REPAIR OF RC BEAMS WITH OPENINGS SUBJECTED TO TORSION USING STEEL PLATES

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ABSTRACT

This paper presents the results of an experimental investigation on the behavior of RC beams with openings repaired by steel plates and subjected to pure torsion. The experimental study includes testing of seven RC beams divided into three groups. The parameters considered in this study include the steel plates configuration, opening width and steel plate thickness. The experimental work consists of one solid specimen, four specimens with openings of 300 x 150 mm and two specimens with openings of 500 x 150 mm. The results of the tested beams include cracking and ultimate torques, angle of rotation, toughness, and mode of failure. A cost effectiveness study was performed to compare the different repair configurations used in this research. The experimental results showed that using full steel plates in repairing beams with opening significantly improved the ultimate torsional capacity of such beams.

Keywords: RC beams; Repairing; Opening; Steel plates; Torque

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1. INTRODUCTION

In the last decades, the torsional moment was considered to have a minor effect on the different structural elements, and most of design engineers ignored it. As a result of that, they increased safety factors by depending on conservative flexural design and on the stirrups provided for the

shear design. In many structural members, the torsional moment is one of the main steps in the design process which governs the design. These members include curved girders, edge beams of slabs and shells, spiral stairs and eccentrically loaded beams.

Many researches were carried out on RC members subjected to pure torsion or torsion combined with bending, shear and normal force which their provisions were available in various codes. These codes do not provide special guidelines for the design of RC beams with openings subjected to torsion. Openings are important in RC beams for passing the utility ducts and pipes which are necessary to accommodate the essential services like electricity, air condition, water supply, computer networks and telephones. Passing these ducts through opening in the beams, leads to great saving in the space below such beams causing reduction in the overall height of the building. The repairing or strengthening of beams is a need to enhance their properties such as strength capacity, torsional strength, toughness and ductility to withstand the additional loads applied to the existing structure members.

The influence of the number of openings, the spacing between stirrups, and depth of beams on the torsional behavior of simply supported RC beams with openings were investigated by Abdo and Mabrouk [1]. Mansur et al. [2] investigated the torsional behavior of reinforced concrete beams with large rectangular opening. The behavior of T- shaped RC beam specimens with large rectangular openings subjected to pure torsion was studied by Salama et al.[3]. Makhoul [4] studied the torsional behavior of strengthened beams. His research concentrated on the influence of strengthening by steel stirrups and steel links techniques on the torsional behavior of Z shaped beams with openings. Also, Holman and Cook [5] investigated the torsional behavior of RC spandrel beams repaired using adhesive bonded steel plates.

According to Etman and Marzouk [6], strengthening of solid beams subjected to pure torsion with steel plates increased the ultimate torque by 22% compared to control beam. Fawzy [7] studied the influence of using steel plates and carbon fiber reinforced polymer (CFRP) sheets on the torsional behavior of strengthened RC specimens with and without opening. He found that using steel plates was more effective than FRP in increasing the torsional capacity and toughness of the specimens. Fawzy et al. [8], found that strengthening of RC beams with and without opening by different configurations of CFRP sheets increased the ultimate torque especially the configuration of 90° wrapping of both top and bottom chords and solid parts around the opening.

Domat [9] investigated experimentally and analytically the influence of strengthening RC beams subjected to torsion with CFRP sheets. The results indicated that full wrapping technique was the most effective configuration in resisting torsional moment. Also, strengthening using CFRP strips having an angle of 45° with the beam axis increased the ultimate torsional capacity compared to vertical strips. The spacing between strips was also a significant factor in resisting torsional moment. Atea [10] studied the influence of using CFRP laminates in strengthening RC flanged T-beams subjected to torsion. He found that using anchors with CFRP strips wrapping was more efficient than strips without anchors. Moreover, wrapping the web and flange separately did not show significant improvement in torsional capacity.

Hekal et al. [11], investigated the torsional behavior of RC beams strengthened with Steel or CFRP Plates with different techniques. It was concluded that all strengthening techniques improving the torsional capacity, ductility specially while using CFRP plates or steel plates fixed by both epoxy and steel dowels. Askandar and Mahmood [12], studied the effect of using Near-Surface Mounted Steel Bars (NSM) in strengthening RC beams subjected to torsion and bending. They found that using NSM steel bar improved the torsional resistance and decreased the ductility of all beams. Moreover, the 90° NSM steel bar configuration was more effective than the 45° NSM steel bar configuration.

