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EXPERIMENTAL STUDY ON BONDING ENHANCEMENT METHODS BETWEEN CFRP STRIPS AND STEEL PLATES BY DOUBLE-LAP SHEAR TEST

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ABSTRACT

One of the ways to confront the problem of debonding failure of externally-bonded carbon fiber reinforced polymers (CFRP), used for strengthening of steel members, is to provide a proper and practical bonding detail. If the high stress-concentration zones of the bonded strip such as curtailment points of CFRP or member discontinuities are suitably detailed or reinforced, then bonding resistance will be improved. This paper describes experimentally the methods which successfully prevent the premature debonding failure of externally-laminated steel members. The double-lap shear test set up has been chosen as a frame work to compare the results. Therefore bond zones includes shear stresses and peel stresses. The mechanical clamps in different arrangements were examined as a bond-enhancement detail. Also, the effect of the length of the CFRP laminate was investigated along with different types of end mechanical anchorage. Finally, a simple and efficient bonding enhancement method has been proposed, in the form of overlapping the critical debonding zones using steel plates. The test results show that both the overlapping and clamping methods considerably increase the bonding resistance, but the former method is preferable because of its simplicity for installation and because in this case further increase of strength is obtained.

Keywords: Steel members; debonding failure; bonding enhancement; clamp.

1. INTRODUCTION

One of the increasingly used methods for upgrading the strength of the existing structures is the using of externally-bonded carbon fiber reinforced polymers, CFRP. Some advantages including the light weight, high strength, easiness of installation and the large length of the plates that can be delivered to construction sites show the preference of CFRP to externally-

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bonded steel plates for strengthening of the structures. In general, other conventional strengthening techniques need more labor cost and have disadvantage of requiring splice plates due to the limited length of steel strips. Steel structures like concrete structures can be strengthened using CFRP in the forms of woven dry fibers (sheets) or pultruded laminates[1]. Strengthening 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. The strength and stiffness of steel bridges and steel beams can be improved by bonding CFRP laminates to their tension faces[2, 3, 4]. Nevertheless, this extra strength could be accessible only if any new failure mechanisms generated as a consequence of member strengthening would be under control. 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 failure modes which should be precisely investigated. The abrupt and complex nature 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. Debonding of the CFRP laminate from the steel member can happen in three different ways: 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 adherents 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. Other factors are generally considered as the parameters that can intensify the stress concentration at the critical regions of the CFRP-to-steel interface. 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 the 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 off or damaged points of the steel member. Most of the research works have been concentrated on characterization of the debonding failure at points of discontinuity [5, 6, 7, and 8]. Some researchers have focused on another kind of debonding failure occurring to a member in the post-yielded stage near the regions where the parent steel tends to be plasticized [9, 10, 11, 12].

Many analytical methods have been developed for predicting the debonding failure and reasonable adjustments with some experimental results have been reported. The procedures usually followed for the simulation of debonding can be divided into two groups: strength analysis-based and fracture mechanics-based groups. According to strength models of the first group, debonding failure takes place only when interfacial stresses satisfy a failure criterion dependent on measured strength properties of involved materials [5, 13]. On the other hand, some researchers believe that the strength-based failure criterion methods are more suitable for ductile and gradual failure modes than for brittle failure modes like debonding (see, for instance, [14]). In the fracture mechanics-based methods, the propagation of a crack near to the points of stress singularities (e.g., two ends of the strengthening plate) is analyzed. To predict crack propagation, the energy released rate (ERR) must be evaluated for the numerical model and compared with the critical fracture energy of the interface which is a property of the materials, determined from experiments. It should be mentioned that any procedure used to predict debonding failure needs an efficient tool for stress analysis as a prerequisite. For this purpose, several methods for stress analysis have been adopted including: simple relations of strength of materials, closed-form solutions of governing deferential equations for specific conditions and more rigorous method of finite element analysis [13, 14, and 15].

