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EXPERIMENTAL INVESTIGATIONS ON INNOVATIVE CRACK REPAIR METHODS AND REINFORCING STEEL STRUCTURES WITH ADHESIVLY BONDED CFRP – LAMELLAS

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Abstract. The paper describes some of the experiments carried out at the Chair of Steel and Timber Construction to reinforce steel with adhesively bonded CFRP lamellas.

The first topic deals with the repair of cracks in steel structures exposed to fatigue. The aim was to extend the remaining service life of these components by means of adhesively bonded CFRP lamellas and then to compare the results obtained with established methods for repairing cracks. In order to improve the informative value of the investigations, several test parameters such as adhesive candidates, temperature, creep effects, degrees of prestressing, load levels and the position of the reinforcement measures were varied.

The second set of topics examined the extent to which a typical steel beam-to-column connection can be reinforced with the help of adhesively bonded CFRP lamellas.

Keywords: steel, CFRP, adhesive, fatigue, crack repair, reinforcement measure, experiments.

Introduction

The need for efficient repair measures is particularly evident in the partially unsatisfactory condition of the German road bridge structures. Today around 13% of German bridges on federal roads are in an insufficient or inadequate condition according to the BASt (Federal Highway Research Institute) categorization. In the near future the stability of bridges is already significantly impaired or no longer given. That means repair measures or the retrofitting are often unavoidable. Such endangered steel structures often show fatigue cracks in places of increased stress concentrations. One of the main reasons for this is the increased volume of sheared traffic over the past three decades. With the constant further development of the adhesive technology, new possibilities in the field of repair measures are available. Due to the versatility of adhesives and the so far little experience in the use of bonded CFRP lamellas to reinforce fatigue-damaged steel structures, this article deals with this innovative and promising topic.

On the backround earthquake-proof constructions it is very important to use designs with good ductility and high energy dissipation properties regarding seismic events. Furthermore, joints often represent a weak point in the structural system. Therefore, a typical beam-to-column connection strengthened with adhesively bonded CFRP lamellas were the subject of the study presented in this paper. Compared to traditional joining techniques the adhesive bonding technology offers several advantages: The cross-sectional weakening caused by bolted reinforcement plates as well as the notch effect and the negatively acting residual stresses caused by repair welding can be avoided. Moreover, different materials can be connected – thus, CRFP lamellas can be used to reinforce existing steel structures.

In the last 10 to 15 years a lot of investigations regarding the retrofitting of existing steel structures with adhesively bonded CFRP lamellas were carried out. In Linghoff et al. Part 1 and 2 (Linghoff et al., 2010; Linghoff & Al-Emrani, 2010) the feasibility of retrofitting steel I-profiles were successfully examined experimentally and with FEM simulations. The failure modes of CFRP reinforced steel structures were investigated by Narmashiri and Al-Emrani (2012). Some of the first guidelines regarding CFRP reinforced steel concrete composite girders were formulated by Rizkalla and Dawood (2006) and by Schnerch et al. (2007). In addition, it could be shown, that steel frame corners can be strengthened with adhesively bonded CFRP lamel-

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las to reduce stability problems respectively the bearing capacity of steel corners can be increased (Pasternak & Meinz, 2006). The references are to be understood as a selection of published research work that can be further supplemented.

1. Reinforcement of fatigue-stressed steel parts with adhesively bonded CFRP lamellas

An innovative reinforcement measure using slack or pre-tensioned adhesively bonded CFRP lamellas shows great potential for the repair of cracks in steel structures subject to fatigue (Kasper et al., 2019, 2020a, 2020b). The established methods such as repair welding, drilling the crack tip or screwing of prestressed steel sheets have some significant disadvantages compared to the innovation method using adhesively bonded CFRP lamellas. During repair welding, new indefinable notch details can arise and represent new starting points for cracks. Bolted solutions and screw holes always represent cross-sectional weakenings as well as places for stress concentrations. The new method with adhesively bonded CFRP lamellas does not have any of the disadvantages mentioned, since neither additional heat is introduced into the existing structure nor weakening of the cross-section occurs.