Kandekar and Talikoti [13], investigated the torsional behavior of RC beams strengthened with aramid fiber reinforced polymers, AFRP. The results showed that full wrapping and strips of 100 mm width schemes improved the ultimate and cracking torques of the tested beams by 140%, and 80% respectively. According to Alabdulhady et al. [14], strengthening of RC beams with fiber reinforced cementitious matrix (FRCM) composites was considered one of the best techniques that enhanced the torsional behavior. Moreover, the full wrapping configuration was more effective than the U wrapping. Finally, it was found that the influence of PBO-FRCM was similar to that of using CFRP and GFRP composites in strengthening beams subjected to torsion.

In this research, the effect of different configurations of steel plates in the vicinity of the opening is investigated. A cost analysis is also conducted to reach the most effective configuration for the repair process.

2. EXPERIMENTAL PROGRAM

2.1. Materials

Trial concrete batching was prepared to achieve characteristic strength of 30 N/mm² after 28 days. This concrete was used to fabricate seven beam specimens. Super plasticizer and high range water reducing additive (Addicrete BVF, 2017) [15] was added to the mixture to achieve specific workability because of the intensity of reinforcement at top and bottom chords of the opening. The components of the concrete mix used in this research is shown in Table 1.

Table 1 Components of the concrete mix

Content	Unit per 1 m ³
Cement (kg)	350
Water (Litre)	195
Coarse Aggregate (Dolomite size No 1) (kg)	625
Coarse Aggregate (Dolomite Size No 2) (kg)	625
Fine Aggregate (Sand) (kg)	650
BVF (Litre)	4

The steel plates used in strengthening the beam specimens in this investigation were of thicknesses of (3 and 6) mm. A tension test was performed to evaluate their mechanical characteristics and the results were 380.5, 432.3, and 1.902×10^5 N/mm² as yield stress, ultimate strength, and Young's modulus, respectively, with 27.7 % as the elongation for the steel plates of 3 mm thickness. The corresponding results for the 6 mm plate were 447.4, 634.7, and 2.24×10^5 N/mm² and 24.4 %. In addition, high tensile steel bolts of grade (8.8) were used to ensure the full contact between steel plates with concrete surface. The utilized bolts were 200 mm in length and 12 mm in diameter. Their mechanical characteristics were 812.9, 964.9, and 4.06×10^5 N/mm² as yield stress, ultimate strength, and Young's modulus, respectively, and 66.4 % as ultimate reduction in area. Also, Kemapoxy 165 (2017) [16] was used as an adhesive material between the steel plates and concrete surface. The grades of steel according to the tension test were 36/52 and 24/36 for the main reinforcement and stirrups, respectively, and 37 for the utilized steel plates.

2.2. Specimen details

The effect of steel plates configuration, opening width and steel plate thickness are the main parameters considered in this study. Table 2 shows the details of the tested groups. The experimental program included seven RC beams having the same cross-sectional dimensions

of 150 x 350 mm and overall span of 1400 mm. This length was divided into three parts; the middle part was 1000 mm which was the test zone. The two end parts were 200 mm in width and 350 mm in length, and were heavily reinforced to be safe against pre-mature failure during testing. Fig. 1 shows the details of the tested beam specimens. These specimens include one solid beam, four beams with openings of dimensions 300 x 150 mm and two beams with openings of dimensions 500 x 150 mm. The beams were reinforced longitudinally with eight high tensile steel bars of 10 mm diameter. In addition, two branches closed stirrups made of 6 mm diameter spaced at 150 mm were used as a transversal reinforcement. The reinforcement details of the specimens are shown as in Fig. 2.

Table 2 Details of the tested groups

Group	Beam No.	Parameter Studied	Repairing Method
A	C-0	Configuration (Full plate & strips)	Control beam without opening
	C-300		Control beam with opening 300 x 150 mm
	R-300-3		RC beam with opening 300 x 150 mm repaired by full steel plates with 3 mm thickness
	R-300-3-S		RC beam with opening 300 x 150 mm repaired by steel plate strips with 3 mm thickness
B	C-0	Opening width (300 & 500 mm)	Control beam without opening
	C-300		Control beam with opening 300 x 150 mm
	C-500		Control beam with opening 500 x 150 mm
	R-300-3		RC beam with opening 300 x 150 mm repaired by full steel plates with 3 mm thickness
	R-500-3		RC beam with opening 500 x 150 mm repaired by full steel plate with 3 mm thickness
C	C-0	Steel Plate Thickness (3 & 6 mm)	Control beam without opening
	C-300		Control beam with opening 300 x 150 mm
	R-300-3		RC beam with opening 300 x 150 mm repaired by full steel plates with 3 mm thickness
	R-300-6		RC beam with opening 300 x 150 mm repaired by full steel plates with 6 mm thickness

In the above table, C represents control specimen; R represents repaired beam; S represents strips; 0 represents no Opening; (3, and 6) represents steel plate thickness in mm; (300, and 500) represents opening width in mm.

