CONTROL OF INTERFACIAL STRESSES IN BEAMS STRENGTHENED WITH PRESTRESSED CFRP LAMINATES

R. Haghani, M. Al-Emrani* and R. Kliger

Civil and Environmental Engineering Department, Chalmers University of Technology, Sweden
Email: Reza.haghani@chalmers.se

ABSTRACT

The outstanding mechanical properties of Carbon Fiber Reinforced Polymers (CFRP), such as high strength-to-weight ratio, high modulus of elasticity, high corrosion resistance and durability have made them suitable for strengthening applications. High capacity of CFRP laminates may not be completely used due to weakness of the adhesive joint used to bond the laminate to the structure. To use CFRP laminates more efficiently, prestressing might be applied to the laminate before bonding. Although prestressing has several advantages and improves the structural behavior of the strengthened member, a major problem with this strengthening scheme is the very high interfacial stresses which are built up at the end of the laminate. One way to deal with the problem is to clamp the laminate using mechanical anchors which often are made of steel plates. There are, however, couple of problems involved in using mechanical anchors such as high cost of manufacturing, installation and inspection, corrosion risk and durability and making fatigue prone points in steel structures due to drilling. Increasing demands on strengthening technique incorporating prestressing necessitate new techniques for controlling the interfacial stresses in the bonded joint without using mechanical anchors. In this paper, possible techniques to reduce the magnitude of the interfacial stresses along the bond line have been investigated. The methods include changing the geometric and mechanical properties of the strengthening components and modifying the distribution of interfacial stresses along the bond line. FE-analysis has been used to examine the effectiveness of each technique. It has been shown that using step prestressing method is the most effective one and by that interfacial stresses might be reduced by a factor of ten, which in many cases allows using high initial presressing forces in the laminate without the need to use mechanical anchors.

KEYWORDS

Prestressed laminate, Strengthening, Interfacial stresses.

INTRODUCTION

Due to the increasing number of old bridges all around the world [ACI 1996], the subject of strengthening and upgrading such structures have become a serious concern for bridge industry during the past three decades. Today, railway and highway authorities are dealing with a large number of aging and inefficient bridges. The most important requirement for a suitable strengthening method is that it should cause minimum disruption of the traffic flow over the structure during the strengthening time. Other important issues are compatibility from material and structural point of view, imposing minimum additional self weight to the structure, avoiding possible side effects such as creating fatigue prone details, minimum maintenance and aesthetic aspects. Today there is increasing needs for new effective strengthening and upgrading methods for existing bridge structures fulfilling the above restrictions.

By advances in polymer engineering and production of composite materials with very good mechanical properties, bonding fiber reinforced polymers was considered as an effective method for strengthening of bridges. Composite materials used for strengthening purposes in bridge engineering are usually in form of laminate and are bonded to the structure by a structural adhesive like epoxy resins. Among existing FRP composites carbon based composites are the most favorable due to their durability and outstanding mechanical properties. CFRP laminates are produced in a wide range of strength (up to 3000 MPa) and stiffness (450 GPa). In addition, CFRP materials have very high resistance to corrosion and environmental attacks. An obstacle to use the high capacity of these laminates is that usually adhesively–bonded joints are not strong enough and fail before the laminates are stressed up to their ultimate strength. A solution to use CFRP laminates more efficiently is to employ prestressing in the laminate before bonding to structure. The advantages of using prestressing in
strengthening concrete structures include; reduction of deflections due to the camber effect obtained by prestressing, reducing the width of existing cracks in the concrete and delaying the onset of new cracks, which has a substantial positive effect on the durability of the structure and increasing the yield load of the reinforcements. Prestressing can also be used to compensate for prestress loss in initially prestressed concrete structures and some increase in the shear capacity may also be achieved by induction of the prestressing force (El-Hacha et al. 2001). Prestressing might also be utilized for strengthening and repair of steel structures to enhance the fatigue behaviour of the structural member.

A major problem using prestressed laminates is the high interfacial stresses that are built up at the ends of the laminate. Depending on the initial prestressing force, the magnitude of these shear stresses might be several times higher than the ultimate strength of conventional structural adhesives. When applied to concrete structures, shear stresses caused by very low prestressing levels (around 5% of ultimate tensile strength of the laminate) might cause covering of the concrete at the ends of laminate (El-Hacha et al. 2001). In most cases, it is necessary to anchor the laminate mechanically to avoid such failure mode (Nordin 2003). In the case of steel structures, the failure mode would be governed by shear strength of the adhesive or the interlaminar strength of the laminate used. Mechanical anchorages are often rather expensive, difficult to install and may suffer from corrosion (Aram et al. 2006). Besides these shortcomings, the side effects of using such anchors are expected to be serious in steel structures due to the need for drilling holes for installation bolts. Advantages brought by using prestressing strengthening schemes, necessitate thorough studies of existing and new prestressing systems, their behaviour and long-term performance. In addition, new methods and techniques that can be used to control the interfacial stresses in strengthening systems employing adhesively-bonded prestressed laminates will also be very attractive.