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 the 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, perforating the adherents for better interlocking and wrapping the laminate's ends in CFRP sheets are outstanding. 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 of the cases. The previously reported research indicates that considerable enhancement can be achieved using this detail, [17, 2]. Nevertheless, this method is not applicable to the reinforcement of the regions other than laminate curtailment points, for instance at the regions that the laminate is continuous and the stress concentration is due to the damaged surface of the parent steel. Also, preparation of reverse taper for thin laminates is not easy. Clamping method is preferable in the cases in which either the peeling stress affects significantly the debonding failure or the tapering can not be usable. Perforation of adherents can render the potential of interlaminate debonding and stress concentration but with the decrease of cross section of the laminate or steel member, [16]. Wrapping the CFRP sheets around the tension flange and part of the web of an externally laminated beam at cut points of the laminate may improve the bonding capacity, [19]. Steel clamp can be used to withstand the predicted peeling stress if it properly designed and positioned over the ends of the laminates[20].

The characteristics of each method are usually identified using properly defined experiments. Several testing methods, although not generic yet, are usually recommended to be used in assessment of the bonding strength of the joints detailed with different methods. Among them, the double-lap shear test (or double-strap tension test) is commonly used to investigate the details of the joint between CFRP and steel.

This paper attempts to demonstrate the efficiency of using suitably detailed CFRP-adhesive-steel joints for the enhancement of the bonding strength at critical zones. Several existing joint configurations together with a proposed one are compared experimentally through the double-lap shear test. The criteria for the superiority of a joint are assumed to be the maximum failure load. The effect of reverse tapering and spew fillet of excessive adhesive were not included in this research because only small thickness of CFRP laminates (1.2 mm) were used in this study and, as mentioned before, reverse tapering are not usable in the critical zones except the ends of the laminates. As an alternative, an overlapped cover steel plate was proposed to improve the bonding strength.

2. EXPERIMENTAL STUDY

2.1 Materials

The properties of the adhesive , CFRP and steel used in this experimental investigation are shown in details in Table 1.

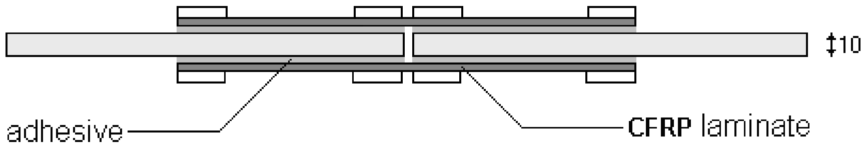
These properties are obtained after experimental tests in the laboratory of strength of materials in the University of Tabriz.

Table 1: Typical material properties of steel, CFRP and adhesive

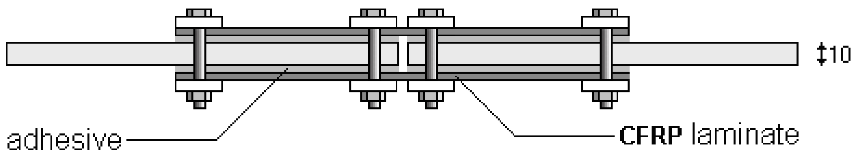
Material	Elastic modulus(GPa)	yield stress(MPa)	ultimate strength(MPa)	Description
Steel	199	260	370	DIN-St 37 .
CFRP	160.78	-	2540	Sika CarboDur S512
Adhesive	9.95	-	24.75	Sikadur-30