Figure 1 Details of the tested beam specimens

Figure 2 Reinforcement details of specimens

2.3. Details of repairing techniques

The experimental program includes testing of seven RC beams subjected to torsion. Specimens C-0, C-300, and C-500 were used as control beams without repairing. Specimens R-300-3, R-300-3-S, R-300-6, and R-500-3 were repaired by steel plates with different configurations and thicknesses. Beam R-300-3 was repaired by one full steel plate with dimensions of 500 x 350 mm in width and depth, and with thickness of 3 mm on the two sides of the beam. Beam R-300-3-S was repaired by using four strips of steel plates with thickness of 3 mm on the two sides of the beam. Beam R-300-6 was repaired by one full steel plate with dimensions of 500 x 350 mm in width and depth, and with thickness of 6 mm on the two sides of the beam. Finally, beam R-500-3 was repaired by one full steel plate with dimensions of 700 x 350 mm in width and depth, and with thickness of 3 mm on the two sides of the beam. Fig. 3 shows the details of repairing configurations.

The beam specimens C-0, C-300, and C-500 were loaded till failure. While specimens (R-300-3, R-300-3-S, R-300-6, and R-500-3) were loaded till a diagonal crack due to torsion appeared, then the load was released. These specimens were then repaired and reloaded again till failure. In the repairing process, the locations of the bolts were marked. Then, holes were drilled in the front and back sides of each beam as shown in Fig. 4(a). The concrete surface of specimens was then made free from painting, dust or other impurities by using polishing grinder machine as in Fig. 4(b). The surface of steel plates was then roughened by using a grinder to increase the cohesion between steel plates and the applied KEMAPOXY 165 as shown in Fig. 4(c). The adhesive material (KEMAPOXY 165, 2017) was then applied on the steel plates, bolts and the holes to ensure complete bonding between concrete and bolts. Finally, the steel plates were fixed in their locations and the bolts and nuts were fastened by spanners to ensure full bonding between steel plates and the concrete beam as in Fig. 4(d).

Figure 3 Details of repairing configuration

(a) The drilling process of the holes

(b) The concrete surface cleaning process

(c) The roughening process of the steel plates Surface

(d) The process of fastening bolts and nuts

Figure 4 Details of repairing process

2.4. Test setup and instrumentation

Fig. 5 shows the test setup of the experimental work. The tested specimens were simply supported on movable supports which allowed beams to rotate about its longitudinal axis. Loading was applied by using hydraulic jack with capacity of 100 ton. The hydraulic jack was connected to a load cell which transferred the readings by data logger to be ready in Excel sheet. The applied vertical load was equally distributed on the two concrete cantilevers at both ends of the beam by using a rigid steel I-beam to produce pure torsional moment. Two LVDTs were installed at the mid span of each cantilever to measure the vertical displacement at various loading stages, while the load on each cantilever was applied in increments. The utilized LVDTs were of 100 mm stroke. All LVDTs readings were recorded in a data sheet. The rotation angles are measured by dividing the average of the two readings of LVDTs at each load by the horizontal distance between LVDT location and the beam centerline. The torque is measured by multiplying the applied force on each cantilever by the horizontal distance between the loading point and the beam centerline.

The reinforcement strain was measured using electrical strain gauges having gauge dimensions of 6 mm and 2.2 mm as length and width, respectively. The strain gauges have gauge factor of 2.12 and 120 Ohm as electrical resistance. Before casting the concrete, three strain gauges were placed in each beam. The first strain gauge was located at the first stirrup beside the opening, while the second strain gauge was fixed at edge stirrup and the third strain gauge was placed on the bottom longitudinal bar. Two other strain gauges were installed at the steel plates to measure their strain. The first strain gauge was at the bottom chord steel plate, while the other strain gauge was at the top corner of the steel plate. Fig. 6 shows schematic view for the strain gauges locations.

Figure 5 Test setup

Figure 6 Schematic view for locations of strain gauges

3. RESULTS AND DISCUSSION

Table 3 shows the results of all tested beams and compared with the unrepaired reference specimens in each group. For group A, the cracking torque was 9.13 kN.m for the solid beam C-0, while it was 4.06 kN.m for beam C-300 with opening 300 x 150 mm. On the other hand, the cracking torques of the repaired beams R-300-3, and R-300-3-S are 3.65 kN.m and 4.26 kN.m, respectively. It has to be noted that in this group the full steel plate configuration had the highest ultimate torque of 13.19 kN.m followed by the steel strips configuration with an ultimate torque of 10.56 kN.m.

