Polytechnic Journal
Polytechnic Journal

Volume 13 | Issue 2 Article 7

November 2023

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How to Cite This Article

Anwer, Hoshang Hayder and Taha, Bahman Omar (2023) "Strengthening of Reinforced Concrete Beams with Circular Openings Using Near Surface Mounting Steel Bars," *Polytechnic Journal*: Vol. 13: Iss. 2, Article 7.
DOI: https://doi.org/10.59341/2707-7799.1721

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Keywords

RC beams; Near surface-mounted; Circular openings; Strengthening Schemes; Shear Strengthening

ORIGINAL ARTICLE

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Abstract

This study investigated the effectiveness of using near-surface mounted (NSM) steel bars to restore the shear strength of deep beams and deal with the presence of openings in slender beams. fourteen simply supported reinforced concrete beams were tested with varying shear span-to-depth ratios (a/h) of 1.5 and 3.61, divided into two groups, and subjected to a two-point load configuration. Some beams had openings at different positions, classified as large or small with opening height ratios (ho/h) of 0.4 and 0.2, respectively. In the second group, six specimens were reinforced with nsm steel bars in three stirrup configurations (square, diamond, and parallelogram) surrounding the openings. All specimens had a cross-section size of 100 mm × 150 mm and a total length of 2000 mm. The results of the test indicated that having openings in the beams led to reductions in ultimate load capacity for different beam types. Specimens reinforced with diamond stirrup bars showed an increase in ultimate load capacity of up to 33.1%, while those with square and parallelogram stirrup bars improved by up to 21.5% and 26.5%, respectively. Minor variations in bar diameter had slight effects on ultimate load capacity, resulting in a 10% increase for the parallelogram scheme and 7% for the square scheme. The reductions in ultimate load capacity due to openings were 45 % for large circular openings in the shear zone of deep beams, 18.7 % for large circular openings in slender beams subjected to shear, 14.6 % for large circular openings affecting both shear and flexural behavior and 19.5 % for small openings impacting shear and flexural behavior in slender beams.

Keywords: RC beams, Near surface-mounted, Circular openings, Strengthening schemes, Shear strengthening

1. Introduction

In a practical context, transverse openings in reinforced concrete beams serve as a means to facilitate the passage of various service lines, such as networks of pipes and ducts. These service lines are essential for functions like water supply, sewage, air-conditioning, electricity, telecommunications, and networking equipment within a building. The inclusion of web openings in the design enables the architect or engineer to decrease the overall height of the structure, especially in the case of tall buildings, leading to a more cost-effective design. To eliminate the ceiling problem generated by suspending such service pipes and ducts, it has recently been the usual practice to provide holes through the floor beams for the passage of utility pipes and ducts [1]. Transverse openings introduce complexity into the behavior of beams by inducing a sudden alteration in the beam's cross-sectional dimensions. Additionally, since the opening serves as a vulnerability point, the zone of potential failure invariably traverses through it. Possible outcomes encompass a reduction in overall strength, shear resistance, crack width, and rigidity. The existence of a web opening in a reinforced concrete beam poses various challenges to the beam's performance, such as reduced rigidity, increased cracking, excessive deflection, and a decline in beam strength [2,3] In addition, There is a significant distribution of forces and internal moments within a continuous beam. Therefore, it is crucial to evaluate how openings impact

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Received 17 July 2023; accepted 3 October 2023.

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https://doi.org/10.59341/2707-7799.1721

the strength and performance of reinforced concrete beams, and designing them requires special attention and careful consideration. This research examines two distinct categories of RC beams: slender and deep beams, both with and without openings. Deep beams find extensive use in a variety of structural applications, including high-rise buildings, long-span structures (for example, as transfer girders), footings, and water reservoirs, as previously mentioned [4,5]. While deep beams typically experience shear failure at their ultimate limit state, accurately characterizing their shear capacity is crucial. Recent codes [6] A beam can be classified as "deep" when the ratio of its span to its overall depth (L/h) is less than or equal to 4. Deep can also be characterized as having a shear span-to-overall component depth ratio (a/h) of less than or equal to 2, a span-to-depth ratio (L/d) of less than or equal to 4, or a shear span-to-depth ratio (a/d) of less than or equal to 2. In the case of deep beams, their strength is usually controlled by shear due to their dimensions, provided that the correct quantity of longitudinal reinforcement is employed.

The primary goal of this study is to explore how the presence of openings affects the performance of RC beams and assess the feasibility of reinforcing these structural elements using Near Surface Mounted (NSM) steel bars.

1.1. Near surface mounted of beam opening

This section presents the categorization of RC beams with web openings based on the size and position of the openings. Openings are divided into two classes: small and large openings and the decision on the optimal position of the opening depends on its size. Web openings can assume various shapes, including circular, rectangular, diamond, triangular, trapezoidal, and irregular shapes. Among these, circular and rectangular openings are the most commonly encountered in practical applications [7]. Regarding the size classification of openings, there is no universally agreed-upon demarcation line. Many researchers refer to openings as "small" or "large" without precise criteria. Small openings are typically described as circular, square, or nearly square in shape [1,8]. On the other hand [9], suggests that an opening in a circular shape may be categorized as large if its diameter is greater than 0.25 times the web's depth. Nonetheless, it is crucial to highlight that the core of distinguishing an opening as either small or large depends on how the beam reacts structurally.

If the opening is sufficiently small to retain conventional beam-like characteristics, where traditional beam theory remains applicable, it can be labeled as a small opening. Conversely, if the presence of openings disrupts the beam-like behavior, the opening may be designated as a large opening.

The near surface-mounted strengthening technology has achieved public acceptance in civil construction applications and may generate reliable strengthening and repairing solutions for existing concrete structures. Near-surface mounted (NSM) steel rebars may be a feasible method for improving the flexural and shear strength of defective concrete (RC) elements [10]. Concrete structures often require reinforcement or rehabilitation to prolong their lifespan. This need arises from various factors, including heightened service loads, environmental impacts, construction and design flaws, and mechanical damage. External strengthening methods, such as the application of fiber-reinforced polymers and steel plates, are employed as part of the externally bonded reinforcement process [10].

The NSM rebar reinforcement method is at a higher risk of experiencing mechanical damage, vandalism, and fire hazards, along with unintended consequences arising from the presence of surrounding concrete covers. This characteristic is extremely crucial for this condition since the bars are located extremely near the surface, making them more susceptible to environmental effects. The NSM technology was initially utilized to reinforce a bridge deck slap in Finland in 1940 [11]. Near Surface Mounted techniques, which entail cutting grooves in concrete covers and inserting rebar into them with a particular groove filler (epoxy or cement mortar), have shown to be successful.

2. Experimental work

2.1. Materials properties

In this test, all the test samples were produced using standard Portland cement supplied by (Iberia Ready Mix Concrete Company). The Directorate of Construction Laboratory-Hawler conducted tests to evaluate both the chemical and physical properties of the cement, with compliance with the specifications defined in IQS-5-84. The natural crushed gravel with a maximum size of 12.5 mm and natural sand as the fine aggregate were used according to ASTM limits (C33). The casting and curing process utilized water suitable for drinking. The mixing proportion of cement, sand, and gravel was (1:2.86:2.52) by weight. In the NSM method, epoxy paste, specifically polypoxy-NF was applied to adhere the steel bar within the groove. and the properties of the epoxy paste were provided by the manufacturing company as shown in Table 1. The

Table 1. Technical specification of epoxy past.