On the basis of empirical values gained from completed projects, a catalog of requirements for the selection of suitable adhesive systems is first created:

- Young's Modulus: >~3 000 MPA.
- Shear strength: >20 MPA.
- Ultimate strain: >2%.
- non-significant creep effects.
- Application temperature; – 23 °C to + 67 °C.
- viscosity: spreadable.
- processing time: 20–30 min.

On the basis of the catalog of requirements and preliminary investigations, two two-component adhesives based on epoxy resin with high strength and rigidity as well as low creep behavior are selected (MC DUR 1280 and Sikadur-370). Due to its frequent use in bridge construction, the structural steel S355 is used for the steel joining parts. For optimal use of the adhesives, the steel surfaces are subjected to a blasting process and then cleaned with the help of acetone. The CFRP lamellas "Sto S&P Schlitzlamellen Typ 150/2000" from S&P Clever Reinforcement GmbH were used for the reinforcement measures examined here. According to the manufacturer, the lamellas have a modulus of elasticity of 168,000 MPa, a tensile strength of 2,350 MPa, an ultimate strain of at least 15‰, a width of 20 mm and a nominal thickness of 1.4 mm. In order to be able to better characterize the selected adhesives, tests are carried out on modified thick lap shear samples (Figure 1).

The adhesive MC-DUR 1280 shows in comparison of the two selected adhesives a higher tensile strength and a higher shear modulus. The samples of the Sikadur-370 adhesive on the other hand show greater ultimate strain.

In the case of a reinforcement measure with adhesively bonded CFRP lamellas, the application of a lamella preload can extend the remaining service life of a component. Due to the pre-tension, permanent stress is induced into the adhesive layer. Creep processes in the adhesive structure lead to the reduction of this prestresses. In order to be able to better assess the adhesive behavior, the tendency of the adhesive candidates to creep is checked in further tests under different ambient temperatures. For this purpose, modified lap shear tests for temperatures of – 30 °C, 23 °C, 50 °C and 80 °C are statically loaded for 1000 h each. In a previous project, a suitable device was developed for the experiments, which consists of a steel construction with an articulated support for a steel lever arm (Figure 2).

The results (Figure 3) show lower creep deformations for the applied stresses for the adhesive MCDUR 1280 at room temperature compared to the second adhesive Sikadur 370. As expected, an increase in the creep deformations of the two adhesive candidates can be observed for a higher temperature.

In order to be able to assess the potential of the reinforcement method presented here, fatigue tests are carried out on reinforced steel components S355, in which a defined crack is made beforehand. CT specimens notched on one side and flat center notched steel specimens (MT specimens) are first provided with a fatigue crack and then reinforced with slack or prestressed CFRP lamellas. The remaining service life is then determined in fatigue tests. In this project, the influence of various parameters such as the lamella preload, the adhesive stiffness, the load level and a one-sided or two-sided application is examined (Figure 4).

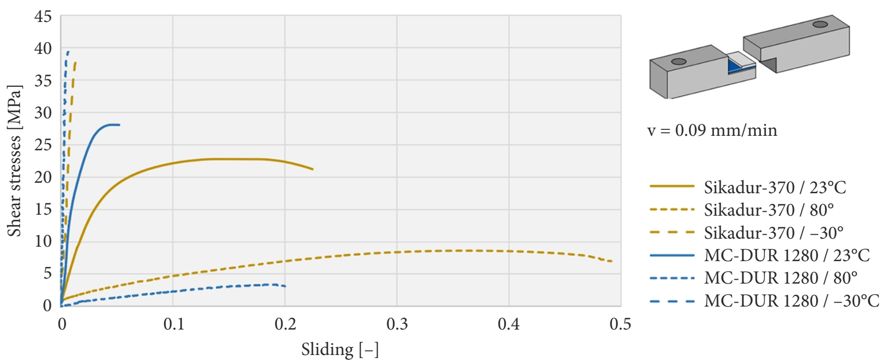

Figure 1. Results of lap shear tests (Kasper et al., 2020a)