2.2 Specimen preparation and testing setup

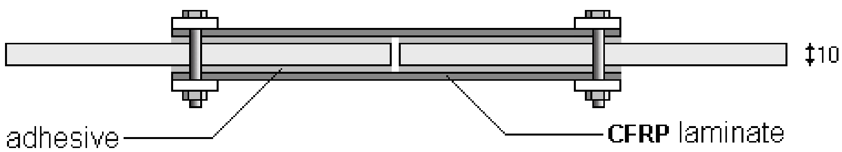
The experimental program consisted of twenty double-lap shear coupon tests. The geometrical form of the spew fillet was identical for all the specimens. A number of parameters such as the length of the joint, the number and location of the clamping devices in the clamping method of joint reinforcement and the number, location and the thickness of patched(overlapped) steel plates in the proposed method were included in this study. 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). A typical double-lap shear test configuration is shown schematically in Fig. 1. The specimens were tested by a standard tension-test machine as shown in Fig. 2 and the loading speed was 0.2 kN per second. Three representative specimens belonging to three joint configurations are seen in Fig. 3(a, b and c). The steel plates, CFRP laminates and the clamping of the ends of the CFRP laminates used for the reduction of bond stress concentration at spliced lap joints in steel members have been briefly investigated by some researchers [18] and [20]. In their work, only one double-lap shear coupon test reinforced with a pair of steel plates at the ends of the CFRP laminate has been addressed. As their results indicate, the installation of the steel clamps near the splice plate ends helps to increase the joint capacity in comparison with the unclamped specimen. No clamp has been installed near the joint gap in their work where this location is understood as another region of high stress concentration. In this study, each steel clamp is comprised of a pair of 50mm x 160mm x 12mm steel plates and two bolts of grade A490 with a diameter of 12mm. The bolts are fastened by a torque wrench up to the level less than which is required for flexural yielding of the steel plates.



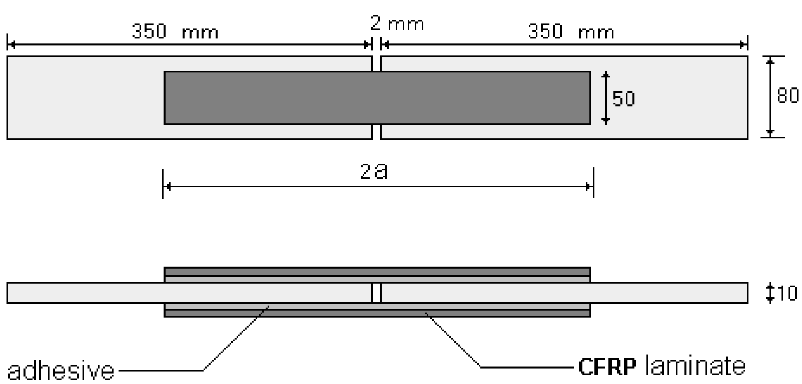
(d) With two steel patches on each of bond length



(c) With double clamp on each of bond length



(b) With single clamp on each of bond length



(a) without any enhancement

Figure 1. Different configuration of enhancement methods

An additional layer of epoxy resin with the thickness of 1mm is spread on the CFRP laminate at the clamped area. This prevents the CFRP laminate from the probable crushing caused by the compression of the steel plates and a smoother contact surface is produced between the steel plate and CFRP fibers. Furthermore, this layer isolates the steel plates and the CFRP laminate from electrical contact and therefore protects them from galvanic corrosive reaction.

In the proposed method patched steel plates were glued over the laminates with an arrangement similar to the double-clamped joint. The steel plates are 50mm x 80mm with three different thicknesses of 3, 8 and 10mm. One side of each patched plate is prepared in the same way as the guidelines used for the surface preparation of the main steel. The length needed for the patched plates should be greater than the laminate's width and equal to the width of the main steel plate (fig 3 (c)).

