RETROFITTING OF CRACKS IN STEEL CONSTRUCTION
Using CFRP Laminates

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INTRODUCTION

Destroying of steel structures under cyclic loading has been the matter of research by many recently. It can be observed in many fields, but it is particularly dangerous in bridge construction. Parts of steel girder are loaded with relatively small loads that apply regularly. The load causes small elastic stresses that seem to be harmless but repeated with high frequency in areas with stress concentration they create cracks. Under stress concentration one understands defects of first and second type. Type 1 means geometrical discontinuities and type 2 means the internal properties of materials like dislocation or empty spaces within the grains of steel.
Inspired by [1] where centre crack tension (CCT) steel plates were examined under quasi static load with and without additional strengthening (bolted and welded steel stripes as well as CFRP laminates) one decided to make similar experiments under cyclic load and only with CFRP laminates and welded steel stripes. A very similar situation had already been investigated by [2] with pre-stressed CFRP laminates on steel plates with a crack.
As opposed to [1] and [2] one concentrated on the application of fracture mechanics parameters to predict the fatigue behaviour of steel members. Also one focused on the adhesive connection between the CFRP laminates and steel plates.

1 FRACTURE MECHANICS ANALYSIS

1.1 Basis

The cracks appear in the areas of big stress concentration, where all the relocations of the grains are concentrated. That causes the loosing of the connections between the grains. It has been observed that describing the field of stresses near such a discontinuity can be problematic. The results obtained while solving the stress distribution problem with the elastic theory were infinite high independently from the applied loads. The reason for such behaviour is the radius of the curvature that aims to zero in sharp-edged cracks. It is obvious that in actual construction elements with small cracks (smaller than a critical length) still have enough load capacity. Thus the fracture mechanics has been used. Then the mechanical parameters depend on the applied load which can be seen in *Fig. 1*. a).

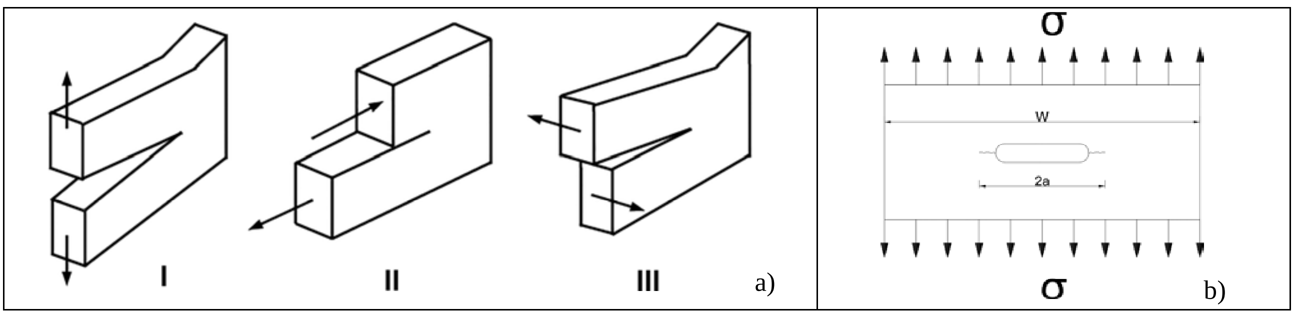

Fig. 1. a) Types of loading, b) CCT

An appropriate stress intensity factor can be calculated based upon the type of loading. It characterizes the entire stress field around the crack. According to [3] for the first type of loading the following stress intensity factor can be defined as in *Eq. 1*.

$$K_I = \sigma \cdot \sqrt{\pi \cdot a} \cdot F_I(\alpha) \quad (1)$$

where a is the half length of the crack (*Fig. 1.* b)),
σ is the acting axial stress,
$F_I(\alpha)$ is the geometrical coefficient.

1.2 Calculation of predicted fatigue life

The lifespan of a construction depends on the number of cycles. It is distinguished between high – and low - cycle fatigue. The first one applies when the number of cycles under dynamic load with constant amplitude is smaller than 10^5. The second one, when the number of cycles is bigger than 10^7. To approximate the fatigue life of a specimen the model developed by Paris can be used. It states the first expression for the fatigue crack propagation in terms of stress intensity factor that can be seen in *Eq. 2*. It describes the fatigue crack growth rate under linear elastic and small scale yielding condition.

$$\frac{da}{dN} = C_p \cdot \Delta K^{m_p} \quad (2)$$

where N is the number of cycles,
C_p, m_p are the material properties ([4]),
ΔK is the range of stress intensity factor.

