ce/papers Proceedings in civil engineering

Ernst & Sohn A Wiley Brand

ORIGINAL ARTICLE

eurosteel AMSTERDAM 2023

Ernst & Sohn A Wiley Brand

Fatigue behaviour of hybrid grouted joints under axial loading

Jakob Boretzki[1] | Matthias Albiez[1] | Jannis Damm[1] | Thomas Ummenhofer[1]

Correspondence

Jakob Boretzki, M.Sc.
Karlsruhe Institute of Technology
KIT Steel and Lightweight Structures, Research Center for Steel, Timber and Masonry
Otto-Ammann-Platz 1
76131 Karlsruhe
Email: jakob.boretzki@kit.edu

[1] KIT Steel and Lightweight Structures, Karlsruhe, Germany

Abstract

Steel constructions made of circular hollow sections are commonly joined by welding or ring-flange bolting. An additional, novel joining method is the so-called hybrid grouted joint. The hybrid grouted joint is characterised by its multi-layered composition. In contrast to state-of-the-art grouted joints, hybrid grouted joints include thin adhesive layers, which are applied on the steel surfaces prior to grouting. Sand grains are embedded in the yet uncured adhesive. After the curing of the adhesive, the surface has a high degree of roughness. This allows a high-performance interlock between fine grain grout and the adhesively bonded sand granules across the contact surfaces in the overlap area. The ability to transfer loads across a wide area with low stress concentrations makes the hybrid grouted joint a promising joint alternative especially regarding the fatigue performance. This paper summarises the main findings concerning fatigue behaviour of the hybrid grouted joint under axial loading. Wöhler diagrams were determined in numerous fatigue tests for two combinations of adhesive and grout.

Keywords

Joining Technology, grouted joint, hollow sections, adhesive, hybrid joint, fatigue

1 Introduction

Besides corrosion and wear, fatigue is one of the main reasons for damage occurring to load bearing elements in steel construction [1]. Constructions in numerous applications are subjected to fatigue loads. Usually, the critical details regarding fatigue are the joints between components.

1.1 Joining methods for circular hollow sections

Circular hollow sections (CHS), are commonly joined by welding or ring-flange bolting [2]. Alternative joining methods are adhesively bonded and grouted joints. Adhesive bonding of CHS is in the focus of recent research [3, 4]. For offshore applications, grouted joints are commonly used. For an overview of the extensive research the authors refer to [5]. Both methods are executed as overlap joints where the annular gap between sleeve (outer CHS) and pile (inner CHS) is filled with an organic adhesive or a mineral grout, respectively. While the adhesive exhibits decisive adhesion to the steel surfaces, the grout has a high stiffness and compressive strength.

1.2 Fatigue resistance of joining methods for CHS under axial loading

The axial fatigue resistance of welded and ring-flange bolted joints is scientifically proven. EN 1993-1-9 [2] regulates the design of respective fatigue-stressed details. Both joints can reach a maximum fatigue class of FAT 71. In the past decades, numerous investigations on grouted joints regarding fatigue resistance were conducted and are summarized in [5]. Fatigue endurance limit amounts to about 20% of the quasi-static load capacity. Fatigue testing on adhesively bonded joints is limited and depends of the specific adhesive and joint geometry but avoids notch details [6].

1.3 Hybrid grouted joints

An additional option to join CHS is the so called hybrid grouted joint. This novel overlap joint type combines grouting and adhesive bonding. The multilayered composition of the annulus characterises this joint type (cf. Figure 1). Thin adhesive layers are applied on both steel adherents, resulting in an adhesive bond on the steel surfaces. In the yet uncured adhesive granules are embedded. The remaining annulus is filled with a fine grain grout. The granules protruding from the adhesive layers provide decisive and full-surface interlocking between the adherents and the grout layer. Due to the confinement by the tubes, compression struts can form in the grout layer.

