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APPLICATION OF ADHESIVELY BONDED CFRP FOR REINFORCEMENT AND REHABILITATION OF FATIGUE DAMAGED STEEL STRUCTURE - ONLY A NICE IDEA? *

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Abstract. *As an alternative to classic repair measures of fatigue-damaged steel structures, adhesively bonded CFRP lamellas are ideal. In this way, disadvantages of the established methods can be circumvented Compared to bolted reinforcing measures, cross-sectional weakening by the bolt is avoided. Heat-induced residual stresses and distortions, as they usually occur during repair welding, can also be excluded. These disadvantages represent a weak point during cyclic loading due to the notch effect.*
To characterize the materials, tests are carried out on small scale specimens. With the help of tests on CT-samples a comparison with established methods such as drilling the crack tip and repair welding is realized. Based on the crack propagation, the great potential of bonded CFRP reinforcements can be deduced. By prestressing the lamellas, the remaining lifetime can generally be further increased. It should be noted, however, that with single-sided prestressing, a precamber of the specimen and, during loading, a secondary bending moment may occur. The combination of bonded CFRP with established methods can be described as particularly effective. With a reinforcement on both sides with pre-stressed plates, up to 7.9 times the remaining service life can be determined in comparison to unreinforced specimens.
The effectiveness of adhesively bonded CFRP lamellas is examined in a German research project. Selected results are presented in this paper.

Key words: *steel structures, bonded CFRP, fatigue, repair, reinforcement.*

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1. INTRODUCTION

Many cyclic loaded steel structures, such as road and railways bridges or large conveyor systems, have an enormous need for rehabilitation. In particular, the average condition of bridges has deteriorated significantly in recent years. A study by the Federal Highway Research Institute in Germany shows that ca. 15% of the road bridges have to be renewed or rehabilitated in the near future [1]. Similar conditions can be observed in other countries. The main reasons for this are the increased volume of traffic, the proportion of heavy-duty traffic and the permissible axle loads in the last three decades, which clearly exceed the traffic load forecasts used for the design of bridges in the 1960s.

According to the current state of the art, fatigue damaged steel structures are strengthened by drilling the crack tip, repair welding or a combination of both. Partially, additional reinforcement measures, e.g. steel sheets or angles, are locally welded or bolted. The disadvantages of those common methods are the high heat input through welding and the associated negatively acting residual stresses as well as the cross-sectional weakening caused by bolts. Additionally, undefined notch details can originate from those repair methods. Frequently fatigue cracks again appear on these notch details after a short period of time.

The strengthening of cracked steel structures using adhesively bonded CFRP lamellas overcomes the before mentioned disadvantages and, as the experimental findings show, can even result in higher remaining lifetimes compared to common repair methods. It allows a strengthening of the existing structure without inducing additional, undefined notch details. Furthermore, it represents a repair method without significantly changing the dead weight. Figure 1 shows potential details for an application of adhesively bonded CFRP lamellas as a method of crack repair.

CFRP are characterized by a high tensile strength, a high modulus of elasticity, which can even exceed the stiffness of carbon steel, and a very low specific weight. Furthermore, they are corrosion and fatigue resistant [2]. First experiences on strengthening steel structures using CFRP materials regarding both quasi-static as well as fatigue behaviour were presented by [3] and [4]. In [5] the effectiveness of a rehabilitation of fatigue-damaged details using welded sheet metal was compared to the effectiveness of a rehabilitation using adhesively bonded CFRP laminates. Initial design recommendations for increasing the remaining service life of steel structures with externally bonded CFRP materials can be found in the "CIRIA Design Guide"[6].

A major advantage of the reinforcement with CFRP lamellas is the possibility of prestressing. The pretension force in the lamellas induces compressive stresses into the steel component superimposing the stresses caused by the fatigue loading and thereby reduces the stress intensity at the crack tip. Two methods of applying prestressed CFRP lamellas for strengthening cracked steel structures have to be distinguished. The pretension force can on the one hand be transmitted into the steel component by an adhesive layer. This way the compressive stresses are concentrated locally on the area around the crack tip. Since the level of prestressing is limited by the strength of the adhesive bond on the other hand pre-stressing systems with fixed anchor points can be used. This way the pretension force is transmitted into the steel component at two discrete points. For the rehabilitation of concrete structures various prestressing systems with fixed anchor points have been developed. As part of the ongoing research project, the influence of adhesively bonded prestressed and non-prestressed CFRP lamellas on the crack propagation rate as a local reinforcement of fatigue damaged steel components is being investigated.

