Research Article

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Rehabilitation of reinforced concrete deep beams by near-surface-mounted steel reinforcement

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Abstract: This article describes an experimental investigation of the behavior of reinforced concrete deep beams repaired by near-surface-mounted (NSM) steel bars. The first beam was loaded under a two-point load up to failure, and the other six deep beams were loaded to 0.4 and 0.75 of ultimate load. Then, they were repaired by NSM steel bars. The bar orientation and angle were the main variables in these beams. The primary goal of this study is to determine whether it is possible to restore the reinforced concrete deep beam with shear reinforcement to its full load-carrying capacity by NSM steel bars as the method of repair. All deep beams were tested with a shear span-depth ratio of 0.8. The test findings showed that the NSM steel repair bars were very effective in restoring the loaded deep beams' full capacity. Moreover, NSM steel bars enhanced the original deep beams' strength capacity from 4.16 to 19.44%. The ultimate load, mechanisms of failure, load–crack width distribution, and load–deflection profile are tracked as results.

Keywords: near-surface mounted, deep beam, shear capacity, configuration, embedded bar

1 Introduction

For some structures, an increase in the capacity of members becomes mandatory for various reasons, such as loading changes, design errors, and corrosion phenomena which cause the deterioration of these elements. Moreover, restoring or increasing beams' capacity needs strengthening not only for flexural but also for shear.

The use of the near-surface-mounted (NSM) method as a technique for repairing and strengthening existing damaged concrete structures has become popular in the last decade [1]. The NSM method is an effective way of shear strengthening the concrete elements [2]. This technique is not only quick and easy but it also takes a little time to install. The most often utilized reinforcing materials for NSM are carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer bars. However, FRP materials remain to be more expensive than steel reinforcements and plates [3]. Due to the geometrical configuration, shear failure is more common in deep beams than in slender beams [4]. Therefore, many researchers have used the NSM technique to strengthen the shear zone only with steel bars or CFRP bars in different configurations. However, shear forces always act in combination with other types of loads such as flexural, axial load, and sometimes torsion, further complicating the problem [5,6]. To reduce the combination effect of stresses, surface-mounted steel plates along beams with different positions were used to increase the shear capacity by Thamrin et al. [7]. These extended plates along a beam serve the beams by resisting the flexural stress at both the flexural and flexural-shear zones so that the extended plates reduce the effect of the combination that may have occurred at flexural-shear zones. Thamrin et al. [7] showed that the shear capacity with steel plates was 17–50% higher than the control beams depending on the position of the steel plates and the ratio of longitudinal reinforcement. Instead of steel plates, mounted steel bars using the NSM technique were used in current research with different configurations. Three longitudinal bars along both faces of two tested beams were mounted, while in the flexural-shear zones, the diagonal and vertical configurations of mounted steel bars were used with three bars each at both faces of the rest beams. The results showed that the shear capacity of beams with longitudinal surface-mounted steel bars was 19% higher than the control beam and the effective scheme of the NSM technique was accomplished by installing three rebars in horizontally drilled grooves at both faces of the beams.

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2 The objective of this study

Due to a lack of good design or poor execution, diagonal cracks are sometimes visible to occupants. So, this needs immediate and low-cost treatment. The NSM technique using steel bars is considered an ideal solution. Therefore, studying the behavior of beam strengthening using the NSM technique in both elastic and plastic loading becomes an urgent necessity. In this research, rehabilitations at the elastic and plastic loading of six deep beams were experimentally done using three configurations of repairing the near-surface reinforcement.

3 Experimental program

Seven reinforced concrete deep beam specimens were used in the experimental program under a two-point loading to study the use of steel bars NSM in repairing damaged RC deep beams to 40 and 75% of the ultimate load of control beams. The first beam specimen was the control deep beam without repair, and the other specimens were repaired with steel bars near the surface mounting in various directions. Table 1 presents various configurations used on beam specimens in the experimental program. The seven specimens were designed to fail in shear instead of flexure.