https://doi.org/10.1002/cepa.2425 wileyonlinelibrary.com/journal/cepa

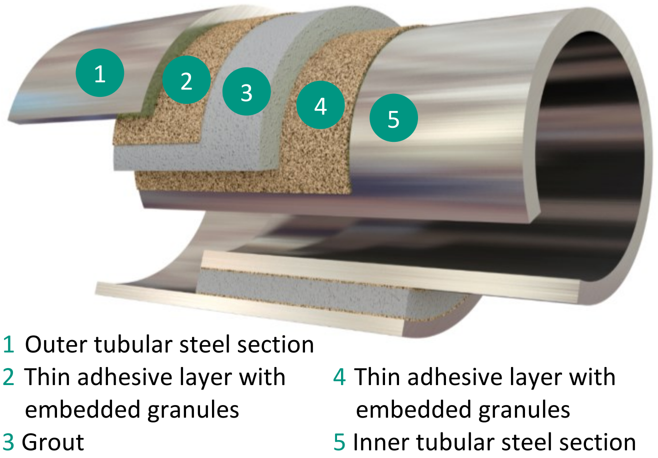

Figure 1 Hybrid grouted joint [7]

Experimental tests with static axial loading show high transferable loads at minimum displacement [8]. Failure occurs in the adhesive layer at the pile. Due to the compression struts, substantial compressive stress results. As this is beneficial for the adhesive's shear strength [9], nominal shear stress in the inner adhesive layer at failure can exceed the adhesive's shear strength determined with thin tensile shear specimens [8]. In order to determine the fatigue performance of this joint type, tests were conducted. Hereinafter, these are presented and the results are given and discussed.

1.4 Scope of this paper

The scope of the investigations presented in this paper is to determine the fatigue strength of hybrid grouted joints. Specimens with two different adhesive-grout combinations are tested on various stress levels. Partially, additional data is collected regarding warming of the adhesive layer and possible gradual damage of the joint.

2 Materials

The materials used are fully documented in [8]. Therefore, in this paper only extracts are presented.

2.1 CHS

The used steel adherents were hot rolled CHS (according to EN 10025-1 [10]) made of S355J2H. Yield strength is 404.25 MPa, tensile strength amounts to 552.75 MPa (data according to inspection certificate). For the sleeve, a CHS with the dimensions D/t = 101.6/10 was used. The pile was a CHS with D/t = 48.3/12.5.

2.2 Grout

As grout, HF10 (Pagel Spezial-Beton, Germany), which is a self-compacting product with a certificate of compliance in accordance to VeBMRver [11], is used. According to the manufacturer's technical data sheet [12] grain size is 0 – 1 mm, amount of water is 0.116 and Young's Modulus is above 35,000 MPa after 28 d of curing. Flexural (R_f) and compressive (R_c) strength at 28 days were determined in [8] according to EN 196-1 [13]. R_f is 17.9 ± 1.3 MPa, R_c is 123.4 MPa ± 2.5 MPa.

2.3 Adhesives

Two different adhesives were used in this study. They were characterized in [14]. The first is a cold-curing toughened 2C-epoxy (Sikadur-370 by Sika AG, Switzerland), hereinafter labelled Sikadur. The second one is an epoxy-based tape (DuploTEC 10490 SBF by Lohmann Adhesives, Germany) delivered in thicknesses of 0.1 mm, and which requires temperatures of 130 °C (for 30 min) to cure, hereinafter abbreviated DuploTEC. Table 1 shows selected properties of the used adhesives. Tensile shear strength was determined in thin lap shear tests acc. to EN 1465 [15]. Tensile strength and Young's Modulus were determined with specimens according to EN ISO 527-2 [16]. The glass transition temperature was determined within a dynamic-mechanical analysis. This specific value identifies the temperature, where put in simple terms the mechanical properties of the adhesive significantly changes. For temperatures above the glass transition temperature a substantial loss in stiffness and strength results. For structural adhesives, the application temperature should be well below the glass transition temperature. [17]

Table 1 Selected properties of the adhesives [14]

Adhesive	Sikadur	DuploTEC
Tensile shear strength [MPa]	27.50 ± 1.16	27.39 ± 1.12
Tensile strength [MPa]	21.5 ± 2.9	28.7 ± 2.9
Young's Modulus [MPa]	3,581 ± 113	1,593 ± 44
Glass transition temperature [°C]	75.84	139.52

2.4 Granules

As granules, quartz sand is used. A composition with a medium grain size of 1.0 mm and a small grain size distribution was selected.