Properties	Values[a]	Test Standards
Color & appearance	Grey/off-white paste	–
Density, (g/cc)	1.85 ± 0.005	ASTM D 1475
Application life, [minutes]	45	–
Compressive strength @7days,(N/mm^2)	>60	ASTM C 579
Flexural strength @7days,(N/mm^2)	>30	ASTM C 580
Tensile strength @ 7 days, (N/mm^2)	>12	ASTM C 307
Shear bond Strength @ 7 days, (N/mm^2)	>40	ASTM C 882
Application thickness, [mm/layer]	0 to 5	–
Service temperature, (C°)	−5 to 70	–
Initial cure, [hours]	Approx. 8	–
Final cure, [days]	7	–

[a] All values given are subject to a 5—10 % tolerance.

concrete exhibited an average compressive strength of 44.27 MPa and an average tensile strength of 4.65 MPa. Table 2 provides the listed properties of the steel reinforcement.

2.2. Identification of beams

The experimental work included testing 14 RC. beams, six of which were strengthened with NSM steel bars around openings in the shear region with different configurations. The samples were divided into two groups according to their (a/d) ratios. All specimens were simply supported and had the same dimensions and flexural and transverse reinforcement (2φ12mm and φ8@85 mm) respectively. Examined beams are distributed into two groups as illustrated in Table 3 with the same cross-section and length which were (2000 mm) long, (100 mm) wide, and (200 mm) high.

2.3. Description of beams

The beams subjected to experimentation have been categorized into two distinct groups, taking into account their (a/d) ratios, as well as the placement and dimensions of their openings. Each group has a control beam (which is un-strengthen and unopened) and group two strengthened specimens made of NSM steel bar using various techniques around openings, as shown in "Figure 1" and "Figure 2". The chosen ratio of shear span to effective depth was (1.5 and 3.61). All openings were kept vertically aligned so that they were centered at the beam depth.

Table 2. Steel bar tensile test outcomes.

Diameter of rebar (mm)	Yield stress (MPa)	Ultimate stress (MPa)	Elongation %
Ø8	534.5	691.3	24.9%
Ø10	583.2	685.3	15.2%
Ø12	548.2	696.4	16.8%

2.4. NSM steel bars procedure

NSM reinforcement is a technique for increasing the flexural strength and stiffness of concrete members by bonding steel bars or fibers within the concrete in the tension and shear zone.

Here are the steps for installing NSM steel bars for RC beams around an opening.

1) Select the reinforcement bars and adhesive material: Based on the design requirements and properties of the existing concrete, choose the appropriate size and type of reinforcement bars and adhesive material.
2) Prepare the surface: Clean and roughen the surface of the beam where the steel bars will be installed to ensure good adhesion between the concrete and adhesive material. Remove any loose or deteriorated concrete to create a clean surface as shown in "Figure 3a".
3) Create grooves or holes: Use a saw or drill to create grooves or holes in the surface of the beam with (1.5 db) depth according to the (Square, Diamond, and Parallelogram) design for the required strengthening capacity as illustrated in "Figure 3b".
4) Install the steel bars: Firmly press the steel bars into place within the grooves or holes created in the surface of the beam according to the design specifications for their positioning as demonstrated in "Figure 4a".
5) Inject the adhesive material: Using a caulking gun or similar equipment, inject the adhesive material into the grooves or holes until they are filled, and remove any excess adhesive as presented in "Figure 4b".
6) Allow the adhesive to cure: Allow the adhesive material to cure for several days while maintaining the temperature and humidity of the surrounding environment within the specified range.
7) Test the strengthened beam: After the adhesive has cured, conduct a load test on the beam to ensure that it meets the required load capacity. Ensure that the load testing is performed by a qualified structural engineer.

2.5. Instrumentation and testing procedures

To identify cracks and monitor their progression, a layer of white paint was first applied to all the

Table 3. Details of the samples.

Group no.	Beam name	Shear span ratio a/d	Opening position	Opening size D (mm)	NSM rebars ∅	NSM Details
Group One	SCB	3.61	N/A	N/A	N/A	N/A
	SBLS	3.61	Shear zone	Large opening D = 80 mm	N/A	N'/A
	SBLF	3.61	Flexural zone	Large opening D = 80 mm	N/A	N/A
	SBLSF	3.61	Shear and Flexural zone	Large opening D = 80 mm	N/A	N/A
	SBSF	3.61	Flexural zone	Small opening D = 40 mm	N/A	N/A
	SBSSF	3.61	Shear and Flexural zone	Large opening D = 40 mm	N/A	N/A
Group Two	DCB	1.5	N/A	N/A	N/A	N/A
	DBLS	1.5	Shear zone	Large opening D = 80 mm	N/A	N/A
	DBLSS8	1.5	Shear zone	Large opening D = 80 mm	∅8 mm	Square stirrup strengthening
	DBLSS10	1.5	Shear zone	Large opening D = 80 mm	∅10 mm	Square stirrup strengthening
	DBLSD8	1.5	Shear zone	Large opening D = 80 mm	∅8 mm	Diamond stirrup strengthening
	DBLSD10	1.5	Shear zone	Large opening D = 80 mm	∅10 mm	Diamond stirrup strengthening
	DBLSP8	1.5	Shear zone	Large opening D = 80 mm	∅8 mm	Parallelogram stirrup strengthening
	DBLSP10	1.5	Shear zone	Large opening D = 80 mm	∅10 mm	Parallelogram stirrup strengthening

SCB = slender control beam; **SBLS** = S. beam (large opening in flexure); **SBLF** = S. beam (large opening in shear); **SBLSF** = S. beam (large opening in shear and flexure); **SBSF** = S. beam (small opening in shear); **SBSSF** = S. beam (small opening in shear and flexure; **DCB** = Deep control beam; **DBLS** = Deep beam L. opening (shear); **LSS8** = L. opening square rebar ∅ 8; **LSS10** = L. opening square rebar ∅ 10; **LSD8** = L. opening diamond rebar ∅ 8; **LSD10** = L. opening diamond rebar ∅ 10; **LSP8** = L. opening parallelogram rebar ∅ 8; **LSP10** = L. opening parallelogram rebar ∅ 10.

specimens. Concrete strain gauges were then affixed to the specimen surfaces using adhesive. The testing procedure utilized a self-supporting loading frame with a 600 kN hydraulic jack. "Figure 5" provides a detailed view of the specimens from the two test groups. A 600 kN load cell was used to measure applied loads. The experiment focused on testing beam specimens arranged in a simple, supported beam configuration. To prevent localized bearing failures during testing, 150x40 × 15 mm steel plates were positioned at the load application and reaction points. Additionally, a protective layer of plaster of Paris-infused felt was inserted between the steel plates and the beam surface at these critical points. A dial gauge was utilized to gauge deflection at the midpoint of the beams.