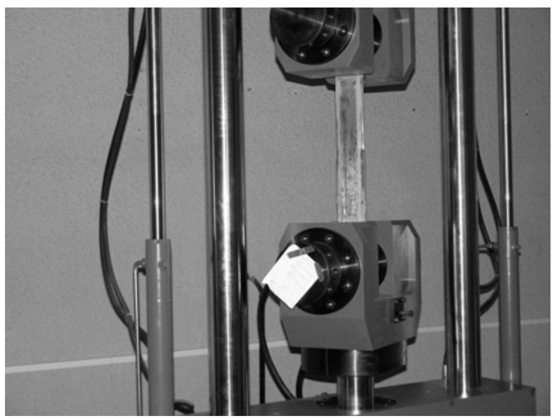
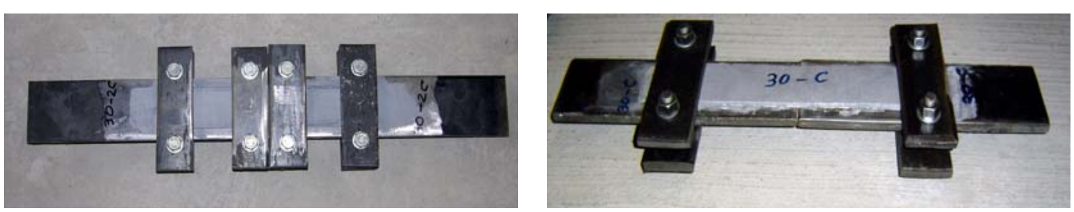


Figure 2. A typical double-lap shear test machine.

(a)



(b)

(c)

Figure 3. Tested specimens with three different details, (a) simple, no clamped, (b) with mechanical clamps, double and single, (c) with overlapped patched steel plate.

This causes the laminate to be encased completely in the space between the patched and main steel members; therefore both sides of the laminate cooperate in transferring shear load from members to laminate. This assemblage can be considered as a way for decreasing the potential of delamination of the joint.

Epoxy adhesives were supplied from the same factory and their physical properties are summarized in Table 1.

The surface preparation guidelines were obeyed identically for all the specimens (according to guidelines of [2]). The conventional modulus CFRP laminates were used for all the tests and a mild surface preparation in the form of sandpapering parallel to fibers direction was conducted. The thickness of the adhesive layer was fixed to 1.0 mm all over the laminate length and this was accomplished by using suitable spacers which did not interfere with the bond line. A normal pressure was applied on the laminate during the hardening time of the adhesive. The curing time and the temperature were two weeks and about 26 degrees of centigrade, respectively. The characteristics of the specimens are described in Table 2.

Table 2: Characteristics of the specimens

Specimen ID	bond length (mm)	2a (mm)	End detail	# of tests	Description
A5	50	102	No	2	only cut ends-no detail
A10	100	202	No	3	only cut ends-no detail
A15	150	302	No	2	only cut ends-no detail
A20	200	402	No	2	only cut ends-no detail
C10-1	100	202	Clamped	1	1 clamp at each end
C15-1	150	302	Clamped	1	1 clamp at each end
C20-1	200	402	Clamped	1	1 clamp at each end
C5-2	50	102	Clamped	1	2 clamps near the gap and end
C15-2	150	302	Clamped	1	2 clamps near the gap and end
C20-2	200	402	Clamped	1	2 clamps near the gap and end
P5-2	50	102	Patched	1	2 Patches near the gap and end
P10-2	100	202	Patched	1	2 Patches near the gap and end
P15-2	150	302	Patched	1	2 Patches near the gap and end
P20-2	200	402	Patched	2	2 Patches near the gap and end

It is worthy to note that in the specimens of C5-2 and P5-2 , since the bond length of these specimens are 50 mm (total length of the CFRP strips are 102 mm), then one clamp in each side of the gap covers bond length and then covers maximum stress regions on each bond length.

3. RESULTS AND DISCUSSION

The specimens were tested by a standard tension-test machine and the load and displacement data were digitally collected. The maximum failure loads as well as the observed collapse mechanisms have been summarized in table 3. No one of the coupon tests was failed by CFRP laminate rupture. The failure of the specimens were brittle and the inspection of debonded faces indicated that the special interlaminate debonding mode was prevalent in most of the tested specimens. It may confirm the fact that the adhesion process had been performed satisfactorily. The interlaminate debonding failure was usually observed in the form of splitting a thin layer of fibers from the rest of the laminates in the critical regions of the bond line. Therefore, a joint detailed with devices which could postpone this type of debonding failure may lead to a higher load capacity of the joint. An overview of the results shows that the installation of mechanical clamping and/or overlapping (patched) steel plates have significantly enhanced the bonding strength.