4 Specimen's geometry

All beams had a cross-sectional dimension of 200 mm × 400 mm, a length of 1,500 mm, and an overall clear span of 1,300 mm. Concrete with a compressive strength of 33.4 MPa at 28 days was used. In reinforced concrete deep beams, three different diameters of deformed steel bar reinforcements (16, 10, and 8 mm in diameter) were used. Three steel bars (16 mm in diameter) bent 90° at either end make up the flexural reinforcement of each beam. As internal compression reinforcement, two deformed steel bars of 10 mm diameter were used. Finally, eight steel bars with an 8 mm diameter were spread along the length of the deep beams as shear reinforcement. Figure 1 shows the dimensions and reinforcing information of the test specimens.

5 Material properties

The deep beams were cast using normal concrete. Concrete's 28-day compressive strength was 33.4 MPa. The yield strength of steel bars was 540 MPa, and the ultimate strength was 640 MPa. The concrete surface and the reinforcing components were joined together using an epoxy adhesive. Sikadur®30 (modulus of elasticity = 1,000 N/mm^2, compressive strength >85 N/mm^2, and tensile strength >17 N/mm^2) was made up of two parts, A and B. Component A was white, while B was black. To obtain a consistent gray color, these two components were mixed in a 3:1 ratio before being employed as a connection.

5.1 Installation of NSM reinforcements

The deep beam specimens were ready to use after 28 days from casting and curing. The damaged RC deep beams are taken to 40 and 75% of the ultimate load of control beams for retrofitting using NSM technology. As a first step in the

Table 1: Details of the test specimens

Beam designation	Description	*a*/*h* ratio	NSM properties' load ratio of the ultimate load (%)	Diameter of NSM steel bars (mm)	Orientation of NSM steel bars
DB-C	Control	0.8	100	—	—
DB-I-0.4*	Repaired	0.8	40	10	Inclined
DB-H-0.4	Repaired	0.8	40	10	Horizontal
DB-V-0.75	Repaired	0.8	75	10	Vertical
DB-I-0.75	Repaired	0.8	75	10	Inclined
DB-H-0.75	Repaired	0.8	75	10	Horizontal
DB-I-0.75-1 face	Repaired	0.8	75	10	Vertical

*The first two characters in the designation (DB) of a beam mean a deep beam, and the first letter after the hyphen refers to the shape of a drilled groove; vertical (V), inclined (I), or horizontal (H). The last number in this designation refers to the loading ratio according to the capacity of the control beam before the rehabilitation is started.

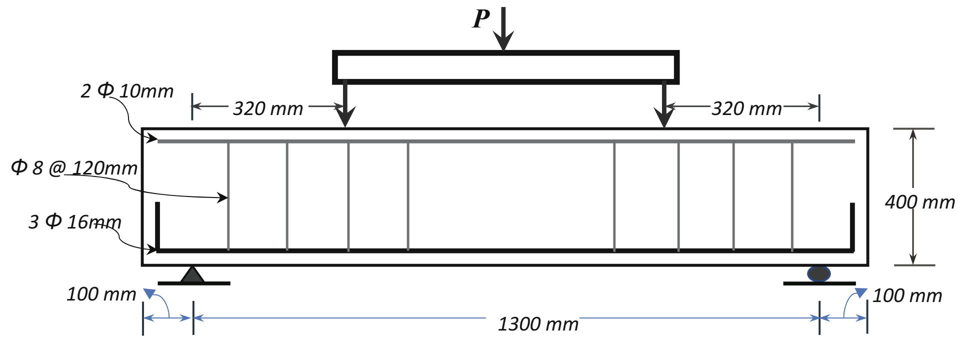

Figure 1: Dimensions and reinforcement details of tested beams (all dimensions in mm).

rehabilitation procedure, the NSM technique is applied by cutting the concrete cover in several directions at the side of the beam by a special cutter. The grooves were cleaned of any loose material, compressed air, and compressed water in some cases to guarantee proper bonding between the epoxy and the concrete. Then, after the epoxy had been partially applied, the steel bar was put into the groove and gently pressed. Hence, the epoxy was compelled to flow around the steel bar. The steps are shown in Figure 2.