3. Results and discussion

3.1. Ultimate load and failure mode

Table 4 contains ultimate stages, decrease in ultimate load, and strength gain results for all groups. The flexural and shear cracking load for the solid specimens in groups one and two was around 19.51% and 10.22% of the ultimate load, respectively. These cracking loads were reached at midspan deflections of 2.1 mm and 0.57 mm, respectively. Ultimately, the solid specimens failed under flexural and shear compression modes of failure. This occurred at an ultimate load of 61.5 kN and 156.5 kN, with corresponding deflections of 16.5 mm and 16 mm, respectively.

In group one, all specimens with openings, specifically those subjected to shear (SBLS), flexural and shear (SBLSF), and shear and flexural combined (SBSSF) failures, experienced failure in the shear zone (shear compression). This failure mode occurred due to separation along planes located above and below the openings. Ineffective reinforcement in the chord above and below the openings, along with the cracking load of the specimens (9 kN, 7 kN, and 7 kN, respectively), corresponded to 18%, 13.5%, and 14.15% of the peak loads, respectively.

In the case of specimens SBLF and SBSF, with openings located in the flexural zone, the failure mode was observed in the flexural zone (flexural

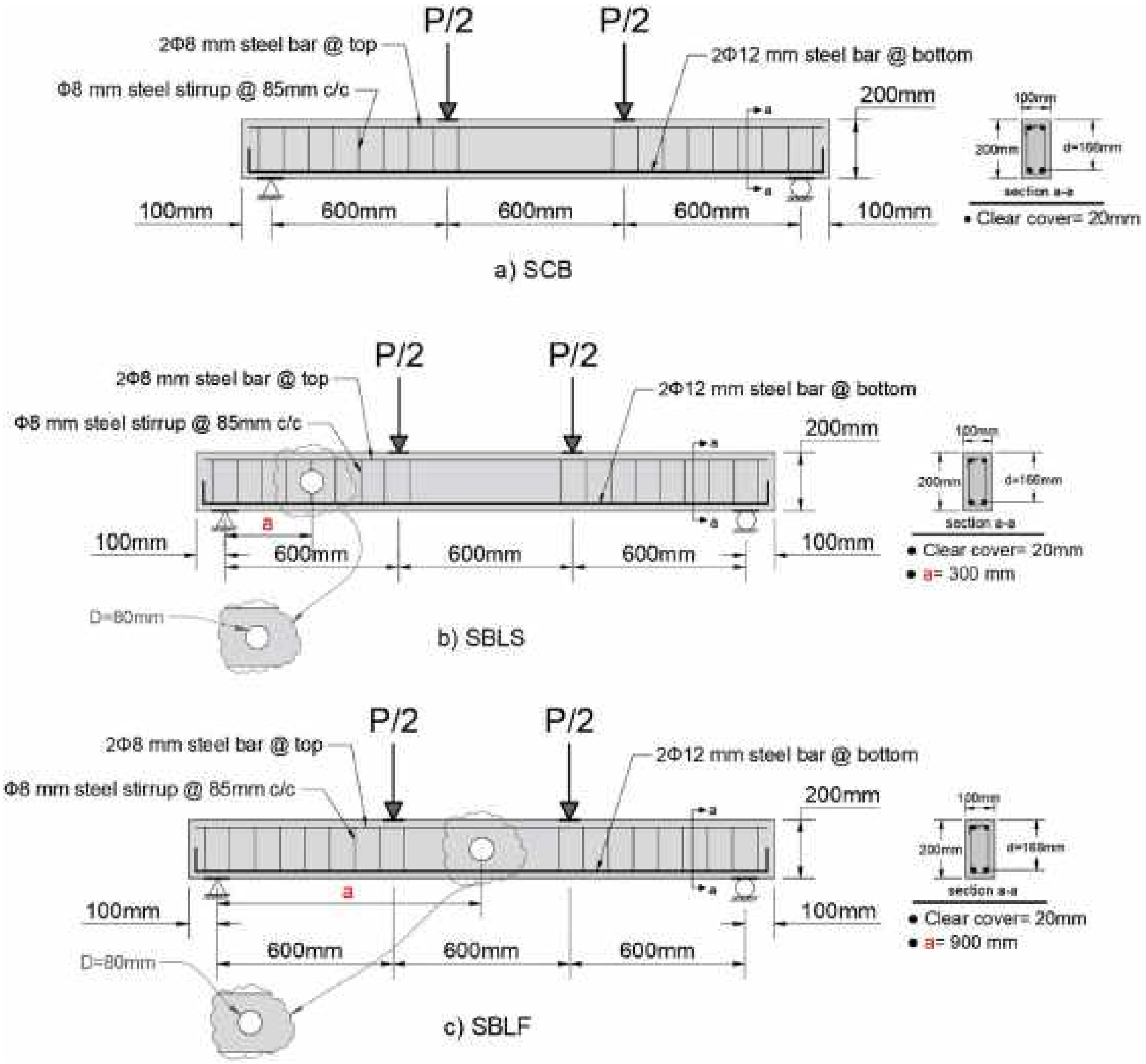
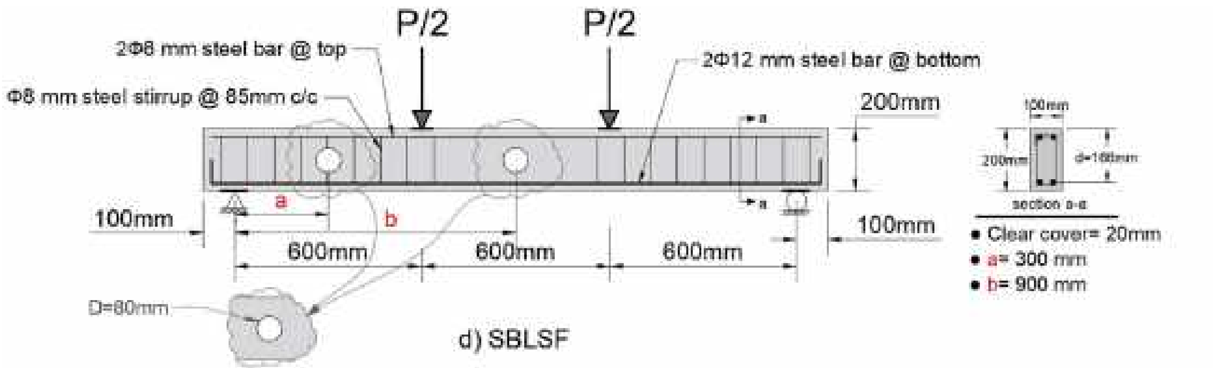


Figure 1 Details of the tested beam in (Group One).