Table 3: Failure loads and characteristics of the tested specimens

Specimen ID	Type	2a (mm)	nd lengthbo (mm)	Failure load(KN)	Mean Failure load(KN)	Increase in load capacity*
A5--1	I	١٠٢	٥٠	٥٧.٧	٥٤.٥	———
A5--2	I	١٠٢	٥٠	٥١.٤		
A10--1	I	٢٠٢	١٠٠	٨٧.١	٨٣	———
A10--2 A10--3	I	٢٠٢	١٠٠	٨٠.٥		
	I	٢٠٢	١٠٠	٨١.٤		
A15--1	I	٣٠٢	١٥٠	٨٨.٣	٨٧.٣	———
A15--2	I	٣٠٢	١٥٠	٨٦.٣		
A20--1	I	٤٠٢	٢٠٠	٧٩.٨	٨٠.٣	———
A20--2	I	٤٠٢	٢٠٠	٨٠.٩		
C10-1	II	٢٠٢	١٠٠	٩٥.٢	٩٥.٢	% ١٤.٧
C15-1	II	٣٠٢	١٥٠	٨٦.٤	٨٦.٤	% ٠
C20-1	II	٤٠٢	٢٠٠	٨٠.٦	٨٠.٦	% ٠
C5-2	III	١٠٢	٥٠	٧٢	٧٢	% ٣٢.١
C15-2	III	٣٠٢	١٥٠	١٢٠.٣	١٢٠.٣	%٣٧.٨
C20-2	III	٤٠٢	٢٠٠	١٢٦.٤	١٢٦.٤	%٥٧.٤
P5-2	IV	١٠٢	٥٠	٩٣.٧	٩٣.٧	%٧١.٩
P10-2	IV	٢٠٢	١٠٠	١١٢.١	١١٢.١	%٣۵.١
P15-2	IV	٣٠٢	١٥٠	١٣٨.٤	١٣٨.۴	%٥٨.٥
P20-2--1	IV	٤٠٢	٢٠٠	١٣٨.٣	١٣٩.۵	%٧٣.٧
P20-2--2	IV	٤٠٢	٢٠٠	١٤٠.٧		

*Increase in load capacity in comparison with type I

In Fig. 4 the results of the simple specimens without any bonding enhancement devices (clips or mechanical clamp) have been shown. According to the diagram, the effective bond length of the specimens are in the range of 100 to 150 millimeters. In Fig. 5 the bonding strength of the specimens with respect to bonding length has been demonstrated for the joints reinforced with clamps only at the ends of laminates(single-clamped) without any clamps near to joint's gap. It is interesting to note that an increase in the length of the bonded laminate causes the bonding strength to decrease slightly. The adverse effect of lengthening the laminate reinforced with end clamps can be attributed to the effective bonding length measured from the gap. While the lengthening of the laminate beyond the effective bond length (about 100mm to 150 mm) does not have any helpful effect on the bonding strength, this causes the clamps to be located far from the effective zone and so they can not effectively cooperate in enhancement of the bonding strength.

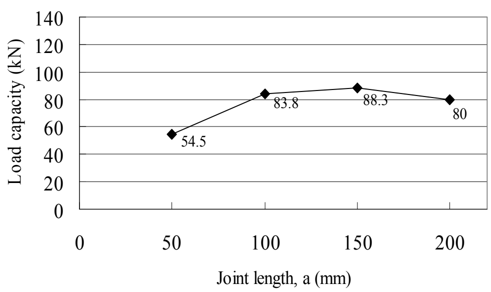


Figure 4. The results of simple specimens (not-clamped)

