REDUCTION OF FATIGUE CRACK GROWTH RATE IN COMPACT TENSION SPECIMENS USING ADHESIVE BONDED CFRP-STRIPS

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ABSTRACT

Carbon fibre reinforced polymer strips (CFRP) are nowadays successfully used for structural concrete retrofitting. Some applications require pre-stressing of the CFRP-strips. The transfer of the pre-stressing force is usually achieved using mechanical anchorage systems. In the scope of a current research project, the usability of CFRP-strips for retrofitting fatigue damaged steel structures is being investigated. Thereby the adhesive bonding of the anchorage region is aspired. In this paper, criteria and testing procedures for the selection of adhesives are described, and the results of constant amplitude fatigue tests on compact tension (CT) specimens are given. In order to assess the long-term transfer of the pre-stressing force between the CFRP-strips and the steel component, in particular, the shear strength and creep behaviour of adhesives were determined. For both types of tests a modified specimen of the thick adherent shear test with an integrated CFRP-strip was used. Five epoxy adhesives and one acrylic-based adhesive were examined. The results of the modified shear tests showed a maximum shear strength of 28.2 MPa. The creep tests were conducted at room temperature under long-term load at a level of 40% of the shear strength of the respective adhesive. The acrylic-based adhesive showed as expected high creep sensitivity and therefore was eliminated from further investigation. In the first test phase of the fatigue testing of CT-specimens, a 20 mm long crack was induced and repaired in different ways in the second test phase: In this paper the fatigue behaviour of the CT-specimens repaired with non-pre-stressed CFRP-strips is compared to those being repaired using alternative methods for crack repairing (repair welding, drilling of the crack tip). The crack propagation during the fatigue tests was measured using RDS propagation gauges. Tests with pre-stressed CFRP-strips are being planned.

INTRODUCTION

There are many examples of retrofitting concrete structures applying adhesively bonded CFRP-strips. For this purpose systems of adhesives and CFRP-strips, for example (DIBt 2008), have been tested and approved. In Figure 1, applications of CFRP-strips for retrofitting bridge structures are shown. Pre-stressed CFRP-strips can be used to reduce bridge deformations caused by the traffic load (vom Berg 2007). To pre-stress the CFRP-strips systems with a fixed and a moveable anchorage connected by the CFRP-strip stress heads at both ends are used (Berset 2002). Because of the success in post-strengthening of concrete structures the usability of CFRP-strips for constructively strengthening steel structures is currently being investigated. In a previously completed research project (Pasternak et al. 2015) the potential of post-strengthening steel structures as well as the fatigue crack repairing using non-pre-stressed CFRP-strips were studied. Additionally, in (Pasternak *et al*. 2015) several FEM analyses of steel-CFRP connections were performed. Within the scope of this project, which has been conducted by the Chair of Steel and Timber Structures (BTU Cottbus-Senftenberg), Institute for Steel Structures (RWTH Aachen) as well as KIT Steel & Lightweight Structures, also a full-scale test of a crane runway, in the form of a 3-point bending test, was carried out.

That test proved the applicability of such CFRP-strips also in full scale, while the strain measurements on the CFRP-surface showed the full-load bearing capacity of the CFRP-strips together with the bonded steel. The test however had to be interrupted due to torsional buckling of the steel I-beam, but the CFRP-strips were not separated from the steel surface (Figure 2).

Figure 1. Two examples of the application of CFRP-strips to a bridge construction (HP-TL);
left: Retrofitting by adhesively bonded slack CFRP-strips;
right: Post-strengthening using a pre-stressing system.

The current research project (IGF-No. 19032 BG) is based on the experience from the previous project (Pasternak et al. 2015) and focuses on the reduction of fatigue crack growth rate using adhesively bonded pre-stressed CFRP-strips. It is being conducted by the above-mentioned research centres. Tests on small and full-scale specimens, as well as theoretical and numerical investigations, are being performed to get a deeper comprehension of the behaviour and the usability of adhesively bonded CFRP-strips for reducing fatigue crack growth rates in steel structures. This paper presents the results of shear and creep tests of selected adhesives as well as the results of fatigue tests of CT-specimens with a pre-induced crack reinforced by adhesively bonded CFRP-strips.

Figure 2. Full-scale test of a crane runway beam (Pasternak et al. 2015).

