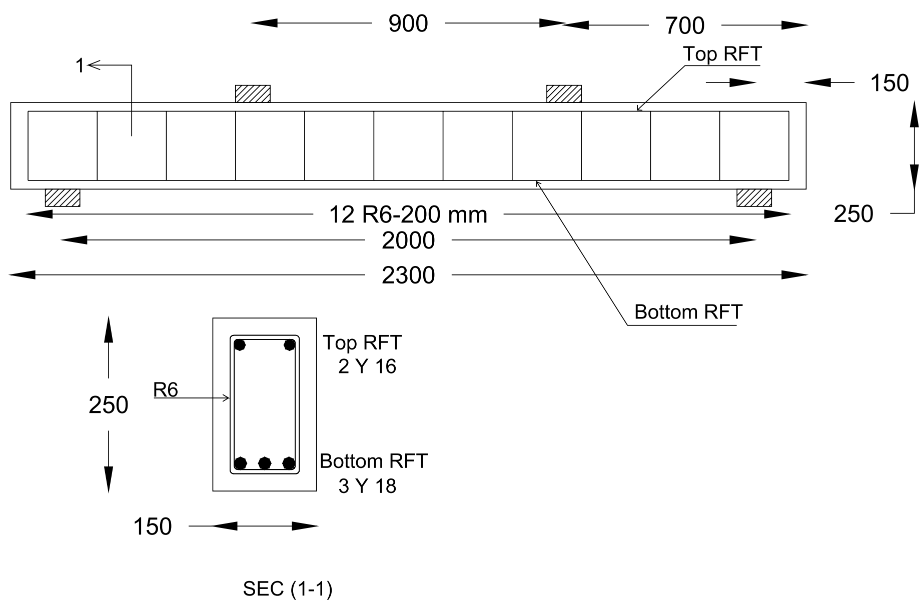

Fig. 2 Beam specimen diminutions and reinforcements details

Table 1 Properties of epoxy as reported by the manufacturer

Properties	For curing Temperature +25 °C	For curing Temperature +55 °C
Tensile strength (MPa)	17.5	28
Compressive strength (MPa)	85	110
Modulus of elasticity (MPa)	10,000	10,000

estimates show that the beams will largely fail in a compression shear mode near the critical shear span (CSS). As a result, it is a representation of a real-life situation of RC beams with low shear strength. Figure 2 shows the specifics of beam specimen diminutions and reinforcements. The manufacturer's values of tensile strength, elastic modulus and ultimate tensile strain of CFRP sheets were equal to 3500 MPa, 225 GPa and 1.56%, respectively.

Sikadur® 30 LP epoxy adhesive resin was utilised in the installation of FRP strips inside the prepared grooves for NSM specimens. This epoxy was delivered by the manufacturer as two components (A + B). Typically, a mixture is made by mixing a ratio of (1:3) from (B:A). This epoxy is suitable to be used in the tropical and hot climates, whereas it is specially designed to perform effectively at hot temperatures (+25 to +55 °C). The mechanical properties of the epoxy are presented in Table 1.

Specimen design and manufacture

MMFRP, a novel type of folded CFRP bar, was created in the lab by physically folding FRP sheets over itself. These bars are made of 235 g/m^2 area density dry unidirectional carbon fibre sheet. The FRP strips were cut off the FRP roll and folded around themselves with varying lengths and widths, which were estimated based on the required design cross-sectional area and variable development lengths needed, as shown in Table 2.

Table 2 Details of CFRP strips

Specimen	FRP strips length (mm)	FRP strips width (mm)	No. of stirrups (one side)	Area of one stirrups (mm^2)	Area of all stirrups (one side) mm^2
B1	0	0	0	0	0
B2	900	124	2	16	32
B3	900	124	3	16	48
B4	1050	124	2	16	32
B5	1050	124	3	16	48
B6	1700	31	4	8	32
b7	1700	124	2	32	64
b8	900	124	4	16	64
b9	1700	41	3	11	32
b10	1700	62	4	16	64

Table 3 Details of specimens strengthening

Specimen	Area of one strip (mm^2)	Strengthening scheme using CFRP sheet	Stirrups spacing (mm)	Area of all stirrups (one side) mm^2	Development length (mm)
B1	0	0	0	0	0
B2	16	NSM CFRP two stirrups	300	32	150
B3	16	NSM CFRP three stirrups	150	48	150
B4	16	NSM CFRP two stirrups	300	32	300
B5	16	NSM CFRP three stirrups	150	48	300
B6	8	NSM CFRP four stirrups	100	32	950
b7	32	NSM CFRP two stirrups	300	64	950
b8	16	NSM CFRP four stirrups	100	64	150
b9	11	NSM CFRP three stirrups	150	32	950
b10	16	NSM CFRP four stirrups	100	64	950

Tin medium-scale RC rectangular beams were used in the test programme. For reference, one beam specimen was left unstrengthened. Table 3 shows how the remaining nine beams were strengthened for shear using MMFRP sheets and the NSM method.