Newman [5] proposed a model that considers the crack - closure effect. During fatigue - crack propagation the crack surfaces remain closed during a part of load cycle. The crack closure is caused by residual plastic deformations remaining in the wake of an advancing crack. The crack – closure concept applying the effective stress – intensity factor range has been used to correlate crack growth rates under applied constant – amplitude loading. *U*, the Elber's coefficient, was determined empirically by Schijve [6], as shown in the *Eq. 3*.

$$U = \frac{\Delta\sigma_{eff}}{\Delta\sigma} = \frac{\Delta K_{eff}}{\Delta K} = \begin{cases} 1 & (R \geq 0.7) \\ 0.69 + 0.45 \cdot R & (-0.5 \leq R < 0.7) \\ 0.465 & (R < -0.5) \end{cases} \quad (3)$$

where R is the stress ratio ($\sigma_{min}/\sigma_{max}$),
ΔK, $\Delta\sigma$ are the applied stress intensity factor range and stress range respectively,
ΔK_{eff}, $\Delta\sigma_{eff}$ are effective stress intensity factor range and effective stress range respectively.

Combining *Eq. 1*, *Eq. 2* and *Eq. 3* it is possible to receive the prognosed number of cycles for the crack propagation from a_0 to a_f in *Eq. 4*.

$$N = \frac{2}{C_p \cdot (m_p - 2) \cdot \left[\sqrt{\pi} \cdot U \cdot \Delta\sigma \cdot F_I(\alpha)\right]^{m_p}} \cdot \left(a_0^{1-\frac{m_p}{2}} - a_f^{1-\frac{m_p}{2}} \right) \quad (4)$$

where a_0 is the initial crack length,
a_f is the final crack length.

1.3 The J – Integral

The J-integral for quasi – static loads can be easily determined. Depending on the phase of instability of crack propagation the different parameters can be specified according to [7].

Although a mathematical description of J-integral is really complicated it has a physical meaning as well. It describes the speed of energy reduction during the crack propagation. The J-integral is independent from the curve of integration as long as Ramberg-Osgood Power Law is in force. If the reduction of stresses developed by simultaneous decreasing load near the crack one can obtain the unloaded zone. There the J-integral loses his independence of the curve of integration and cannot be applied. The J-integral consist of two elements namely elastic and a plastic part. The elastic solution is very well known, but it is difficult to estimate the plastic one. In the first step the point of unstable crack growth should be located. A number of additional conditions concerning maximal applied load, maximal ratio of crack - length to width of the specimen needs to be considered. The critical value of J-integral for static case can be determined according to *Eq. 5*.

$$J_0 = \frac{K^2}{E} + \frac{A^*}{B \cdot (W - a)} \tag{5}$$

where K is the stress intensity factor according to [7],

A^* is the area under the force versus load – point displacement diagram up to the point corresponding to either unstable fracture or the first significant pop – in step,

E is Young's module,

B is the thickness of specimen.

Nevertheless the new quantity ΔJ has been introduced and has been used successfully by Dowling and Begley [8]. Starting with the relation in *Eq. 6* using the range of stress intensity factor the quantity ΔJ can easily been obtained, which is seen in *Eq. 7* [9].

$$J_0 = \frac{K^2}{E} \tag{6}$$

$$\Delta J_0 = \frac{\Delta K^2}{E} \tag{7}$$

1.4 The R-curve

The R-curve describes the resistance of the material against the crack growth in *J(Δa)* coordinate system. The construction rules are described in [7]. To identify the crack initiation point it is helpful to use the R-curve and the blunting line. Blunting line is a one that describes the initial behaviour of the fatigue pre-crack in a fracture specimen under monotonically increasing loads prior to ductile crack extension.