In group B, the cracking torque was 9.13 kN.m, 4.06 kN.m, and 3.04 kN.m for beams C-0, C-300, and C-500, respectively. Such moment was 3.65 kN.m, and 2.03 kN.m for the repaired beams R-300-3, and R-500-3, respectively. The results show that keeping the opening height constant and increasing the opening width from 300 mm to 500 mm, leads to decrease in the ultimate torque from 13.19 kN.m, to 12.18 kN.m, for beams R-300-3 and R-500-3, respectively. The ultimate torque for beams C-300 and C-500 with openings and without steel plates was

9.54 kN.m and 5.68 kN.m, respectively. These results show the significant effect of steel plates in substituting the reduction in cross section of the beam due to the presence of the opening.

In group C, the cracking torque was 9.13 kN.m, and 4.06 kN.m for beams C-0, and C-300, respectively, and 3.65 kN.m, and 4.67 kN.m for beams R-300-3, and R-300-6, respectively. The increase in the steel plate thickness from 3 mm to 6 mm leads to increase in the ultimate torque by only 11 %.

Table 3 Results of all tested beams

Beam	T_{cr} (kN.m)	T_{ult} (kN.m)	θ_{ult} (rad/m)	Increased Capacity %	Mode of Failure
C-0	9.13	10.15	0.011	--	Sudden torsional shear failure
C-300	4.06	9.54	0.018	--	Crushing of concrete and cover separation
C-500	3.04	5.68	0.032	--	Crushing of concrete and cover separation
R-300-3	3.65	13.19	0.021	38 %	Crushing of concrete and cover separation beside the opening
R-300-3-S	4.26	10.56	0.059	11 %	Debonding of steel plates and concrete cover separation
R-300-6	4.67	14.62	0.037	53 %	Crushing of concrete and cover separation beside the opening
R-500-3	2.03	12.18	0.032	114 %	Sudden torsional shear failure through the opening

3.1. Mode of failure

The reference unrepaired specimen C-0 experienced a sudden torsional shear failure close to the supports which occurred suddenly at an ultimate torque of 10.15 kN.m as shown in Fig. 7(a). Control beams C-300, and C-500 failed at an ultimate torques of 9.54, and 5.68 kN.m, respectively. These two beams failed due to separation of the concrete cover and crushing of concrete at the top and bottom chords of the opening as shown in Fig. 7(b) and Fig. 7(c).

The failure of the repaired beam R-300-3 occurred due to separation of the concrete cover near the supports and beside the steel plate at an ultimate torque of 13.19 kN.m with 38% increase in capacity compared to the control beam C-300 as shown in Fig. 7(d). While beam R-300-3-S which was repaired with steel plate strips with thickness of 3 mm around the opening on the two sides of the beam, failed due to a sudden debonding of steel plates subsequent to the splitting of concrete cover at an ultimate torque of 10.56 kN.m with 11% increase in capacity compared to the control beam C-300 as shown in Fig. 7(e).

The repaired beam R-500-3 experienced a sudden torsional shear failure through the opening at an ultimate torque of 12.18 kN.m with 114% increase in capacity compared to the control beam C-500 as shown in Fig. 7(f). The failure of the repaired beam R-300-6 was due to crushing of concrete and cover separation beside the opening at an ultimate torque of 14.62 kN.m with 53% increase in capacity compared to the control beam C-300 as shown in Fig. 7(g).

(a) Crack propagation and mode of failure for the control beam (C-0)

(b) Crack propagation and mode of failure for the control beam (C-300)

(c) Crack propagation and mode of failure for the control beam (C-500)

(d) Crack propagation and mode of failure for beam (R-300-3) after repairing

(e) Crack propagation and mode of failure for beam (R-300-3-S) after repairing

(f) Crack propagation and failure mode for beam (R-500-3) after repairing

(g) Crack propagation and mode of failure for beam (R-300-6) after repairing

Figure 7 Mode of failure of all tested specimens

3.2. Angle of Rotation

The torque - rotation angle relation for the specimens of group A is shown in Fig. 8. The rotation angles were recorded at ultimate torque as 0.011, 0.018, 0.021, and 0.059 rad/m for specimens C-0, C-300, R-300-3, and R-300-3-S, respectively. It was observed that the rotation angle increased by 16 %, and 224 % for the repaired beams R-300-3, and R-300-3-S compared to the control beam C-0.