The following are the test parameters that were investigated:

a) The number of NSM FRP stirrups utilised to strengthen the beams: two, three and four stirrups
b) FRP area used to strengthen the beams: 32, 48 and 64 mm^2 (one-side area)
c) Development length: 150, 300 and 950 mm. Knowing that the FRP sheets ($Ld = 950$) were cut into one slice (1700-mm length) and double-layered inside each groove. Development length is calculated as overlap length of strips as shown in Fig. 3.

Experimental method

Before strengthening, after the beams had been adequately cured for at least 4 weeks, B1 was loaded until it failed and was used as a control beam; the other nine beams were loaded to 75% of B1's load-carrying capability. All specimens after loaded to

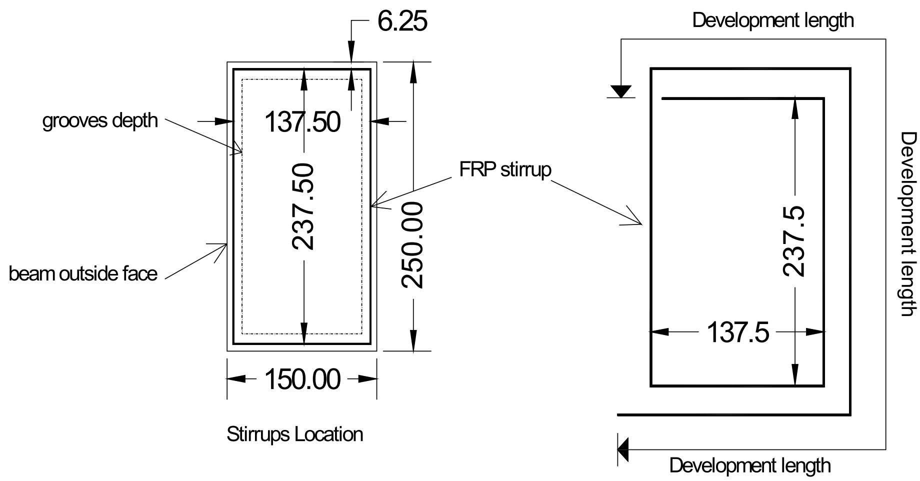

Fig. 3 Calculation method of development length

Fig. 4 Cutting machine

75% of B1's load-carrying capability have two main shear open cracks at CSS zone. The nine beams were unloaded thereafter. All cracks closed after unloading. After strengthening, the nine reinforced RC beams were reloaded until each one failed.

The following is a summary of the strengthening procedure:

1. Making (MMFRP) folded sheets by cutting FRP sheets using a cutting machine (shown in Fig. 4) according to the manufacturer's recommendations to produce FRP strips, then this FRP strips folded over itself as illustrated in Fig. 5a, b and c, after that, install folded strips by pins as shown in Fig. 5d, e and f to produce FRP stirrups.
2. For NSM, grooves were cut into the concrete cover for the beam, as illustrated in Fig. 6.
3. Using epoxy as a filling material for the NSM procedures, install the FRP stirrups into the constructed grooves for NSM, as illustrated in Fig. 7. Figures 8, 9 and 10 show the strengthening systems of nine beams.

Based on the FRP designs depicted in Fig. 7, many grooves were produced at the CSS from all sides for each beam using a HILTI DC-SE20 slitting machine. Each groove is 25 mm wide and 15 mm deep, and it runs the whole of the beam. Compressed air-brushing equipment was used to clean the grooves of dust, dirt and other small particles. After all of the grooves had been made, each beam's FRP stirrups were installed side by side in the grooves.

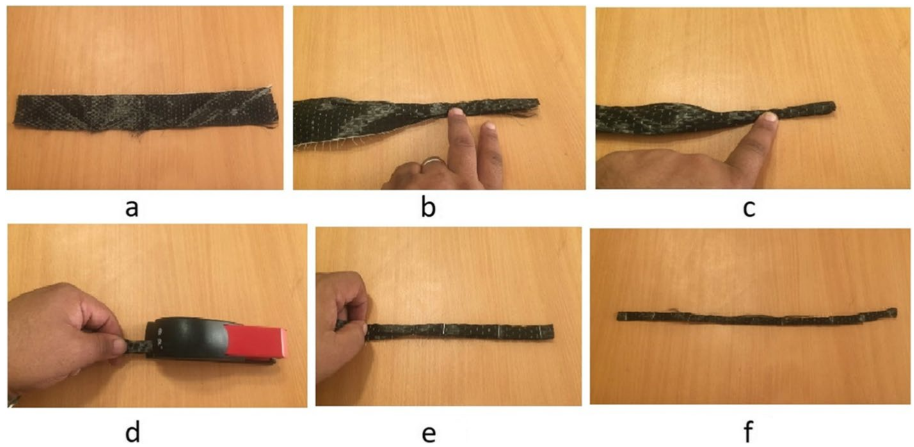

Fig. 5 Manufacturing procedure of MMFRP sheets. **a** Cut FRP sheet to strips. **b** Fold strip over itself. **c** Fold strip again. **d** Install folded strips by pins. **e** Install by more pins. **f** Stirrup ready to use