Figure 3 illustrates the three configurations of repairing using the NSM technique for tested beams. Vertical, inclined, and longitudinal are the drilled near surface grooves. For all beams, three grooves were drilled at each face except the beam (DB-I-0.75-1 face), in which the repairing was at one face only. The retrofitted beams were cured at ambient temperature for 7 days for curing of epoxy adhesive.

5.1.1 Experimental setup and procedure

There were three stages of tested deep beam: initial damage, repair, and tested to failure. The beams were tested until failure with a two-point load test. The specimens were tested under loading rates of 2.5 kN/s. At each stage of the testing procedure, deflection at mid-span as well as the development of cracks and their propagation were recorded.

6 Results and discussion

Under two concentrated loads, the repaired beams were tested in two stages, stage 1 (pre-cracked phase) and stage 2 (rehabilitated phase). Deep beams that were pre-cracked underwent testing until the load reached a value of about 290 and 540 kN (i.e., 40 and 75% of the ultimate load capacity of the control beams), after which the deep beams were repaired using NSM steel bars. The outcomes of the repaired deep beam group will be compared with the control deep beam in a table layout in the sections that follow. Additionally displayed will be plots of load against vertical mid-span deflection and failure mode at ultimate capacity.

6.1 Control beam (DB-C)

It is the reference beam that was loaded until the failure. After applying the load, flexural cracks appeared in the zero-shear zone, followed by web-shear cracks in the shear span as shown in Figure 4. Following this, some web-shear cracks began to expand and intersect, forming diagonal cracks. These diagonal cracks then grew and developed, quickly shattering the beam with an ultimate load of 720 kN.

Figure 2: NSM repairing steps.

