DAMAGED RC BEAMS WITH CIRCULAR WEB OPENING REPAIRED USING DIFFERENT CONFIGURATIONS OF BONDING STEEL PLATE

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Abstract

This paper presents the results of an experimental study regarding the repair effectiveness of steel plates for damaged Reinforced Concrete (RC) beams with a circular web opening at shear zones. It highlights the effect of fixing the steel plates on the damaged beams on the load capacity, deflection, steel strain, steel plate strain and failure mode. In the experimental program, three beams were used, with one solid beam used as a control beam and the other two beams repaired by using two configurations (incline and vertical) of steel plate. The results revealed the efficiency of using steel plates for the repairing of damaged beams with a circular opening, in that it increases the ultimate capacity of the beams significantly and reduces the deflection under the opening. Furthermore, it was found that using an incline configuration of steel plate for repairing of beams with a web opening is much more efficient than the use of the vertical configuration. Using an inclined configuration not only increased the ultimate capacity of the beams, it also changed the mode of failure from shear mode to flexural mode.

Keywords: RC beams, circular opening, repair configuration, steel plate.

1. INTRODUCTION

Reinforcing concrete beams with a web opening are necessary in modern building construction to accommodate essential services like water supply, sewage, air-conditioning, electricity, telephone, and computer network because the floor space is limited in most cases, and it is very important to pass these through a transverse opening in the RC beams. Web openings have various forms such as circular, rectangle, and square. A circular opening is commonly used in the construction of buildings for water supply, natural gas pipes,
electricity cables and telephone lines. The presence of a web opening in the reinforced concrete beams leads to a minus effect on the beams behaviour for things such as beam stiffness, excrescence cracks, excessive deflection, and the beam strength. Furthermore, the presence of an opening changes the beams behaviour to become more complex [1]. The existence of the opening leads to disturbances and discontinuities in the normal flow of stresses around opening, thus leading to the appearance of cracks within the vicinity of the opening. Therefore, the region around the opening needs special reinforcement in order to provide sufficient quantity to control the width of cracks and prevent the possible premature failure of the beam with an opening [2].

Previous studies for RC beams with openings started from 1960 [3-9], and most of these studies are about the behaviour of reinforcing concrete beams with an opening. Some of these studies focused on beams with a circular opening and others on beams with a rectangular opening. Some researchers reported the effect of the opening size on the structural behaviour of the beams [10-13]. Tan and Mansur [14] presented a procedure for a complete analysis and design of RC beams with a rectangular web opening. Mansur et al. [15] presented a method for design RC beams with a circular web opening.

Steel plate is one of the most common materials used for strengthening of undamaged structures and repairing of damaged structures to restore structural performance with respect to service and ultimate load levels. The major attractions of this technique are availability, cheapness, uniform materials properties, high ductility and high fatigue strength. In recent years, there are many researchers and studies about repairing and strengthening RC solid beams by steel plate with different configuration. On the other hand, a very few studies on repairing and strengthening RC beam with opening by steel plate. The results show when plates are fixed to the sides (web) of a beam a large increase in the shear capacity can be realized. It was found that the bolted arrangement provided adequate plate anchorage up to the ultimate capacity of the beams. Furthermore, the adhesively bonded plates provide a very high degree of surface crack control R.A. Barnes et al. [16]. The epoxy bonded steel plate provided an average of 72 % increase as compared to the control beams Bimal, B.A. et al. [17]. Using steel plates for strengthening RC beams with web opening not only restored the beam full shear strength but also changed the mode of failure from shear mode to flexural one Allam et al. [18]. Similar investigation was presented by Alfarabi et al. [19] was in this study beams were without internal stirrups and steel plates were applied instead.

2. EXPERIMENTAL WORK

The experimental program of this study includes two RC beams with a circular web opening as well as a beam without any opening which was considered as a control beam. Table 1 shows the beams description according to the pre-repair damage level, repair material and configuration. The opening zone was repaired using steel plates with two configurations as shown in Figure 1. Each beam has a clear span of 2.2 m and the beam cross section is 150 mm width and 400 mm depth. The RC beams with a circular opening in the shear zone were designed according to Mansur [15], where the beams are reinforced with two 16 mm diameter deformed steel bars, whereas the solid beam is designed according to ACI 318 (2008) code requirements. Figure 2 presents the details of the dimensions and reinforcement of the solid beam. The details of the dimensions and reinforcement of beams with a web opening are shown in Figure 3. Figure 4 shows the static load setup. Table 2 presents the physical properties of the RC beams. The RC beams were tested under two point loads. The
load was applied gradually with a loading rate of 4 Kn/min. The repaired beams were initially damaged under the ultimate load. The repairing procedure included preparing the surface of beams where roughness equipment has been used to get a suitable face to have as much friction as possible with the repair materials. Figure 5 shows the roughness procedures and the fixing of the plate. The surface was cleaned by using air pressure to avoid any dust on the surface. When the concrete surface was prepared, the plate was fixed by using an adhesive material and then left for one week for hardening. The steel plate used in this research has a width of 100 mm and 3 mm thickness. The surface of the steel plate was sand blasted to eliminate rust and to make the surface rougher as shown in Figure 6 and steel plates are shown in Table 3.

