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Procedia Structural Integrity 64 (2024) 1840–1848

Structural Integrity Procedia

www.elsevier.com/locate/procedia

SMAR 2024 – 7th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

Extension of service life: Novel approaches to repairing fatigue-damaged steel structures

Yvonne Ciupack[a], Javier Sacristan[b], Florian Sternsdorff[e], Antonino Montalbano[c], Fabien Choffat[d], Mathias Euler[e]*

[a]*Dresden University of Technology, Endowed Chair of Resource-Efficient Building Design, Dresden 01076, Germany*
[b]*Sika ES,Madrid and 28108, Spain*
[c]*Sika Services AG, 8048 Zürich, Switzerland*
[d]*Sika Technology AG, 8048 Zürich, Switzerland*
[e]*Brandenburg University of Technology Cottbus-Senftenberg, Chair of Steel and Timber Structures, CotMtbus 03046, Germany*

Abstract

This study addresses the challenge of repairing fatigue-damaged steel structures through innovative methods employing toughened epoxy adhesives and carbon fiber reinforced polymer (CFRP) laminates. Harsh environmental conditions and inadequate maintenance contribute to premature deterioration of civil engineering structures. Experimental investigations using compact tension (CT) specimens reveal significant improvements in structural integrity and residual life extension with double-sided CFRP application and appropriate adhesive selection. These findings underscore the importance of optimizing repair methods, offering valuable insights for enhancing structural durability. Further research is necessary to validate these methods for real-world application, particularly regarding debonding behavior and environmental influences.

Peer-review under responsibility of SMAR 2024 Organizers

* Corresponding author. Tel.: +49-351-463-41120 fax: +49-351-463-37289.
E-mail address: yvonne.ciupack@tu-dresden.de

Peer-review under responsibility of SMAR 2024 Organizers
10.1016/j.prostr.2024.09.236

Keywords: Fatigue; Carbon Fiber Reinforced Polymer; Adhesive Bonding; Steel Structures

1. Introduction

Civil engineering structures such as bridges, electricity poles and other infrastructure elements are exposed to a variety of adverse environmental conditions and chemical/physical influences. Damage to steel infrastructure can be associated not only with corrosion deterioration, but also with other factors such as fatigue, increased loads in use, and lack of maintenance, which can cause irreversible damage to the entire structure. These factors can contribute significantly to their premature deterioration and affect their overall durability. In the case of existing steel bridges, the increase in heavy goods traffic, existing design, and construction defects due to a lack of knowledge about the time of construction in the 60s to 80s as well as material defects lead to fatigue damage that requires renovation and retrofitting solutions. According to the U.S. Department of Transportation, 42% of all bridges in the U.S. are at least 50 years old, and 7.5% are considered structurally deficient and in need of extensive refurbishment. The rate of deterioration exceeds the rate of repair or replacement, while the percentage of structurally defective bridges is increasing, Bridge Report, (2020). In the EU, the situation is not much better, it is estimated that 30% of all steel and reinforced concrete railway bridges are more than 100 years old and more than 70% are older than 50 years and need to be rehabilitated or replaced before 2030 to avoid unsafe situations, Lazorenko et al., (2021).

The rehabilitation of bridges requires significant investments to extend their service life or improve their load-bearing capacity to meet the minimum standards according to the new design standards. In line with the EU's recommendations for a circular model in construction and the World Green Building Council to implement novel measures to reduce carbon emissions and energy demand in the construction sector by at least 40% by 2050, it is necessary to develop novel, more sustainable and more efficient retrofit solutions to increase the life expectancy of civil engineering structures, GlobalABC Roadmap, (2020).

Epoxy resin adhesives combined with fiber-reinforced materials (FRP) have emerged as a simple and efficient technique for repairing concrete and reinforced concrete structures, Al-Zu'bi et al., (2022). FRPs offer advantages such as high strength, light weight, and corrosion resistance. Standard epoxy adhesives are relatively stiff compared to other solutions available on the market, have high shear and tensile strength, and are cost-effective. Although they are much more resilient than concrete and other cementitious or inorganic systems, due to their brittle nature, when combined with materials with higher ultimate strain like FRP or steel, are characterized by poor fatigue performance and limited resistance to dynamic loads. Flexural stress can lead to a premature failure of the adhesive layer causing substrate-adhesive debonding and tensile failure in the bottom region, Yiwen Y. et al. (2022), significantly reducing the overall mechanical properties, de Moura et al. (2004).