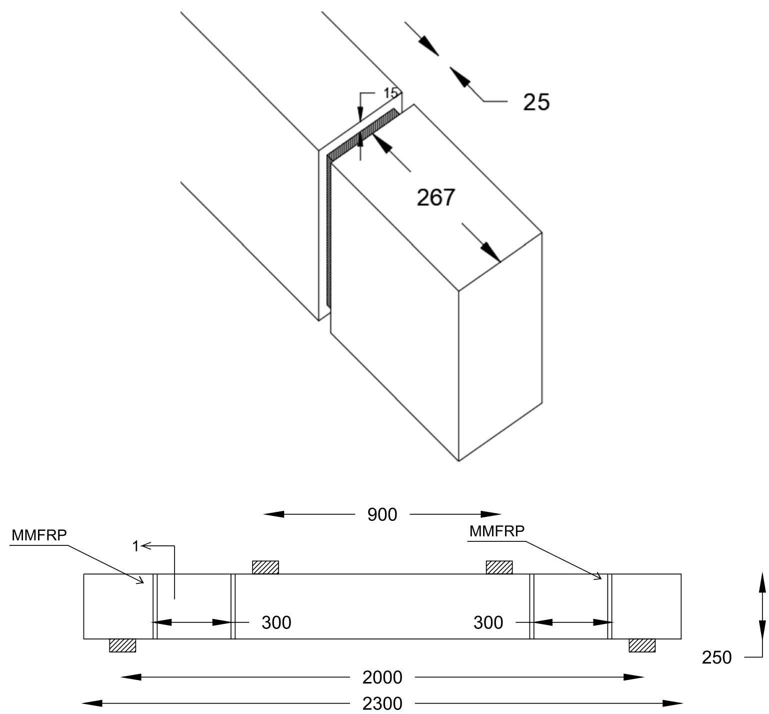

Fig. 6 Illustration drawing to show the NSM strengthening technique (dimensions are in mm)

The beams were loaded with a controlled-displacement loading system to monitor descending peak load zone that used hydraulic to load them in a monotonous 4-point pattern. The beams were loaded at a rate of 0.25 mm/min until they failed.

Results and discussion

Table 4 shows the maximum deflection at failure at mid-span, the contributions of the concrete and CFRP to shear resistance and the gain incapacity owing to the CFRP, defined as "gain = Vf/(Vtot — Vf)". It is worth noting that the shear

Fig. 7 NSM strengthening technique procedure

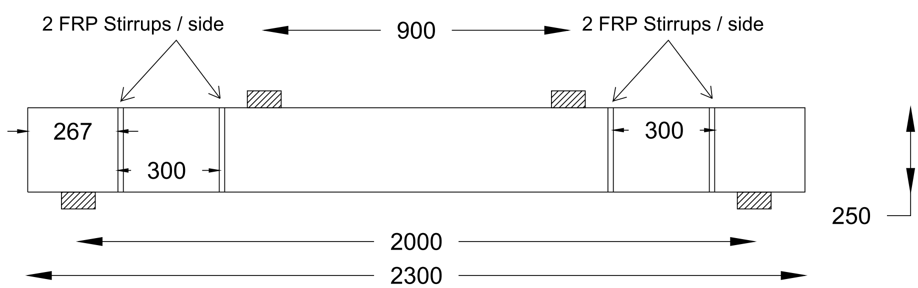

Fig. 8 NSM strengthening systems for B2, B4, and B7

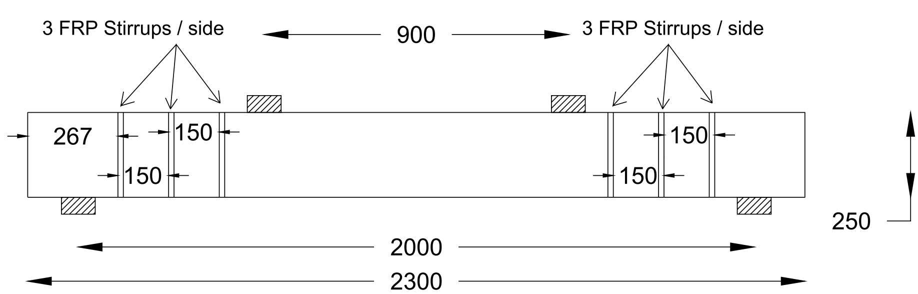

Fig. 9 NSM strengthening systems for B3, B5, and B9

contributions of concrete and steel are computed using the reference specimen's values, and shear failure occurred in all test specimens.