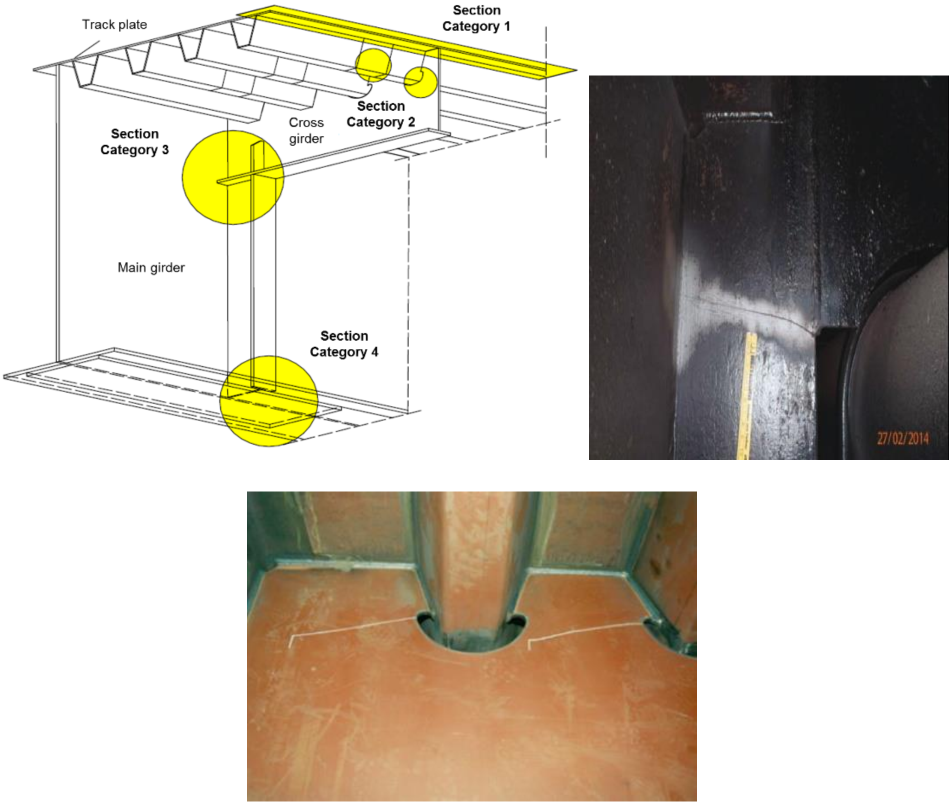

Fig. 1 Crack categories in orthotropic steel deck [7], cracks in categories 2 and 3

2. Preliminary Investigations

The bonding behaviour and the mechanical properties of the used materials highly influence the efficiency of the repair method. For this reason, experimental investigations are carried out to determine the material characteristics of the CFRP lamella and five different adhesives as well as the strength of the adhesive bond between steel and CFRP. To characterize the CFRP´s mechanical properties tensile tests according to DIN EN ISO 527-4 are carried out at the BTU in Cottbus. On average, the 20 mm wide and 1.4 mm thick lamella has an ultimate strength of 3400 MPa and a Young's modulus of 192 GPa. The mechanical properties of five preselected epoxy-based adhesives are determined by tensile tests on injection moulded dumbbell specimens in accordance with DIN EN ISO 527 and by lap shear tests based on DIN EN 14869-2 at the RWTH Aachen. The specimens used in the lap shear tests are modified according to [8] in order to take into account the adhesion between the adhesive and the CFRP. Figure 2 shows the geometry of the modified sample and the used testing device.

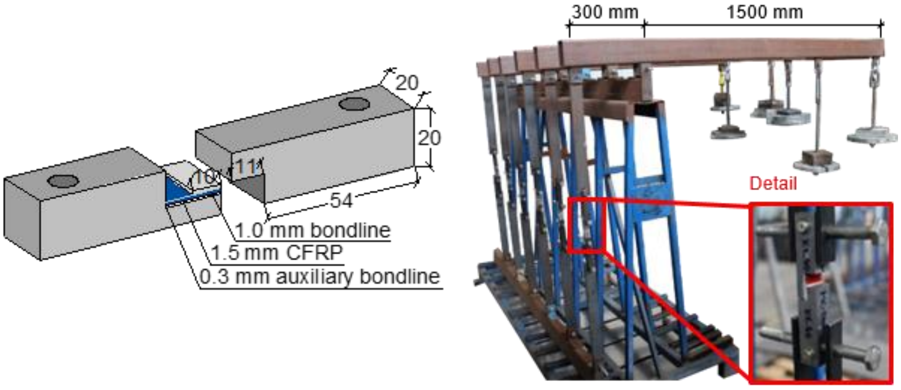

Fig. 2 Modified lap shear specimen [8] and creep testing device [9][10]