2 ADHESIVES AND CFRP LAMINATES

Safe connection has been used as a bonding technology for joining CFRP and steel. This new technology is not often used in steel constructions because of the high complexity. A 2-component epoxy adhesive was recommended by the producer of the CFRP laminates. The high resistance against the dynamical loads is one of the most valuable properties of that type of connection [10]. CFRP laminates exhibit a high resistance to fatigue. They are a type of fibre composites which consists of small carbon fibres and the matrix. Moreover they are light, around 4 times lighter than steel and at once they have a high tensile strength which is 4 times bigger than for steel. It should be considered in order to be able to carry the load that a specific length of the laminate has to be calculated. To be sure that a CFRP – laminate will be activated during the experiment a difference in force (F_{over}) that is required to bring the material to yielding in the full and narrow cross – section have to be determined. The extra length of CFRP (l_{over}) pro half of the specimen can be calculated according to *Eq. 8*. A complete length can be calculated after summing the measuring length of the specimen (l_0) and 2 times l_{over}.

$$l_{over} = \frac{F_{over}}{b_{CFRP} \cdot \tau_{Bm}} \tag{8}$$

where b_{CFRP} is the width of the CFRP laminate,

τ_{BM} is ultimate transverse stress in glue.

3 EXPERIMENTAL PROGRAMM

3.1 Geometry of specimens

The geometry of the specimens was specified according to DIN EN ISO 6892. Steel S235 was used. The width of the specimen in the middle was 170 mm and in the head part 220 mm. The grip part of the machine had a width of 100 mm. The overall length of the specimen was equal to 992 mm. The thickness of the plate was 10 mm. In the upper and lower head additional plates were applied to strengthen the cross–section. A mechanical crack in the middle was created in two phases. In the first one a hole (14 mm) was milled and then two cuts left and right were executed. An overall crack of 40 mm was prepared.

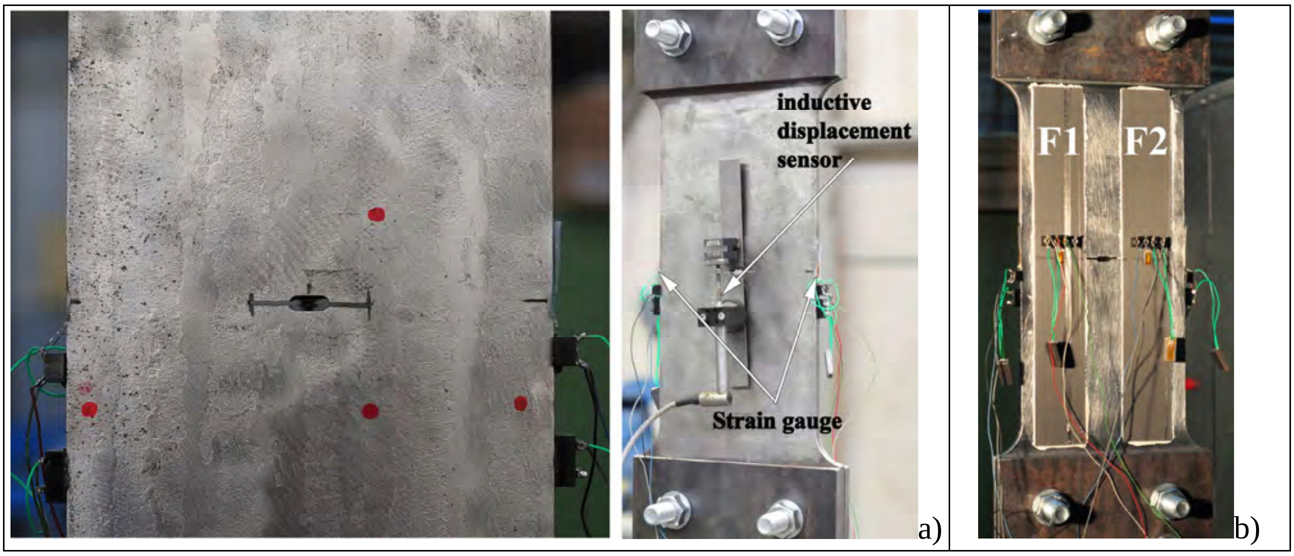

Fig. 2. a) Specimen without improvement, b) Specimen with improvement

The CFRP laminate MC DUR 160/2400 was 50 mm wide and 1.4 mm thick. They were applied on the both sides of the specimen and on the left and right hand side of the crack. MC DUR 1280 glue was used to connect the steel plate with the stripes of laminate.

3.2 Experiment

The series of experiment were planned in four phases. In the first step (V01, V02) the static load was applied on the specimen without any additional improvement. In the second step (V04) the sample was loaded with pure fatigue load without additional support of CFRP as well. At the crack length of around 105 mm the experiment was paused and then started once again. In the third phase the cyclic load was applied on the specimen with improvement. This phase was divided into two stages. First (V03, V05) – pure fatigue on steel plate without any improvement and second (V03CFK, V05CFK) – fatigue on the steel plate with improvement in the guise of CFRP Laminates. In the last phase (V06, V06GS) the alternative improvement was tested, namely the welded steel stripes in the same manner as in the phase no. 3.