2.5 Manufacturing

The manufacturing of the hybrid grouted joint is separated into two steps, the application of the adhesive layers and the grouting. For a detailed description refer to [8].

3 Fatigue testing

3.1 Test campaign

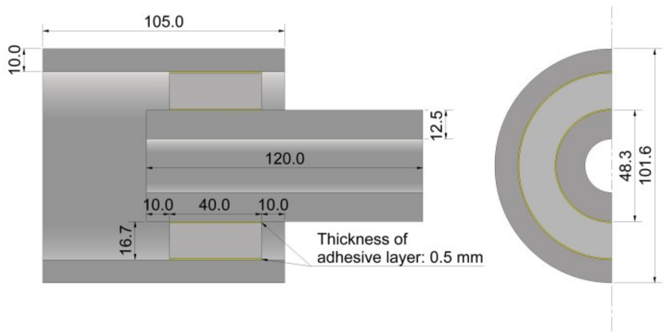

Figure 2 Specimen for fatigue tests [7]

A total of 25 tests under compressive fatigue load were conducted. All specimen had the same geometry. In order to compare the fatigue tests to quasi-static tests, a geometry already tested in [8] was chosen (cf. Figure 2). Its overlap length is 40 mm, the annulus thickness 16.7 mm.

Table 2 Fatigue stresses for both adhesives and different stress levels [7]

	Maximum static shear strength $\Delta\tau_{u,stat}$ [MPa]	Fatigue stress range $\Delta\tau_{fat}$ [MPa]	Q= $\Delta\tau_{u,stat}$ / $\Delta\tau_{fat}$ [-]	Number of specimens tested [-]
Sikadur	26.8	13.6	0.51	3
		15.5	0.58	6
		17.4	0.65	4
DuploTEC	18.8	10.4	0.55	4
		11.8	0.63	6
		13.2	0.70	2

A total of 13 specimens with Sikadur were tested, as well as 12 specimens with DuploTEC. All specimens were tested with a fatigue stress ratio of 0.1. Depending on the used adhesive, different stress levels were chosen for the respective fatigue specimens (cf. Table 2). This is necessary as the quasi-static load capacity of the hybrid grouted joint varied between Sikadur and DuploTEC [8]. This can partially be traced back to the thickness of the adhesive layer, which is 0.1 mm for the DuploTEC instead of 0.5 mm for the Sikadur. The lower embedment of the granules for specimens with DuploTEC leads to higher stress in the adhesive resulting in earlier failure. The quotient Q is calculated by dividing the fatigue stress range and the maximum static shear strength.

3.2 Test procedure

Most of the tests were conducted on two servo-hydraulic testing machines. Here, the test frequency was 8 Hz. Singular tests on low stress levels with predictably high load cycles were tested on a mechanical resonance pulser testing machine. This allowed much higher test frequencies of around 34 Hz. Generally, the test was stopped, either when the specimen failed or when it reached a defined load cycle number of five million. Singular tests were stopped at higher load cycle numbers. The machine displacement at mean load is recorded for all specimens. For one specimen, additional test data is generated. Every 5,000 load cycles, hystereses at 4 different test frequencies (1 Hz, 3 Hz, 5 Hz, 8 Hz) are recorded. This aims at two aspects: identifying any influence of test frequency on the dynamic behaviour, determination of changes in stiffness during the fatigue test hinting a gradual degradation of the joint.