To overcome these drawbacks, various types of toughening methods have been developed during the past years including chemical and physical modification of the epoxy polymer, (Johnsen et al. 2006). However, the introduction of either flexible materials inside rigid epoxies or lowering crosslink density typically leads to increased toughness but usually results in a decrease in stiffness, Unnikrishnan K. P. et al. (2006) and thermal properties, Harada M. et al. (2016). Structural strengthening requires a specific level of stiffness, thus, a substantial decrease in mechanical performance is undesirable. Therefore, achieving simultaneously high mechanical strength and high toughening performance stands out as a primary challenge. Reactive polymers play a successful role as tougheners by creating well-dispersed flexible domains which can be chemically linked to the epoxy matrix. This enhances fracture toughness without impacting the glass transition temperature and improves the fatigue performance of cured epoxy resins, Kasper et al. (2020). Other toughening materials can also be used to overcome this issue but are not cost-effective in high-volume applications, Xiaoquim et al. (2022).

The use of adhesives for repairing and strengthening steel structures offers advantages of great importance over other conventional repairing and refurbishing techniques. Repair welding can result in new, undefined notch details, which, especially in consideration of residual stresses, represent new potential crack initiation points. Bolt or drill holes weaken the cross-section of the component and are new hot spots with increased stress concentrations. Adhesives provide additional benefits, such as their resistance to corrosion and degradation in different aggressive environments. The use of adhesives facilitates the creation of impermeable joints and enable efficient dissimilar materials bonding, providing high capacity for energy and vibration absorption. In fact, adhesive bonding is the best choice for many materials, enabling a more uniform and continuous distribution of the stresses through the joined area.

This study explores the potential of toughened epoxy adhesives in a novel reinforcement method for fatigue-damaged steel structures, applying structural carbon fiber-reinforced polymer (CFRP) lamellas over fatigue cracks to extend the residual life. Experimental investigations using different CT test specimens aim to provide a sustainable solution for retrofitting steel infrastructures, reducing CO2 emissions compared to building new bridges. The novel retrofit solution, combined with toughened epoxy adhesives, opens new avenues for structural bonding in construction, including steel infrastructure retrofitting, seismic protection, and novel material construction.

Nomenclature

a_{ini}	initial fatigue crack length	a_{ult}	final fatigue crack length
f	frequency	D_{Load}	distance of load application points
R	stress ratio	$\Delta\sigma$	stress range
N_a, N_b	number of cycles of a load block 'a' and 'b', respectively		

2. Materials

2.1. Adhesives

Two different toughened epoxy adhesives, (TEPs): SikaPower®-1277 and Sikadur®-370 provided by SIKA were selected for this investigation. Both systems have a common base-formulation, consisting of a thixotropic, solvent-free, bi-component epoxy-based adhesive. The chemical structure comprises a bisphenol-A based epoxy resin, polyurethane prepolymers and a blend of amines as hardeners, with different amounts of silica and carbonate-based fillers to improve the properties of TEPs. A mix ratio of 2:1 (resin to hardener in weight) was used, as recommended by the supplier.

SikaPower®-1277 is designed for strong, impact-resistant bonding of steel, aluminum, and composite substrates like GFRP and CFRP laminates, commonly used in automotive, transportation, and industrial manufacturing.
Sikadur®-370 is a new toughened epoxy (EP) adhesive designed specifically for fatigue-loaded steel structures in the construction sector. It offers high stiffness (modulus of elasticity >3000 MPa), tensile and compression strength (> 17 MPa and 50 MPa respectively), and excellent fracture toughness. Its superior fatigue performance compared to other non-toughened structural two-component epoxy adhesives, which are typically designed for structural reinforcements in concrete, brick, and timber applications under predominantly static loading makes Sikadur®-370 well-suited for strengthening fatigue-damaged steel structures with adhesively bonded CFRP lamellas, Kasper Y et al. (2021), Meier T. et al. (2020). Adhesives mechanical performance was previously characterized by the authors in a previous work Ciupack et al. (2024).