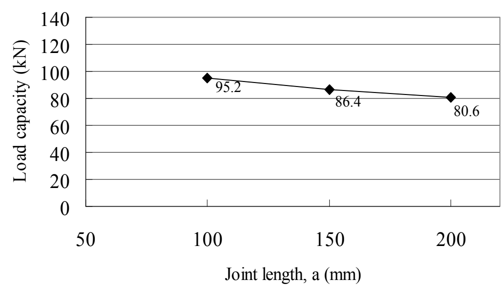


Figure 5. The results of single-clamped specimens

For the joints reinforced with two pairs of mechanical clamps (double-clamped) at the critical points of stress concentration, i.e., near the gap and at the end of the laminate, as the Fig. 6 shows, the increasing of the laminate length is beneficial up to 150 mm (about 66%) and there is a little increase (about 5%) from length of 150mm to 200mm. Any way this type of reinforcing arrangement leads to a joint detailing with no sign of decrease of strength with increasing length of CFRP laminate. The comparison of the graphs of single- and double-clamped joints (series denoted by C1 and C2) with that of not-clamped joints(denoted by A) reveals the fact that adding two mechanical clamps to the end and near to gap of the laminated joint can effectively improve the bonding strength up to 40 percent whereas no significant improvement is gained from using only one clamp at the end (curtailment point) of the laminate. The presence of a gap in tension flange of steel bridge I-girders has been recognized by some researchers[21]. In the cases that the defect in the tension flange of steel beams is manifested by a slit or a gap, the above-mentioned two-clamped detail may be viewed as a reasonable way to enhance the bonding strength of the CFRP laminate used for strengthening.

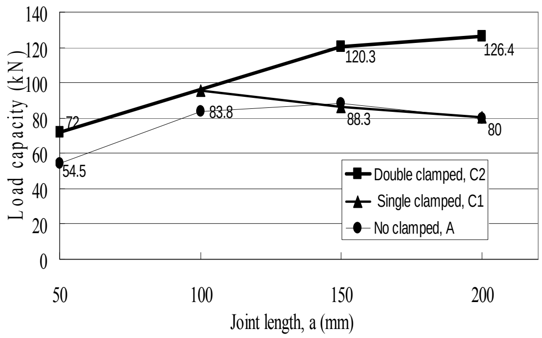


Figure 6. The results of single and double clamped joints

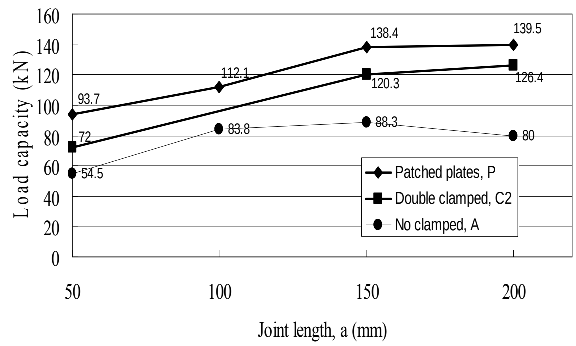


Figure 7. The results of different enhancement details

An innovative method for bonding strength improvement has been proposed in this paper by adding patched steel plates over the stress concentration locations. In this method small pieces of steel plates are glued by epoxy resin to CFRP laminate in an arrangement similar to the two-clamped case. The width of the added plates should be greater than the laminate width and should be equal to joint width(main steel) and thereby the laminate is encased in patched and main steel plates. This assemblage is easier to be constructed and more economic than the mechanical clamps. Smaller pieces of steel plates, no need for drilling of the plates and no using bolts are the advantages of this method over the clamping method. Moreover if these details are to be used, in practice, in the bridges with box girders, the clamping method will be very difficult to be performed, while the patched steel plates can be installed over the laminates wherever it is needed. The results of this kind of joint detail (denoted by P) have been compared with double-clamped and single-clamped cases in Fig. 7. As this figure shows, the reinforcement with patched steel plates for all joint length leads to a superior bonding strength with respect to the reinforcement with mechanical clamps. The average increase of bonding resistance for the joints reinforced with the clamped and patched plates are 35 percent and 60 percent, respectively, in comparison with unreinforced cases. The maximum increase is observed for the joint length of 200 mm for both details i.e., 58 percent and 74 percent for the joints reinforced with clamps and patched plates, respectively. While maximum bonding strength for the unreinforced joints is observed for the bond-length between 100mm to 150mm, an even greater bonding strength is attainable through the longer bond-length (about 200mm) for the reinforced joints. These test results show that both patched (overlapped) steel plates and clamping methods considerably increase the bonding resistance, but the former seems preferable because of its simplicity of installation and economic advantage. The improved behavior observed in the proposed bonding enhancement method indicates that the stress concentration has been successfully reduced in the critical regions. The following factors explain the reasons of reduction of stresses near the patched steel plates: 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.