During fatigue tests, energy is dissipated due to the viscoelasticity of the adhesive, which leads to gradual warming of the adhesive layer. The mechanical properties of adhesives are influenced by temperature, especially in the range of the glass transition temperature (see 2.3). Therefore, the temperature of the adhesive layer of one exemplary specimen is tracked. For this purpose, thermocouples were inserted in the adhesive layer during the application process (cf. Figure 3).

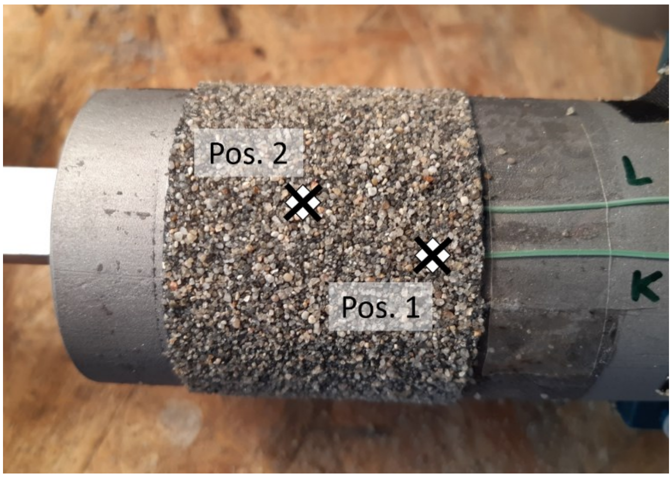

Figure 3 Position of thermocouples in adhesive layer

3.3 Results

3.3.1 *Tests with Sikadur*

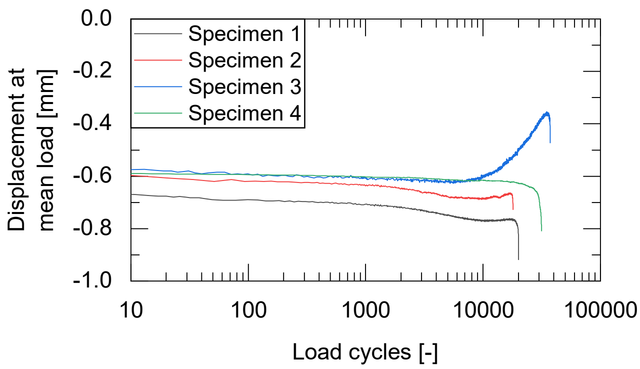

Figure 4 Displacement curves at mean load for Sikadur and a stress range of $\Delta\tau_{fat}$ = 17.4 MPa

At first, the 13 tests conducted with Sikadur are presented. On the highest stress range of $\Delta\tau_{fat}$ = 17.4 MPa (Q = 0.65), 4 tests were conducted. Figure 4 shows their displacement-load cycles graphs. The displacement at mean load remains almost unchanged for the major share of the test duration. A few hundred load cycles before failure, failure is announced by an increase in displacement. The temporal decrease in displacement for Specimen 3 can be explained by an alignment of the test setup, in particular the calotte.

Figure 5 Fracture pattern of a fatigue test with Sikadur for a stress range of $\Delta\tau_{fat}$ = 17.4 MPa

Measured load cycles reach from 18,000 to 37,305 for this stress range. Failure always occurs in the adhesive layer through special adhesive failure accompanied by a small grout fracture cone located at the lower end of the overlap (cf. Figure 5).

The specimen that reached 37,305 load cycles (blue graph in Figure 4) is the one, for which additional test data was collected. Figure 6 shows hysteresis for different test frequencies at a load cycle number of 15,000. As the graphs are congruent, no influence of test frequency f is found in the investigated range of f = 1 Hz to f = 8 Hz.

