FINITE ELEMENT ANALYSIS OF STEEL MEMBERS REPAIRED BY PRESTRESSED COMPOSITE PATCH

A. Bassetti[1], P. Colombi[2] e A. Nussbaumer[1]

[1]*Institute of Steel Construction, Swiss Federal Institute of Technology, EPFL, Lausanne*
[2]*Department of Structural Engineering, Milan Technical University, Milan*
e-mail: colombi@stru.polimi.it

Abstract

At the Institute of Steel Construction (ICOM) of the Swiss Federal Institute of Technology, EPFL, Lausanne, a research is in progress to study the applicability of the adhesively bonded composite patch repair technique to riveted steel bridges damaged by fatigue. The effectiveness of this technique was verified by fatigue tests on small and full scale specimens. Fatigue tests show that the application of carbon fibre reinforced plastic (CFRP) strip and, eventually, the introduction of a compressive stress by pretension of CFRP strips prior to bonding, produces a significant increment of the remaining fatigue life. Numerical analyses are currently in progress to simulate the fatigue crack propagation in the repaired member. A F.E.M. modelling technique using plate theory and refereed to in the literature as the three layer technique is adopted in order to reduce the computational effort. The goal of this paper is to illustrate the influence of the pretension level and laminas stiffness on the stress intensity factor levels by a parametric numerical analysis.

Sommario

Presso l'Istituto di Costruzioni Metalliche (ICOM) del Politecnico Federale di Losanna, EPFL, e` in corso una ricerca rivolta allo studio della fattibilita` della riparazione di ponti chiodati danneggiati per fatica mediante l'incollaggio di strisce di materiale composito. L'efficacia della metodologia e` stata verificata attraverso una serie di prove di fatica su campioni in piccola e grande scala. I risultati mostrano come l'applicazione di strisce di materiale plastico rinforzato con fibre di carbonio (CFRP), ed eventualmente l'introduzione di tensioni di compressione mediante la pretensione del rinforzo prima dell'incollaggio, produca un significativo aumento della vita residua a fatica. Attualmente e` allo studio la simulazione numerica della crescita di cricca per fatica nell'elemento rinforzato. Allo scopo di ridurre l'onere computazionale, e` stata utilizzata una tecnica basata sulla teoria delle piastre e nota

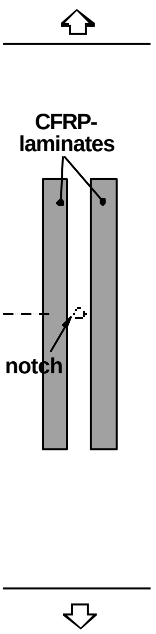
in letteratura come “three layer technique“. Il fine di questo lavoro e` quello di illustrare, attraverso una analisi parametrica, l’effetto della rigidezza delle strisce in composito e della pretensione sui valori del fattore di intensificazione delle tensioni.

1. Introduction

Many of the riveted steel bridges built at the beginning of this century are still in use today. The fatigue lifetime extension of these bridges is a challenge for structural engineers [2] [3] due to their general deterioration in addition to the considerable increment of loads traffic. From the economical point of view it is not realistic to replace all bridges when they attain a certain life. Moreover, there may be a need to retain certain bridges as historical monuments.

Several conventional techniques [2] [3] are available to repair bridge member damaged by fatigue: hole drilled at crack front, cover plates application over the cracked area, replacement of rivets with high strength bolts, cold expansion to create residual compressive stresses and gas tungsten arc remelting of the metal. At the Institute of Steel Construction (ICOM) of the Swiss Federal Institute of Technology, EPFL, Lausanne, a research is in progress to study a novel repair technique [1] [9] of old riveted steel bridges damaged by fatigue. It consists in the application of carbon fibre reinforced plastic (CFRP) strips [4] [5] and, eventually, the introduction of a compressive stress by pretension of CFRP strips prior to bonding. This technique reduces the stress intensity factor by bridging the stresses between the steel or original element and the composite patches. It lessens the stress intensity factor near the crack leading to an improvement of strength and an increment of the remaining fatigue life.