Finally the effect of thickness of patched plates on the bonding strength obtained from the proposed detail has been investigated, too. Three different thicknesses of patched plates including 3, 8 and 10 mm are used for the reinforcement with the same arrangement as the above mentioned two-clamped detail. The bond-length of all three specimens is 200 mm. Each plate has dimensions of 50mmx80mm. The results have been depicted in Fig. 8. The reduction of the thickness of the patched plates from 8mm to 3mm, results in 25 percent decrease of bonding strength. But the bonding strength does not change when the thickness increases from 8 to 10 mm. Therefore the stiffness of patched steel plates is a factor which affects the load capacity of the tested joints. Collapsed specimens with different bonding enhancement details have been demonstrated in Fig. 9.

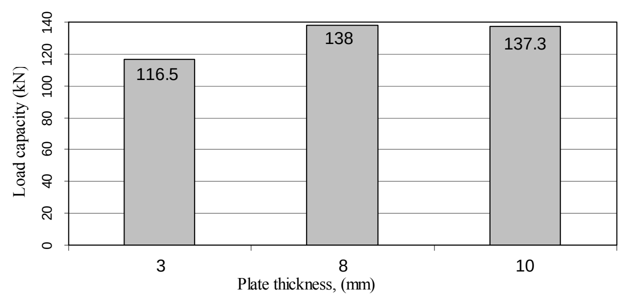


Figure 8. The results for different thicknesses used for patched steel plates

4. CONCLUSIONS

In this paper several methods, which can be reasonably used to postpone the debonding failure of externally-laminated steel members, were studied experimentally. The double-lap shear test set up was chosen as a frame work to compare the methods. An efficient bonding enhancement method was proposed in the form of gluing small patches of steel plates over laminate at the critical debonding zones. Two kinds of anchoring details, i.e. using mechanical clamps and adding patched steel plates, were selected to investigate to what extent they are able to enhance the bonding strength of the CFRP-laminated members.