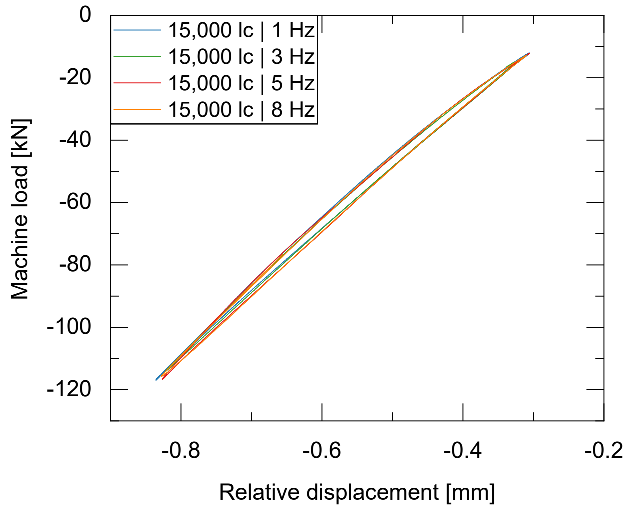

Figure 6 Hystereses of a fatigue test with Sikadur for varying test frequencies

Comparing the hystereses measured at different time steps, shows consistent load displacement behaviour (cf. Figure 7). The gradual displacement of the hystereses on the abscissa happens due to the above-mentioned alignment of the calotte.

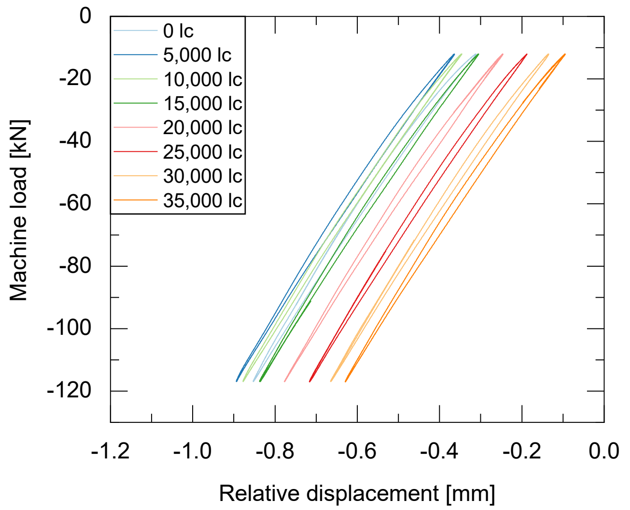

Figure 7 Hystereses of a fatigue test with Sikadur for varying load cycles

The measuring of the temperature shows a slight and linear increase for both measuring points (cf. Figure 8). It remains in a single-digit range and is, even at failure, well below the glass transition temperature of the adhesive. Additionally, real structures will have much lower stress frequencies.

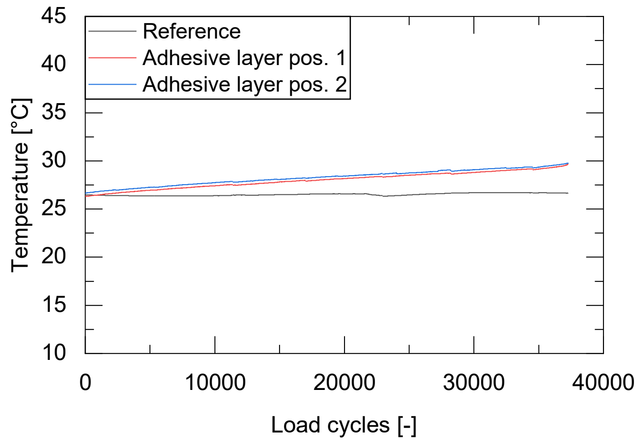

Figure 8 Temperature profile of a fatigue test with Sikadur-370 at two measuring points in the adhesive layer and at a reference measuring point

Decreasing the stress level results in higher load cycles. On the middle stress level of $\Delta\tau_{fat}$ = 15.5 MPa (Q = 0.58), load cycle numbers show an increased scatter with values reaching from 43,007 to 3,483,327. On the low stress level of $\Delta\tau_{fat}$ = 13.6 MPa (Q = 0.51), three specimens are tested. Only one fails at 3,750,190 load cycles. The two other tests are stopped without failure at 10 million and 19 million load cycles. Figure 9 shows the results of all fatigue tests in a Wöhler diagram.

