EXPERIMENTAL STUDY ON BONDING IMPROVEMENT OF CFRP STRIPS USED FOR STRENGTHENING OF STEEL BEAMS

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ABSTRACT

The strengthening of aging steel structures has become a task for civil engineers in recent years. The steel girders in aging bridges are among the structures which can be effectively strengthened by epoxy bonding carbon fiber reinforced polymers (CFRP) laminates to the damaged tension face of the girders. Though this method is very simple to use, it usually suffers from the problem of debonding failure of CFRP strip used for strengthening of steel members. Therefore it is worthwhile to provide a proper and practical bonding enhancement detail. In this paper, a method of adding steel patch plates on CFRP strip is introduced. Eight steel beam specimens which are artificially damaged at their mid-span (notched) and then repaired with CFRP laminates are tested through a four-point loading setup. Also, double-lap shear tests are performed to validate the effect of using the proposed method in comparison with another anchoring method known as mechanical clamping. The effect of different bonding lengths of the CFRP laminates is investigated, too. The experimental results of the repaired steel beam specimens show that adding small pieces of steel plate (patches) over CFRP laminate and beam’s flange at high stress concentration zones can increase the bonding strength about 50% in comparison with the beams repaired with no patches. The results of double-lap shear tests show that the methods of adding steel patches and mechanical clamping increase the bonding resistance up to about 59% and 35%, respectively, in comparison with the cases of without patches or clamps.

Keywords: CFRP; steel members; debonding failure; bonding enhancement; clamp; patch

1. INTRODUCTION

There are many factors which cause aging civil structures to become inadequate and lose their serviceability: e.g. deterioration of materials by environmental corrosive agents, increase of magnitude and repetition of loads acting on the structures, design and construction errors, etc. Particularly, steel structures may be seriously damaged by fatigue and corrosion leading to decrease of the load bearing capacity of the structures. One of the

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efficiently used methods for rehabilitation of the existing damaged steel structures is to use bonded carbon fiber reinforced polymers, CFRP. Some advantages including light weight, high strength, easiness of installation, large length of the plates that can be delivered to construction sites and simplicity in fitting complex profile cause CFRP to be preferred to the bonded steel plates for strengthening of structures. In general, other conventional strengthening techniques are labor intensive and disruptive to the serviceability of the structure, especially, the bridge structures. Steel structures like concrete structures can be strengthened by using CFRP in the forms of woven dry fibers (sheets) or pultruded laminates [1]. Strengthening of steel structures with CFRP materials is a viable solution for flexural rehabilitation. In addition to flexural strengthening of old steel structures, the CFRP reinforcement may be useful in increasing the load bearing capacity of the structures to accommodate new serviceability conditions. In the steel or composite bridges, the strength and stiffness of steel girders can be improved by bonding CFRP laminates to their tension faces [2, 3, and 4]. Observations by researchers show that, in many bridges, the damage is manifested by formation and growth of fatigue cracks in the vicinity of the fatigue sensitive locations [5]. This type of defected girders can also be strengthened using CFRP, [6]. Nevertheless, different failure mechanisms are generated as a consequence of member strengthening which must be precisely identified. The potential for lateral-torsional buckling, probable local buckling of beam’s web and flange in compression, plastifying of high stressed zones, tensile rupture of CFRP and debonding of CFRP laminate are among the failure modes which should be carefully considered. The prevalence of debonding failure has distinguished it from the other mechanisms so the major part of research works has been focused on the clarification of this phenomenon. As a consequence of debonding, the joint action between CFRP and strengthened member is removed and this is dangerous since the load bearing capacity of the system may reduce to a value less than what is demanded. Debonding of the CFRP laminate from the steel member can happen in three different cases: sliding at CFRP laminate-to-adhesive interface, sliding at adhesive-to-steel interface and inner delamination of the fibers. There are many parameters affecting the potential for debonding failure and among them the presence of high stress concentration zones, the elastic modulus of CFRP and adhesive, the thickness of the laminate and the adhesive, the surface preparation of the adherends and defects such as the void inclusion in the adhesive layer are remarkable. Apart from fabrication factors, regions of high stress concentration have been recognized as the focus of probable debonding initiation. The interfacial shear stress produced by the tensile force of the laminate together with the peeling stress, issued by the curvature of the beam and/or other local deformation of the adhesive layer, are understood to play the main role in the debonding failure. These stresses are normally concentrated at places where geometrical discontinuity such as abrupt changes either in the cross-section or along the length of the laminated member takes place, e.g., laminate curtailment points and the cut points of the steel members. This paper focuses on the cut (notched) steel beams strengthened by CFRP laminates (strips). It is intended to investigate how the debonding failure can be prevented or delayed using a simple and efficient detail. To this end, a method of adding steel patches on CFRP strip at highly stressed zones will be introduced. Eight steel beam specimens being artificially damaged at their mid-span (notched) and repaired with CFRP laminates are tested through a four-point
loading setup. Also, double-lap shear tests are performed to confirm the effect of using the proposed method in comparison with another anchoring method known as mechanical clamping. The load bearing capacity as well as the load-deflection curves of the specimens are obtained and the effectiveness of the proposed detail is discussed. The effect of different bonding lengths of the CFRP laminates will be investigated, too.