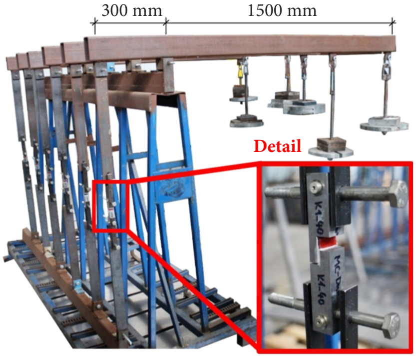

Figure 2. Device for creeping test (Kasper et al., 2020a)

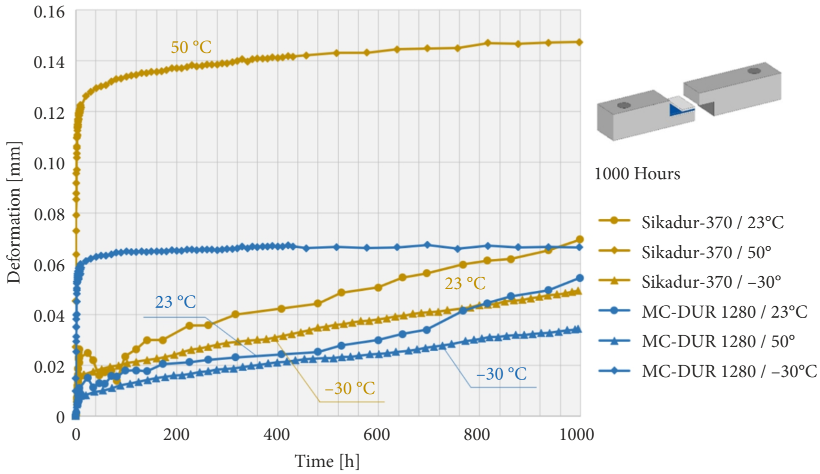

Figure 3. Results for creeping tests (Kasper et al., 2020a)

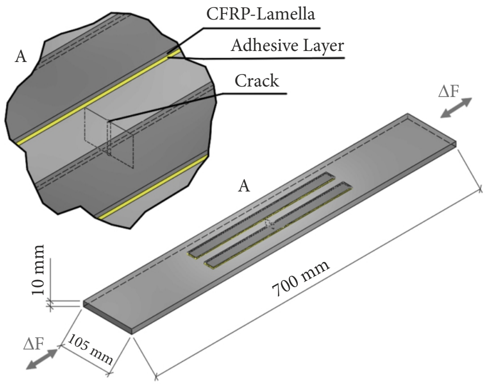

Figure 4. Scheme for MT specimen (Kasper et al., 2020b)

The remaining lifetimes obtained from tests on unreinforced samples serve as a reference for quantifying the reinforcement measure. The geometry of the test specimen (MT samples) is shown in Figure 4. The steel sheets (material S355 J2) have a thickness of 10 mm, a width of 105 mm and a length of 700 mm.

Figure 5 shows the remaining lifetimes with a stress range of 100 MPa and a stress ratio of R = 0.1 for one-sided and two-sided reinforcement using the adhesive Sikadur-370. In the case of two-sided reinforcement, the remaining service life tends to increase with increasing preload force. With a pretensioning force of 6 kN per lamella (two-sided reinforced), 7.9 times the remaining service life is achieved compared to the unreinforced reference samples. However, a reduction in the remaining service lifetime can be recognized for the lamellas attached on one side with the same pre-tensioning force. This could be cause by an additional secondary bending moment as a result of an eccentricity. This effect is particularly important if the structural conditions only allow one-sided application.

In addition, an investigation is carried out to optimize the new repair method. To maximize the increase of the service lifetime of the test specimen, it is possible to combine the use of adhesively bonded CFRP lamellas with conventional methods. In order to be able to evaluate the benefits of this approach, CT samples with an a/W ratio of 0.6 in according to ASTM E 399 are used. The repair methods examined were repair welding, drilling of crack the tip, CFPR lamellas bonded on one side, which were used both prestressed and non-prestressed, and combinations of these methods. A force amplitude of 10 kN, a stress ration of 0.5 and a test frequency of 14 Hz are used. The results are shown in Figure 6.