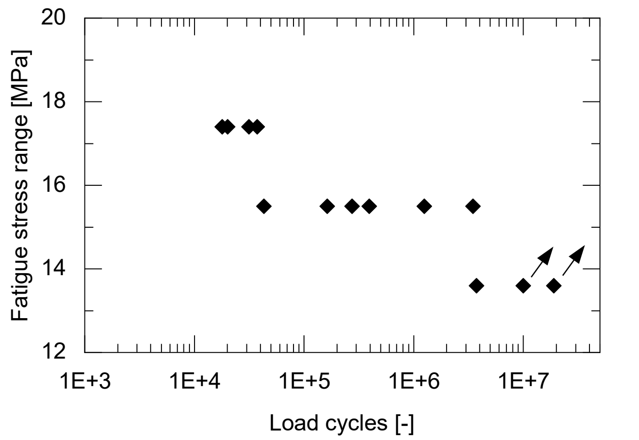

Figure 9 Wöhler diagram of fatigue tests with Sikadur

The fracture pattern of all fatigue test is similar as observed for the high stress level. The course of the mean displacement shows similar behaviour as well. Displacement remains constant right up to a few hundred load cycles before failure. Therefore, the authors refrain from presenting the additional fracture patterns as well as displacement-load cycle graphs.

3.4 Tests with DuploTEC

A number of 12 tests were conducted with the second investigated adhesive (DuploTEC). On the low load level (Q = 0.55), one specimen is stopped at 10 million load cycles, the other fails at 20.7 million. On the middle stress level (Q = 0.63), scatter is high, ranging from 55,729 to 1.6 million load cycles. The high stress level (Q = 0.70) yields 3 specimens with low load cycle numbers. The fourth specimen on this stress level is stopped at 5 million load cycles without failure. Figure 10 sums up the fatigue tests on specimens with DuploTEC.

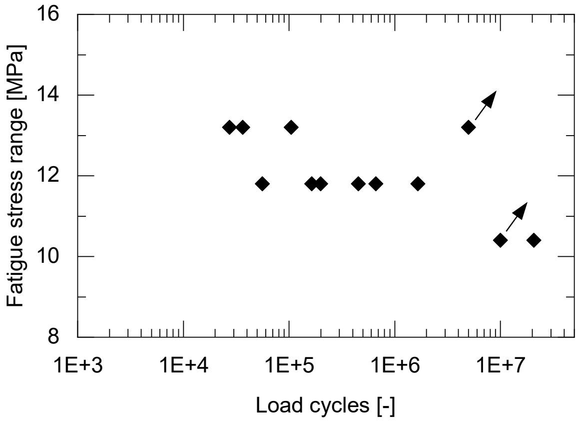

Figure 10 Wöhler diagram of fatigue tests with DuploTEC

As the fracture pattern is comparable for all specimens, only one exemplary fracture pattern is displayed (cf. Figure 11). As observed for the tests with Sikadur, failure occurs in the adhesive layer at the pile as special cohesive failure. As before, it is accompanied by a small grout fracture cone located at the lower end of the overlap.

Figure 11 Fracture pattern of a fatigue test with DuploTEC for a stress range of $\Delta\tau_{fat}$ = 13.2 MPa (right: pile with grout cone, left: sleeve with remaining grout layer)

One specimen ($\Delta\tau_{fat}$ = 13.2 MPa, Q = 0.70, load cycles: >5,000,000) is cut via waterjet. This shows that no damage is visible in the overlap area, even after the high number of load cycles (cf. Figure 12).