The experimental determination of the tensile properties is carried out strain-controlled with a rate of 1 %/min, while the shear properties are determined displacement-controlled with 0.09 mm/min. Based on the results, two adhesives are selected for the use in the following experimental investigations. Table 1 summarizes the mean values of the mechanical properties for the two chosen adhesives.

Table 1 Mechanical properties of the chosen adhesives (Epoxy 1= MC DUR 1280, Epoxy 2= SIKAdur 370)

	Epoxy 1	Epoxy 2
Tensile strength [MPa]	33.5	23.1
Young's Modulus [MPa]	8812	3858
Shear strength [MPa]	32.6	24.4
Shear Modulus [MPa]	1780	450

As can be seen from the Table 1, Epoxy 1 has a higher stiffness and a higher tensile and shear strength. Epoxy 2 in contrast has a higher deformation capacity in the quasi-static tests, which is regarded as beneficial concerning a possible detachment of the lamella under fatigue loading. In the installed condition, the bondline is stressed by permanent loads, such as the prestressing force and the mean fatigue load. Therefore, creep tests on the modified lap shear specimens (see Figure 2) are carried out at the BTU to investigate the deformation behaviour under a long-term loading. It is known that the creep behaviour of adhesive layers is significantly influenced by the ambient temperature. For this reason, the tests are carried out at four temperatures, which are shown in Table 2.

Table 2 Experimental conditions for creep tests

Temperature	Lap shear strength quasi-static test Epoxy 1 / Epoxy 2	Stress level creep test Epoxy 1 / Epoxy 2
80°C	3.4 / 9.9 MPa	1.4 / 4.0 MPa
50°C	4.8 / 14.9 MPa	1.9 / 6.0 MPa
23°C	32.6 / 24.4 MPa	11.3 / 9.5 MPa
-30°C	33.3 / 37.2 MPa	13.3 / 14.9 MPa

The thermal conditions reflect the expected operating conditions of the adhesive joint according to EC3. The determination of the load level of the permanent load is based on 40% of the quasi-static shear strength, which has also been determined at the corresponding temperatures. Figure 3 shows the mean curves of the deformation for a long-term loading of 1000 hours for various temperatures and adhesives.

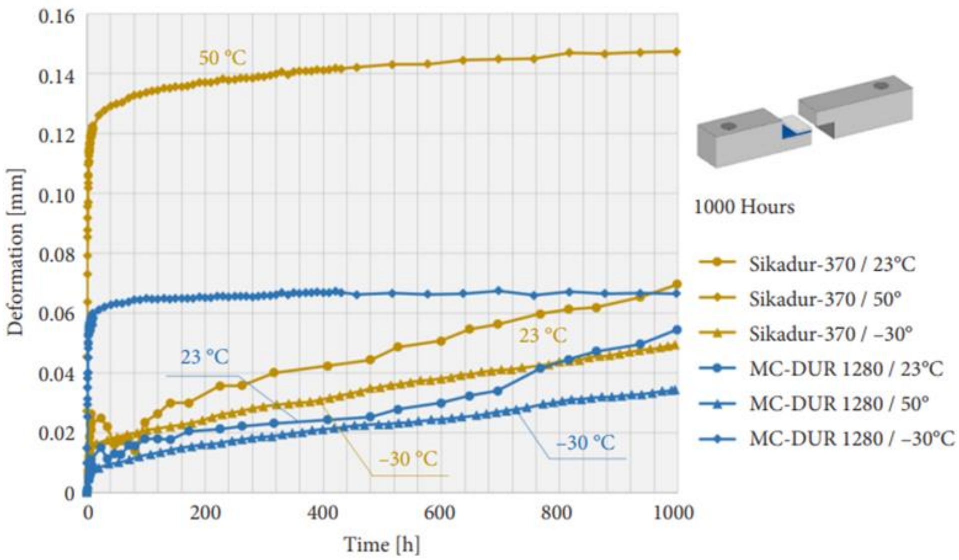

Fig. 3 Results of the creep tests [10]