SELECTION OF ADHESIVES

General Remarks

To repair fatigue cracks with adhesively bonded pre-stressed CFRP-strips the pre-stressing force in the CFRP-strip has to be transmitted to the steel component by the bond. Thus, the shear resistance of the used adhesive is of particular importance and furthermore, the adhesive bond must uphold the pre-stressing level during the intended service life of the fatigue crack repair measure. Therefore the shear strength and the creep behaviour of six different adhesive systems were investigated. Both types of tests were carried out on small-scale specimens with an integrated CFRP-strip (Figure 3), in accordance with (Meschut 2015). The CFRP was taken from 20 mm wide so-called slot-lamellas (with a tensile strength of 2350 MPa and a Young's modulus of 168000 MPa). Based on the test results and the other adhesive´s characteristics like glass transition temperature, handling and curing behaviour two epoxy systems were chosen for further investigation.

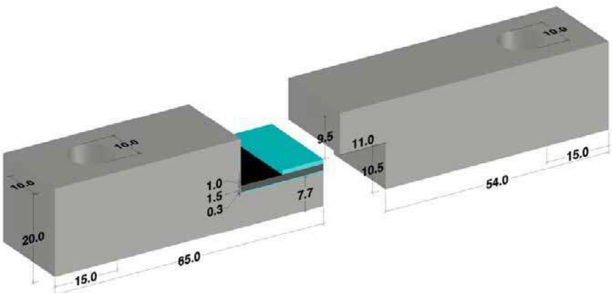
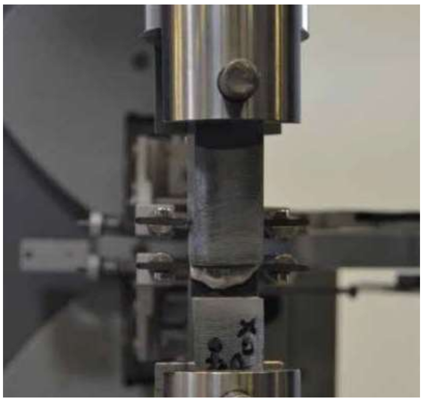


Figure 3. Geometry of the small-scale test specimen: modified thick adherent shear test with an integrated CFPR-strip, cf. (Meschut 2015).

Quasi-static tests

The quasi-static tests were conducted for six adhesive systems, among which were five different epoxy systems (from five different manufacturers) and one acrylate-based adhesive. In order to prepare the tests specimens, the CFRP-strip coupon was glued onto the longer leg with a 0.3 mm thick adhesive layer, before the second leg was bonded over a smaller area onto CFRPstrip with a 1.0 mm thick adhesive layer. The specimens were tested by subjecting them to a controlled tensile displacement (see Figure 4 left) until failure occurred at the thicker, but smaller, adhesive layer. For most specimens failure was cohesive near substrate, and mixed towards steel or CFRP. The diagram in Figure 4 right shows the shear stress-strain curves. The test results were averaged and smoothed for better evaluation for each adhesive system. Clearly, the lower load capacity of the acrylate system can be observed, while also for the epoxy adhesives differences with regard to stiffness and load capacity can be noted.



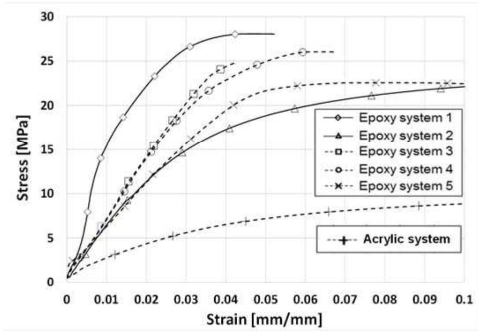


Figure 4. Quasi-static shear tension tests; left: test setup with extensometer measurements; right: test results shear stress-strain curves.