The effectiveness of prestressed CFRP-plates to arrest the crack propagation was first investigated on notched steel plates [2] [3] (see Fig. 1). Results of the fatigue tests are shown in the crack length to cycles diagram of Fig. 2. All the specimens were tested under constant amplitude using a stress range equal to 80 MPa in the nominal section of the unreinforced specimen. The stress ratio was R=0.4, with reference to the stresses in the original specimen. The reference tests are given in Fig. 2 by the unreinforced steel plates. By reinforcing the steel plates with non-prestressed CFRP strips (*Sika CarboDur S512*: nominal Young's modulus E=155 GPa; thickness t=1.2 mm), fatigue life of specimens is increased by a factor of about three.



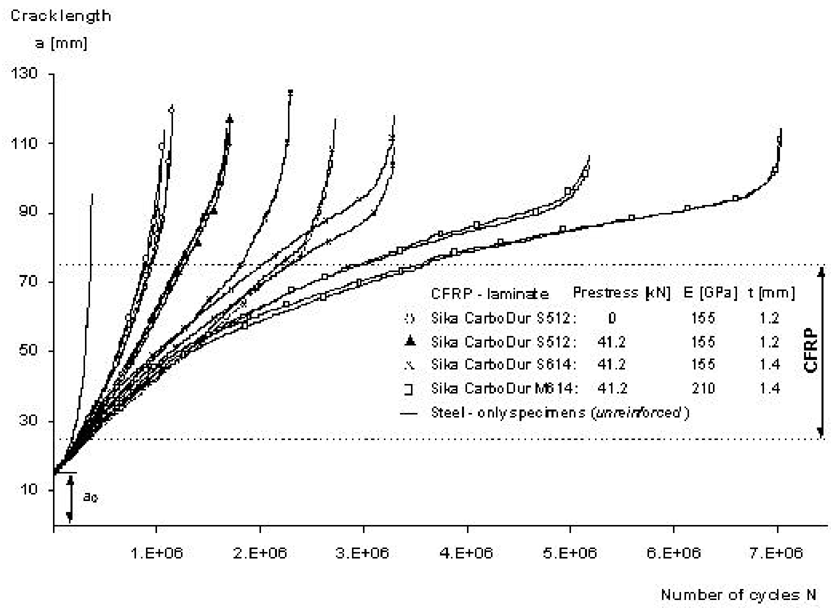


Figure 1. Notched plate. *Figure 2. Crack length vs. cycles for the notched plate.*

If the composite strips are prestressed prior to bonding with a tensile force of 41.2 KN (corresponding to a prestress of 632 MPa in the CFRP cross-section), the fatigue life is increased by a factor of about six. Even longer fatigue life was achieved by stiffer CFRP-strips (*Sika CarboDur M614*: nominal Young's modulus E=210 GPa; thickness t=1.4 mm) prestressed with 41.2 KN. With this reinforcement configuration the fatigue life is increased by a factor of about twenty.
The goal of this paper is to investigate numerically the effect of the prestress and stiffness level of the CFRP-laminas, the adhesive thickness and the debonding size region between the composite and the plate on the stress intensity factor, the parameter governing crack propagation rate and thus fatigue lifetime. To this end a finite element model is developed. It is based on Mindlin plate theory in order to reduce the computational effort connected to a full three dimensional analysis.