In general, the characteristic increase of creep deformations with an increasing temperature can be derived from the diagram. For the design of adhesively bonded prestressed CFRP lamellas as a reinforcement measure, it is of particular importance to know the operating temperature range. Furthermore, it can be seen that Epoxy 2 allows larger creep deformations, suggesting a greater degradation of the pretension force compared to Epoxy 1. Both adhesives show distinct primary creeping. It is not solely attributable to the solving of secondary valence bonds and repositioning of chain segments. This behaviour is superimposed by load eccentricities due to the experimental setup, which result in twisting of the sample halves.

3. Tests on Centre-notched Specimens

3.1. Specimen

In order to investigate the influence of adhesively bonded CFRP lamellas on the crack propagation rate in steel components, fatigue tests are carried out on centre-notched specimens at BTU. The test specimen consists of a 10 mm thick steel sheet made from S355 J2 with a length of 700 mm and a width of 105 mm. In order to create an initial crack, which subsequently is to be strengthened, a notch is induced in the middle of the specimen using the method of wire erosion. The bond length is dependent on the mechanical properties of the adhesives and is chosen according to [11]. For Epoxy 1 the bond length is 150 mm and for Epoxy 2 the bond length is 220 mm. Figure 4 schematically shows the test specimen for Epoxy 1 with end anchoring, which are to prevent a failure at the end of the lamellas due to high peel stresses.

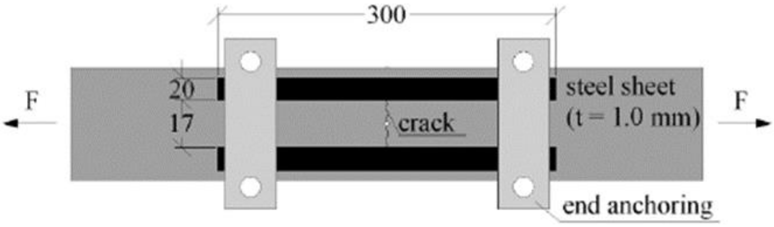

Fig. 4 Centre-notched specimens with single-sided adhesively bonded CFRP strips and end anchoring [10]

The CFRP lamellas are applied under laboratory conditions to the blasted steel surface (Sa 2½ according to DIN EN ISO 8501-1). Before applying the adhesive, the surfaces need to be thoroughly cleaned with acetone and lint-free cloths. In order to realize the bondline thickness of 1 mm, glass beads with the corresponding diameter are sprinkled into the not yet cured adhesive layer. After the joining process, the samples cure for 7 days under normal climatic conditions (temperature of 23°C ± 2°C and relative humidity of 65% ± 4%) and under uniform contact pressure. If the CFRP strips are to be prestressed, this is done directly before the application of the lamella to the adhesive layer. Within the scope of the research project, a special prestressing device was developed at KIT Karlsruhe for this purpose. It consists of a substructure in form of a profile U240 and fixed anchorages at its ends. Clamping jaws, that are connected to the anchorages over a system of threaded rods, nuts and linkages, are used to fix the CFRP lamellas. Intermediate blasted aluminium plates provide a more uniform distribution of the clamping force on the lamellas and a higher coefficient of friction in order to prevent slippage of the CFRP lamellas. The pretension force is applied by tightening nuts at the anchorages and monitored by a combination of load cells at the preload point of the device and strain gauges on the lamellas. After the curing process and before releasing the sample, end anchors are applied to prevent a detachment of the lamella ends (see Figure 4).

3.2. Test setup and procedure

The influence of the adhesive stiffness, the pretension force and the load level on the remaining lifetime of the centre-notched specimens is investigated. The experimental matrix is summarized in Table 3.

Herein LL stands for the load level, P for the prestress grade, $\Delta\sigma$ for the stress range in MPa and R for the stress ratio. The pretension force specified in kN applies to each CFRP lamella.