2.2. CFRP

This study investigates the suitability of four distinct CFRP materials for repairing fatigue cracks in steel structures through experimental analysis. To assess their material properties, 280 mm long specimens are subjected to tensile tests following the standards outlined in DIN EN ISO 527-4. CFRP strips measuring 60 mm in width and 1.8 mm in nominal thickness, denoted as materials V1, V2, and V3, undergo loading until failure at a loading rate of 0.5 mm/min. These CFRP variants, developed within the research project CFK TrafficPatch (2023), have been refined in fiber volume fraction and matrix material composition based on fatigue tests conducted on CT specimens, as described below.

The specimens of variant V4 are 20 mm wide and 1.4 mm thick and are subjected to tensile loading at a rate of 2 mm/min until failure. Variant V4 demonstrates superior Young's modulus and tensile strength compared to variants V1 to V3 and has already proven effective in reinforcing concrete components as slot-adhered carbon-fiber strips, FASS (2019), DIBt (2015). Table 1 presents the results of the tensile tests, in accordance with DIN EN ISO 527-1, providing mean values derived from at least 5 test results per specimen for Young's modulus, tensile strength, and elongation at break.

Table 1. Results of tensile tests according to DIN EN ISO 527-4 (mean values).

Material parameter	CFRP V1	CFRP V2	CFRP V3	CFRP V4
Young's Modulus E [MPa]	74,600	106,100	150,500	179,000
Tensile strength f_u [MPa]	1,100	970	1,360	3,426
Elongation at break [%]	1.48	0.88	0.89	1.80
Axial stiffness [N/mm]	134,280	190,980	270,980	250,600

3. Fatigue tests

3.1. Specimens

The experimental investigation of fatigue crack propagation in fatigue-damaged steel components, with and without adhesively bonded CFRP laminates, is carried out using compact tension (CT) specimens. The geometry of the CT specimens conforms to ASTM E 399 standards, featuring an a/W ratio of 0.4 and a specimen thickness of 10 mm, as depicted in Fig. 2. The specimens are constructed from steel grade S355, a common material used in bridge design.

The chosen geometry of the CT specimens aims to replicate the fatigue crack behavior typically observed at orthotropic decks of steel bridges. Specifically, attention is given to welded butt joints of longitudinal stiffeners, cracks arising at extended cutouts of the crossbeam webs in cases involving continuous longitudinal stiffeners, and longitudinal stiffeners within the transverse system. Fig. 1 illustrates selected details of the orthotropic deck pertinent to this innovative repair approach.

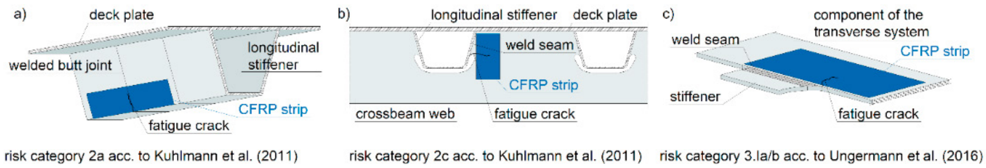

Fig. 1. Details and risk categories for the orthotropic deck with bonded CFRP applications (a) welded butt joints of longitudinal stiffeners; (b) cutouts of the crossbeam webs; (c) welded stiffeners in the transverse system.

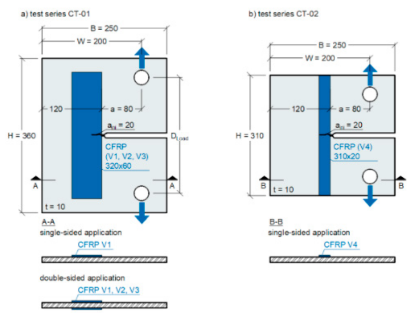

Fig. 2. Geometry of CT specimens for (a) test series CT-01 (CFK TrafficPatch, 2023); (b) test series CT-02 (FASS, 2019). All dimensions in mm.

In the initial test series, CT-01 (CFK Traffic Patch, 2023), variants V1, V2, and V3 of CFRP laminates are employed for repairing fatigue damage, both in single-sided and double-sided arrangements. Additionally, within the CT-01 test series, the adhesives Sikadur®-370 and SikaPower®-1277 are scrutinized. The bonding area for these CT specimens measures 320x60 mm², with an adhesive layer thickness of 1.0 mm.