Fig. 9 shows the torque - rotation angle relation for the specimens of group B. The results indicate that repairing of specimen with full steel plates with thickness of 3 mm as in specimen R-500-3 did not have a significant effect on the angle of rotation in comparison with the control specimen C-500. The angle of rotation increased by 16 % for specimen R-300-3 which repaired with the same 3 mm steel plates configuration. The corresponding angles at the ultimate torque were 0.011, 0.018, 0.032, 0.021, and 0.032 rad/m for specimens C-0, C-300, C-500, R-300-3, and R-500-3, respectively.

From Fig. 10, the angles of rotation for the specimens of group C at the ultimate torque were 0.011, 0.018, 0.021, and 0.037 rad/m, for specimens C-0, C-300, R-300-3, and R-300-6, respectively. It is noted that repairing of specimen R-300-6 with full steel plates of 6 mm thickness increased the angle by 102 %. The increase in angle of rotation was 16 % for specimen R-300-3 which repaired with full steel plates of 3 mm thickness.

Figure 8 The torque - rotation angle relation for group A specimens

Figure 9 The torque - rotation angle relation for group B specimens

Figure 10 The torque - rotation angle relation for group C specimens

3.3. Comparison between the repaired beams

Fig. 11 shows the results of the repaired specimens of group A as compared to the reference beam C-300. The torsional toughness is defined as the area under the torque - rotation angle curve which refers to the absorbed energy capacity from the beginning of loading till the failure of the specimen. It was observed that specimen R-300-3-S repaired by steel strips had the highest increase in torsional toughness by 248 % followed by specimen R-300-3 repaired with full steel plates by 5 %.

From Fig. 12, the results of the specimens of group B are compared with control specimen C-300 and C-500. Specimen R-500-3 which repaired with full steel plates with thickness of 3 mm had the highest increase in torsional toughness by 59 % followed by specimen R-300-3 repaired by 3 mm steel plates with 5 % increase.

Fig. 13 illustrates the summary of results of the specimens of group C compared with control specimen C-300. The results show that specimen R-300-6 which repaired with full steel plates with thickness of 6 mm had the highest increase in torsional toughness by 96 % followed by specimen R-300-3 repaired by 3 mm steel plates with 5 % increase.

Figure 11 Results of the repaired specimens of group A compared to the control beam C-300

Figure 12 Results of the repaired specimens of group B compared to the control beams C-300, C-500

Figure 13 Results of the repaired specimens of group C compared to the control beam C-300

3.4. Cost Analysis Study

A cost analysis study was performed to compare between the different repair configurations used in this research. The results may help structural engineers to decide the most effective repair method and configuration in beams with openings under torsional loading. The results show that the repair using steel strips instead of full plate gives the lowest capacity gain per unit price as shown in Fig. 14. Also, using of steel plates for repair against torsion is greatly effective specially for wide openings. The steel plates provided at the beam sides proved to be an accepted substitute for the concrete taken out by the opening.

Figure 14 Percentage of capacity gain per unit cost (USD) for repaired specimens

4. CONCLUSIONS

Based on the experimental results of this research and within the investigated parameters, the following conclusions can be made:

1. Keeping the opening height constant, the opening width of 30 % of the tested span decreased the ultimate torque by 6 % only. The ultimate torque decreased by 44 %, when the openings width reached 50 % of the tested length. This shows that opening width is very critical in beams subjected to torsion.
2. Using full steel plates configuration is more effective than using steel strips in repairing beams with openings subjected to torsion. The ultimate torque increased by 38 %, and 11 % in case of using full steel plates and steel strips respectively. The angle of rotation increased by 16 %, and 224 % in case of repairing with full steel plates and steel strips respectively.
3. Repairing of beams with openings of 300 mm and 500 mm width using full steel plate of 3 mm increased the ultimate torque by 38 % and 114 %, respectively.
4. The ultimate torque increased by 38 % and 53 %, using steel plates with thickness of 3 mm and 6 mm, respectively. The torsional toughness increased by 5 % and 96 % in case of repairing with steel plates with thickness of 3 mm and 6 mm, respectively.
5. The angle of rotation for the repaired specimens increased by 16 % and 102 % in case of repairing with steel plates with thickness of 3 mm and 6 mm, respectively.
6. The results show that the repair using full plates instead of steel strips gives more effective capacity gain per unit price.
7. The steel plates provided at the beam sides proved to be an accepted substitute for the concrete taken out by the opening.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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