The test procedure is divided into three phases: In the first test phase, an initial crack with a length of 40 mm is created by applying a fatigue load according to Table 3. At KIT Karlsruhe a method to repeatedly produce the same initial crack length in each specimen was developed. Using a copper wire, bonded onto the specimen at the point of the desired

Table 3 Test conditions and number of specimens respectively for the experimental investigations on centre-notched steel sheets

	Epoxy 1			Epoxy 2		
	P1	P2	P3	P1	P2	P3
kN	0	5	10	0	3	6
LL 1 $\Delta\sigma$= 50 MPa R = 0.5	2	2	2	2	2	2
LL 2 $\Delta\sigma$= 70 MPa R = 0.5	2	2	2	2	2	2
LL 3 $\Delta\sigma$= 100 MPa R = 0.1	2	2	2	2	2	2

crack tip, and a voltage source linked to an electric circuit an input signal is placed into the test machine. When the initial crack tip reaches the copper wire a drop in voltage occurs. Using a shutoff criterion, the test machine automatically stops when a defined voltage value is undercut. In the second test phase each cracked specimen is strengthened by applying two CFRP lamellas on one side of the specimen following a fatigue test of each strengthened specimen in the third test phase. The fatigue test is carried out until the crack reaches a total length of 80 mm. The experiments run force-controlled with a frequency of 8 Hz. During the tests the machine force, the surface strains in the middle of the lamellas as well as the crack propagation to both sides are registered continuously.

3.3. Test results

The evaluation of the crack propagation during the third experimental phase is of particular interest, since the efficiency of the reinforcement measures is in the foreground of the investigations. For load level 1 (LL 1) the crack propagation curves are exemplary shown in Figure 5. For reasons of clarity, only the mean curves derived from the measurements of the crack propagation to both sides are given.

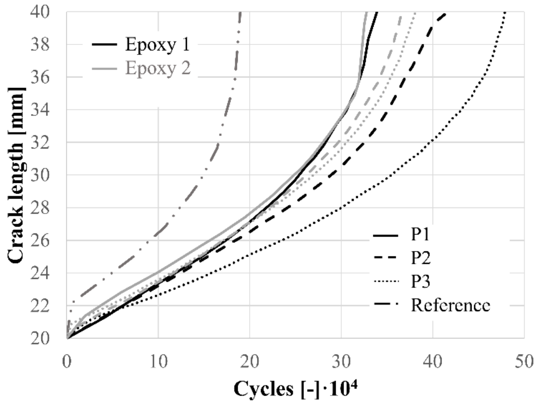

Fig. 5 Mean crack propagation curves for LL 1

A comparison of the results for the CFRP reinforced specimens with the results for unreinforced reference specimens shows the effectiveness of the developed repair method. A decrease in the crack growth rate can be observed with an increase in the pretension force. Whether this observation is generally valid for other load levels will be examined below. When plotting the number of cycles for the achieved crack length of 80 mm over the prestress grades, the curves in Figure 6 are obtained. In order to allow statements about the efficiency, the results are compared with the reference tests at the respective load levels.

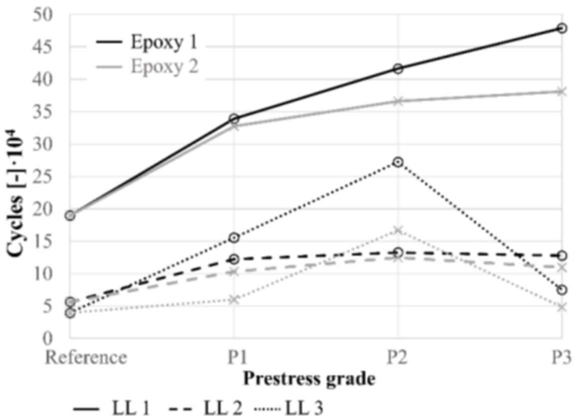

Fig. 6 Influence of the prestress grade on the remaining life-time of the centre- notched specimens

There is generally an increase in the remaining life-time with an increase in the pretension force for load level 1. In the cases of LL 2 and 3, the increase in the number of cycles can only be observed for the prestressing levels P1 and P2. If the prestress force is further increased, the remaining service life decreases. This phenomenon can be explained by the negative influence of single-sided reinforcement. The introduction of an eccentric tensile force on the 10 mm thick steel sheet creates a secondary bending moment causing a precamber, which increases with an in-creasing pretension force. For all test results, it can be observed that longer remaining lifetimes are achieved using Epoxy 1. It is assumed, that the reason for this behaviour lies in the higher stiffness of Epoxy 1 compared to Epoxy 2. A comparison of the remaining lifetimes as a function of the load level results in the curves shown in Figure 7.