Table 1: Description of RC beams

<table>
<thead>
<tr>
<th>Beams</th>
<th>Steel bar diameter (mm)</th>
<th>Steel tensile stress (MPa)</th>
<th>Rupture steel stress (MPa)</th>
<th>Concrete compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>16</td>
<td>521</td>
<td>603</td>
<td>30.35</td>
</tr>
<tr>
<td>B1</td>
<td>16</td>
<td>521</td>
<td>603</td>
<td>30.35</td>
</tr>
<tr>
<td>B2</td>
<td>16</td>
<td>521</td>
<td>603</td>
<td>30.35</td>
</tr>
</tbody>
</table>

Table 2: Properties RC beams

<table>
<thead>
<tr>
<th>Beams</th>
<th>Pre-repair damage level</th>
<th>Repair material</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>B1</td>
<td>Ultimate Load</td>
<td>Steel Plate</td>
<td>Inclined</td>
</tr>
<tr>
<td>B2</td>
<td></td>
<td></td>
<td>Vertical</td>
</tr>
</tbody>
</table>

Table 3: Steel plates material properties

<table>
<thead>
<tr>
<th>Materials</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>Tensile strength (MPa)</th>
<th>Modulus of Elasticity (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>100</td>
<td>3</td>
<td>400</td>
<td>200,000</td>
</tr>
</tbody>
</table>

Figure 1: Vertical configuration (left) and incline configuration (right)
Figure 2: Details of dimensions and reinforcement of the solid beam
Figure 3: Details of dimensions and reinforcement of beams with opening

Figure 4: Static load test setup

Figure 5: Surface preparation and steel plate fixing
3. EFFECT REPAIR OF STEEL PLATE
This section presents the results of testing damaged RC beams with a circular web opening which were repaired using steel plates with different configurations. Two beams, B1 and B2, were tested and repaired with the two configurations incline and vertical as shown in Figure 1. The results cover the load, deflection, strain, crack patterns and mode of failure for the beams in two stages, the pre and post repair stages.

3.1 Effect on load deflection relationship
The load against deflection at both the mid-span and under the opening are presented in Figures 14 and 15 respectively. The results of Figure 7 show that the maximum mid-span deflection of the control beam (CB) is 18.74mm at the failure load of 230 kN, while the maximum deflection of beam B3 at the pre-repair stage is 4.14mm at the failure load of 140 kN. The maximum deflection of beam B4 at the pre-repair stage was 4.34 mm at the failure load of 140 kN. The failure of the control beam (CB) was a flexural failure at mid-span, while for beams B1 and B2 the failure was a shear failure in the opening at the pre-repair stage. The maximum mid-span deflection for beam B3 at the post-repair stage was 11.57mm at the failure load of 225 kN, and the failure was a flexural failure at mid-span, whereas the maximum mid-span deflection for beam B4 at the post-repair stage was 9.85 mm at the failure load of 215 kN and the failure was steel plate de-bonding at the opening.

The results of Figure 8 show the maximum deflection at the shear zone for the control beam (CB) is 10.08 mm at the failure load of 230 kN, while the maximum deflection at the opening for beam B3 at the pre-repair stage is 6 mm at the failure load of 140 kN. The maximum deflection at the opening for beam B1 at the post-repair stage is 5.91 mm at the failure load of 225 kN. Furthermore, the maximum deflection at the opening for beam B2 at the pre-repair stage is 5.94 mm at the failure load of 140 kN, and the maximum deflection at the opening for beam B2 at the post-repair stage is 7.23 mm at the failure load of 220 kN.

The results show that repairing beam B1 with the incline configuration of steel plate reduces the deflection at the opening. It could be seen that the deflection at the pre-repair stage for beam B1 at a load of 140 kN is 6 mm, while the deflection at the post-repair stage at the same load of 140 kN is 3.4 mm. The contribution of the incline configuration for steel plates reduces the deflection at the opening by 76%. It can be seen that the deflection at the pre-
repair stage for beam B2 at a load of 140 kN is 5.94 mm, while the deflection at the post-repair stage at same load of 140 kN is 4.64 mm. The presence of the vertical configuration of steel plates reduces the deflection at the opening by 28%.