Total shear resistance = Pu/2

Resistance due to concrete and steel = Pu for B1/2

Resistance due to CFRP = total shear resistance — resistance due to concrete and steel

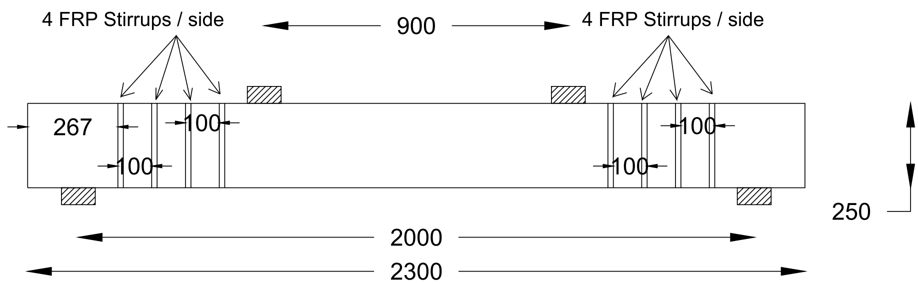

Fig. 10 NSM strengthening systems for B6, B8, and B10

Table 4 Experimental results

Specimen	Pu	Total shear resistance	Resistance due to concrete and steel	Resistance due to CFRP and epoxy	Gain due to CFRP and epoxy	Deflection mid. span
	KN	KN	KN	KN		Mm
B1	145	72.5	72.5	0.0	0%	9.0
B2	203	101.5	72.5	29.0	40%	12.2
B3	201	100.5	72.5	28.0	39%	8.8
B4	208	104.0	72.5	31.5	43%	18.5
B5	214	107.0	72.5	34.5	48%	13.1
B6	229	114.5	72.5	42.0	58%	17.7
B7	243	121.5	72.5	49.0	68%	15.0
B8	225	112.5	72.5	40.0	55%	13.0
B9	230	115.0	72.5	42.5	59%	15.8
B10	252	126.0	72.5	53.5	74%	16.0

Gain due to CFRP = resistance due to CFRP/(total shear resistance — resistance due to CFRP)

The CFRP-strengthened specimens failed due to FRP debonding and shear diagonal tension failure. Figure 11 depicts the failure conditions of each specimen. The next paragraphs go through the specifics of specimen failures.

Specimen B1

A twin shear-cracks pattern was seen in control specimen B1, which had not been strengthened. The shear crack began at the CSS of the beam, between the support and the point loads. The shear crack spread at around a 42° angle. One-hundred forty-five kilonewton was the shear failure load for the specimen B1 specimen.

Specimen B2

A 16-mm^2 area, a closed jacket with a development length of 150 mm and strips spaced 300 mm were used to strengthen this specimen. The cracking started at around the same stress level for all beams, which was around 80 kN. Specimen B2 had a shear failure load of 203 kN. CFRP resulted in a 40% increase in shear capacity. During loading, all of the specimens modified with CFRP strips exhibited local strip debonding. Each local strip-debonding event resulted in a significant reduction in the beam’s load-carrying capacity, but the load

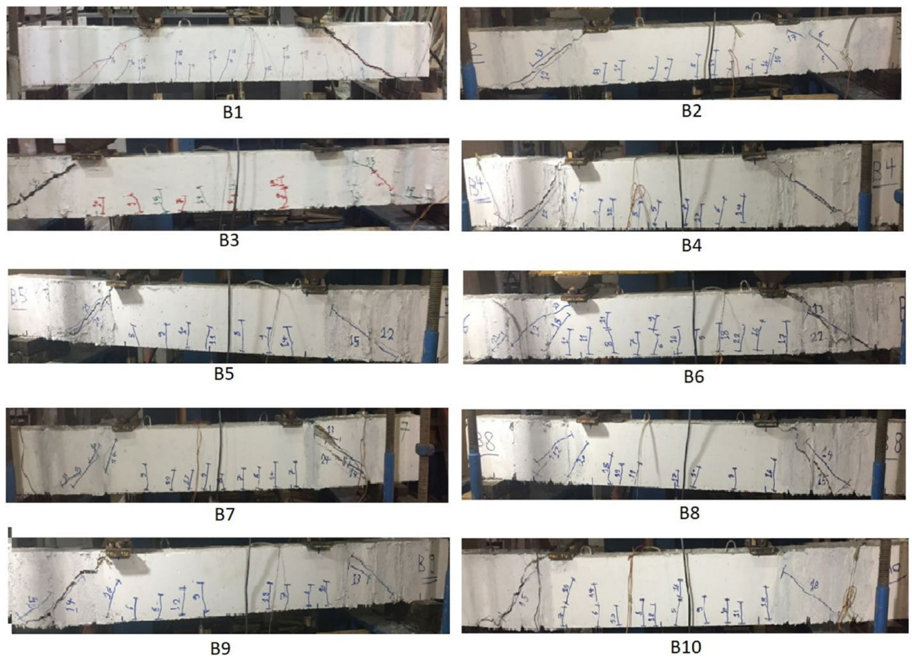

Fig. 11 Failure shape of specimens

continued to rise as the shear cracks spread, contacting the empty CFRP strips along their path.