The standardization for the illustration in Figure 6 is based on a reference experiment in which the 20 mm long crack was implemented without any repair measures (Figure 7). Compared to the reference sample, the positive influence of the adhesively bonded CFRP lamellas on the extension of the service life under cyclical loading can be clearly recognized. The best results will be obtained with a combination of different repair methods. Combining prestressed adhesively bonded CFRP lamellas with drilling the crack tip and repair welding, a remaining service life of up to 1154% was achieved in the test. But even with slack bonded CFRP lamellas, an increased remaining service life of 286% was achieved.

2. Investigations on beam-to-column connections reinforced with adhesively bonded CFRP lamellas

Against the background of the earthquake-proof design of steel structures, it makes sense to use structures with sufficient ductility and energy dissipation capacity. The joints are often a critical point in such systems. Therefore reinforcement measures for connections with adhesively bonded CFRP lamellas were investigated (Sternsdorff et al., 2020). In all tests the height of the column I-cross section is 320 mm and the width 180 mm. For the flanges and stiffeners a steel S275JR is used, for the webs 235JR. The CFRP lamellas of the type Carbodur S542/80 (530 mm × 50 mm × 1.2 mm) are bonded to the steel surface with the help of the two-component epoxy resin based adhesive Sikadur-30 Normal. The tests are carried out in a quasi-static velocity.

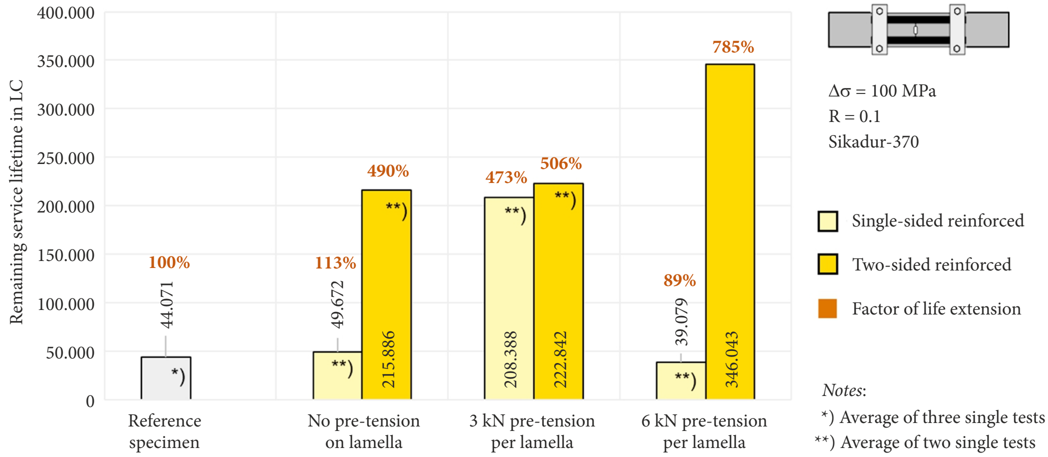

Figure 5. Remaining lifetimes of MT specimens without and with adhesively bonded CFRP single-sided and double-sided reinforcement (adhesive: Sikadur-370, LN100), (Kasper et al., 2020b)

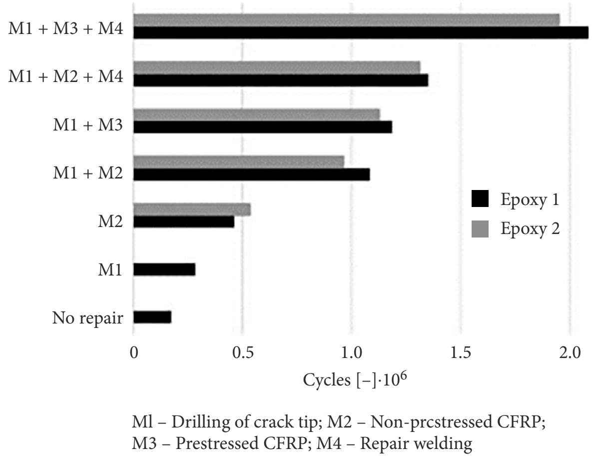

Figure 6. Comparison of the remaining lifetimes of CT specimens strengthened by various crack repairing methods (Kasper et al., 2019)