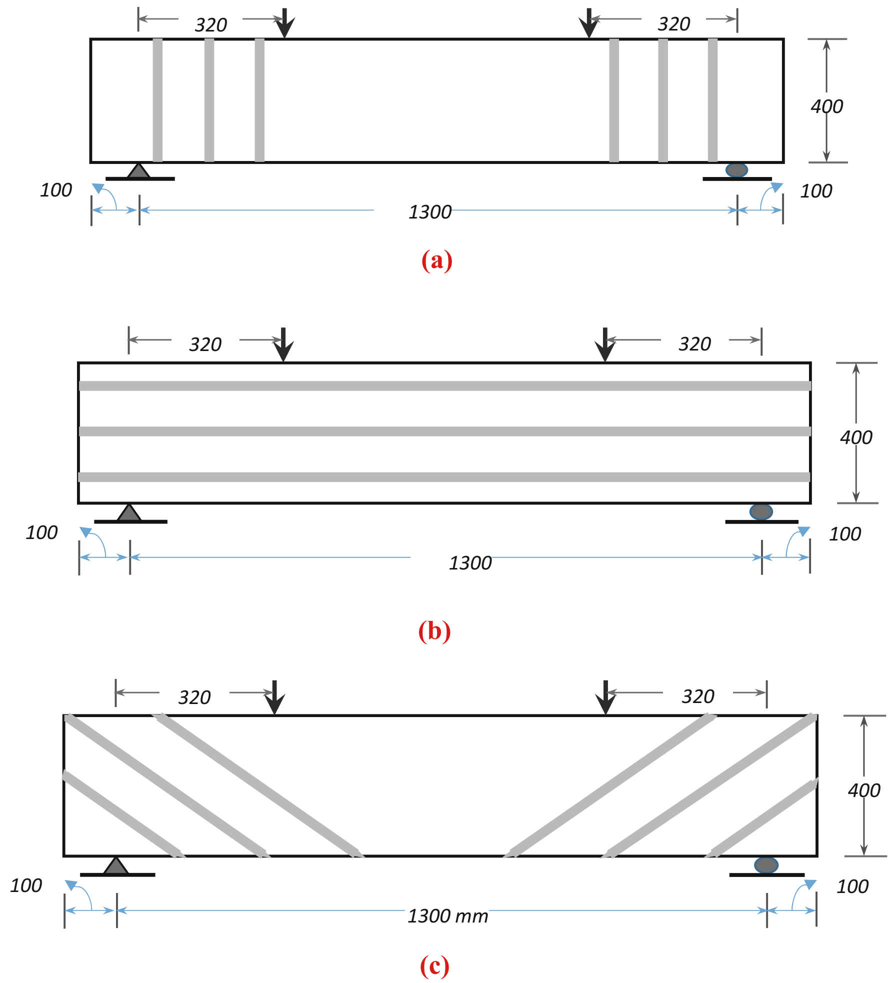

Figure 3: Vertical, horizontal, and inclined configuration of the repairing NSM steel bars: (a) vertical, (b) longitudinal, and (c) inclined.

6.2 Repaired deep beams

6.2.1 Beam DB-V-0.75

This deep beam was pre-cracked until the load reached an approximate value of 540 kN (i.e., 75% of the control beams' ultimate load). In addition to the flexural cracks, visible web shear cracks were clear along the beam at this load level. Three vertical groves were made at each shear zone for both sides of the beam. Steel bars were installed inside these groves using epoxy. After completing the curing time of epoxy, the beam was tested again (Figure 5) by increasing the load, and the previously developed flexural and shear cracks extended upward and diagonally. It was observed that the shear crack crossed the strengthened rebars while the flexural cracks expanded vertically. Finally, the concrete crushing occurred in the flexural zone at the top of the beam at an ultimate load of 740 kN. Figure 6 shows the load–deflection curve compared with the behavior of the control beam. An increase of 20 kN was achieved in the capacity compared to the control beam.

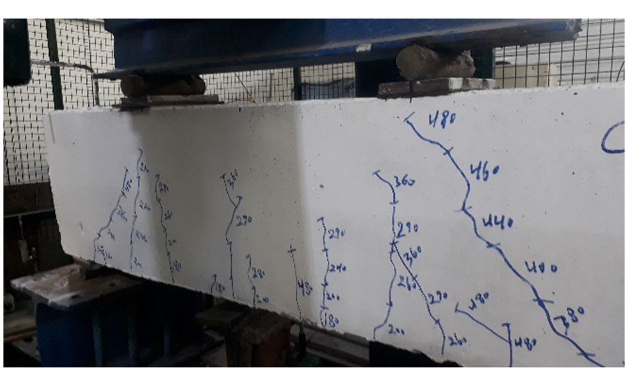

Figure 4: Control specimen (DB-C) during testing.

6.2.2 Beam DB-I-0.75

The same strengthening procedure was carried out on this beam but with a diagonal-shaped groove at the shear zone.

Figure 5: Specimens DB-V-0.75 during testing.

Figure 7: Specimen DB-I-0.75 after testing.

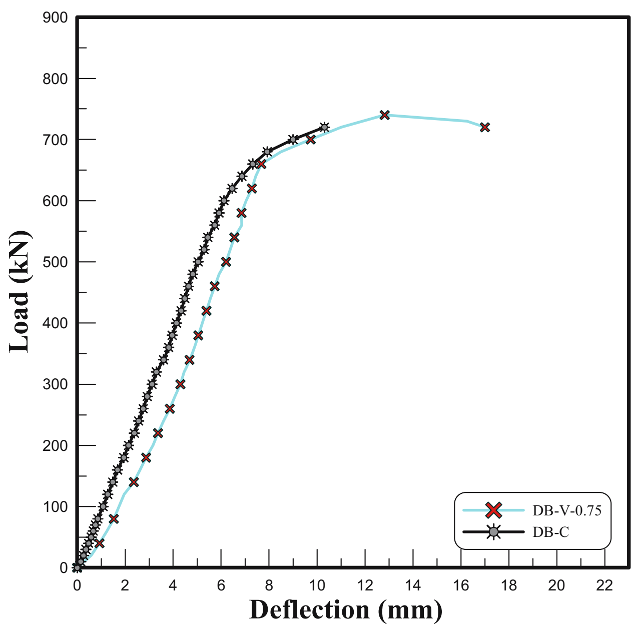

Figure 6: Load–deflection of beam DB-V-0.75.