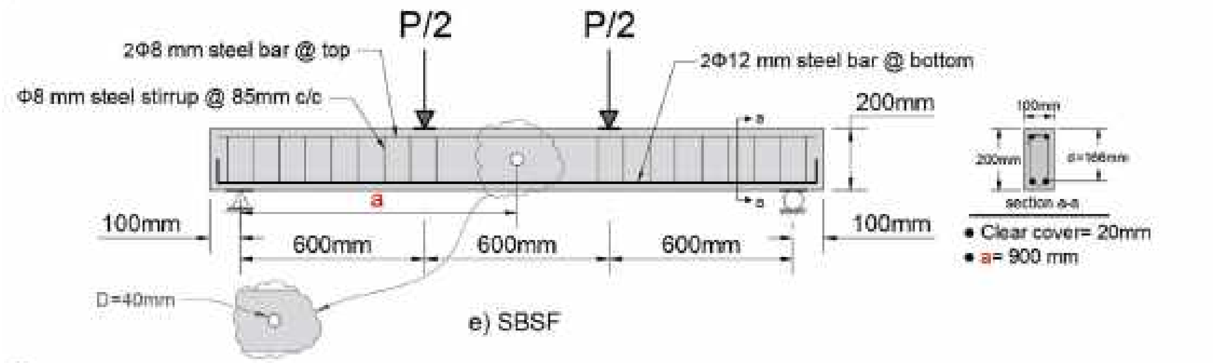
compression). The flexural cracking failure mode in reinforced concrete beams can arise from various factors, such as excessive bending moments, high tensile stresses in the bottom fibers, inadequate reinforcement, insufficient concrete cover, or excessive loading. These factors can contribute to the development of cracks and eventual failure in the flexural zone of the beams. The cracking load of specimens SBLF and SBSF was recorded as 8 kN and 10 kN, respectively, with a corresponding decrease in ultimate loads of 5.7% and 4.8%.

Within group two, the presence of openings or cracks in the shear zone of a reinforced deep concrete beam can result in shear failure. Shear failure occurs when the applied shear forces exceed the beam's capacity to withstand them. Comparing the ultimate and shear cracking loads of the DBLS specimens with the solid specimens in group two (DCB), the DBLS specimens exhibited cracking loads that were approximately 15.7% and 10.22% of the ultimate load, respectively. These cracking loads were observed at midspan deflections of 0.57 mm and 0.58 mm, respectively. Ultimately, both the solid specimens and DBLS specimens failed due to shear diagonal compression modes of failure.

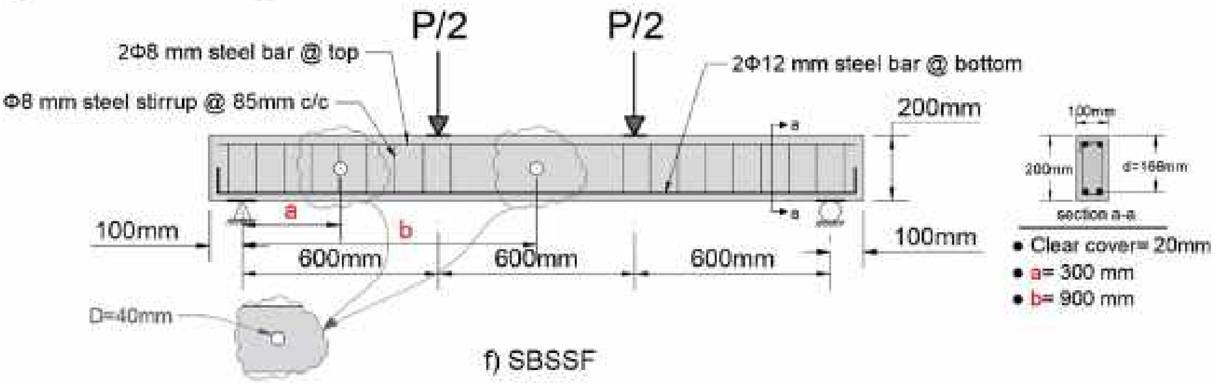
The presence of diagonal compression failure in an RC deep beam with openings can have detrimental effects on its load-carrying capacity and structural integrity. The openings weaken the beam's ability to effectively transfer and distribute



d) SBLSF



e) SBSF



f) SBSSF

Figure 1. (continued).

shear forces. Consequently, the beam develops diagonal cracking or shear deformations that can propagate and lead to failure. Based on the test results for the reinforced specimens, the diamond-shaped DBLSD8 and parallelogram-shaped DBLSP10 demonstrated significant enhancements in ultimate load capacity when compared to the remaining strengthened specimens, achieving load increases of approximately 33.1% and 33.33%, respectively. Specifically, their ultimate loads improved to 128.5 kN and 129 kN.

3.2. Crack pattern and failure mode

3.2.1. Un-strengthened specimens - group one

"Figure 6" and "Figure 7" display the crack patterns observed at the point of failure for all beams. The crack patterns and modes of failure varied among the beams due to differences in the presence, position, and sizes of the openings.

"Figure 6a" illustrates the crack pattern exhibited by the solid specimen SCB. Initially, the first flexural crack emerged close to the midspan upon reaching a load of 12 kN. Subsequently, diagonal cracks emerged in the shear spans near the support plates. With the progression of the load, the flexural cracks extended from the midspan towards the loading direction. Simultaneously, new flexural cracks developed while existing ones extended vertically upward. Ultimately, the beam experienced failure through flexural compression, resulting in concrete crushing.

"Figure 6b—f" provides a visual representation of the crack pattern observed in opening specimens