Creep tests

In order to determine the long-term behaviour of adhesives under predominant shear stress, two specimens for each of the six adhesive systems were exposed to a long-term shear loading at room temperature. The creep test stress level was chosen to be equal to 40% of the shear strength of the respective adhesive. This means that, for example, in the case of the two-epoxy systems that were subsequently selected for further investigation, the nominal shear stresses in the bond lines were 11.3 MPa (System 1) and 9.5 MPa (System 2). The extension in load direction of the test specimens has been measured between two fixed points on the two sides of the test specimens using a mechanical measuring device (Figure 5, left), over a total time of 1000 hours at regular intervals. At the beginning (first 8 hours) the measurements were made every 20 minutes and then in the longer intervals from 60 minutes up to 48 hours. The time-extension curves for the tested epoxy systems are given in Figure 5, middle. After 1000 hours, the measured extension of the specimens bonded with epoxy System 2 was 0.070 mm, while the epoxy System 1, despite the higher absolute stress level, exhibited a lower extension of 0.054 mm. Both selected epoxy adhesives – as well as epoxy systems 3 and 4 – can be characterized as creep resistant. For comparison, the tested specimens bonded with acrylate system failed after 47 hours, whereby a maximum extension of 0.76 mm was measured before failure (Figure 5, right).

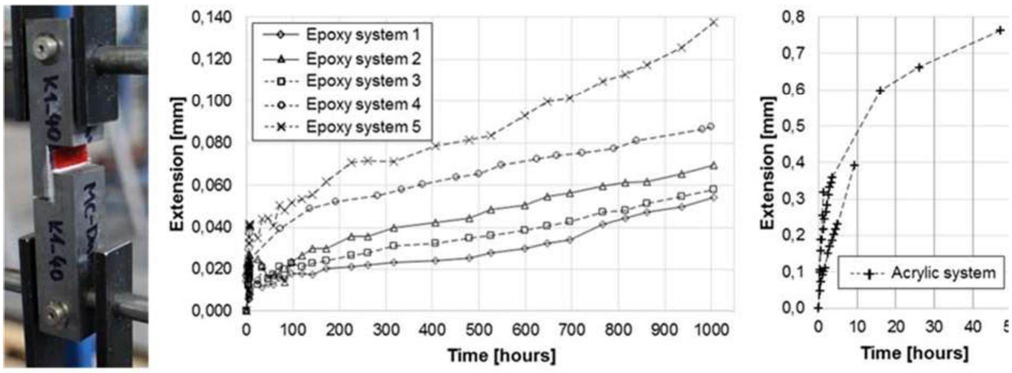


Figure 5. Creep tests; left: the specimen in the testing frame; middle: test results for epoxy systems; right: test results for acrylic system.

Selection of two adhesive systems

Based on the test results given above, the epoxy Systems 1 and 2 were chosen. While System 1 was rated top with regard to shear strength, high stiffness and low creep behaviour, the decision in favour of System 2 was based on the basis of using an adhesive system which offers some additional ductility before failure, while still maintaining high shear strength and low creep tendency.

EXPERIMENTAL INVESTIGATIONS ON COMPACT TENSION SPECIMENS

General Remarks

CT-specimens are commonly used for the determination of fracture mechanical characteristic values of steel (Heckel 1975) and its geometry is chosen following (ASTM E 399). Furthermore, in (ASTM E 399) standard geometry proportions of CT-specimens including different fatigue crack starter notches are defined. In order to determine the fatigue crack growth rate in steel, the fatigue tests were carried out on CT-specimens (Figure 8), similar to the ones used in (Ljustell 2013). After choosing these two adhesives, the fatigue tests were conducted on the CT-specimens with bonded CFRP-strips to reduce the crack growth rate in comparison with conventional methods used for crack repair.

Since the objective of these tests was not the determination of fatigue behaviour of steel, but the testing of crack repairs by means of CFRP-strips, the thickness of the CT-specimens was reduced to 10 mm, following (Noack 2008). The obtained ratio between the dimension "w" (see Figure 10,left) and the thickness of CT-specimen is equal to 20. All specimens were produced from a S355 J2 steel. A starter notch is situated at mid-height of the CT-specimen. The starter notch has the form of a half circle with a diameter of 10 mm, which continues with a 5 mm long sharp edged cut (see the figures in Table 1 for detail). Under cyclic loading in plane of the CT-specimens surface, a fatigue crack is initiated perpendicular to the notch axis at the end of the starter notch.

Crack propagation measurement and the test phases

The crack initiation is followed by the crack propagation. In the first test phase, a 20 mm long fatigue crack was created in the specimens. Table 1 (test phase 1) illustrates the crack initiation at the end of the starter notch and the crack tip propagation almost parallel to the notch. The monitoring of the crack growth during this first test phase was carried out visually and by RDS propagation gauges. To verify the results given by the signals of the crack propagation gauges, the visual control was continuously carried out. It was observed that the visual measurement of the crack propagation can be used here with sufficient accuracy. At the end of the first test phase, for each CT-specimen, a dye penetrant inspection has been performed (Figure 6, left).