For the subsequent test series, CT-02 (FASS, 2019), only the CFRP variant V4 is utilized in a single-sided configuration, in conjunction with the adhesive Sikadur®-370 . The bonding area measures 310x20 mm², the adhesive layer thickness 1.0 mm. Furthermore, this test series investigates combinations of bonded prestressed and non-prestressed CFRP laminates with established crack-repair techniques in steel structures. Selected findings are detailed in this article, with additional information and test results accessible in Kasper et al. (2021) and Kasper et al. (2019). Fig. 2 provides a visual representation of the test specimens from both CT-01 and CT-02 test series.

3.2. Testing procedure

The fatigue tests on CT specimens commence by inducing crack initiation in the base material through cyclic tensile loading until reaching a crack length of a_{ini} = 20 mm. Monitoring the initial crack length a_{ini} is achieved using a thin copper wire coupled with the testing machine control, a procedure derived from FASS, (2019) to ensure reproducible crack initiation. Subsequently, the repair process involves adhesively bonding the CFRP laminates according to the aforementioned conditions. Following a 7-day adhesive curing period, fatigue testing is conducted on the pre-damaged, repaired CT specimen.

For the CT specimens in the first test series, CT-01, fatigue testing is executed with a stress range of $\Delta\sigma$ = 210 MPa, a stress ratio of R = 0.1, and a testing frequency of f = 6 Hz. Termination criteria for experiments in the first test series are met when the load application points shift more than 40 mm apart (ΔD_{Load} > 40 mm), as illustrated in Fig. 2. Crack growth is determined using the beach mark method, following procedures outlined by Aljabar et al. (2018) and Emdad et al. (2015). The ratio of the number of cycles N_a of a load block 'a' with R = 0.1 to the number of cycles N_b of the load block 'b' with R = 0.5 is N_a:N_b = 3:1.

In the fatigue tests for the second test series, CT-02, the stress range is $\Delta\sigma$ = 67 MPa, stress ratio R = 0.5, and frequency f = 14 Hz. The failure criterion for the second test series is a total crack length of a_{ult} = 40 mm. Crack growth is monitored using crack measurement sensors attached to the backside of the repaired specimen, a feasible approach due to the single-sided arrangement of the CFRP laminate. Table 2 provides a summary of the test conditions and specimen configurations for both test series, CT-01 and CT-02.

Table 2. Testing conditions and specimen configurations for the test series CT-01 and CT-02.

Specimen configuration/testing conditions	Testing series CT-01	Testing series CT-02
CFRP variants	V1, V2, V3	V4
a_{ini} [mm]	20	20
Adhesives	Sikadur®-370, SikaPower®-1277	Sikadur®-370
Application of CFRP	single-sided, double-sided	single-sided
Condition of CFRP	non-prestressed	non-prestressed, prestressed
Stress range $\Delta\sigma$ [MPa]	210	67
Stress relation R [-]	0.1	0.5
Testing frequency f [Hz]	6	14
Failure criterion	$\Delta D_{Load} \geq$ 40 mm	a_{ult} = 40 mm

4. Test results

4.1. Influence of application

Fig. 3 illustrates the crack growth curves from the CT-01 test series, displaying specimens repaired using adhesives Sikadur®-370 (Fig. 3a) and SikaPower®-1277 (Fig. 3b). These curves are contrasted with results from three reference specimens (depicted by black curves) where no crack repair was conducted following crack initiation at a_{ini} = 20 mm. The dashed lines for the repaired specimens represent extrapolated crack growth from the last measurable beachmark until reaching the failure criterion $\Delta D_{Load} \geq 40$ mm.

Notable distinctions in the crack growth curves underscore the favourable impact of double-sided application of CFRP laminate (indicated by yellow curves) compared to single-sided application (blue curves). By employing non-prestressed CFRP laminates of type V1 in a double-sided application, the number of cycles until reaching the failure criterion, denoted as residual life, can be quadrupled for Sikadur®-370 adhesive compared to single-sided application and octupled for SikaPower®-1277, respectively. The influence of adhesive formulation is also evident in the crack growth rate: while the crack growth rate increases with crack length for specimens bonded with Sikadur-370, it decreases for specimens repaired with SikaPower®-1277. The observed reduction in crack growth rate for the specimens repaired with SikaPower®-1277 can be attributed to the more benign deformation behaviour of the adhesive layer. This allows for larger crack opening widths without damage due to the lower Young's modulus compared to Sikadur®-370, Ciupack et al. (2024). Consequently, the forces can be better redirected into the CFRP lamella as the crack progresses. Further studies should be conducted to investigate the influence of the debonding behaviour of low modulus EP adhesives in comparison to high modulus EP adhesives on the crack growth rate of the aforementioned specimen.