Specimen B3

A 16-mm^2 section of closed jacket CFRP sheet with a development length of 150 mm and strips spacing of 150 mm was used to strengthen this specimen. Specimen B3 had a shear failure load of 201 kN. CFRP increased shear capacity by 39%.

Specimen B4

A 16-mm^2 area, a closed jacket with a development length of 300 mm and strips spaced 300 mm were used to reinforce this specimen. Specimen B4 had a shear failure load of 208 kN when it failed. For specimen B4, the increased development length resulted in a modest improvement in shear capacity. CFRP resulted in a 43% increase in shear capacity.

Specimen B5

This specimen was reinforced with two 16-mm^2 closed jacket CFRP sheets, each having a development length of 300 mm and a strip spacing of 150 mm. Specimen B5 had a shear failure load of 214 kN. For specimen B5, the increased development length resulted in a modest improvement in shear capacity. CFRP resulted in a 48% increase in shear capacity.

Specimen B6

This specimen was reinforced with 8-mm^2 closed jacket CFRP sheet with a development length of 950 mm and strips spacing of 100 mm. The shear failure load for specimen B6 was 229 KN. The addition of a second CFRP layer to specimen B6 resulted in a small increase in shear capacity. CFRP resulted in a 58% increase in shear capacity.

Specimen B7

This specimen was reinforced with two 32-mm^2 closed jacket CFRP sheets, each with a development length of 950 mm and a strip spacing of 300 mm. Specimen B7 had a shear failure load of 243 kN when it failed. The addition of a second CFRP layer to specimen B7 resulted in a small increase in shear capacity. CFRP resulted in a 68% increase in shear capacity.

Specimen B8

A 16-mm^2 area, a closed jacket with a development length of 100 mm and strips spaced 150 mm were used to strengthen this specimen. The shear failure load for specimen B8 was 225 KN. The addition of a fourth CFRP stirrup to specimen B8 resulted in a small increase in shear capacity. CFRP resulted in a 55% increase in shear capacity.

Specimen B9

Using a development length of 950 mm and strips spacing of 150 mm, this specimen was strengthened with 11-mm^2 double layers of closed jacket CFRP sheet. The shear failure load for specimen B9 was 230 kN. The addition of a second CFRP layer to specimen B9 resulted in a small increase in shear capacity. CFRP resulted in a 59% increase in shear capacity.

Specimen B10

This specimen was reinforced with two 16-mm^2 closed jacket CFRP sheets, each with a development length of 950 mm and a strip spacing of 100 mm. The maximum shear failure load for specimen B10 was 252 kN. The addition of a second CFRP layer to specimen B10 resulted in a small increase in shear capacity. CFRP resulted in a 74% increase in shear capacity.

Figures 12, 13 and 14 depict each load-deflection curve depending on the development length for a specimen with the same total area and spacing. The final strength of

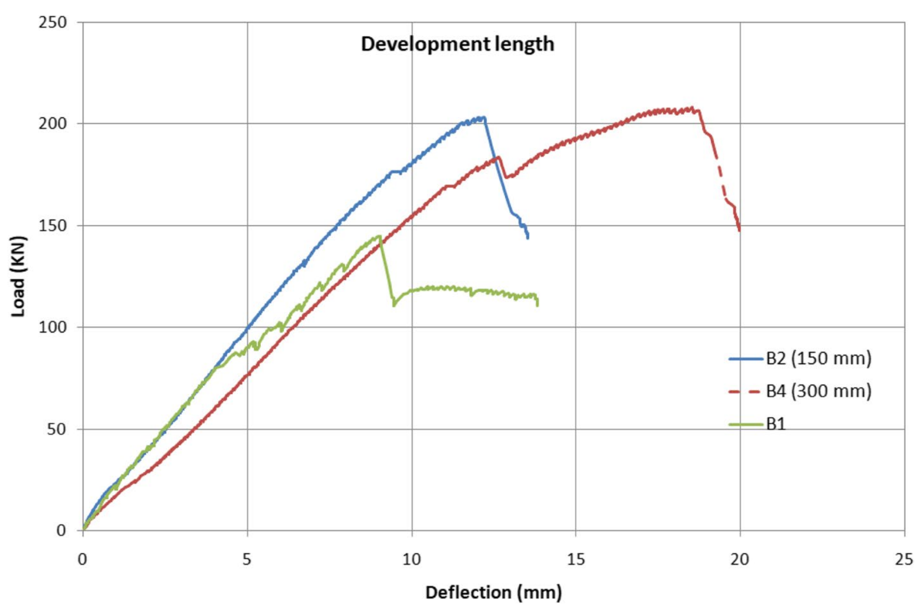

Fig. 12 Load-deflection curve of specimens with 32 mm^2 strips area and 300 mm spacing