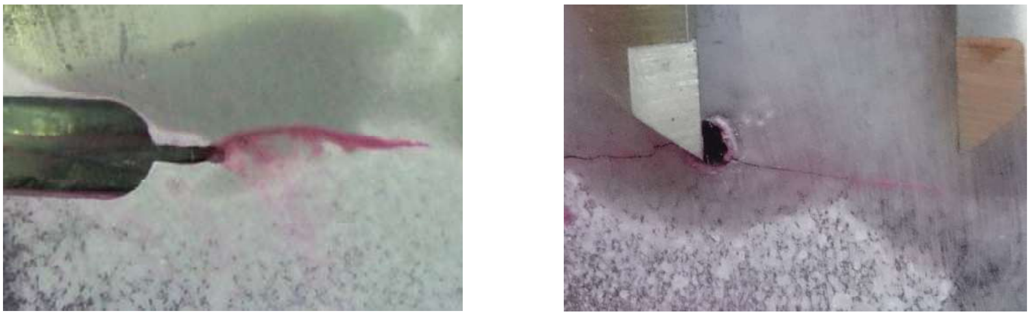


Figure 6. Dye penetrant inspection; left: After the first test phase (specimen "welding 01"); right: after Second test phase (specimen "welding 01").

During the second test phase, the crack propagation was monitored for further 20 mm using RDS sensors, until the total crack length reached a length of 40 mm (see Table 1, test phase 2). After the test the dye penetrant inspection of the whole fatigue crack was performed again (Figure 6, right).

Between the first and second test phase, two commonly used crack repair methods were carried out:

- drilling of the crack tip or
- drilling of the crack tip combined with repair welding,

and compared to test specimens without crack repair.

The aim of these investigations was to obtain data for further comparison with the crack repairing method using CFRP-strips. If the drilling of the crack tip after the first test phase is applied, the observation of the crack growth velocity in phase two is only possible within a further length of 18 mm because of the position of the drilled hole. However the final crack length in all three cases is 40 mm. The crack propagation measurement procedure is shown in (Table 1).

Table 1. Crack propagation measurement procedure.

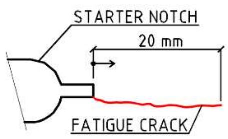
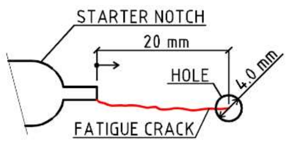
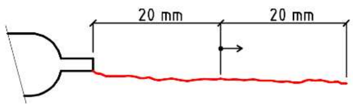
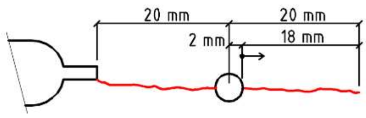
Test phase	No crack repair	Drilling of the crack tip and repair welding
1.		
2 .		

Figure 7 shows the preparation steps of the respective repair welded CT-specimen: After the drilling of the crack tip, steel in the region along the fatigue crack was removed for weld preparation. For that a “V” groove was ground to 2/3 of the depth of material thickness on both sides of the CT-specimen (step 3, Figure 7). In the next step, the region was X-welded using manual metal arc welding with basic coated electrode ISO 2560-A: E 46 4 B42 H5. It is important that during the welding procedure the hole with the diameter of 4.0 mm was not filled. Finally, the elevation of welding seam was ground to create an even steel surface (step 6 on Figure 7).

If only the drilling of the crack tip is carried out, the preparation of the CT-specimen for the second test phase ends at step 2 in Figure 7. For the specimens without any reparation the dye penetrant inspection was performed before the second test phase was started. In that case, the final crack is not interrupted by a hole (see Table 1).