Figure 7: Load vs. deflection at mid-span curves for beam CB and beams B1 and B2 at pre and post repair stages

Figure 8: Load vs. deflection at shear (under opening) for CB and beam B1 in pre and post repair stage
3.2 Effect on steel bars strain and stirrups

The load against the main steel bar strain at mid-span for the control beam (CB) and beams B1 and B2 at the pre and post repair stage are shown in Figure 9. It can be seen that the steel reached the yield limit at a load of 195 kN for beam CB, while for beam B1 the steel bar reached the yield limit at a load of 200 kN at the post-repair stage, and for beam B2 at the load of 190 kN at the post-repair stage. For beams B1 and B2 at the pre-repair stage, the curve showed that the steel did not reach its yield limit, where the failure happened at the opening (shear failure) before the steel reaches its yield limit. It can be seen that there is an immediate increase in the strain values when the first crack occurs at a load of 45 kN for beam B1 and at a load of 35 kN for beam B2 at the pre-repair stage. The results show that the higher strain is 4714 µst at a load of 200 kN for beam CB, while the higher strain is 3371 µst at a load of 220 kN for beam B1 at the post-repair stage, and the higher strain for beam B2 is 3645 µst at a load of 215 kN at the post-repair stage. Therefore the presence of the steel plate reduces the strain in the steel bar. The steel reaches the rupture strain when the failure occurs in both beams CB and B1 at the post-repair stage. For beam B2, the steel reaches a strain of 4456 µst which is less than the rupture limit.

The load against the shear stirrups strain at the opening for the control beam (CB) and beams B1 and B2 at the pre and post repair stages are shown in Figure 10. It can be seen that the steel reached the yield limit at a load of 120 kN for beam B1 at the pre-repair stage, whereas the steel reached the yield limit at a load of 130 kN for beam B2 at the pre-repair stage. It can also be seen that the peak value of strain at the opening for the shear stirrups was 1500 µst and 1487 µst at a load of 140 kN for beams B1 and B2 respectively. The results show very low values of strain after repairing the damaged beams, and that's because of the contribution of the steel plate which reduces the strain in the steel bar. It is clear in Figure 17 that an immediate increase in the strain values is presented when the first crack occurs.

Figure 9: Load vs. strain of steel bar at mid-span for beams CB, B1 and B2 at pre and post repair stage
The steel plate strain gauges were fixed at two positions around the opening. The first strain gauge (SGS 1) is the closest to the point of the applied load at the top and the second strain gauge (SGS 2) is the closest to the supports at the bottom as shown in Figures 11 and 13 respectively. The load against the steel plate strain for the two strain gauges for both beams B1 and B2 is presented in Figures 12 and 14 respectively. The results show that higher strain is recorded at the first strain gauge (SGS1) which is located between the point of the applied load and the opening. The maximum value recorded for beam B1 is 447 µst in SGS1, which is considered a small value compared to the ultimate strain of the steel plate, while the maximum value recorded is 349 µst in the SGS2 at the bottom. Both strain gauges SGS1 and SGF2 indicate that the steel plate is able to support the load without any release in strain up to failure. On the other hand, the results show that SGS1 indicates a release in the steel plate strain beyond a load of 100 kN where new cracks start to appear in the adhesive layer between the steel plate and the concrete surface in beam B2. The decrease in the value of strain continues until the de-bonding failure occurs. The strain gauge SGF2 also shows a release in the value when the cracks start to appear between the steel plate and the concrete surface. From Figure 14, it can be seen that the curves for both strain gauges SGS1 and SGS2 showed changes in the trend after the cracks appeared between the steel plate and the concrete surfaces.
Figure 11: Position of CFRP strain gauge around opening for beam B1

Figure 12: Position of steel plate strain gage around opening for beam B2

Figure 13: Load vs. strain of CFRP laminates at shear for beam B1
3.4 Crack pattern and failure mode

The first crack was observed at a load of 45 kN for beam B1 and at a load of 35 kN for beam B2 at the pre-repair stage. The cracks at the pre-repair stage started appearing around the opening and mid-span. The trend of the cracks around opening was from the opening toward the point of the applied load at the top and from the opening toward the support point at the bottom. As the load increased, the cracks started to become wider and propagated toward the point of the applied load. In the post-repair stage for beam B1, cracks started propagating at mid-span and became wider when the load increased until the failure, whereas, the repair area around the opening didn’t show any new cracks. This indicated the contribution of steel plate increased the stiffness of the beam at the opening and prevented the appearance of new cracks, whereas in the post-repair stage for beam B2 cracks started propagating from the opening toward the point of the applied load, and the amount of cracks also increased at mid-span. The space between the top corner of the opening and the point of applied load witnessed the emergence of many cracks that have been implemented between the steel plate and the concrete surface, and this then led to the de-bonding failure.