During the tests without any improvement the average displacement in the middle of the crack and strain in steel on the left and right side of the specimen were measured. In the specimens with improvement additionally a strain on the CFRP/steel stripes was evaluated.

In order to take advantage of fracture mechanics criterions additionally crack propagation must be measured. The photogrammetry was one of the possible solutions. The problem was that it could be used only for specimens without any improvement. Another issue was the crack size. New solution with crack gauges was used in order to monitor crack growth during the whole experiment.

Two static tests were conducted. The first one was controlled with the force and the other one with the displacement. The test speed of the first one was 1 kN/s and of the other 2 mm/min.

The force for the fatigue experiment was calculated according to [7]. The maximal applied load F_{max} was equal to 200kN and the minimal force was equal to 20kN. That results in a load ration R = 0.1. The load was applied on the specimen with a frequency of 5Hz.

4 DISCUSSION OF THE RESULTS

According to the already described Paris model a number of cycles that could be applied in order to get a defined crack growth could be calculated. For the crack growth from a_0 = 43 mm to a_f = 104 mm by the stress range of 140 N/mm^2 a life of N = 4350 cycles was predicted following *Eq. 4.* In reality the V03 endured 80 343 cycles without any improvement. That shows a weak point of the model that according to [11] can underestimate a fatigue life of specimens. The crack propagation mechanism by static and dynamical loads is totally different which can be seen in *Fig. 3*. The fatigue cracks are really thin and can be barely seen by a human eye. The camera had also problems to recognize this defect.

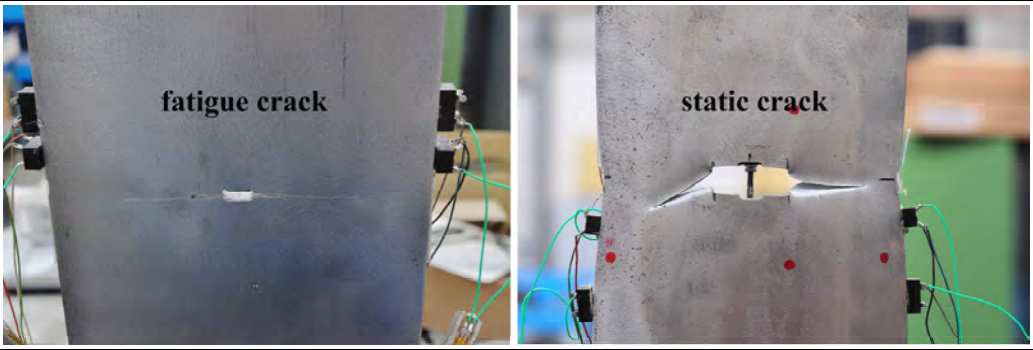

Fig. 3. The difference between fatigue and static crack

For V01 and V02 the J-integral parameter was calculated; for the force controlled experiment J = 536.23 kN/m and for the displacement controlled J = 650.25 kN/m. These are very similar to the results from [1] although a different geometry was used. The J-integral is not dependent on the geometry of the specimen. The J-integral for a force controlled is then in [1] equal to J = 653.65 kN/m and for the displacement controlled J = 670.45 kN/m. This critical value is calculated up to the point of stable crack propagation. During the first fatigue test it was observed that a reinforced steel plate with CFRP laminates (V03CFK) was able to be loaded additionally with the same force amplitude for 147 037 cycles. It was noticed that due to the reinforcement a life of a construction was longer than without reinforcement. That confirms that the use of CFRP guarantee a better performance of the construction. For a very similar experiment that was made by [2] but with prestressed CFRP – laminates for steel S355 under an applied stress range of 80 N/mm^2 and R = 0.4 the specimens without any improvement were able to endure on average 166 000 cycles and the specimens with CFRP 226 000 cycles.