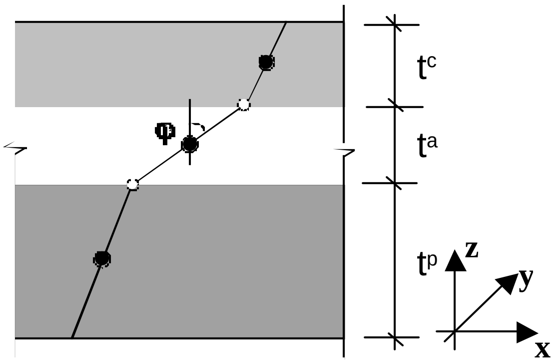
2. Finite element model

One of the most challenging aspects of bonded composite repair technology is the stress analysis of the repaired structure and the consequent stress intensity factor evaluation [6] [7] [10]. Three dimensional finite element analysis of composite patch repair have been conducted [10] in the literature. Since the thickness of the adhesive is much smaller than the plate and composite patch one, a three dimensional model becomes very expensive due to the large number of elements required across the thickness to get acceptable aspect ratios in the adhesive layer.
In [7] a finite element analysis was conducted where plain stress two-dimensional elements were adopted to model the cracked plate and composite patch. Shear spring elements were used to model the adhesive. In [10] a finite element method was employed which consisted of a two-dimensional Mindlin plate elements with transverse shear deformation capability to model both the cracked plate and the composite patch. Again shear spring elements were introduced to model the adhesive. The shear springs were connected to the cracked plate and the composite patch through displacement constraint equations which satisfy the Mindlin plate assumptions. In [6] the three layer technique was proposed to model a composite bonded repaired cracked plate. This technique uses two dimensional finite element analysis, consisting of three layers, to model the cracked plate, adhesive and composite patch. It is not required to replace the adhesive layer by shear spring elements (non continuum body) since the adhesive is modelled as an elastic continuum medium. In this way the characteristics of the adhesive which would be required to model non linear material behaviour are captured. Constraints are used to enforce the compatibility along the plate-adhesive and the adhesive-patch interface based on Mindlin assumptions (see Fig. 3). The Mindlin plate theory assumes linear displacement field in the plate thickness. In the three layers technique, all three layers, cracked plate, adhesive and composite patch, are assumed to have a linear displacement field along the thickness and they satisfy the relations [6]:

$$
\begin{aligned}
u^c &= \bar{u}^c + \varphi_y^c \cdot z^c & \qquad u^a &= \bar{u}^a + \varphi_y^a \cdot z^a & \qquad u^p &= \bar{u}^p + \varphi_y^p \cdot z^p \\
v^c &= \bar{v}^c - \varphi_x^c \cdot z^c & v^a &= \bar{v}^a - \varphi_x^a \cdot z^a & v^p &= \bar{v}^p - \varphi_x^p \cdot z^p \\
w^c &= \bar{w}^c & w^a &= \bar{w}^a & w^p &= \bar{w}^p
\end{aligned}
\tag{1}
$$

where $\overline{u}, \overline{v}, \overline{w}$ are the mid-plane displacements along the x, y and z directions (x and y are in the plate plane and z is in the thickness direction), respectively, $\overline{\varphi}_x, \overline{\varphi}_y$ are the rotations of the cross section along the x and y axis (see Fig. 3). Note that the superscript symbols p, a and c are used to denote the plate, adhesive and composite patch, respectively. At the plate-adhesive interface, where the z co-ordinates for the cracked plate and the adhesive are equal, and at the adhesive-composite patch interface, where the z co-ordinates for the adhesive and the composite patch are equal, the displacement field's equations reduce to (see Fig. 3) [6]:

$$\begin{array}{lll} u^c = u^a & v^c = v^a & w^c = w^a \\ u^a = u^p & v^a = v^p & w^a = w^p \end{array} \tag{2}$$



<u>plate-adhesive interface</u>

$$u^a = u^p \Rightarrow \overline{u}^a - \overline{u}^p - \varphi_y^a \cdot \frac{t^a}{2} - \varphi_y^p \cdot \frac{t^p}{2} = 0$$

$$v^a = v^p \Rightarrow \overline{v}^a - \overline{v}^p + \varphi_x^a \cdot \frac{t^a}{2} + \varphi_x^p \cdot \frac{t^p}{2} = 0$$

<u>composite-adhesive interface</u>

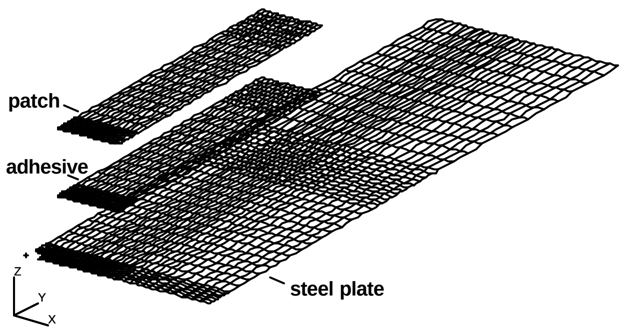
$$u^c = u^a \Rightarrow \overline{u}^c - \overline{u}^a - \varphi_y^c \cdot \frac{t^c}{2} - \varphi_y^a \cdot \frac{t^a}{2} = 0$$

$$v^c = v^a \Rightarrow \overline{v}^c - \overline{v}^a + \varphi_x^c \cdot \frac{t^c}{2} + \varphi_x^a \cdot \frac{t^a}{2} = 0$$

Figure 3. Modelling of bonded repair and necessary constraints at the interfaces.