In this paper, the development of interfacial stresses in beams strengthened with bonded prestressed laminates is studied using FE-analysis. The effect of various material and geometrical on distribution of interfacial stresses is also investigated. A number of different techniques that can be employed to reduce the magnitude of the interfacial stresses along the bond line have also been investigated. It has been shown that among several possible methods to decrease the magnitude of interfacial stresses, revision of initial prestressing force distribution along the laminate is the most effective technique and interfacial stresses might be dramatically decreased by this method.

**DESCRIPTION AND VALIDATION OF FE-MODEL**

The model used in this study consists of an HEA 180 steel beam strengthened by a prestressed CFRP laminate. Total length of the beam is 2.0 m with free span of 1.8 m and the length of the CFRP laminate is 1.6 m. The laminate is prestressed with 100 kN which is modeled as thermal load. All parts in the model, including steel, adhesive and CFRP laminate are modeled using plane stress elements and interfacial stresses are monitored in the middle of the adhesive layer. Because of symmetry, only half of the beam needed to be modeled. The modeled beam and also meshing at the end part of the laminate could be seen in Fig.1.

![Beam model and meshing at the end part](image1.png)

<table>
<thead>
<tr>
<th>$E_x$ (GPa)</th>
<th>$E_y$ (GPa)</th>
<th>$E_z$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0 GPa</td>
<td>5.5 GPa</td>
<td>7 GPa</td>
</tr>
<tr>
<td>165 GPa</td>
<td>200 GPa</td>
<td>300 GPa</td>
</tr>
<tr>
<td>1 mm</td>
<td>2 mm</td>
<td>3 mm</td>
</tr>
<tr>
<td>2 mm</td>
<td>4 mm</td>
<td>-</td>
</tr>
</tbody>
</table>

![Comparison between FE model and analytical solution for shear stress](image2.png)
In the study, when the value of each parameter is varying the values of all other parameters are kept constant. These fixed values are shown in bold in the table attached to Fig. 1. After the convergence study to find the optimum size of elements, validation of the FE-model has been checked by the comparison of the results for shear stress distribution from the model and analytical solution proposed by Al-Emrani et al. 2006 shown in Fig.2.

PARAMETERS AFFECTING INTERFACIAL STRESSES

Effective parameters on shear stress distribution in beams strengthened with prestressed laminates include; the E-modulus of the laminate and adhesive as well as the thickness of the adhesive layer and the laminate (Al-Emrani et al., 2006). Taking a look at the equation for shear stress distribution in the mentioned study shows that the magnitude of the shear stress is a function of the variation of the axial prestressing force in the laminate. This implies two important points; the positive effect of a gradual change in the axial stiffness of the system and the benefit of any possible decrement in the slope of the axial force distribution along the laminate. The first observation is the base for plate-end tapering as a method to control the shear stresses at the end of laminate. The second statement, form the base for a new technique to employ a controlled introduction of prestressing force along the laminate near the ends. The last mentioned technique is referred to as step prestressing method in this paper. As a consequence of the more gradual introduction of the axial force in these two methods, a corresponding reduction of peeling stresses at the ends of the laminate may be expected. The interaction between axial force and peeling stress has been illustrated by Al-Emrani et al. 2007. Thus, it can be concluded that these treatments also have a beneficial effect on the principal stress in the joint, which is normally used for design of adhesive joints.

THE EFFECT OF MATERIAL PARAMETERS

The main two material parameters affecting the magnitude and distribution of interfacial stresses are the E-modulus of the laminate and the E-modulus of the adhesive. In this study, four different stiffness classes for laminates have been considered including 165, 200, 300, 400 GPa. Figs.3 and 4 show the shear and peeling stress distribution for the four different laminates, respectively. It can be seen that the maximum value of the shear stress decreases by increasing the stiffness of the laminate. This can simply be explained by the fact that a stiffer laminate undergoes lower initial elongation (or strain) for the same level of prestressing force. The imposed shear deformation and consequently the shear stress would be lower for stiffer laminates. In the case of peeling stresses, due to interaction of the shear and peeling stresses, the less shear stress causes less bending moment at the end of the laminate which causes less peeling stress. In addition the stiffer laminate provides higher bending stiffness at the end of the laminate and consequently higher rotational resistance leads to less normal deformation in the adhesive layer and less peeling stress.

The second parameter is stiffness of the adhesive layer. Three different adhesives with E-modulus of 4, 5.5 and 7 GPa have been investigated. Figs.5 and 6 show the effect of adhesive stiffness on shear and peeling stress distribution, respectively.