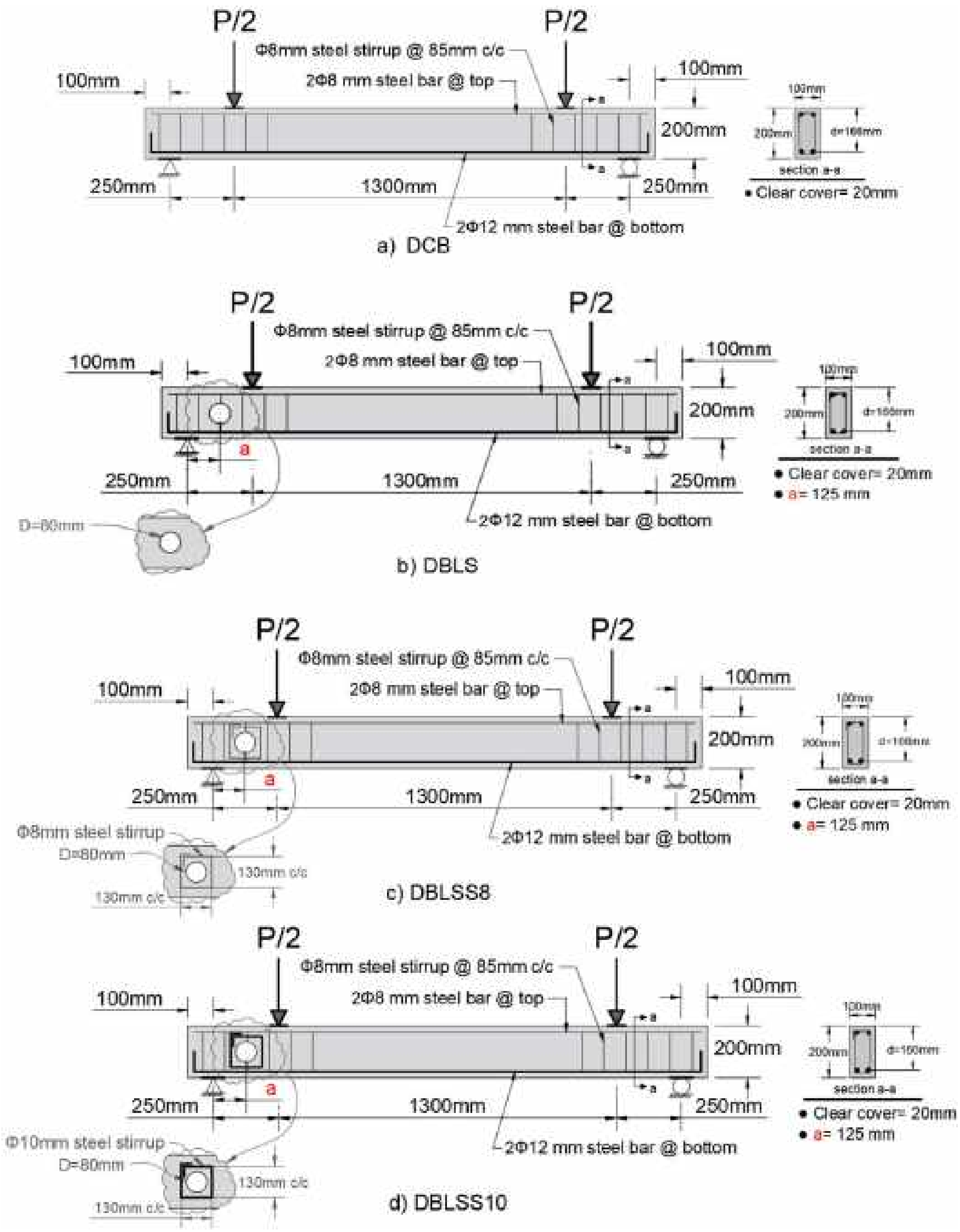


Figure 2 Details of the tested beam in (Group Two).

SBLS, SBLSF, and SBSSF. Initially, when the openings are situated in the shear zone or a combination of shear and flexural zones, a diagonal shear crack initiates at the bottom of the openings near the support. Upon reaching a load of approximately 10 kN, a diagonal first crack forms, traversing the center of the opening in the west shear span of the specimens. Concurrently, several flexural cracks develop in the middle span of the beams.

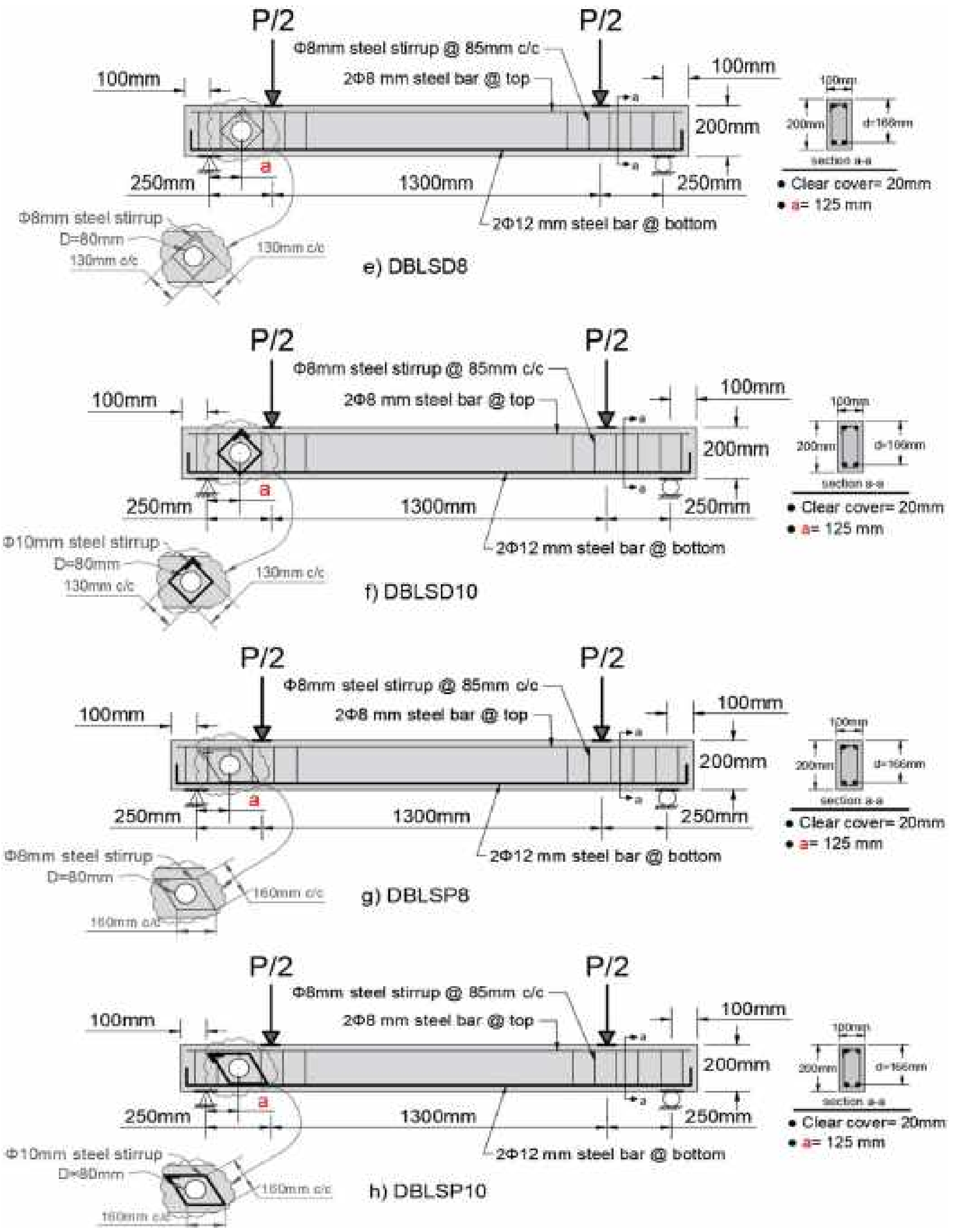
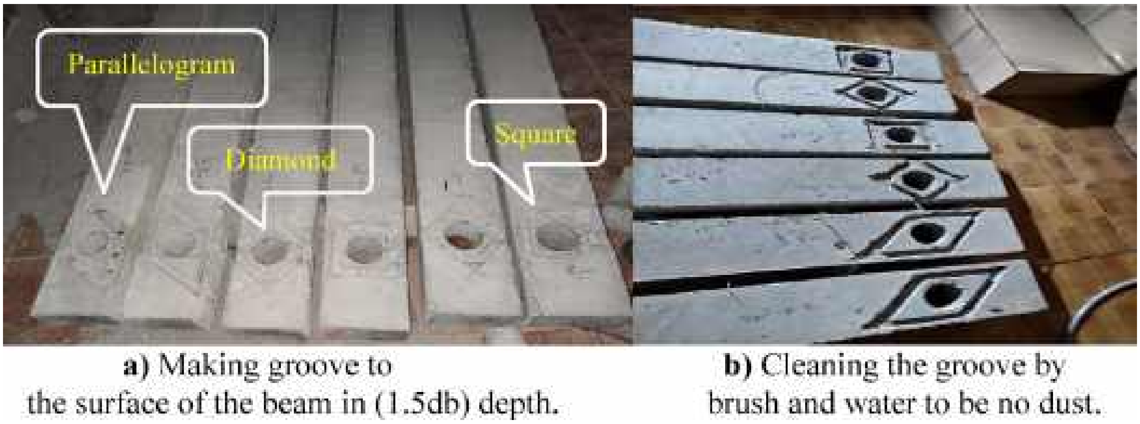


Figure 2. (continued).