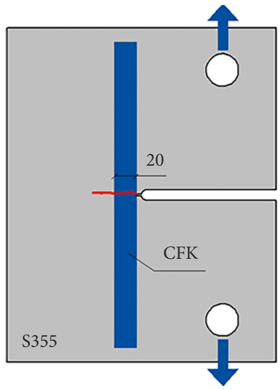

Figure 7. Scheme for the CT specimen (Kasper et al., 2020b)

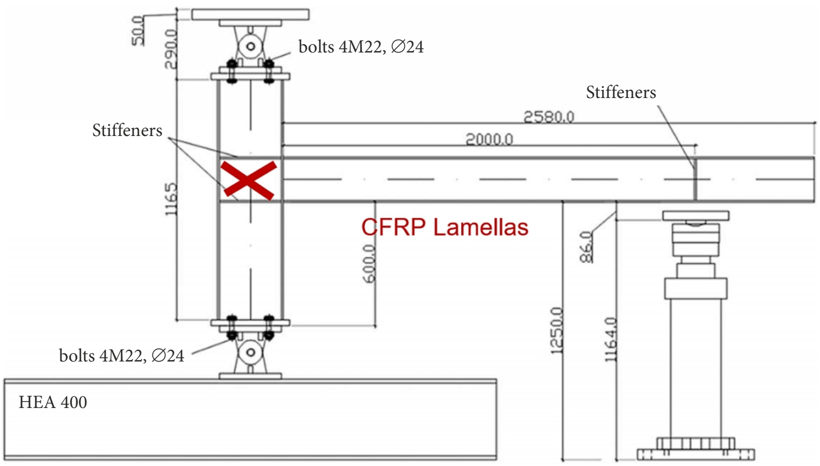

Figure 8. Experimental setup for a test series with a reinforced column web (Sternsdorff et al., 2020)

In this project a beam-to-column connection with a reinforced column web shall be investigated at the Institute of Steel Structures of the National technical University of Athens. Figure 8 shows the experimental setup. The column is about 1165 mm high and the cantilever length is 2580 mm. An actuator applies a load at the cantilever in a distance of 2000 mm to the joint. The first test serves as a reference for the following experiment with a reinforced column web in the area of the frame corner, whereby two CFRP lamellas are adhesively bonded crosswise on each side of the column web.

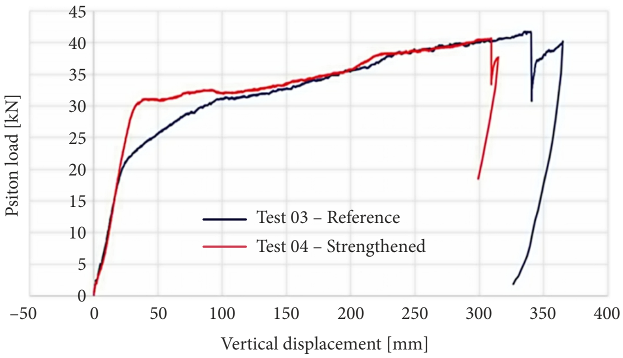

Figure 9. Results for the test series with a reinforced column web (Sternsdorff et al., 2020)

The relationship between the actuator force and the vertical displacement of the testing machine is again used to evaluate the test results (Figure 9). At the beginning a linear-elastic range is recognizable for both curves. After that, the load increase for the reference curve is significantly reduced and the deformation of the web plate in the region of the frame corner successively begins. Meanwhile the load capacity for the reinforced specimen increases in the elastic range by up to 50%. After that the adhesive layers abruptly fail, with the reinforcements completely detached from the rest of the steel structure. The deformation of the web progresses continuously. At the point of the maximum load the web plate of the reference experiment and the reinforced variant failed abruptly. Thereafter the curves stabilize and rise again until both experiments were manually aborted. The 50% increase in the load-bearing reserves in the linear-elastic range shows the benefit of reinforcing existing steel structures with adhesively bonded CFRP lamellas. Since it will be possible to use these reserves for the design of structures. In this way, the construction of a new structure can be avoided which has both economic and ecological advantages. It is also possible to preserve historical building heritage for future generations.