3. Results

The commercial finite element code ABAQUS® was used to perform the analyses using the three layer technique. The notched plate geometry is reported in Fig. 1 [2] [3]. The central notch consists in a hole and two initial through-thickness cracks, each 5 mm long and 0.1 mm wide. The hole diameter, 20 mm, and the plate thickness,10 mm, are representative of rivet holes and thickness of plates used in riveted members. The notched steel plates were reinforced on both sides with two 50 mm CFRP-strips placed at a distance of 15 mm from the edges of the central hole. Since composite patches are located on both side of the plate only one eighth of the specimen was meshed as a continuum medium using standard eight-noded shell elements (see Fig. 4). The stress intensity factor values, corresponding to the maximum load level (133 Mpa), was computed for various crack size by the finite element analysis. A debond between the adhesive and the composite patch or the adhesive and the composite patch could occur [6] [10] as a result of an imperfection during the bonding process or due to the high stress state near the crack tip. This reduces the effective area and the amount of stresses being bridged between the cracked plate and the composite patch. Based on the experimental results [3] the debond crack was assumed to lie in the plate-adhesive interface with a semi-elliptical shape. The major semiaxis b was equal to the crack size a plus the dimension of the plastic zone at crack front in plate and was aligned with the crack path. The minor semiaxis c was then located in a direction orthogonal to the crack one (see Fig. 5). A parametric analysis was performed in order to investigate the sensitivity of the stress intensity factor levels to variations in the composite Young's modulus, adhesive thickness, pretension level in the patches and size of the debonded region.



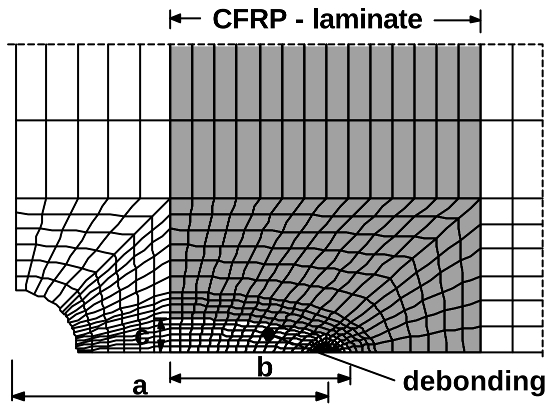


Figure 4. Three layer F.E.M 1/8 model.

Figure 5. Detail of F.E.M. model.

The strain energy release rate was computed by using the standard virtual crack extension method and converted into the stress intensity factor by assuming plane stress state for the local stress field near the crack. Figures 6 to 9 illustrate the results of the parametric analysis. The reference value of the model parameters are: 173.54 GPa (experimental average value) for the composite Young's modulus, 0.3 mm for the adhesive thickness, no prestress in the composite patch and 1/5 for the ratio *c/b* of the semi-elliptical debonded region. The position of the CFRP strips is indicated in each picture. The stress intensity factor values are normalised with respect to $\sigma_y \sqrt{\pi a}$ and reported as a function of the crack size a (the crack size is measured from the central axis of the plate and thus includes the hole radius). Fig. 6 depicts the sensitivity of the stress intensity factor to the composite patch Young's modulus. Since the stiffness of the composite patch is proportional to its Young's modulus, more stresses are bridged between the plate and the composite patch as the stiffness of the bonded repair increases. Moreover, stiffener strips limit crack opening of long cracks and then produces an additional reduction of the stress intensity factor if the whole crack is strengthened by the patch.