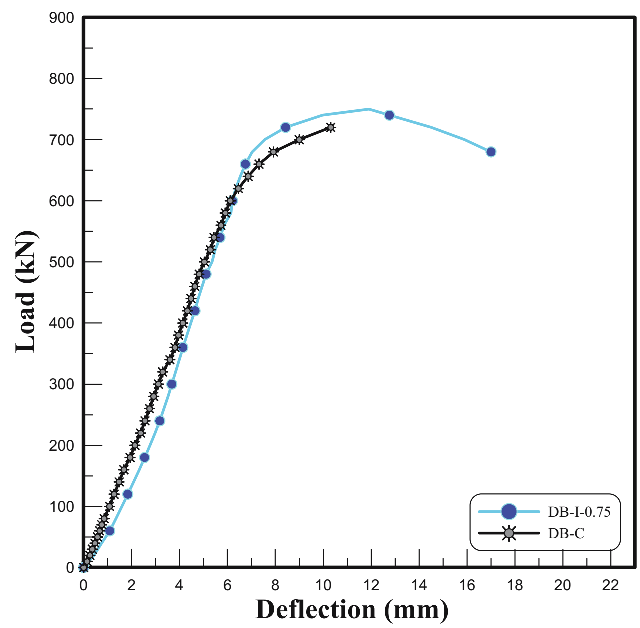

Figure 8: Load–deflection of specimen DB-I-0.75.

With reloading, hairline flexural cracks extended upward while the hairline web cracks started to extend diagonally. Expansion and elongation were noticed for both cracks until the beam's failure was reached. The failure occurred in the crushing of the concrete of the top fiber at the flexural zone but with an ultimate load of 750 kN. Figures 7 and 8 show the cracks' elongation and load–deflection curves compared to the control beam.

6.2.3 Beam DB-H-0.75

Repairing of this specimen was done by mounting three steel bars in horizontal grooves extending along the beam at both faces. The hairline cracks that developed before repairing, as a result of loading the beam to 75% of the capacity of the control beam, were clear at both the flexural and flexural-shear zone. After reloading, the extension and elongation occurred to only the hairline cracks at the flexural-shear zone. In contrast, flexural cracks remained without changing due to the mounted reinforcement. Figure 9 shows the behavior of the beam before and after the reloading.

The failure occurred by crushing a massive amount of concrete diagonally in the flexural-shear zone. The ultimate load of the beam was 830 kN. Figure 10 shows the load–deflection curve of the beam compared with the control beam. This technique achieved a 16% increase in capacity.

Figure 9: Specimen DB-H-0.75.

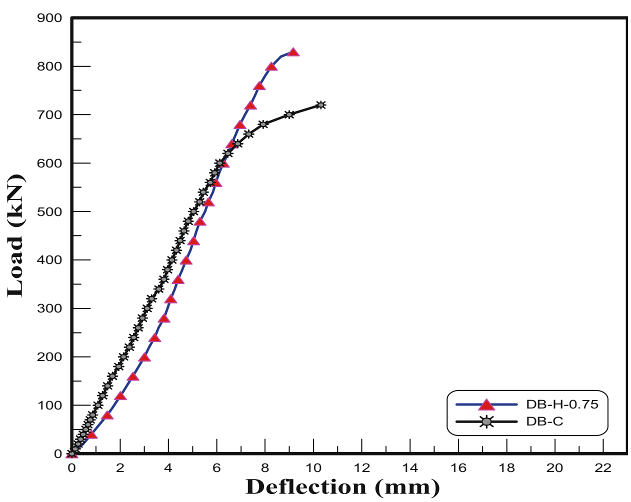

Figure 10: Load–deflection of specimen DB-H-0.75.