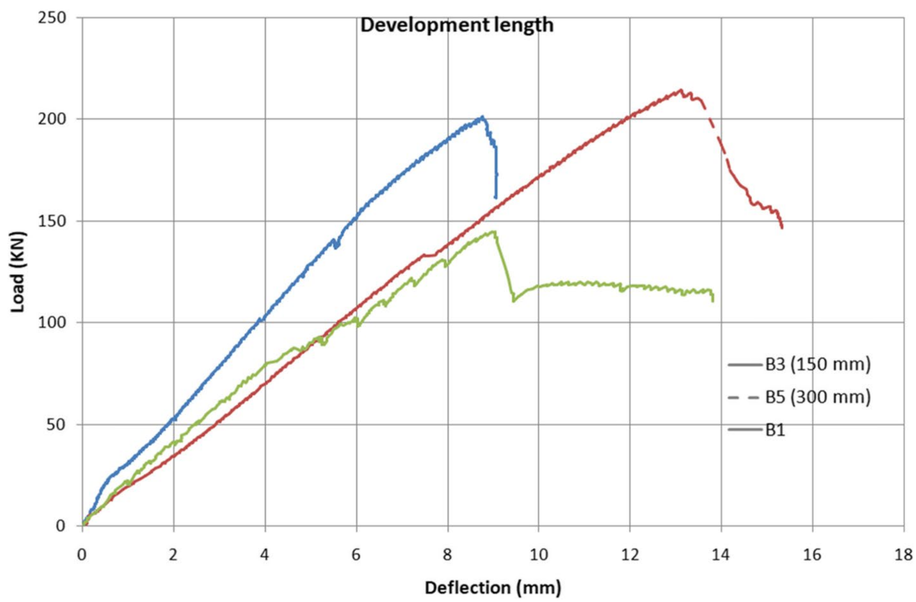

Fig. 13 Load-deflection curve of specimens with 48 mm^2 strips area and 150 mm spacing

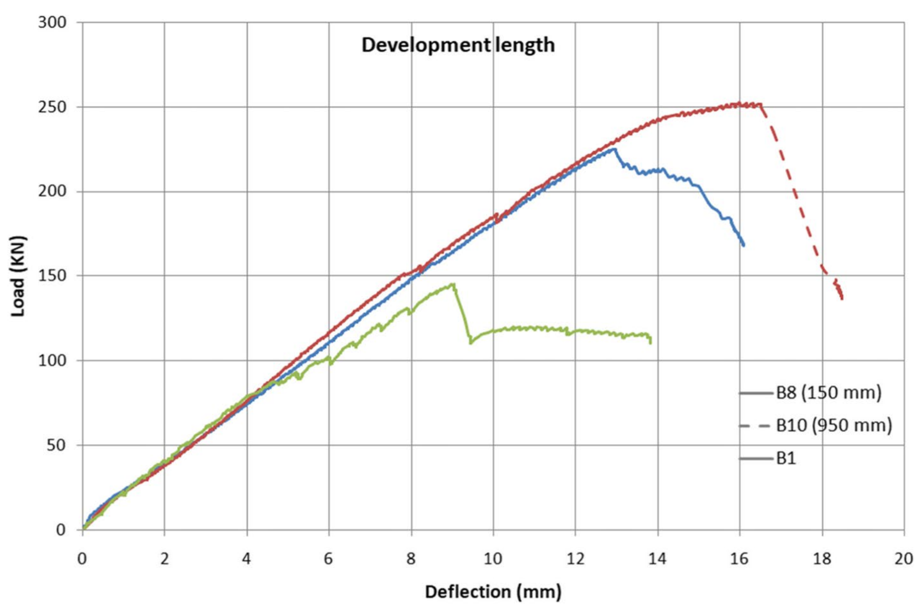

Fig. 14 Load-deflection curve of specimens with 64 mm^2 strips area and 100 mm spacing

the specimen is directly related to the development length of CFRP stirrups, as shown in Figs. 12, 13 and 14. The reason for the difference in stiffness between specimens B2 and B4 and also B3 and B5 is the difference of compressive strength of a 28-day cube (28.5 MP for B4 and B5, 31.5 MP for B2 and B3).

Figures 15 and 16 depict each comparative load-deflection curve for a specimen based on strip spacing for a specimen with the same total area and development length. Figures 15 and 16 show that the specimen's final strength is inversely related to the stirrups spacing.