2. PREVIOUS WORKS

Using CFRP to strengthen steel structures has been an approved method in the field of rehabilitation of aging structures, [2]. There are a number of research works [7, 8, 9 and 10] on rehabilitation of steel and steel-concrete composite bridges which have shown that the method of CFRP bonding to tension flange of defected girders is a very effective method, though it is sensitive to debonding failure mode. The study on debonding failure mode of CFRP-strengthened beams, as a very prevailing case, has become the focus of many research works in recent years, [6]. Many successful analytical modelings have been proposed for stress analysis of bonded CFRP near points of discontinuity in elastic range, [11, 12 and 13]. Some researchers have focused on another kind of debonding failure occurring in members in post-yielded stage near the regions where the parent steel tends to be plasticized [14, 15 and 16]. Also, many analytical methods such as strength-based and fracture mechanics-based methods have been developed for predicting the debonding failure load capacity and reasonable adjustments with experimental results have been reported.

Another research field as worthy as the subject of debonding failure prediction is the development of practical methods for reducing the stress concentration or generally methods for enhancement of the bonding strength at critical points. Among them, providing a spew fillet of excess adhesive at the ends of the joint, increase of adhesive thickness of the bond line, tapering of the laminates at the ends, mechanical clamping and wrapping the laminate's ends in CFRP sheets are outstanding, [17]. The reverse tapering of the laminates at two ends has been exploited as a simple and efficient method for bonding enhancement and is the first choice in most cases. The research reported earlier indicates that considerable enhancement can be achieved using this detail, [1]. Nevertheless, this method is not applicable to reinforce regions other than laminate curtailment points, for instance at regions where the laminate is continuous and the stress concentration is due to the damaged surface of the parent steel, like as the case of a slotted (or notched) beam. Also, preparing reverse tapering of thin laminates is not easy. Clamping method is preferable in the cases in which either the peeling stress affects significantly on debonding failure or the tapering is not applicable. Perforation of adherends may render the potential of interlamine debonding but with a cost of decrease in cross section of the laminate or steel member. Wrapping the CFRP sheets around the tension flange and part of the web of an externally laminated beam at cut points also may improve the bonding capacity, [17]. Several testing methods are usually recommended to be used in the assessment of bonding strength of the joints detailed with different methods. Among them, the double-lap shear test (or double-strap tension test) has been commonly used to investigate the details of the joint between CFRP and steel. As mentioned before, this paper proposes a simple and suitable detail applicable for reinforcing
(anchoring) of the bonded CFRP laminates used for strengthening of notched steel beams. The proposed detail will be compared with the other existing methods such as mechanical clamping. As an initial estimate, the criteria for the superiority of a joint are assumed to be the maximum failure load attained by each detail. The effect of reverse tapering and spew fillet of excessive adhesive were not included in this research because only small thickness of CFRP laminates (1.4 mm) were used here and, as mentioned before, reverse tapering is not usable for notched beams which are to be studied in this research.

3. EXPERIMENTAL STUDY

For the purpose of increasing the strength of joint (bonding) between CFRP laminates and steel members, the effectiveness of the method of adding steel patches over CFRP laminates was examined by testing eight small-scale slotted steel beams. For the slotted beam specimens, the lower flange and the web were cut with a band saw. The slot was extended to the fillet of the upper flange and terminated to a hole with a diameter of 30 mm. This hole was produced in order to reduce the stress concentration at the end of the slot. All the steel beam specimens were I-shaped with, 150cm long and 14cm high. Furthermore, a number of double-lap shear tests were performed to confirm the capability of the proposed method in comparison with another reinforcing method which is known as mechanical clamping.