6.2.4 Beam DB-I-0.75-1 face

This beam is similar to beam DB-I-0.75, except that its rehabilitation was conducted to one face of the beam. As a result, this beam's capacity was roughly equivalent to that of the control beam. The failure occurred due to the concrete crushing under the point load (Figure 11). Figure 12 shows the load–deflection curve compared with the behavior of the control beam.

It may be concluded that this procedure does not contribute to an increase in the load capacity, so its capacity reached 700 kN.

6.3 Beam DB-H-0.4

This beam is similar to beam DB-H-0.75, except that its repair was done after loading to 40% of the capacity of the control beam. At 180 kN, the first vertical hair flexural crack appeared, followed by web cracks at the shear zone. The number of cracks has increased with increasing load.

Figure 11: Specimen DB-I-0.75-1 face.

The web shear cracks extended diagonally. Finally, the beam capacity reached 860 kN, resulting in more elongations and extension of flexural-shear cracks. This behavior was similar to that of beam DB-H-0.75, but with higher capacity. The

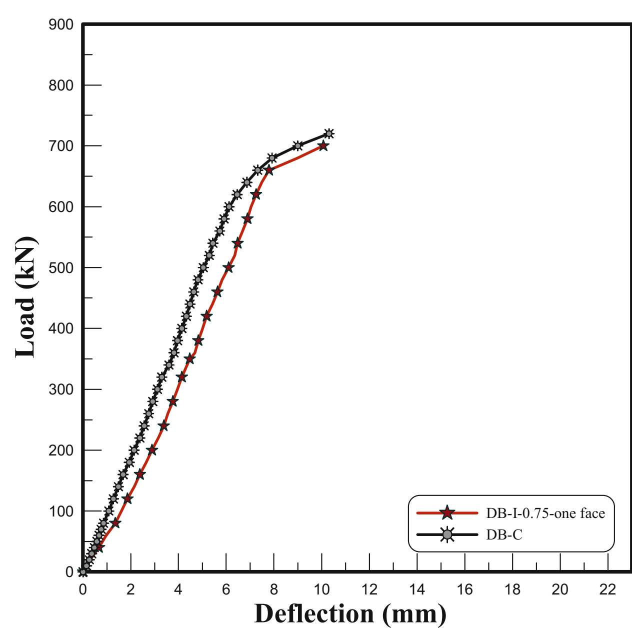

Figure 12: Load–deflection of the specimen DB-I-0.75 face.

Figure 13: Specimen DB-H-0.4.

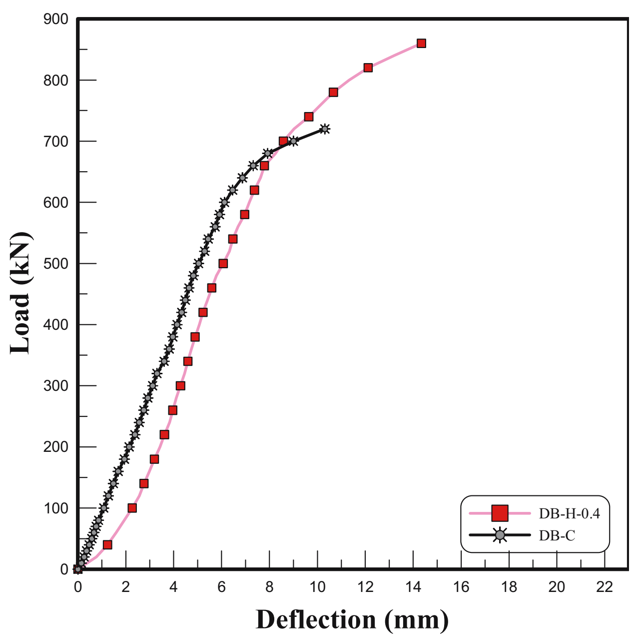

Figure 14: Load–deflection of specimen DB-H-0.4.

increase in the capacity was 19% of the capacity of the control beam (Figure 1 of the control beam and Figure 13). Figure 14 shows the beam's load–deflection curves.