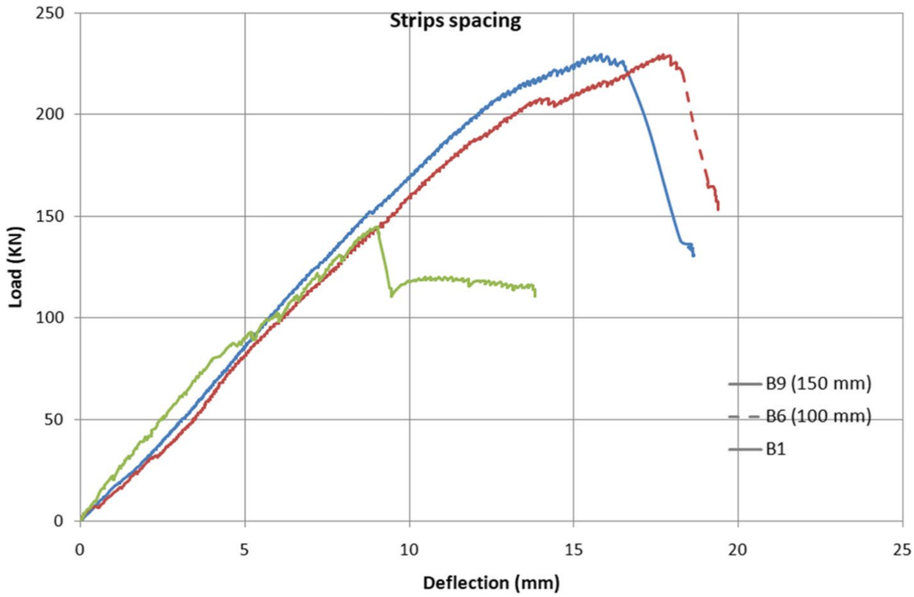

Fig. 15 Load-deflection curve of specimens with 32 mm^2 strips area and 950 mm development length

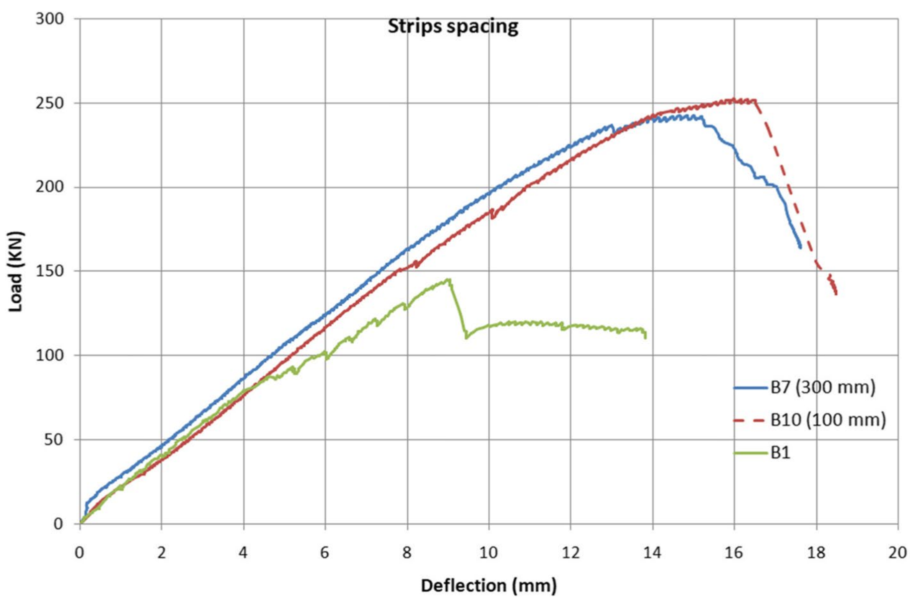

Fig. 16 Load-deflection curve of specimens with 64 mm^2 strips area and 950 mm development length

Figure 17 depicts each load-deflection curve based on the total area of the stirrups for a specimen with the same stirrup spacing (100 mm) and development length (950 mm). The specimen's final strength is precisely related to the stirrup's overall area, as shown in Fig. 17.

In comparison with the matching reference specimens, the NSM strengthening system demonstrated a considerable rise in Pu with a gain percentage ranging from 39 to 74%, as shown in Fig. 18. This demonstrated the NSM application's efficacy in shear strengthening RC beams. On the other hand, the efficiency of the strengthening system varied depending on the factors that were examined.