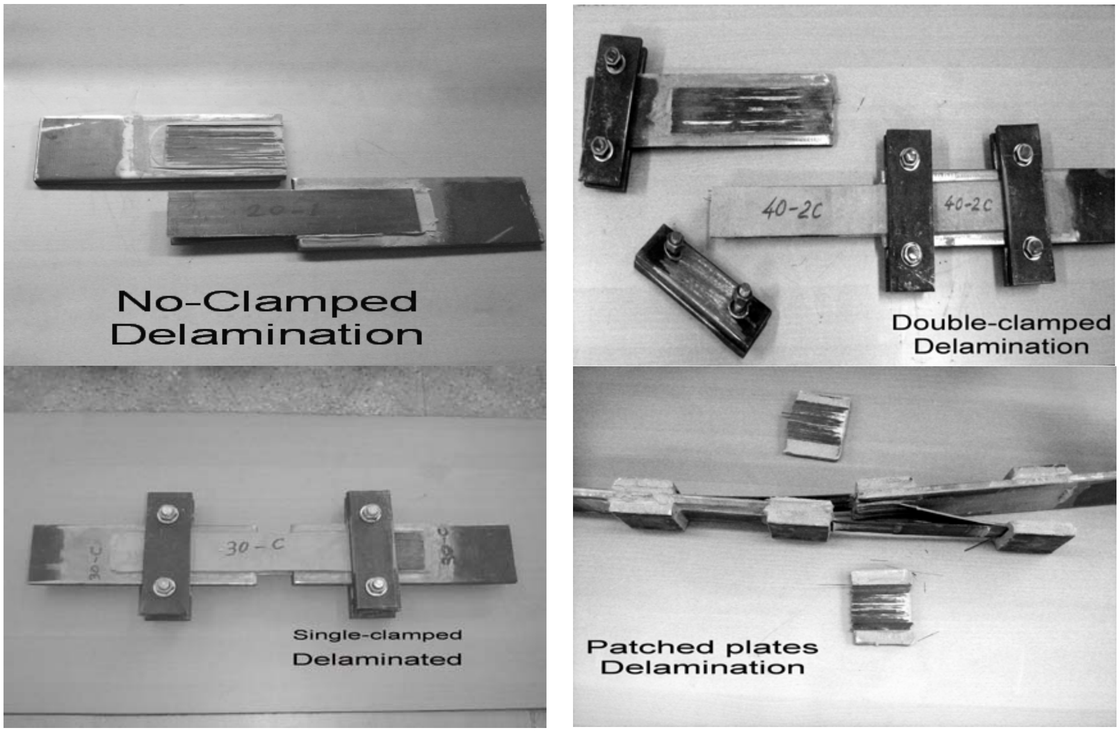


Figure 9. Collapsed specimens with different details

Also, the effect of the length of the CFRP laminate was investigated along with different types of end mechanical anchorage. For this purpose, an experimental program consisting of twenty double-lap shear coupon tests was conducted. It was intended to study the effect of the additive devices as the reinforcement tools which could be installed at every location with high potential for debonding and not limited to the ends of the laminates.

The geometrical form of the spew fillet was identical for all the specimens. The method of reverse tapering of the laminates was excluded from this study because it is only usable at the curtailment points of the laminates. Moreover the thicknesses of the used laminates were too small to be properly tapered. A number of parameters such as the length of the joint, the number and location of the clamping devices in the clamping method of joint reinforcement and the number, location and the thickness of overlapped steel plates in the proposed method were considered in this study. The specimens's debonding mechanisms in the failure load are in the form of interfacial and delamination.

On the basis of the experimental studies presented, the following conclusions are found:

1. For the double-shear lap joints without any reinforcing device the highest strength is observed for the joint length about 100mm to 150mm. For the longer joint there was no increase in the load capacity.

2. Using details comprised of clamps only at the ends of the laminates did not show any significant improvement in bonding strength of the joints. The increase of the joint length had an adverse effect on the joint strength detailed with this method.

3. Using details with two clamps, one at the end and the other near the gap, can

effectively enhance the load capacity of the joints up to 40 percent in comparison with unreinforced detail.

4. If the patched steel plates are used instead of clamps in the double-clamped detail, a further increase of strength about 25 percent is attained. The joint strength increased from an average of 35 percent for double-clamps to an average of 60 percent for the patched steel plates. In addition to enhancement in bonding strength, the proposed detail with the patched steel plates is easier and more economic for installation than the double-clamped details. The participation of both faces of the CFRP laminate, encased in the space between the patched and the main steel plates, seems to be the reason for the improved behavior of the joint.

5. The thickness of the patched plates affects the bonding strength of the reinforced joint. The reduction in the thickness of the patched plates from 8mm to 3mm, results in 25 percent decrease of bonding strength. But the bonding strength does not change when the thickness of patches increases from 8 to 10 mm. Thus it is shown that increasing the thickness of the patches from an optimum value is not necessary. This optimum thickness for each specified case can be found by experiment. Therefore, the stiffness of patched steel plates is a factor which affects the load capacity of the tested joints. The accumulation of epoxy resin beneath the patched plate by itself should not be thought of the reason for the enhanced strength capacity of the joint detailed with the proposed method.

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