Figure 15: Specimen DB-I-0.4.

6.3.1 Beam DB-I-0.4

After loading this beam to 40% of the capacity of the control beam, the rehabilitation of this beam started (Figure 15). With reloading, flexural and web cracks developed and extended upward and diagonally until failure, which resulted from the concrete crushing at the flexural zone. The beam failed at 770 kN with an increase in capacity by 7%. Figure 16 depicts the load–deflection curve of this specimen.

6.4 Capacity and mode of failure

According to the experimental results, deep beams repaired in shear with NSM steel bars are structurally affected and are restored to stiffness and strength values that are almost equivalent to or greater than those of the control deep

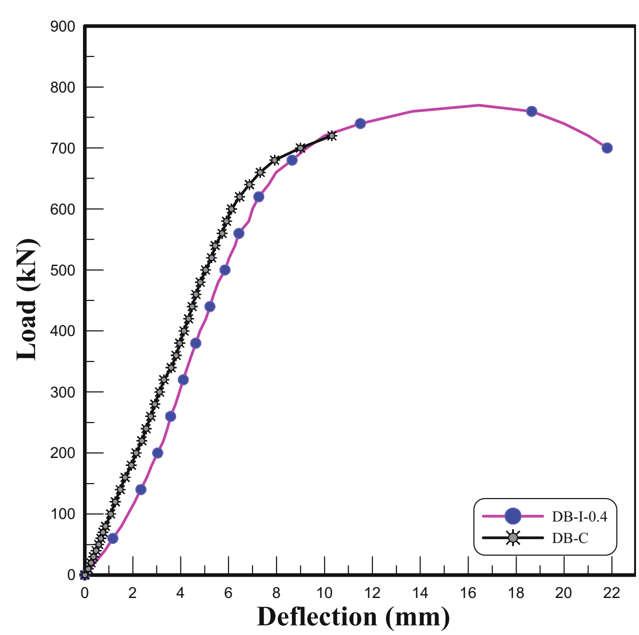

Figure 16: Load–deflection of specimen DB-I-0.4.

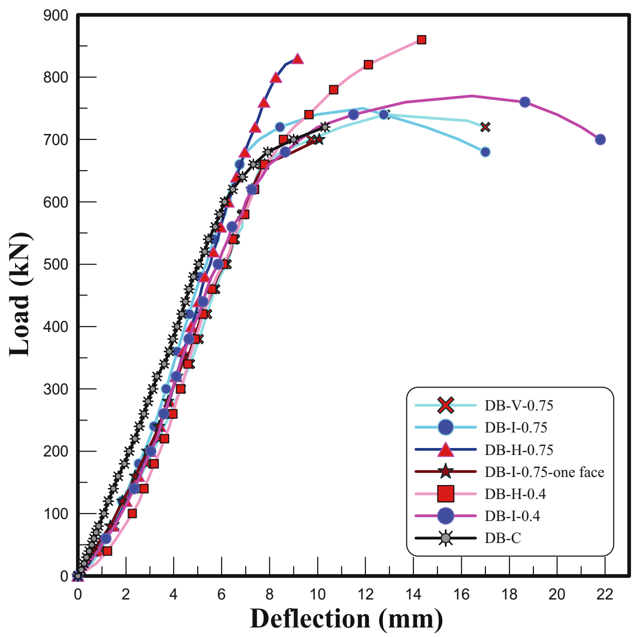

Figure 17: Load–deflection curves of all tested beams.

beams. Depending on the direction of repair, the main failure mode in the experimental work ranged from concrete crushing in a compression zone to shear failure.

Figure 17 shows the load–deflection curves of all tested beams. The best increase in the flexural capacity compared with the capacity of the control beam was achieved by DB-H-0.4 and DB-H-0.75. For both beams, the NSM technique was accomplished by installing three rebars in horizontally drilled grooves at both faces of the beams. The increase in capacity may arise due to the following reasons.