The failure pattern can be classified as a substrate-specific cohesive failure according to DIN EN ISO 10365 (European Committee for Standardization, 1995). The Figure 10 shows the deformed test specimen for the reference after testing and the failure pattern of the adhesive.

Conclusions and outlook

It was shown that innovative reinforcement measures for the repair of cracks in steel structures have great potential. CFRP lamellas that are slackly bonded can extend the remaining service life of fatigue stressed steel parts up to three times. When using pretensioned CFRP lamellas, it should be noted that single-sided application can reduce the remaining load cycles, whereas a two-sided use of pretensioned CFRP lamellas can significantly increase the service life. A particularly high increase in the remaining service life can be achieved with a combination of several repair methods. That would be the drilling of the crack tip, the adhesively bonding of pre-tensioned CFRP lamellas and the repair welding. Furthermore it has been shown that adhesively bonded CFRP lamellas are also suitable for reinforcing existing steel frame structures in order to increase their load-bearing capacity in the linearly elastic range. This makes it possible to preserve historically valuable building substance, which saves scarce resources and protects ecosystems.

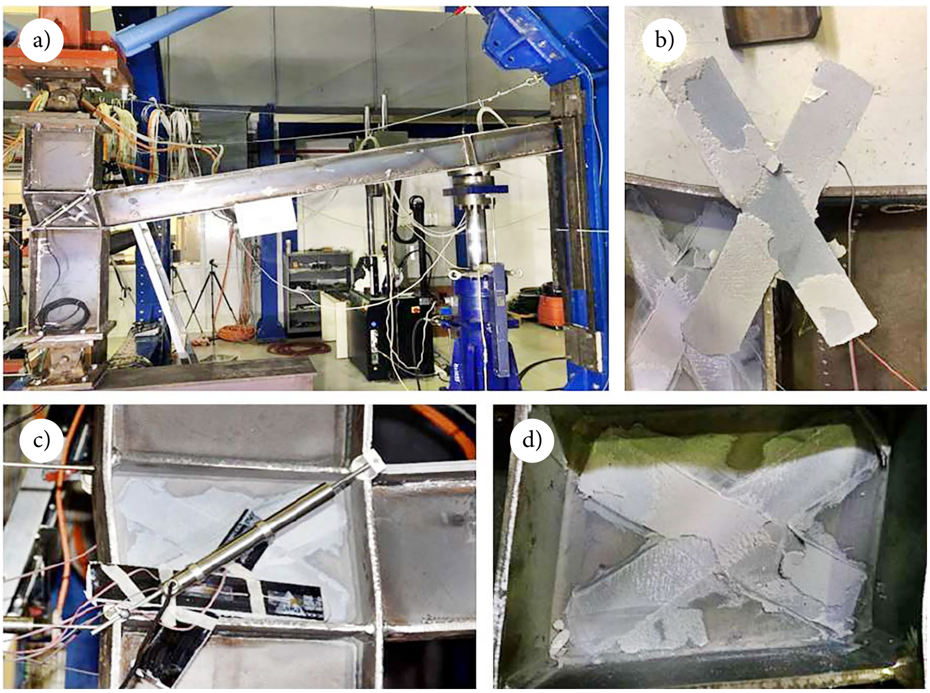

Figure 10. a) Deformed reference specimen after testing, b) Failure of the adhesive at CFRP lamellas after testing c) Detached reinforcements during the test, d) Failure of the adhesive at the column web after testing (Sternsdorff et al., 2020)

Due to its versatile and simple application, adhesive technology has great potential in the area of innovative reinforcement measures. Against the background of the current large and in the future still increasing need for renovation of German bridge structures and other steel structures, the positive research results obtained are of particular importance. The focus of further research results should be on the fatigue and creep behavior of adhesive bonds, whereby in particular damaging influences such as temperature and ambient humidity should be taken into account. For the area of application with reinforcements with adhesively bonded CFRP lamellas in earthquake areas, the adhesive behavior under seismic loads is of particular importance, since adhesives can heat up under cyclical loads and thus lose their strength or rigidity.

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