3.1 Materials

**Epoxy:** A two-component epoxy with the traditional name of Sikadur-30 was used for bonding the CFRP laminate to the steel flange surface. The epoxy had a mix ratio of 3:1 by weight for the components A and B, respectively, and with a pot life of 40 minutes at +25°C. The mean values for the modulds of elasticity and tensile strength measured for four dog bone specimens were 9.95 GPa and 24.75 MPa, respectively.

**CFRP:** A unidirectional pultruded carbon strip with a traditional name of Sika-Carbodur-S514 was used in all the tests. This product, manufactured by Sika Co., has a nominal modulus of elasticity of 165 GPa and a minimum tensile strength of 2800 MPa. The nominal elongation of 1.7% at break point was reported by the manufacturer. The mean value of elastic modulus measured for four specimens of CFRP laminates was 160.78 GPa and the tensile strength and ultimate elongation were not measured because the laminates were to be stressed well below their nominal break points.

**Steel:** The steel material used in the tested hot rolled sections, steel strips and steel patches was standard DIN-St37 steel. For the used hot rolled section of IPE14 (according to DIN standard), the measured mean elastic modulus for four specimens cut from the flange and web of the section were 195.8 GPa and 209.45 GPa, respectively. The measured yield strength for those specimens was 285 MPa and 316.5 MPa for flange and web, respectively. The specimens had dimensions of 25×300 mm and were tested in a standard universal testing machine.

3.2 Specimen preparation and testing setup

The steel I-shaped sections of IPE14 were first cut into 1.5 m long spans. Then a slot was
made in the tension flange and the web of the beams at mid-span by a cut extending up to near the upper fillet of the cross section, terminating to a hole of 3 cm in diameter which was made by a flame saw. This hole was made for the purpose of removing the tip of the slot which is a location of high stress concentration. As it was expected and approved by the test, the unstrengthened notched beam had a negligible measured load bearing capacity, \( P < 1.0 \text{ kN} \). A schematic arrangement of the testing set up together with a tested specimen is depicted in Figure 1(a, b and c).

Surface preparation of the steel and CFRP surfaces must be performed to improve the chemical bonding between the adherend’s surface and the adhesive. To prepare a chemically active surface, first the steel surface was abraded to remove the rust and other particles as much as the real color of the steel appeared. Then, the surface was cleaned by acetone to remove oxides and greasy materials. The CFRP laminates were abraded a little with sandpaper and cleaned with methanol. Finally, the eight beam specimens with different joint details were made, as shown in Figure (2). The characteristics of the tested beams are summarized in Table (1).

![Figure 1](a) Test set up and specimens’ characteristics: (a) Four-point loading set up for beam specimens, (b) cross section of strengthened beams, (c) universal testing machine, (d) a double-lap shear specimen
In the double-lap shear tests, each specimen was comprised of a pair of 8x100x350 mm steel plates which were joined to each other by a pair of CFRP strips at both sides, as is shown in Figure 1(d). Three groups each with four specimens of bonding lengths of a=50, 100, 150 and 200 mm were prepared, but with three different details, as depicted in Figure 3 (a), (b) and (c), respectively. Tension force was applied to the specimens until they were broken. The monotonic loading rate remained constant at about 0.025mm per minute during all the tests.

<table>
<thead>
<tr>
<th>No.</th>
<th>Specimen ID</th>
<th>Bonding length, a(mm)</th>
<th>Joint detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>B-40-2P</td>
<td>200</td>
<td>Two pairs of patches</td>
</tr>
<tr>
<td>(2)</td>
<td>B-60-2P</td>
<td>300</td>
<td>Two pairs of patches</td>
</tr>
<tr>
<td>(3)</td>
<td>B-80-2P</td>
<td>400</td>
<td>Two pairs of patches</td>
</tr>
<tr>
<td>(4)</td>
<td>B-80-2PO</td>
<td>400</td>
<td>Two pairs of patches with a hole</td>
</tr>
<tr>
<td>(5)</td>
<td>B-80-3P</td>
<td>400</td>
<td>Three pairs of patches</td>
</tr>
</tbody>
</table>
4. EXPERIMENTAL ANALYSIS

The applied load as well as the vertical displacements at the loaded point was measured for the beams and their graphs were traced. All the beams were failed in debonding scenario because load capacity of the other probable failure modes had been already estimated to be well below the failure load. The Figure 4(a) shows a beam specimen which is restrained laterally using wooden blocks in the testing machine. The double-lap shear test set up is depicted in Figure 4(b).