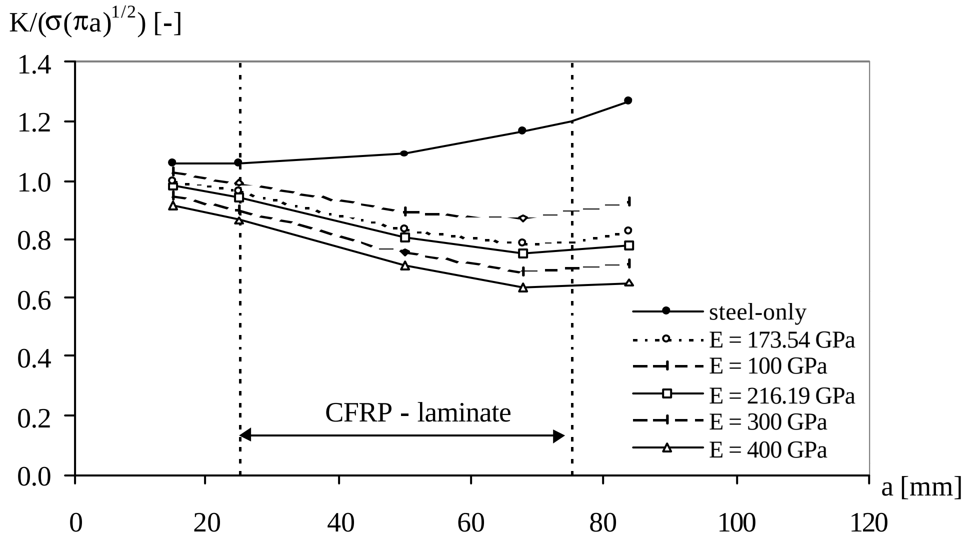


Figure 6. Stress intensity factor vs crack length as function of the patch Young's modulus.

Fig. 7 illustrates the effect of the adhesive thickness on the stress intensity factor values. Clearly, as the adhesive thickness increases the composite repair becomes less and less efficient. This is due to a reduction of the capacity of the adhesive layer to bridge the stress across the crack region. This effect is very important for long cracks where the capacity of the bonded repair to limit crack opening is reduced as the shear deformation of the adhesive layer increases with thickness. The effect of the prestress level is reported in Fig. 8. A pronounced reduction, in particular for short cracks, of the stress intensity factor is achieved by increasing the prestress value. Short cracks introduce in fact, compared to long cracks, a small perturbation of the stress field produced by prestress. On the contrary, long cracks give a significant perturbation of such a stress field and then the efficiency of the bonded repair is decreased. Fig. 9 illustrates the effect of the size of the debonded region on the patch repair. Clearly, as the debonded area increases, the stresses bridged between the crack faces are narrowed. Moreover, the stiffening effect on the crack face is reduced by debonding.

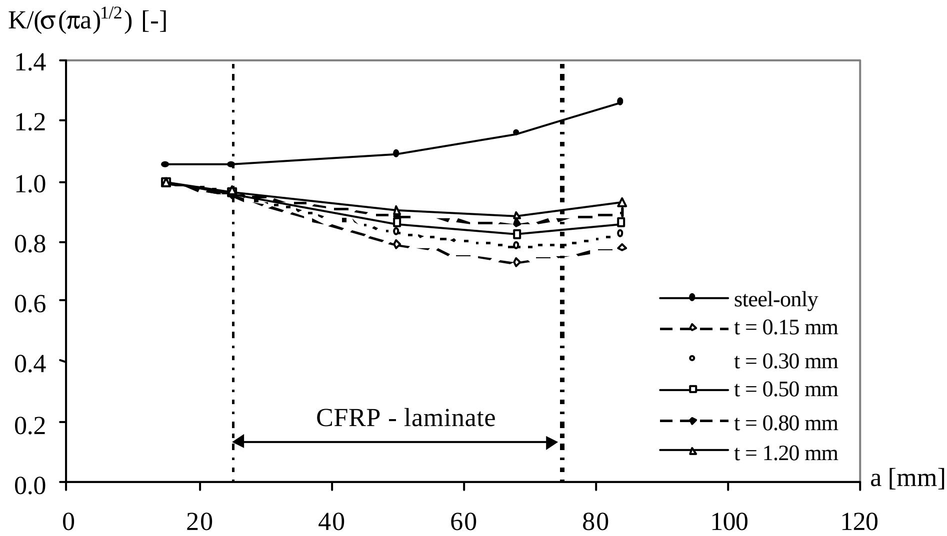


Figure 7. Stress intensity factor vs crack length as function of the adhesive thickness.