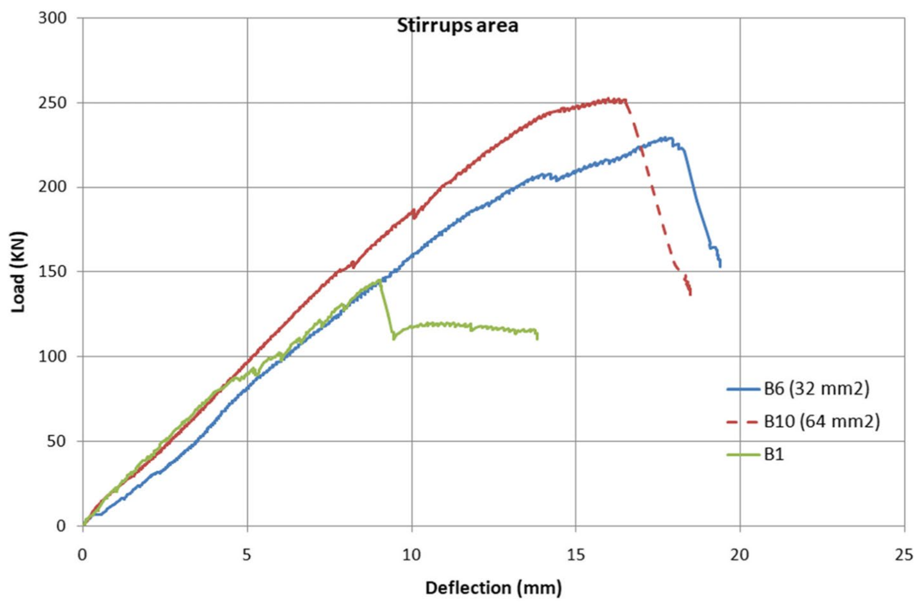

Fig. 17 Load-deflection curve of specimens based on the spacing of the strips

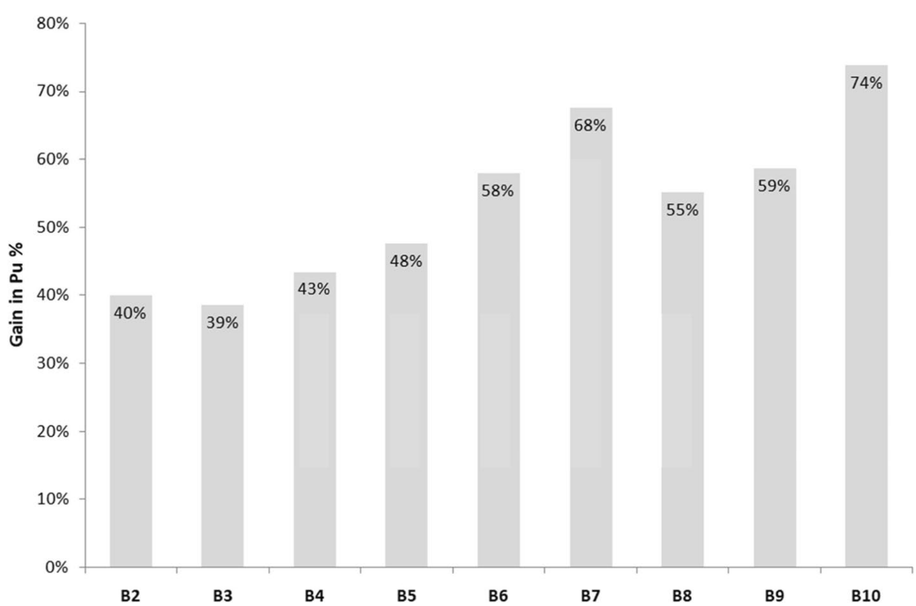

Fig. 18 Gain in Pu % for strengthened specimens

Conclusions

In this study, an experimental method was used to explore the behaviour of RC beams when strengthened in shear using the NSM technology with new MMFRP sheets. From the findings of this study, the following conclusions may be taken.

- Beams strengthened in shear using NSM MMFRP sheets showed a 74% increase in shear capacity and increase in the number and propagation of new fractures as compared to the control beam.

- The development length and total area of CFRP strips are directly related to the ultimate strength of beams strengthened in shear with NSM MMFRP sheets.
- The ultimate strength of NSM MMFRP sheets-strengthened beams under shear is inversely related to the strip spacing.
- The suggested sheets substantially improved the ductility of the shear specimens.

Abbreviations

NSM	Near-surface mounted
EB	Externally bonded
FRP	Fibre-reinforced polymer
MMFRP	Manually made fibre-reinforced polymer folded sheet
RC	Reinforced concrete
GFRP	Glass fibre-reinforced polymer
CFRP	Carbon fibre-reinforced polymer
BFRP	Basalt fibre-reinforced polymer
AFRP	Aramid fibre-reinforced polymer
LD	Development length
CSS	Critical shear span
Vf	Contribution of FRP strips in the shear strength
Vtot	Total shear strength
Pu	Ultimate load-carrying capacity

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Authors' contributions
Corresponding author MGA is a researcher who did the experiment and wrote the manuscript. And HMS read and approved the final manuscript.

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Availability of data and materials
All data and materials will be available upon request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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