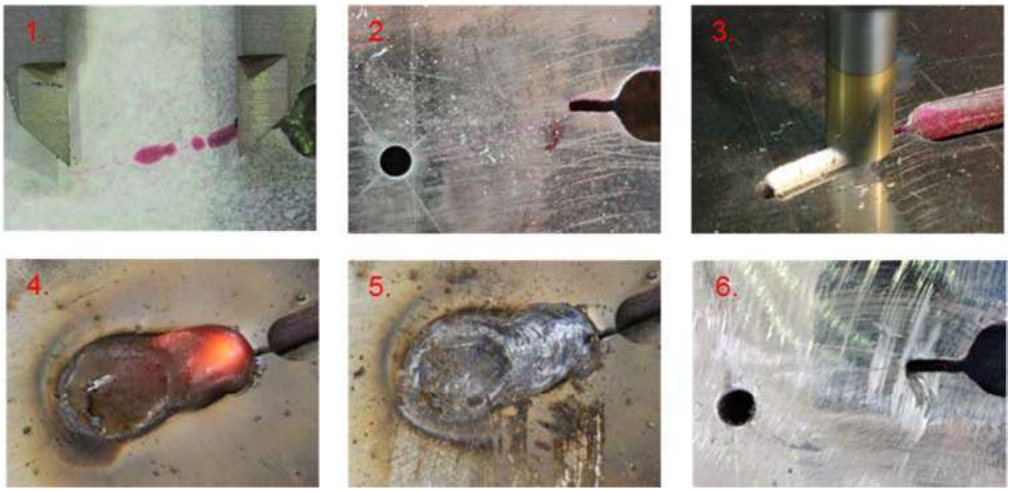


Figure 7. Preparation of the CT-specimen "welding 02" for the second test phase; 1. dye penetrant inspection; 2. drilling of the crack tip; 3. removal of the damaged metal; 4. repair welding; 5. removal of slag; 6. grind of welding seam elevation.

Test setup and results

Figure 8 shows the test setup of both test phases of the CT-specimens. In order to measure the crack growth rate an RDS propagation gauge was placed on one side of the CT-specimen (Figure 8, right above). The other side of the CT-specimen was painted white for a visual crack propagation control, and equipped with one extensometer (Figure 8, right below). The tests were performed on a hydraulic testing machine (maximum load up to 100kN). To reduce the moment transfer of the load two cylinders made of high-strength steel were placed in the two holes of the CT-specimen and clamped. The tests were conducted in a force controlled regime. In the first test phase (crack length smaller than 20 mm) cyclic loads with a load range of ΔF = 40 kN and a mean load of 40 kN was applied. Therefore, the upper force was 60 kN and the stress ratio R = 0.33.

For the second test phase, the parameters of the cyclic load were changed to a load range of ΔF = 30 kN and mean load of 25 kN (R = 0.25), because of the 20 mm increase of the load eccentricity, compared to the first test phase.

The test results of both test phases are given in Figure 9. For both applied crack repair methods, two tests were performed. Figure 9 shows six curves, as the results of two further tests without any crack repair were taken into comparison. The curves in both test phases are nearly bilinear, with a slower crack progression at the beginning. The curves define a relation between the crack length and corresponding number of cycles. The crack lengths limits are 20 mm for the first and 40 mm for the second test phase, respectively (Table 1). All tests were performed at a load frequency of 5 Hz. To create a 20 mm long fatigue crack between 12 to $18*10^3$ cycles were necessary (Figure 9, left).

Figure 8. Test setup; left: CT-specimen in the testing machine; upper right: Detail of the RDS propagation gauges; lower right: Extensometer and white painted area for visual crack control.

In the second test phase, the measurement was started at the end of the crack (which is the middle of the drilled hole). For this reason for the first two millimetres of crack length progress no cycles are needed (both specimens “drilling” and “welding”, Figure 9, right). The diagram shows that both crack repair methods are effective at the beginning of the second test phase only. In the case of not repaired crack (for both specimens), approx. 2.0x10³ cycles were required for the first 1 mm of crack propagation. In the case of the specimens with the repaired cracks, 5.7x10³ and 7.2x10³ cycles were needed to achieve the same results for “drilling” and “welding” repairs, respectively. This means that the welding repair resulted in the highest resistance to repeated crack initiation. When the crack tip is situated behind the outer edge of the drilled hole, the fatigue crack propagation is no more influenced by the examined crack reparation methods.