The results show that repairing beam B1 with an externally bonded steel plate transferred the behaviour of the beam from brittle behaviour (shear failure) at the pre-repair stage to ductile behaviour (flexural failure) at the post-repair stage. This is the optimal status that a repaired RC beam with a web opening can achieve. On the other hand, the results show that repairing beam B2 with an externally bonded steel plate as a vertical orientation shifted the failure from a shear failure in the opening at the pre-repair stage to a steel plate de-bonding failure at the post-repair stage. The mode of failure for beams as shown in Figure 15.
Figure 15: The mode failure of beams CB, B1 and B2 at post-repair stage
3.5 Configurations comparison of steel plate

From the aforementioned results, it can be observed that beam B1 achieved a higher ultimate capacity than beam B2. The increase in the ultimate load for beam B1 was 60%, whereas for beam B2 it was 53%. The results show that the maximum deflection for beam B1 at the post-repair stage was 11.57 mm at a load of 225 kN, whereas the maximum deflection for beam B2 at the post-repair stage was 9.85 mm at a load of 215 kN. The deflection at mid-span for beam B1 is more than for beam B2 because the failure for beam B1 occurs in mid-span as a flexural failure while the beam B2 failure occurs at the shear level as steel plate de-bonding.

It can be seen that the maximum deflection for beam B1 is 5.91 mm at a load of 225 kN at the opening, whereas the maximum deflection for beam B2 is 7.33 mm at a load of 215 kN. Beam B1 has a lower deflection at the opening from beam B2 because the beam B4 failure occurs at the opening as steel plate de-bonding, while the beam B1 failure occurs at mid-span as a flexural failure. The lower deflections at the opening indicate the contribution of the inclined configuration of steel plate.

It can be seen that the steel bar strain at mid-span for both beams at the pre-repair stage didn’t reach the yield limit because the failure at this stage for both beams occurs in the opening zone. After repair, beam B1 reached the yield limit at a load of 200 kN, whereas beam B2 reached the yield limit at a load of 190 kN. However, the strain of the steel bar in mid-span for beam B1 reached the rupture strain when the failure occurs as a flexural failure, while the steel bar in mid-span for B2 didn’t reach the rupture limit because the failure occurs at the shear zone as a steel plate de-bonding failure. The results also show the strain of the strips at the shear zone with the opening for beam B1 reached the yield limit when the load was 120 kN at the pre-repair stage, whereas beam B3 reached the yield limit when the load was 130 kN. After repair, the strain of the stirrups for beam B1 shows very low values because of the contribution of the inclined steel plate, while the strain of the stirrups for beam B2 shows high values because of the de-bonding of the vertical steel plate. The results show that for beam B1, both strain gauges SGF1 and SGF2 indicate that the steel plate with the incline configuration is able to support the load without any release in strain up to failure. On the other hand, the strain of the vertical steel plate configuration for beam B2 for both strain gauges SGF1 and SGF2 showed changes in the trend after the cracks appeared between the steel plate and the concrete surfaces.

The crack trends for both beams are almost the same around the opening when the failure occurs at the pre-repair stage. In the post-repair stage the crack patterns are different for each beam depending on the form of failure, for beam B1 many cracks appeared at the mid-span, whereas for beam B2 the cracks started increasing and widening between the vertical steel plate and the concrete surfaces until the de-bonding failure occurs. The contribution of the inclined steel plate shifted the mode of failure in beam B1 from a brittle failure at the opening to a ductile failure at mid-span, while the vertical configuration didn’t change the brittle behaviour of the repaired beam.

From the results of both beams B1 and B2, it was found that using an incline configuration for repairing beams with a circular web opening is more efficient than using a vertical configuration.

4. CONCLUSION

The present study aimed to investigate the repair effectiveness of damaged RC beams with a circular web opening using externally bonded steel plates with different configurations. The study was based on the comparison of the load, deflection, strain and crack pattern and
failure mode. The study also investigates the effect of the configuration of repairing materials on the repair effectiveness. Based on the experimental results of the tested beams, the following are the main conclusions.

- Repairing an RC beam with a circular web opening using steel plate increases the load capacity and decreases the deflection and steel strain.
- External repairing of the beam opening using an incline configuration of steel plate is more effective than using a vertical configuration.
- Using an incline configuration changed the behaviour of the beams failure from brittle to ductile.

REFERENCES