The determination of CFRP laminate arrangement depends on the conditions of the orthotropic deck component. For instance, for fatigue cracks along welded butt joints of longitudinal stiffeners, only single-sided application is feasible. In the specimens of test series CT-01, the residual life could be increased on average by a factor of 2.4 with single-sided reinforcement and the use of Sikadur®-370 adhesive, and 2.5 with SikaPower®-1277, respectively. The influence of adhesive formulation is of secondary importance in this context. The reason for this is the eccentric loading of the specimen during the fatigue test due to the single-sided reinforcement. This results in a secondary bending moment, which generates normal stresses at the ends of the laminates in the adhesive layer, overlapping with the shear stresses.

Table 3. Results of test series CT-01: residual life (mean values).

	Reference	Sikadur®-370		SikaPower®-1277	
		single-sided	double-sided	single-sided	double-sided
Residual life [-]	19,950	47,575	209,900	50,875	419,425
Factor of residual life extension [-]	1.0	2.4	10.5	2.5	21.0

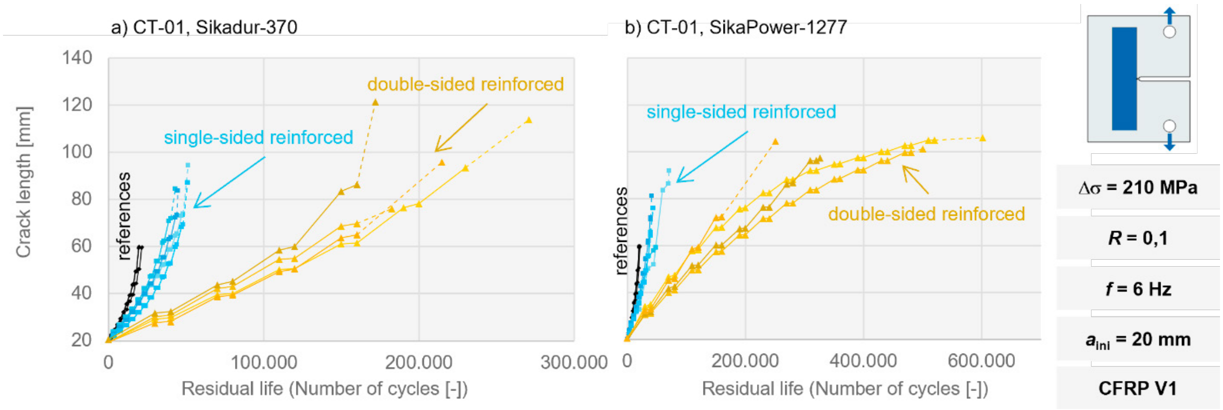

Fig. 3. Crack growth in CT specimens of test series CT-01 with initial crack (20 mm) repaired using (a) Sikadur®-370; (b) SikaPower®-1277.

4.2. Influence of CFRP composite characteristics

The stiffness of the CFRP laminate significantly influences the achievable extension of residual life, particularly in non-prestressed applications. This is evident when comparing the test results for reinforced CT specimens using different CFRP materials. In Fig. 4a, the factors of residual life extension (FRLE) are presented for test series CT-01 and CT-02 on fatigue-damaged CT specimens repaired using Sikadur®-370 adhesive and laminates of types V1 and V4. The use of CFRP type V4, compared to V1, results in an approximately 30 % increase in FRLE. Notably, despite V4 having only 1/3 the width of V1, its Young's modulus is approximately 2.4 times larger than that of V1. Furthermore, when comparing test series CT-01 and CT-02, the different loading scenarios and failure criteria must be considered.