The failure of SBLS, SBLSF, and SBSSF occurs abruptly in the east shear span, representing a shear-compression failure. This is due to the shear resistance sections proving to be more effective than the flexural sections for failure when the load reaches 50 kN, 52.5 kN, and 49.5 kN, respectively.

Beams SBLF and SBSF experienced failure due to concrete cracking on the bottom surface within the pure bending zone. Additionally, during the early



a) Making groove to the surface of the beam in (1.5db) depth.

b) Cleaning the groove by brush and water to be no dust.

Figure 3. Grove procedure for specimens-group two.

stages of the post-cracking phase, the beams exhibited the initial flexural cracks primarily at the bottom of the opening. These cracks were observed throughout the mid-span at loads of 8 kN and 10 kN for SBLF and SBSF, respectively.

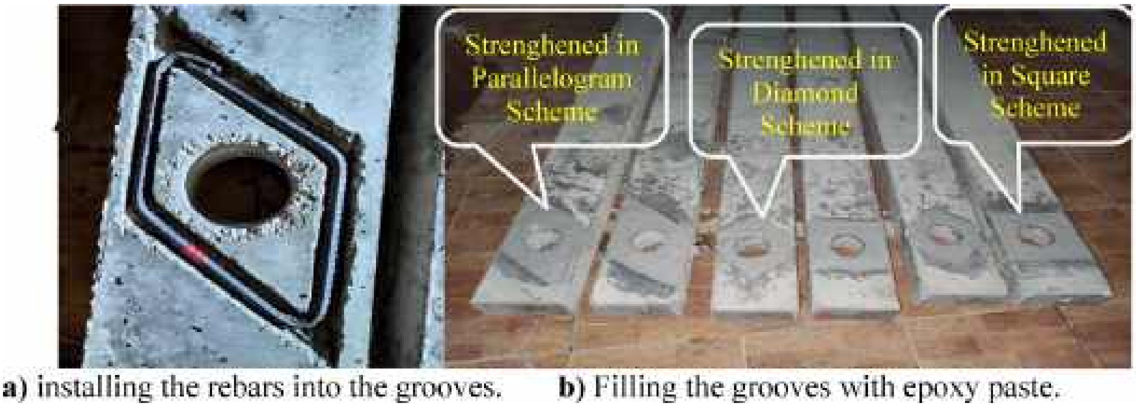
As the load increased, cracking occurred outside the constant moment zone, following a similar pattern of flexural cracking. However, the cracking in this region happened at a higher load level. Furthermore, in beam SBLF, there were instances of diagonal shear cracks initiating near the support, whereas no diagonal cracks were observed in beam SBSF.

3.2.2. *Strengthened specimens - group two*

"Figure 7" displays the crack pattern observed in the specimens of group two strengthened beams following testing. The dashed lines indicate the placement of NSM-steel stirrup rebars, which were embedded around the openings to reinforce the shear zones. Initially, prominent flexural cracks emerged in the middle span of the strengthened beams. Subsequently, diagonal cracks were observed around the openings in the strengthened beams.

"Figure 7a" illustrates the crack pattern observed in the solid specimen DCB. At an applied load of 16 kN, the initial flexural crack became apparent in proximity to the midspan. Following this, diagonal cracks emerged within the shear spans adjacent to the support plates. As the load continued to advance, these diagonal cracks propagated from the supports toward the loading direction.

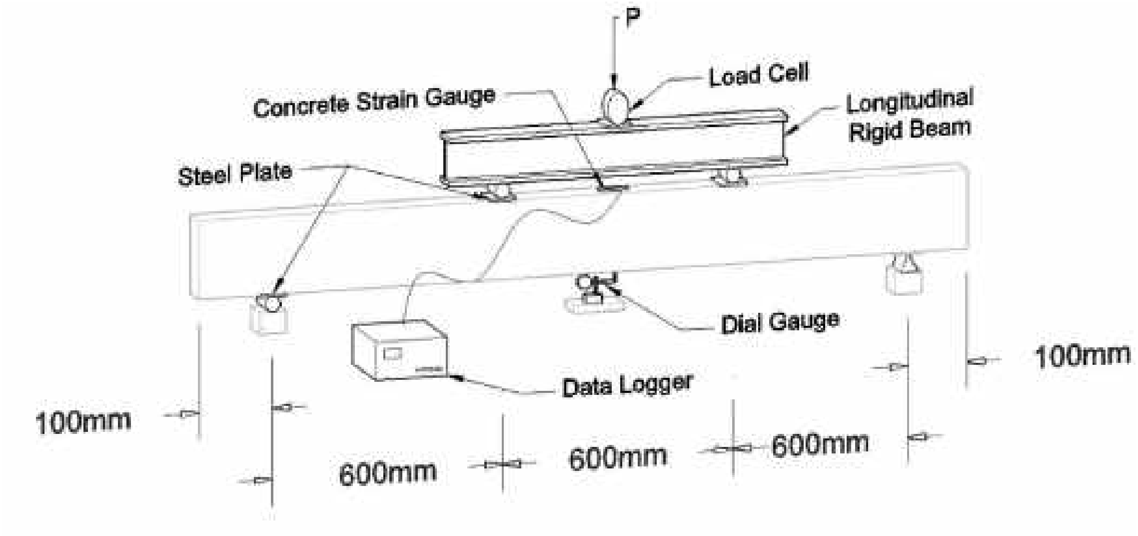
Simultaneously, the commencement of flexural cracks within the constant moment region was observed. As the applied load advanced, these pre-existing cracks underwent extension while additional shear cracks emerged. Ultimately, at a load of 156.5 kN, the occurrence of two distinct splitting cracks within the east and west shear spans precipitated the sudden failure of the beam.