Figure 3. Effect of E modulus of the laminate on shear stress distribution

Figure 4. Effect of E modulus of the laminate on peeling stress distribution
THE EFFECT OF THE GEOMETRICAL PARAMETERS

The geometrical parameters, investigated in this study, include thickness of the laminate, thickness of the adhesive layer and normal and reverse tapering of laminate at the end. Figs. 7 and 8 show the shear and peeling stress distributions for different thicknesses of the laminate and Figs. 9 and 10 show the same for different thicknesses of the adhesive layer. As can be seen, the peak shear stress is less for thicker laminate. This is due to less initial strain of thick laminate for a specific prestressing force in comparison to that for thin laminate. Peak peeling stress is also less for thicker laminate and this is due to the higher bending stiffness of the thicker laminate as well as lower shear stresses along the bond line for thicker laminate.

As can be seen in Fig. 9 increasing the thickness of the adhesive layer has a positive effect on shear stress reduction. This positive effect is expected as the shear deformation in the thicker adhesive layer will be less, given the same longitudinal displacement of the laminate. In the case of peeling stress, Fig. 10, the same trend can be observed. The reason here is the interaction of the shear and peeling stresses. Redistribution of the shear over a longer length and thus reduction in peak shear value decreases the bending moment in the laminate at the end which produces peeling stresses at the laminate end. The other geometrical parameter which affects the distribution of interfacial stresses along the bond line is tapering the end of laminate. Tapering of the laminate ends might be exerted in either normal or reverse configuration. The tapering length considered in this paper is 16 mm, which is four times the thickness of the laminate. No adhesive fillet has been considered at the end of laminate.
As can be seen in Fig. 11, normal tapering (with the tapering length considered here) has no significant effect on shear stress reduction. The reduction is more considerable in the case of reverse tapering. However, reverse tapers are normally very limited in structural engineering applications due to their complexity and are more used in aerospace industry. Fig. 12 shows a comparison of the peeling stress distribution between tapered and non-tapered situation. Effect of tapering has been discussed by Al-Emrani et al. 2007. They have shown that tapering the laminate might increase the peeling and principal stress at the end of the laminate. Nevertheless, it can be seen that due to the reduction in shear stress in the case of reverse tapering, the value of the peeling stress has also been decreased and is distributed over a longer transfer distance.

**THE EFFECT OF STRESS-FREE END**

As mentioned before, the reduction in slope of the axial force distribution along the laminate leads to a corresponding reduction in shear stress. One way of achieving this, is to leave a part of the laminate near its ends without prestressing. This part will partially restrain the shear deformation and thus shear will be distributed over a longer distance, which reduces the peak value. As a consequence, the location of peak shear is moved some distance away from the end of laminate. This is very beneficial with reference to peeling stress, because the bending resistance of a section in a point away from the laminate end is much higher than the corresponding value at the end. This behavior could be compared by bending resistance of a fixed end cantilever beam at the end and resistance of a double fixed end beam in the mid span. Figs. 13, 14 show the shear and peeling stress distribution for stress-free ends with various distances from the laminate end. As can be seen this technique has a significant effect on the magnitude and distribution of shear and peeling stresses. It is also clear that increasing the length of the stress-free part over a specific value will not result in further reduction of shear stress.
THE EFFECT OF STEP PRESTRESSING

In Fig. 15, the transfer of the axial force has been done in two or three steps instead of just one. As can be seen the shear stress has been decreased dramatically. Fig. 16 also shows the significant effect of step prestressing on peeling stress reduction. By increasing the number of steps, the magnitude of maximum shear and peeling stresses can be decreased substantially and totally be controlled by the number of steps. This method has been implemented at EMPA (Stocklin and Meier 2001) successfully. In their procedure, the CFRP laminate is prestressed against a separate auxiliary beam. Starting from the mid span and using accelerated curing of the adhesive by elevating the temperature, different steps can be exerted and in each step the prestressing force is reduced by a specific value.

CONCLUSIONS

Using prestressed laminates in strengthening of structures has found a rapid interest. Therefore, comprehensive studies are needed to understand the behavior of these systems. A major problem using prestressed laminates is the high interfacial stresses that are generally obtained in the bond line near the ends of laminate. Using mechanical anchors has been suggested as a solution to this problem. However, there are some questions about the efficiency and long term behavior of these mechanical devices. In this paper, the effect of various material and geometrical parameters including stiffness of the adhesive and laminate, thickness of the adhesive layer and laminate and tapering of the laminate end on the distribution of shear and peeling stresses along the bond line have been investigated. Also, two principal techniques based on revising the distribution of prestressing force in the laminate have been presented. It was found that neither material nor geometrical changes in strengthening scheme can decrease the interfacial stresses to a level that allows omitting the mechanical anchors. The free-stress end has a significant reduction effect on shear and peeling stresses but the maximum reduction that can be achieved is limited. Therefore, it can only be considered when low level of prestressing force in the laminate is used. Step prestressing was found to be the most effective technique to decrease the interfacial stresses. Practical ways need to be developed for application of this method.
REFERENCES


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