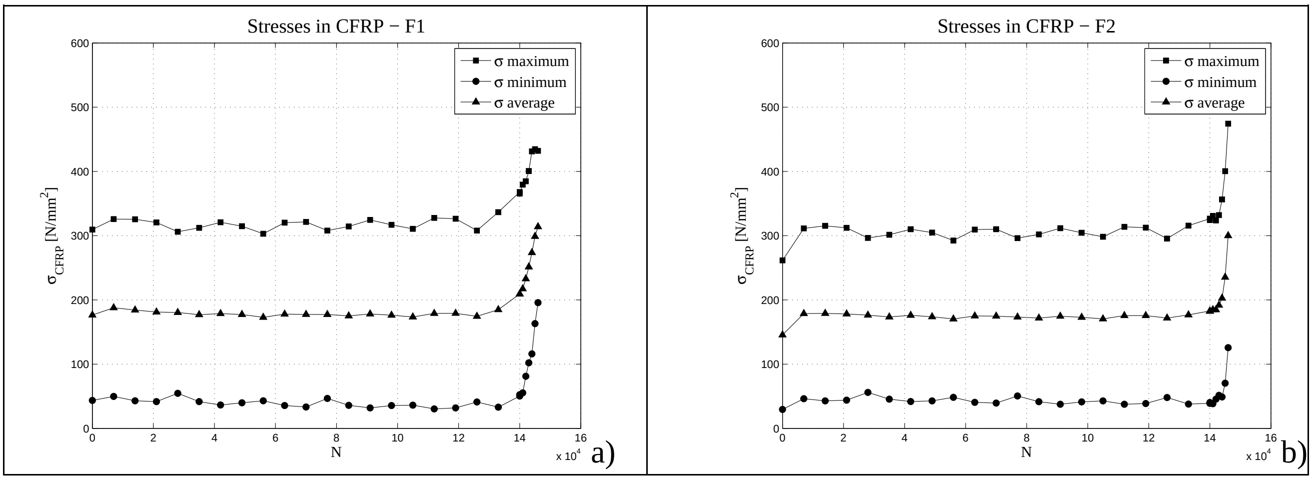

Fig. 4. a) Stresses in CFRP F1, b) Stresses in CFRP F2 (see *Fig.2.* b))

Because of the eccentricity that was caused due to the small rotation of the CFRP laminate during bonding process an additional moment was applied on the specimen. That induced higher tensile stresses in the CFRP on the right side which can be seen in *Fig. 4.* a) and b). The compression and tensile stresses in steel were also observed. As a result a sudden debonding of the CFRP on the right side of the specimen was noticed. The losing of adhesion between CFRP laminates and steel can be seen on the *Fig. 5.* The experiment is still conducted and the final results will be presented at the conference.

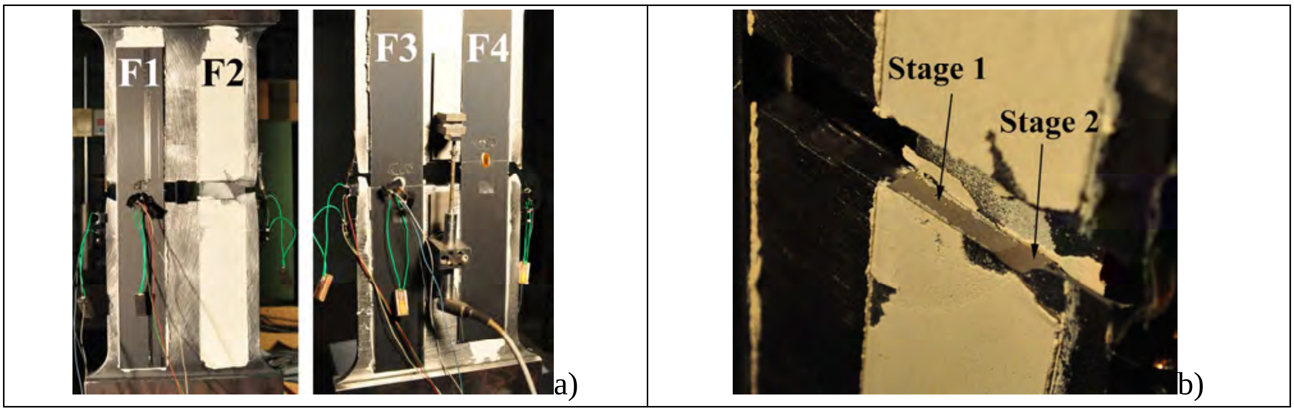

Fig. 5. a) Debonding of CFRP laminates, b) Fracture of specimen

5 CONCLUSIONS

The crack growth propagation can be slowed up down using CFRP laminates as a method for repairing.
The retrofitting of steel construction with cracks is possible for the described specimens.
The number of cycles will grow for a retrofitted steel plate with a crack.

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