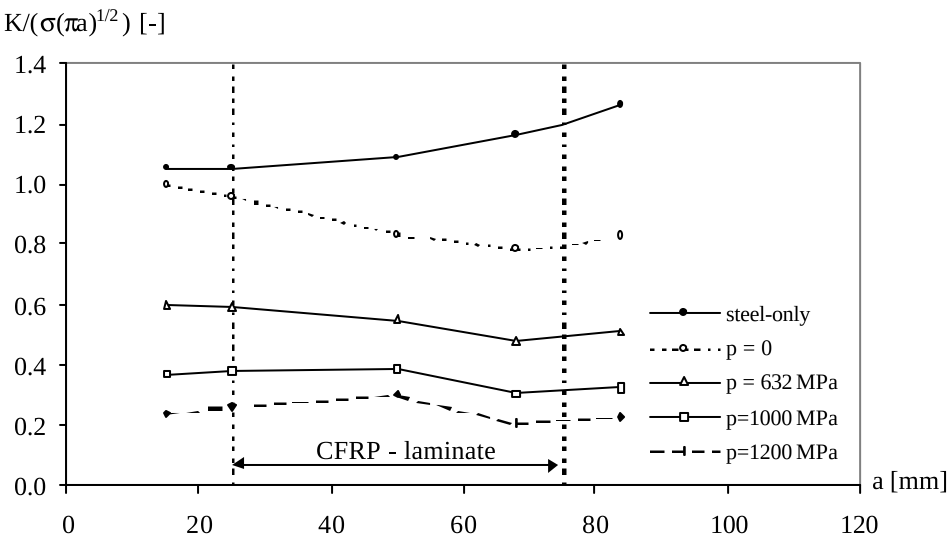


Figure 8. Stress intensity factor vs crack length as function of the pretension level.

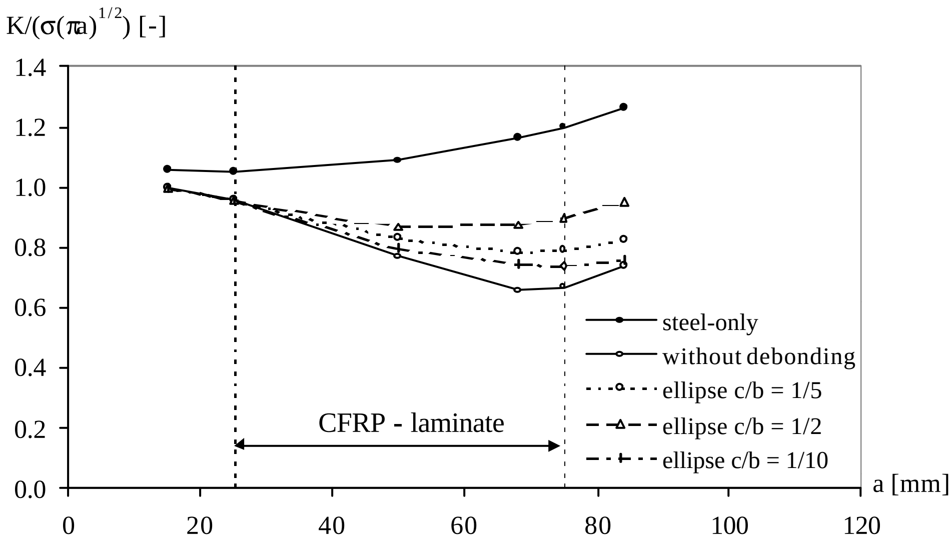


Figure 9. Stress intensity factor vs crack length as function of the patch debonded area.

4. Discussion and conclusions

A two dimensional finite element analysis of a composite prestressed patch bonded repair of crack plate was performed in this paper by the three layer technique. It is based on Mindlin plate theory and it avoids a very expensive three dimensional finite elements analysis.