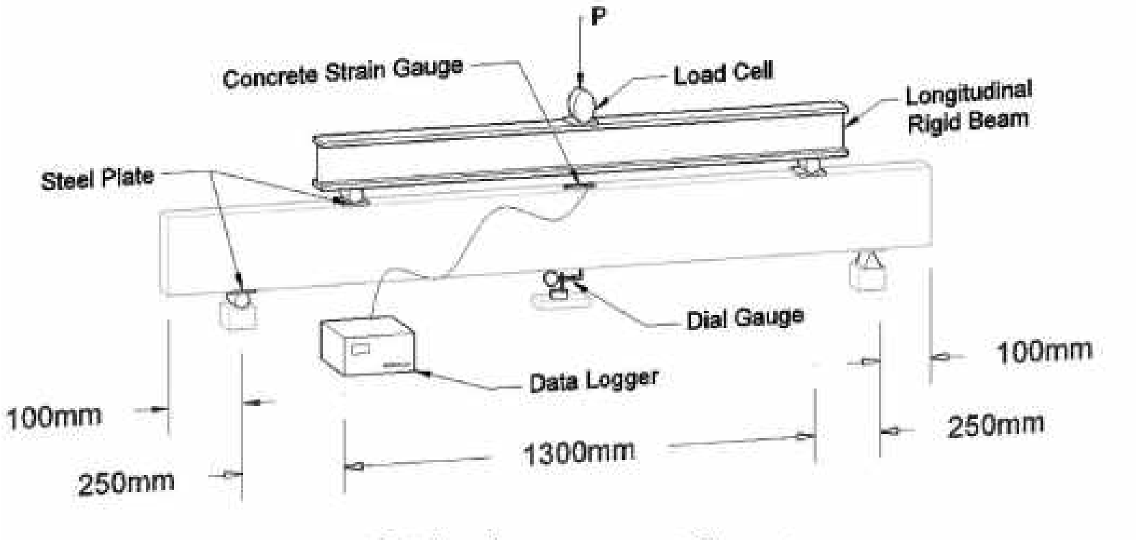
a) installing the rebars into the grooves.

b) Filling the grooves with epoxy paste.

Figure 4. Installation of steel rebars and filling of the grove by epoxy.



a) Load arrangement-Group one.



b) Load arrangement-Group two.

Figure 5. Loading arrangement with measuring instrumentation.

"Figure 7b" depicts the crack pattern observed in specimen DBLS. During the initial stages, at a load of 13.5 kN, a diagonal shear crack originated in the vicinity of the opening's lower corner, near the support. Subsequently, with a slight increment in the load, another shear crack formed on the opposite side of the beam. Additionally, a total of fifteen flexural cracks emerged within the constant moment region at the mid-span of the beam. Eventually, the beam experienced failure at a load of 86 kN, characterized by a diagonal compression mode of failure.

The beams depicted in "Figure 7c–h", wherein the openings were reinforced using square, diamond, and parallelogram steel stirrup rebars, exhibited a notable increase in deflection in comparison to the unstrengthened specimen. The implementation of these strengthening strategies played a significant role in enhancing the beam's overall stiffness. Notably, the introduction of strengthening bars in the form of square, diamond, and parallelogram stirrups resulted in an obstruction of the load path, as indicated by the red hidden line. This obstruction consequently led to the formation of multiple cracks surrounding the openings. Furthermore, it is noteworthy that all of the strengthened beams ultimately experienced failure in a shear compression mode.

Table 4. Summary of test results.

Group no.	Specimens	First Cracking stage		Ultimate stage		Decrease in ultimate load[a]%	Strength gain[b] %	Failure mode
		Pcr (kN)	Δcr (mm)	Pmax (kN)	Δpeak (mm)			
Group one	SCB	12	2.1	61.5	16.5	—	—	Flexure compression
	SBLS	9	1.03	50	9.62	18.7	—	Shear compression
	SBLF	8	0.88	58	11.38	5.7	—	Flexure compression
	SBLSF	7	1.09	52.5	9.8	14.6	—	Shear compression
	SBSF	10	1.36	58.5	10.7	4.8	—	Flexure compression
	SBSSF	7	0.89	49.5	8.77	19.5	—	Shear compression
Group two	DCB	16	0.57	156.5	16	—	—	Diagonal compression
	DBLS	13.5	0.58	86	7.41	45	—	Diagonal compression
	DBLSS8	15	0.98	109.5	10.2	30	21.5	Shear compression
	DBLSS10	18.5	1.04	125.5	11.18	19.8	31.5	Shear compression
	DBLSD8	11	0.73	128.5	11.73	17.9	33.1	Shear compression
	DBLSD10	25.5	1.46	120	9.71	23.3	28.3	Shear compression
	DBLSP 8	18	0.75	117	10.27	25.2	26.5	Shear compression
	DBLSP 10	20.5	0.98	129	9.62	17.6	33.3	Shear compression

Pcr = Cracking Load; **Δcr** = Midspan Deflection at the first cracking stage; **Pmax** = Ultimate Load; **Δpeak** = Midspan Deflection at the Peak Load.

[a] Concerning the SCB specimen in group one and DCB in group two.

[b] Concerning the DBLS specimen.

a) The patterns of crack observed and the failure mode for specimen SCB.

b) The patterns of crack observed and the failure mode for specimen SBLS.

c) The patterns of crack observed and the failure mode for specimen SBLF.

Figure 6 Crack patterns and failure mode for group one specimens.

d) The patterns of crack observed and the failure mode for specimen SBLSF.

e) The patterns of crack observed and the mode of failure for specimen SBSF.

f) The patterns of crack observed and the failure mode for specimen SBSSF

Figure 6. (continued).

3.3. Load-deflection behavior

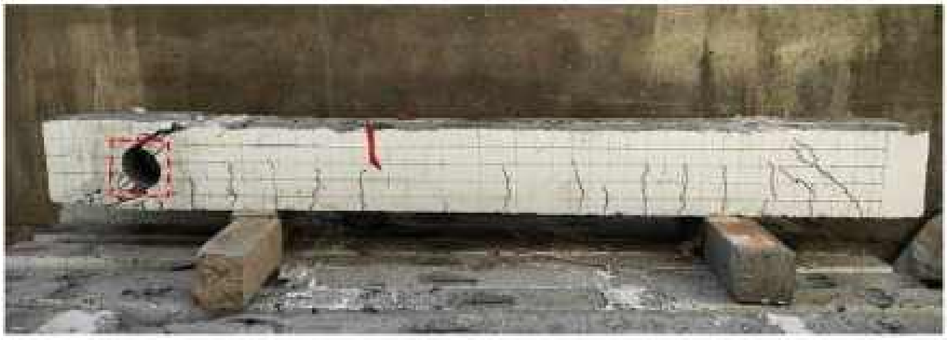
“Figure 8” and “Figure 9” depict the load versus deflection at the midpoint of each specimen in the beam groups. The load and deflection relationship is a valuable tool for understanding how a beam behaves under loads. Typically, two distinct stages of behavior can be observed. Initially, there is a linear segment with a steep slope, indicating the beam is uncracked. As the load reaches the point of cracking, the slope decreases because of the gradual development of cracks in the beam. Eventually, The cracking process stabilizes, resulting in an almost linear segment until the beam fails, and the test type is load-controlled.

For beams having openings lower ultimate load and deflection were observed which means that these beams have smaller areas under the curves (lower work done by forces) as shown in “Figure 8” Beam SBLS, SBSF, and SBSSF have openings in shear span more effect in ultimate load and ultimate deflection compare with those beams having opening in flexure.

In “Figure 9” the increase in ultimate load and deflection was observed for beams DBLSD8, and DBLSP10, near the surface mounted in configurations of diamond with stirrup 8 mm and parallelogram stirrup 10 mm more effective in load-deflection curve.

a) The patterns of crack observed and the failure mode for specimen DCB.

b) The patterns of crack observed and the failure mode for specimen DBLS.