4.1 Experimental analysis of retrofitted notched beams and discussion

At first step the beams are made notched and one of the beams is tested in a four-point bending configuration as seen in Figure 1(a) to measure the force that the notched beam can tolerate. It was observed that the unstrengthened notched beam can not tolerate the force of 1.0 kN and the notch entirely affects the strength of the beam and its load bearing capacity is negligible. Then the notched beams are retrofitted by CFRP strips with a measured elastic modulus of $E = 160\text{GPa}$ and with a cross sections of 1.4 mm x 50 mm.
In the three test specimens identified by B-40, B-60, and B-80, referring to Table (1), only the CFRP strip is bonded to the lower (bottom) flange with an adhesive of the type sikadur-30. The length of the CFRP strip in the specimen of B-40 is 40 cm: 20 cm in each side of the notch. The length of the CFRP strips in the specimens of B-60 and B-80 are 60 cm and 80 cm, respectively, with a length of 30 cm and 40 cm in both sides of the notch in each of these specimens. As it is mentioned in the specimens of B-40, B-60 and B-80, only the CFRP strips are bonded to the tension flange of the beams and no other clamps and clips are used. In the next three specimens which are identified by B-40-2P, B-60-2P and B-80-2P, for retrofitting of the beams, the CFRP strips are bonded to the bottom flange of specimens and also for improving the debonding of the strips, steel patches are employed and bonded to each CFRP strip and each bottom flange of the beam on four points. Two steel patches are bonded to the end sides of CFRP strips and the bottom flange of the beams and two other steel patches are bonded to CFRP strips and the bottom flange of the beams on two sides of the notches as it is seen in Figure 2.

In another specimen identified by B-80-3P, six steel patches are bonded to the CFRP strip and bottom flange of the beam on six points, three points on each side of the notch. Four–point bending experiments are carried out for all of the specimens. Results show that the retrofitted specimens without any steel patches, i.e., the specimens of B-40, B-60 and B-80 have been strengthened fairly well. Results also show that the specimens with steel patches, i.e., B-40-2P, B-60-2P and B-80-2P have an improved strength in comparison with the specimens without any steel patches. In Figures 5-7 the load-deflection curves for the six specimens are shown. The horizontal axes illustrate the deflection of the beams and the vertical axes illustrate the applied load. Figures 5-7 illustrate that the retrofitted techniques are effective and the beams have achieved to tolerate loads of about P=26.5 kN (i.e. 0.29Pp). The plastic collapse load of IPE14 section, Pp can be calculated having the section plastic modulus of Zp=88.4 cm³, steel yield strength of Fy=285 N/mm², span length of L=140 cm and distance between applied loads of 2b=30 cm as follows

$$P_p = \frac{4M_p}{(L-2b)}$$

where

$$M_p = F_yZ_p$$

Using equations (1) and (2) plastic moment and plastic collapse load are obtained as M_p=25.19 kN.m and P_p=91.6 kN, respectively.

Figures 5-7 also show that the specimens of B-40-2P, B-60-2P and B-80-2P with steel patches on two end points of the CFRP strips and on two sides of the notches tolerate loads of 37.3 kN (0.41Pp), 39.2 kN (0.43Pp) and 41.2 kN (0.45Pp), respectively. It is worth noting that the notched beams with no retrofitting CFRP strips could not tolerate any bending load (P< 0.01Pp). Furthermore, by bonding steel patches to the CFRP strips and the bottom flanges of the notched beams it is observed that the maximum force that the retrofitted notched beams with the bond lengths of 20cm, 30cm and 40cm can tolerate increases by 46%, 51% and 56%, respectively. Figure 8 shows that the maximum load that a retrofitted notched beam by just a CFRP strip can tolerates is almost the same for different bond
lengths. This Figure also shows that the maximum load that a retrofitted notched beam by a CFRP strip and steel patches can tolerate increases by increasing the bond length.

In the specimen B-80-3P, in which three steel patches are bonded to the CFRP strip and the bottom flange of the notched beam on each side of the notch with the bond length of 40 cm, the maximum load that the retrofitted beam can tolerate is 43.9 kN (i.e. 0.48Pp). In Figure 9, load-displacement curves are plotted for the specimens of B-80-2P and B-80-3P. In this Figure it is observed that by adding one extra steel patch to each side of the notch, the maximum load that the retrofitted beam can tolerate increases by 66% with respect to the specimen B-80, which has no steel patch.