Remarkable is the strong decrease of the remaining lifetime for LL 2. The stress range is lower than for LL 3, but a higher stress ratio R and thus a higher mean stress counteracting the prestress seam to lead to a decrease in the remaining lifetime. Also, in the comparison in Figure 7 the negative influence of the single-sided prestressed reinforcement with an increasing prestressing grade can be observed. For these reasons, it is desirable to realise a two-sided reinforcement with prestressed CFRP lamellas, if this is possible in the respective application. Tests with double-sided bonded and prestressed CFRP lamellas are currently performed at the KIT and confirm the negative influence of the secondary bending moment. Table 4 summarizes the results of the normalized remaining lifetimes of the specimens for the experiments presented here. The reference test (without bonded CFRP lamella) of the respective load level is assumed to be the reference value.

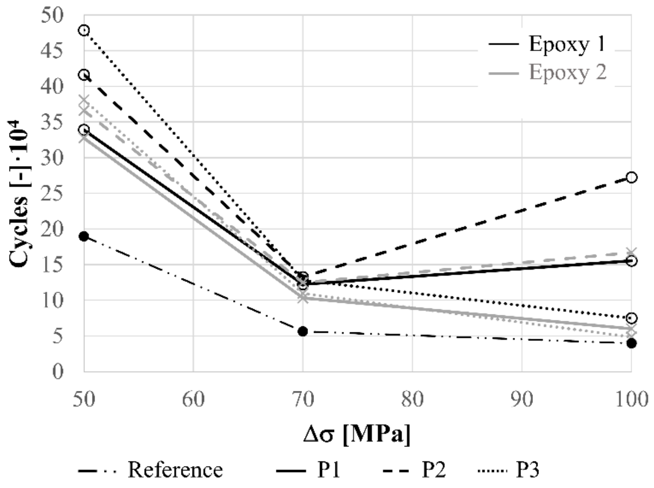

Fig. 7 Influence of the load level on the remaining life-time of the centre-notched specimens

Table 4 Normalized test results for the remaining lifetimes of the centre-notched specimens

	LL 1	LL 2	LL 3
Epoxy 1 – Single-sided reinforced			
P1	1.8	2.2	3.9
P2	2.2	2.4	6.9
P3	2.5	2.3	1.9
Epoxy 2 – Single-sided reinforced			
P1	1.7	1.8	1.5
P2	1.9	2.2	4.2
P3	2.0	1.9	1.2

4. Optimization of the Crack Repairing Method

If in practice higher demands are placed on the remaining service life than can be achieved by the sole application of bonded CFRP strips or conventional methods, it is possible to combine different repair methods. The gain that can be obtained by combining different methods is experimentally investigated on CT (compact tension, Fig. 8) specimens with an a/W-ratio of 0.6 according to ASTM E 399 at the BTU. Repair welding, drilling of the crack tip, single-sided bonding of prestressed and non-prestressed CFRP lamellas as well as combinations of these methods are considered. The test procedure is analogous to the investigations of centre-notched samples. A force amplitude of 10 kN, a stress ratio of 0.5 and a test frequency of 14 Hz are used. More detailed information on the experiment can be found in [9]. Figure 8 shows the results for the third test phase.

The standardization for the illustration in Figure 9 is based on a reference experiment in which the crack in the third test phase was created without any repair measure. The high potential of adhesively bonded CFRP lamellas can be confirmed for all test results. Prestressing of the lamellas (prestressing level P2 is used) leads to a further increase in the sustainable number of load cycles. The remaining life can be further enhanced by combining different repair methods, such as drilling of the crack tip, repair welding and bonding of prestressed CFRP lamella (M1+M3+M4 in Figure 9).

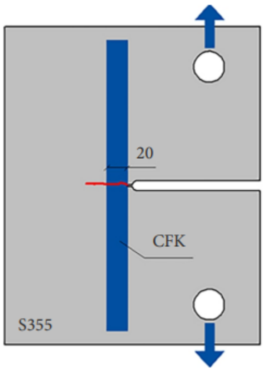

Fig. 8 CT specimen [10]