The parametric analysis shows that the application of high stiffness prestressed CFRP strips on cracked plates reduces the stress range at crack tip. Moreover, CFRP laminas bonded perpendicular to the crack path limit crack opening and then reduce stress intensity factor at crack tip. Note that in fatigue crack propagation, the dominant parameter is the stress intensity factor range and not its maximum value. In this sense the compressive stress field produced by the pretension of composite patch promotes crack closure and then it lessens the stress intensity factor range. Sensitivity analysis clearly shows a different effect of the prestressed reinforcement on small cracks compared to long cracks. For short cracks the limitation of the crack opening by CFRP without pretension is marginal (see Fig. 6 and 7). On the contrary, CFRP laminas narrow the stress intensity factor of long crack even without pretension since the process zone and a large portion of the crack is covered by the patch. Fig. 6 and 7 clearly show in fact that the best situation is given by a crack length equal to roughly 70 mm. Pretension of the composite strips was then introduced [2] [3] to narrow the stress field for small cracks. Pretension level have a significant effect on the stress intensity factor, in particular for small cracks (see Fig. 8). For this kind of cracks, compared to long cracks, a small perturbation of the compressive stress field introduced by the pretension is achieved. Shear deformation of the adhesive layer has a significant effect of the efficiency of the bonded repair. Fig. 7 shows that as the adhesive shear deformation increases with adhesive thickness, the efficiency of the bonded repair technique is reduced. Debonding of the composite patch at the plate-adhesive interface plays an important role for long cracks (see Fig. 9). For this kind of cracks debonding reduce the bridging effect of composite patch and the stiffening effect on the crack faces. Researches are in progress to compute the energy release rate along the bond line. To this end the indirect modified crack closure model [8] will be used as in [6] [10]. This is probably a key factor for the evaluation of the effective stress intensity factor range as preliminary results clearly show.

Acknowledgement

The financial supports to the second author by the Italian Ministry of the University and Scientific and Technological Research and to the first and third authors by the Swiss National Science Foundation is gratefully acknowledged. Thanks are also expressed to Sika AG – Zürich for supplying composite materials.

References

[1] Ammar N., *"Rehabilitation of Steel Bridge Girder with Graphite Pultrasion"*,CCM Report 96-26, University of Delaware, **1996**.

[2] Bassetti A., Liechti P., Nussbaumer A., *"Fatigue Resistance and Repairs of Riveted Bridge Members"*, Fatigue Design and Reliability, Elsevier, 207-218, **1999**.

[3] Bassetti A., Nussbaumer A., Hirt M., *"Crack Repair and Fatigue Life Extension of Riveted Bridge Members Using Composite Materials"*, Bridge Engineering Conference, 26-30 March 2000, Sharm El-Sheikh (Egypt), to appear.

[4] Deuring M., *"Verstärken von Stahlbeton mit Gespannten Faserverbundwerkstoffen"*, Report 224, EMPA, 1993.

[5] Meier U., *"Strengthening of Structures using Carbon Fibre/Epoxy composites"*, Construction and Building Materials, **9**, 341-351, **1995**.

[6] Naboulsi S., Mall S., *"Modelling of a Cracked Metallic Structure With Bonded Composite Patch Using The Three Layer Technique"*, **35**, 295-308, **1996**.

[7] Ratwani M.M., *"Analysis of Cracked Adhesively Bonded Laminated Structures"*, AIAA J., **17**, 988-994, **1979**.

[8] Rybicki E.F., Kanninen E.F., *"A Finite Element Calculation of the Stress Intensity Factors by a Modified Crack Closure Integral"*, Eng. Fract. Mech., 9, 931-938, **1977**.

[9] Sen R., Liby L., Spillet K., Mullins G., *" Strengthening Steel Composite Bridge Members using CFRP Laminates"*, Non-metallic (FRP) Reinforcement for Concrete Structures, **1995**.

[10] Sun C.T., Klug J., *"Analysis of Cracked Aluminium Plates Repaired by Bonded Composite Patches"*, AIAA J., **34**, 369-374, **1996**.