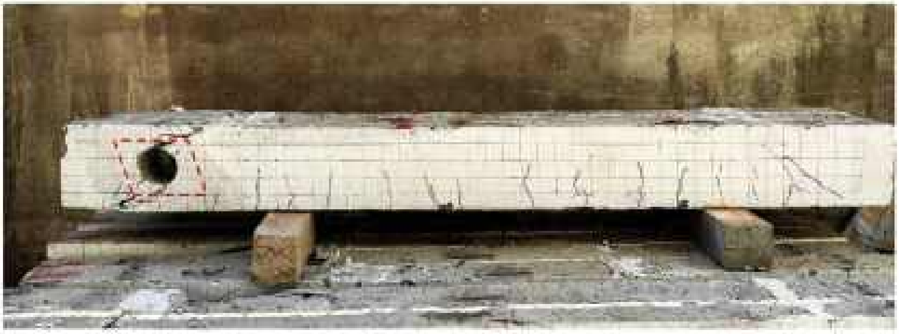
c) The patterns of crack observed and the failure mode for specimen DBLSS8.

d) The patterns of crack observed and the failure mode for specimen DBLSS10.

Figure 7 Crack patterns and failure mode for group two specimens.

e) The patterns of crack observed and the failure mode for specimen DBLSD8.

f) The patterns of crack observed and the failure mode for specimen DBLSD10.



g) The patterns of crack observed and the failure mode for specimen DBLSP8.

h) The patterns of crack observed and the mode of failure for specimen DBLSP10.

Figure 7. (continued).

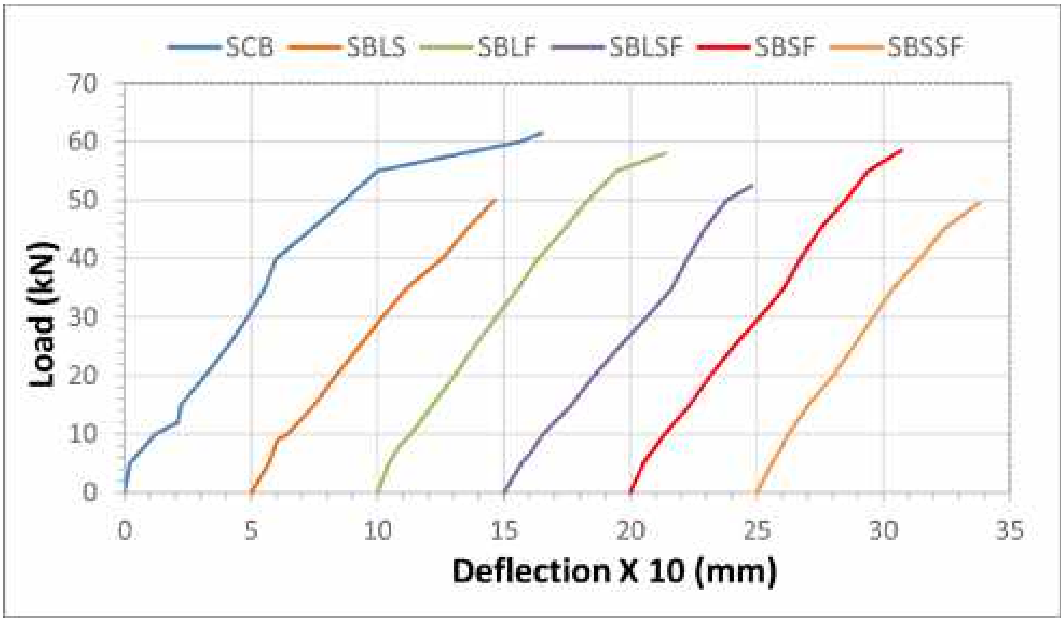


Figure 8. Load deflection curves for group one.

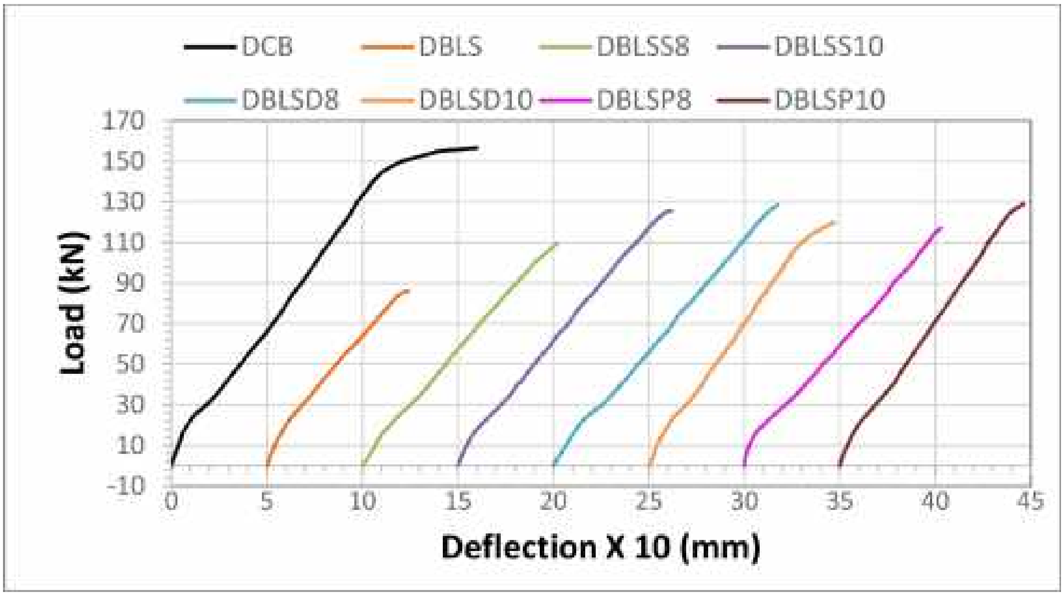


Figure 9. Load deflection curves for group two.

4. Conclusion

In this study, an experiment was conducted to investigate the behavior of reinforced concrete (RC) beams with strengthened openings using NSM steel bars. Based on the findings of the study, the following conclusions can be derived.

1) The introduction of openings in the beam led to reductions in the ultimate load by 18.7%, 14.6%, and 5.7% for the beam with large openings located in the shear, shear with flexure, and flexure zones, respectively.
2) By incorporating small-sized openings in the flexure and shear with flexure zones, the ultimate load of the beam experienced a reduction of 4.8% and 19.8%, respectively.
3) The utilization of 8 mm steel stirrups in various configurations (square, diamond, and parallelogram) to reinforce the openings did not increase

the first cracking load. Nonetheless, it significantly enhanced the ultimate load by approximately 21.5%, 33.1%, and 26.5% for the beam with large openings located in the shear zone, respectively.

4) The addition of 10 mm stirrup bars in square, diamond, and parallelogram configurations resulted in an improvement in the beam capacity, with percentage increases of approximately 31.5%, 28.3%, and 33.3% observed for the samples where significant openings are situated close to the load, respectively.

Conflict of interest

There is no any conflict of interest statement.

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