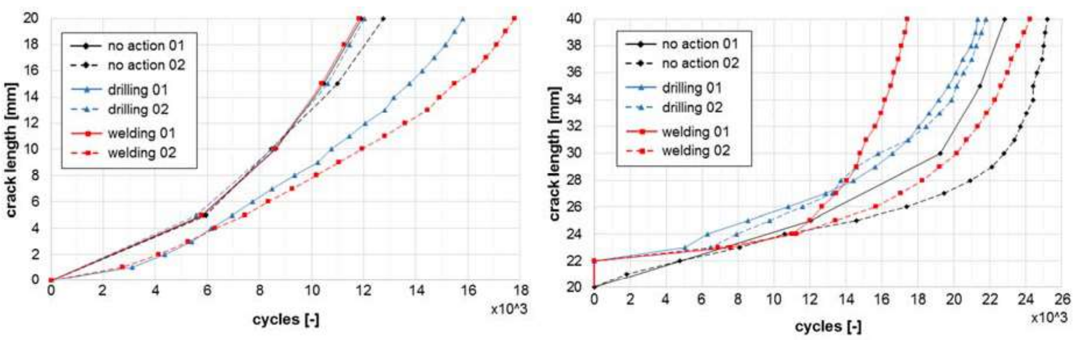


Figure 9. Fatigue crack growth rate; left: First test phase; right: Second test phase.

Compared to the other specimens, the CT-specimen repaired by welding marked “welding 01” showed a rapid increase of the crack growth velocity in the second part of the second test phase, i.e. for a crack length longer than 24 mm onwards. Up to that crack length, the two specimens “welding 01” and “welding 02” perform similarly. Thus, the reason for this effect cannot be directly related to the quality of the manual metal arc welding (human factor). The explanation for this may rather come from the metallurgical changes during the welding procedure, which can occur by the heat input (see Figure 7, step 4) in the heat affected zone. According to (Schulze 2010) the cooling rate influences the formation of martensite, which increases the susceptibility to cracking. The specimens “welding 01” and “welding 02” were welded at different times without measurement of the heat development and cooling rate.

To avoid these additional influencing effects coming from the welding process, the combination of the drilling of the crack tip and adhesively bonded CFRP-strips was chosen for further investigation. Also the drilling of the crack tip is with rather low expenditure and can be performed reproducible under in-situ conditions. Furthermore, these CT-specimens showed good results in comparison with the non-repaired specimens.

Fatigue crack repairing with CFRP-strips

The aim of the fatigue tests of CT-specimens is to compare the currently used methods for crack repair with the new method using adhesively bonded CFRP-strips. For the fatigue tests, adhesively bonded CFRP-strips were combined with the drilling of the crack tip, as described above. The following shows the results of the fatigue test of a CT-specimen prepared with a bonded non-pre-stressed CFRP-strip using epoxy system 1 (Figure 5).

The 20 mm-wide CFRP-strip with a thickness of 1.5 mm was placed at the end of the starter notch. The width of the CFRP-strip corresponds to the crack length (cf. Table 1, phase 1), which was completely covered by it. The thickness of the adhesive layer was 1.0 mm. Figure 10 shows the preparation of the CT-specimen for the second test phase. Cut wire blasting was applied for the preparation of the steel surface prior to bonding of the CFRP-strip, which was bonded on one side of the CT-specimen. The strain on the outer surface of the CFRP-strip was measured using strain gauges. At mid-height of the CT-specimen (at the starter notch) three strain gauges were spread over the CFRP-strip width. In addition to these three sensors, two more sensors were placed along the middle axis of the CFRP-strip, at a quarter of the height of the CT-specimen (Figure 10, right).