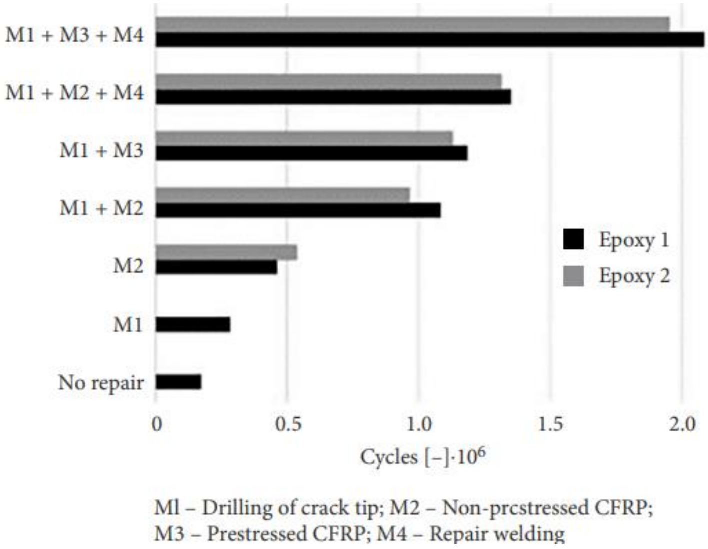

Fig. 9 Comparison of the remaining lifetimes of CT specimens strengthened by various crack repairing methods

The standardization for the illustration in Figure 9 is based on a reference experiment in which the crack in the third test phase was created without any repair measure. The high potential of adhesively bonded CFRP lamellas can be confirmed for all test results. Prestressing of the lamellas (prestressing level P2 is used) leads to a further increase in the sustainable number of load cycles. The remaining life can be further enhanced by combining different repair methods, such as drilling of the crack tip, repair welding and bonding of prestressed CFRP lamella (M1+M3+M4 in Figure 9).

5. Conclusion and Outlook

The presented test results clearly show the high potential of adhesively bonded CFRP lamellas for a crack repair of cyclically loaded steel components. Depending on the adhesive and the loading conditions, the remaining lifetime of the specimens can be extended up to 690 %. For an application, it is essential to know the load level and define the material properties and the prestress grade, so that negative influences from the secondary bending moment are avoided. Further research needs to be done to design the reinforcement measure accordingly. If possible, a double-sided reinforcement is recommended. A combination of bonded CFRP lamellas with established methods, allows a further increase of the sustainable load cycles and is particularly suitable for high demands on the remaining service life of fatigue damaged steel constructions.

As could be shown in creep tests, it can be assumed that the pretension force is reduced by the primary and secondary creeping. The creep deformations increase with increasing temperature. In order to verify the effectiveness of the developed repair method in a practical application, measurements should be carried out on a selected bridge structure after the application of a local CFRP reinforcement.

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PRIMENA LEPLJENOG CFRP-A ZA OJAČANJE I REHABILITACIJU ČELIČNIH STRUKTURA OŠTEĆENIH ZAMOROM MATERIJAL – SAMO LEPA IDEJA?

Lepljene CFRP lamele su idealne kao alternativa klasičnim merama popravke čeličnih konstrukcija oštećenih zamorom. Na ovaj način nedostaci standardnih metoda se mogu zaobići. U poređenju sa merama za ojačanje sa zavrtnjima, izbegava se slabljenje poprečnog preseka zavrtnjem. Zaostali naponi i izobličenja izazvana toplotom, koja se obično javljaju tokom popravnog zavarivanja, takođe se mogu izbeći. Ovi nedostaci predstavljaju slabu tačku tokom cikličnog opterećenja zbog efekta zareza.

Da bi se okarakterisali materijali, ispitivanja se sprovode na uzorcima malih razmera. Uz pomoć testova na CT-uzorcima se realizuje poređenje sa utvrđenim metodama kao što su bušenje vrha pukotine i remontno zavarivanje. Na osnovu širenja prsline može se zaključiti da lepljene CFRP armature imaju veliki potencijal. Prednaprezanjem lamela, preostali životni vek se generalno može dodatno produžiti. Treba, međutim, napomenuti da kod jednostranog prednaprezanja može doći do preklapanja uzorka i, tokom opterećenja, do sekundarnog momenta savijanja. Kombinacija lepljenog CFRP-a sa tradicionalnim metodama može se opisati kao posebno efikasna. Sa obostranim ojačanjem sa prednapregnutim pločama, može se odrediti i do 7,9 puta preostali vek trajanja u poređenju sa neojačanim primercima.

Efikasnost lepljenih CFRP lamela se ispituje u nemačkom istraživačkom projektu. Odabrani rezultati su predstavljeni u ovom radu.

Ključne reči: *čelične konstrukcije, lepljeni CFRP, zamor, popravka, armature.*