Another specimen is B-80-2PO which is similar to the specimen of B-80-2P. The difference between the above two specimens is that the CFRP strips used for the specimen B-80-2PO were perforated so that one hole of diameter 18 mm was made beneath each steel patch. These holes were intended to make an adhesive link between the steel patches and the beam’s flange. Figure 10 shows that the load bearing capacity of the specimen B-80-2PO is about 31.9 kN which is 23% less than that of specimen B-80-2P and this is attributed to the fact that the holes have decreased the effective width of the CFRP strips. But it is interesting to see in Figure 10 that the behavior of the B-80-2PO after the first peak load is more smooth (ductile) than B-80-2P, which needs to be further investigated.

**Figure 5.** Load-deflection curves for the specimens of B-40 and B-40-2P

**Figure 6.** Load-deflection curves for the specimens of B-60 and B-60-2P
Figure 7. Load-deflection curves for the specimens of B-80 and B-80-2P

Figure 8. Comparison of load bearing capacity of the strengthened beams with different details

Figure 9. Load-deflection curves for the specimens of B-80-2P and B-80-3P
4.2 Experimental Analysis of Double-Lap Shear Tests and Discussion

The experimental program consisted of twelve double-lap shear coupon tests. The geometrical form of the spew fillet was identical for all the specimens. The parameters included in this study were the length of the joint and the type of reinforcing detail. The tested specimens were divided into three groups: the first denoted by “A” comprised of specimens without any enhancement device (called plain joints); the second denoted by “C” comprised of specimens with bolted clamps and the third denoted by “P” comprised of specimens with overlapped steel plates (patched over the critical regions).

The comparison of the results is demonstrated in Figure 11. As this Figure shows, the reinforcement with patched steel plates for all joint lengths leads to a superior bonding strength with respect to the reinforcement with mechanical clamps and with no reinforcement. The average increase of bonding resistance for the joints reinforced with clamped and patched plates are 35% and 59%, respectively, in comparison with unreinforced cases. The maximum increase of 58% and 74% belong to the joints of length 200mm which are reinforced with clamps and patches, respectively. These test results indicate that both methods of adding patches and clamps considerably increase bonding resistance, but the former is preferable in practice because of its simplicity for preparation and installation. The feasible behavior observed in the proposed bonding enhancement method indicates that the stresses have been reduced in the critical regions. The following factors may explain why the patches improve the joint behavior: the reduction of shear stress because of the extended bonding area provided by the patched steel plates wider than CFRP laminate; the reduction of peeling stress; the presence of thicker layer of epoxy resin beneath the patched plates which causes the stresses to be reduced; the cooperation of the outer surface of the CFRP laminate in load transfer through the joint; the reduction of delaminating stresses by virtue of the participation of both sides of laminate in load transferring mechanism which is relevant to the encasement condition provided by adding patched steel plates.
Figure 11. The results of double-lap shear tests

5. CONCLUSIONS

In this paper a method for the improvement of bonding strength between laminates of carbon fiber reinforced polymer (CFRP) and steel beams was introduced. In this method small patches of steel plates are attached as cover plates to the CFRP strip at the locations of high stress concentration. Eight notched steel beams of 1.5 m in span were prepared by cutting their tension flange and web at mid-span. Then the beams were repaired by attaching of one layer of CFRP laminate to their slotted lower flange. One half of the specimens were repaired by a standard method of gluing the laminate to the cut tension flange and in the other half the steel patches were added to cover the laminate's extremes and sides of the gap. The beams were tested in a standard four-point loading setup until failure occurred. Also, double-lap shear tests were performed to confirm the effectiveness of the used method in comparison with another method of adding mechanical clamps to the joint. The effect of the length of the CFRP laminate was investigated, too. Based on the results of the experimental investigations, the following conclusions are obtained:

1. The method of adding patch steel plates and mechanical clamping can increase the strength of double-lap joints up to 59% and 35% in average, respectively, in comparison with joints without any reinforcing devices.

2. If patched steel plates are used to repair notched beams, the load bearing capacity of the beams increases 50% in average with respect to the beams strengthened with no patches. The participation of both faces of the CFRP laminate, encased in the space between the patched and main steel plates, seems to be the reason for the improved behavior of the joint.

The proposed reinforcing method can be effectively used for enhancement of the bonding strength between CFRP strips and steel members. The installation process of the method is very simple and cost-effective. In practice, steel patches can be fixed to repaired beams by magnetic holders until the epoxy hardens.
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