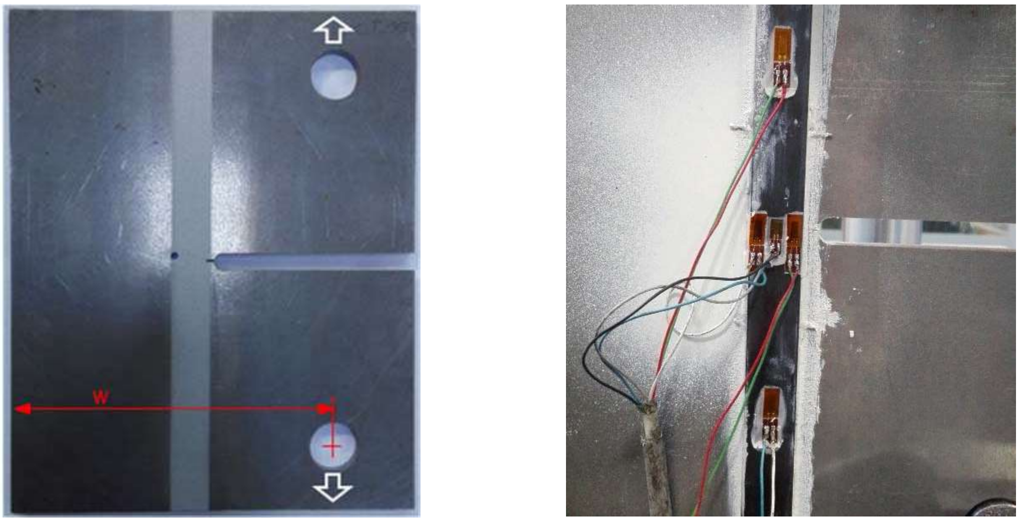


Figure 10. CT-specimen before the second test phase left: cut wire-blasted surface; right: bonded CFRP-strip with measuring equipment.

The test parameters remained the same as in the second test phase of the previous tests. A cycle load range of $\Delta F = 30$ kN, a mean load of 25 kN and a test frequency of 5 Hz were used to determine the crack growth rate between a crack length of 20mm and 40 mm. For reasons of clarity, the obtained test result with non-pre-stressed CFRP-strip is compared only with the test results of the samples repaired by drilling the crack tip (Figure 11).

Figure 11 shows that the total number of cycles in the second test phase increased from approximately 22×10^3 cycles (drilling) to 36×10^3 cycles (CFRP). At the beginning of this test phase (until a crack length of 25 mm) no influence of the CFRP-strip could be seen. After this point, the specimen with CFRP-strip showed a significantly smaller crack growth rate compared to the specimens with a drilled crack tip. The tensile stress in the CFRP-strip, calculated from the measured strain of its outer surface, achieved a value of 370 MPa at the end of the test (at the upper force of 40 kN). This points out that the epoxy adhesive bond was capable of transmitting forces from the CT-specimen to the CFRP-strip. The high Young's modulus of the CFRP-strip contributed to smaller displacements at the end of the starter notch and, subsequently, a smaller crack growth rate compared to the drilled specimens.

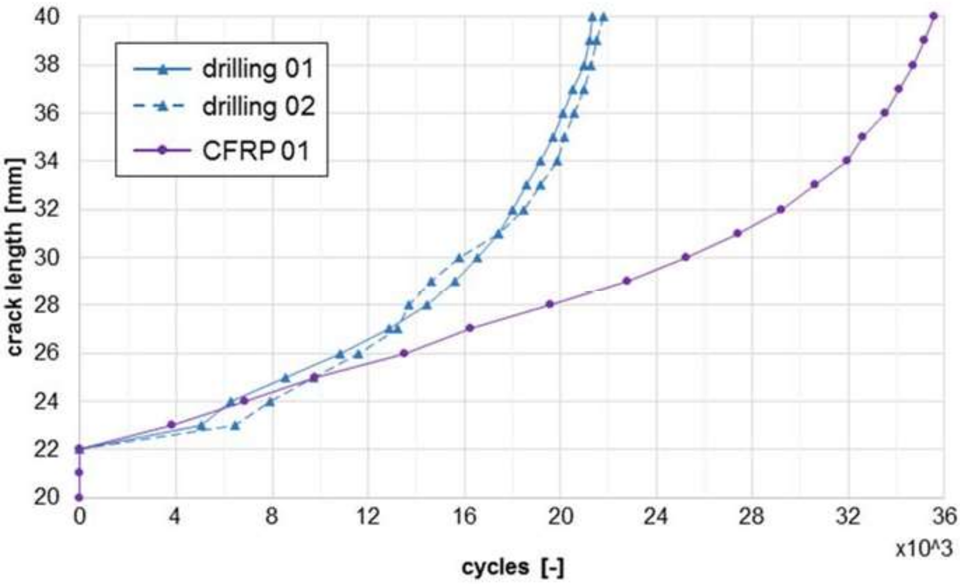


Figure 11. Comparison of the fatigue crack growth rates in the second test phase.

CONCLUSION

The fatigue test of a sample repaired by an adhesively bonded non-pre-stressed CFRP-strip showed a big potential for repairing fatigue cracks in steel. The test results showed a slower increase of the fatigue crack growth rate in the CT-specimen compared to the drilled specimens. This result gives good reason to further investigate the method of strengthening fatigue damaged steel structures using adhesively bonded CFRP-strips. Pre-stressing the CFRP-strip before the application might result in even slower crack growth rates and therefore is in the particular focus of the project investigations in the near future.

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