1- For both these beams, it was noticed during the test that the flexural cracks developed in the pure moment zone before planting the bars remained as they were after the planting without any change despite the increased applied load. This indicates that these mounted bars significantly stopped cracks from elongating and expanding. Moreover, these embedded bars have the same role in resisting flexural stresses in the shear-flexural zone due to their extension along the beam.
2- Unlike the rest of the beams, the failure occurred by crushing the concrete diagonally at the shear zone. The mounted steel bars played a role in resisting the flexural stresses and only the shear stresses, which were responsible for failure. Contrary to all other beams that were strengthened using the I and V embedded bars in the shear zone, the failure (crushing of the top fiber of concrete) occurred in the pure bending zone. It may be concluded that the near-surface rebars extended along the beam significantly increased the flexural capacity.

It is worth mentioning that the repairing of deep beams using inclined and vertical configurations contributed to some degree by increasing the shear capacity of beams via shifting the failure to the flexural zone instead of flexural-shear zones, where the failure was by the crushing of the top fiber in mid-span of beams and not diagonally at the flexural-shear zone as it was in the control beam. All beams strengthened by the vertical and the diagonal configurations showed capacities higher than the capacity of the control beam, as can be seen in Table 2.

6.5 Elastic and plastic deformation

Table 2 shows the maximum strength of all tested beams. Note that all beams strengthened after loading to 0.4% of the capacity of the control beam, beams (DB-I-0.4, DB-H-0.4) achieved a capacity more than the capacity of beams strengthened after loading to 0.75% (DB-V-0.75, DB-I-0.75, and DB-H-0.75.). During the test, no cracks were observed, and both beams (DB-I-0.4 and DB-H-0.4) were in the elastic deformation. During the elastic stage, both the original stirrups and the newly mounted bars contributed to the capacity increase.

Table 2: Ultimate capacity of all tested beams with an increasing ratio in the capacity

Specimen designation	Flexural crack	Percentage of flexural crack load of ultimate load (%)	Shear crack in the right shear span	Percentage of shear crack load of ultimate load (%)	Ultimate load capacity	Increase in ultimate load (%)
DB-C	170	23.6	319	44.3	720	—
DB-I-0.4	145	18.8	312	40.5	770	6.94
DB-H-0.4	180	21	326	37.9	860	19.44
DB-V-0.75	140	18.9	265	35.8	740	2.78
DB-I-0.75	160	21.3	285	38	750	4.16
DB-H-0.75	185	22.3	300	36.1	830	15.27
DB-I-0.75-1 face	130	18.6	252	36	700	-2.78

The latter beams had reached the plastic deformation under loading to 75%, where many flexural and diagonal cracks were developed reaching this loading. Therefore, only the newly mounted rebars contributed to the increase in capacity. Hence, the difference in the capacity of these two groups was clear and it may be concluded that the rehabilitation of beams in the elastic rather than plastic stage positively affects the shear capacity.

7 Conclusions

The results of an experimental study to evaluate the behavior of structurally damaged reinforced concrete deep beams repaired with NSM steel bars are presented in this study. The location of the retrofitting and the direction of the NSM steel bars were the primary factors considered. In the elastic deformation, the repairing of two deep beams was done after loading to 40% of the capacity of the control beam, while at 75% of loading, the other four beams were repaired. Vertical, inclined, and horizontal grooves were used to apply the NSM technique.

Three important conclusions from this study are as follows:

1. The three configurations used in the repairing have contributed to increasing the capacity of beams in a range of 4.16–19.44% compared with the capacity of the control beam.
2. The more effective scheme of the NSM technique was accomplished by installing three rebars in horizontally drilled grooves at both faces of the beams. This increase in capacity extends the longitudinal rebars along the beam.
3. It is also concluded that repairing beams in the elastic rather than in the plastic stage positively affects the capacity.

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