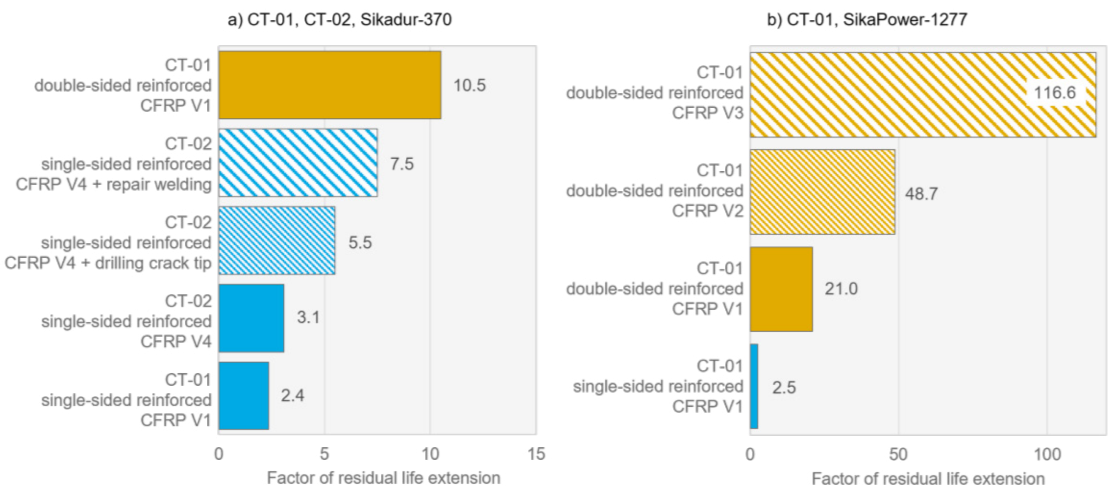

Fig. 4. FRLE for CT specimens of test series CT-01 and CT-02 repaired using (a) Sikadur®-370 and CFRP V1 and V4; (b) SikaPower®-1277 and CFRP V1, V2 and V3.

In test series CT-01, the residual life of single-sided reinforced specimens could be increased by 77 % through a combination with established crack repair methods in steel construction, such as drilling at the crack tip, and by 142 % for repair welding (including drilling at the crack tip), respectively. This result offers valuable insights for further improving the repair method, especially for practical application in exclusively single-sided accessible fatigue details, such as welded butt joints of longitudinal stiffeners. Additional information on the potential when combined with other repair methods can be found in Ciupack et al. (2019). The greatest FRLE in test series CT-01 and CT-02 can be achieved through the double-sided application of CFRP laminate type V1, as also demonstrated in Fig. 3.

In Fig. 4b, the comparison of results from fatigue tests CT-01 is depicted for CT specimens reinforced with laminate types V1, V2, and V3 using SikaPower®-1277 adhesive. The FRLE can be increased by 132 % for double-sided reinforced specimens when using CFRP V2 and by 455 % for V3, respectively, compared to CFRP type V1. The number of cycles until reaching the failure criterion averaged 2.36 million for tests with CFRP laminate V3. In a validation test on a CT specimen reinforced with CFRP type V1 and SikaPower®-1277, and adjusted loading conditions with $\Delta\sigma$ = 180 MPa, R = 0.1, and f = 6 Hz, no crack propagation was observed even after 4.0 million load cycles.

5. Conclusion

In conclusion, this study systematically investigated the efficacy of CFRP materials in repairing fatigue cracks in steel structures using two different toughened EP adhesives. Through experimental analysis using CT specimens, it was demonstrated that the choice of CFRP material, adhesive, and application method significantly impacts the extension of residual life and crack growth rates. Notably, double-sided application of CFRP laminate, particularly stiffer materials, showed the most promising results in terms of increasing residual life. Furthermore, the combination of CFRP reinforcement with established crack repair methods in steel construction showcased notable improvements in residual life, especially in single-sided accessible fatigue details. These findings provide valuable insights for optimizing repair methods for fatigue-damaged steel structures, contributing to enhanced structural integrity and residual life. Further research and validation of these methods are necessary to validate their effectiveness in real-world applications.

Many studies focusing on bonded CFRP reinforcements in fatigue-loaded steel structures have primarily addressed feasibility considerations. However, to gain a deeper understanding of the behavior of this innovative repair method, future research should explore the debonding behavior under cyclic loading and environmental influences.

Acknowledgements

The project CFK-TrafficPatch was funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) based on a resolution of the German Bundestag. The IGF research project (IGF-No. 19032 BG) of the "Research Association on Welding and Allied Processes of the DVS, Aachener Straße 172, 40223 Düsseldorf" has been funded by the AiF within the program for sponsorship by Industrial Joint Research (IGF) of the German Federal Ministry of Economic Affairs and Energy, based on an enactment of the German Parliament. The authors would like to thank the project partners, as well as the Research and Materials Testing Institute (FMPA) of Brandenburg University of Technology Cottbus-Senftenberg for their support in planning and conducting the experiments.

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