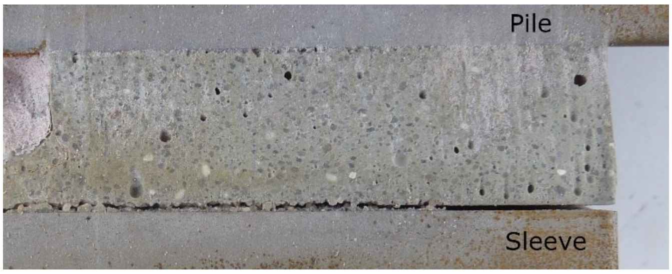

Figure 12 Fracture pattern of fatigue test (DuploTEC, $\Delta\tau_{fat}$ = 13.2 MPa, load cycles: >5,000,000)

The gap between the grout layer and the adhesive layer on the sleeve only appears after the waterjet cut. It is caused by the residual stresses in the sleeve. When the cross section is cut open, these stresses cause it to expand, resulting in the visible gap. Apart from this subsequently appearing gap, no other cracks in grout or adhesive layer are visible.

4 Discussion

First, based on the results of the tests, it can be stated that the hybrid grout joint has a high resistance to fatigue loading. For a stress level of 50 % of the quasi-static strength, runners or very high load cycles (above 20 million) can be generated reliably for both adhesives. With increasing stress level, fatigue life decreases. Especially on the middle stress level, load cycle numbers scatter decisively. This behaviour is known from literature (e.g. [18]). With decreasing stress level, the number of crack nuclei reduces. This makes crack propagation on lower stress levels particularly sensitive for imperfections. As only singular specimens were tested until failure on the low stress level, but several tests were considered as runners, no assertions regarding the respective scatter can be made.

Figure 13 summarises all results of the fatigue tests. The service life for both adhesives is compared. Two graphs are inserted which describe an estimated chance of survival of 50%. It is determined by assuming a normal distribution of the number of load cycles of the failed specimens on the middle and higher load level. Based on this, the 50% quantile is calculated for each stress level and both adhesives. These values define the course of the respective graph. The functions of both graphs are negative logarithmic. For better visibility, the graphs are extrapolated down to 10^4 and up to $2*10^6$ load cycles. Assuming these graphs describe the relation between fatigue stress range and load cycles, two observations can be drawn: Firstly, the graphs have similar gradients. Secondly, for the same aimed service life, the bearable stress level is about 5.0 MPa higher for specimens with Sikadur in comparison to specimens with DuploTEC. This behaviour is congruent to the results derived in the quasi-static investigations [8].

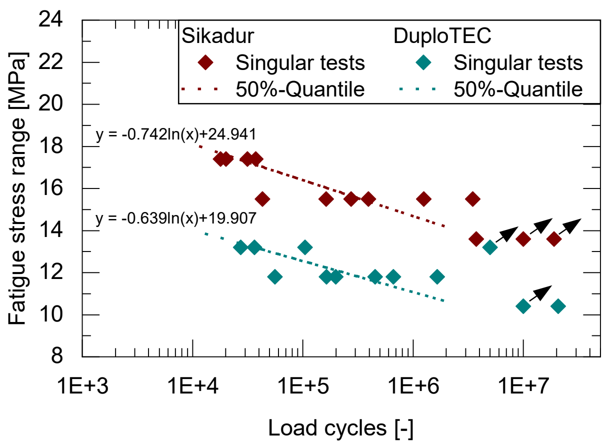

Figure 13 Wöhler diagram of all fatigue test with median (50%-Quantile) for both adhesives

5 Conclusions

In the present paper, the fatigue performance of the hybrid grouted joint is investigated. Based on a total of 25 fatigue tests, the following conclusions can be drawn:

- The hybrid grouted joint has a high resistance against fatigue loads. For the investigated specimens, fatigue strength is about 50% of the quasi-static strength.
- Assuming a normal distribution of the number of load cycles of the failed specimens, the relation between fatigue stress range and load cycles can be approximated with a negative logarithmic function.
- For both investigated adhesives, this derived function has a similar gradient. Though, its respective constant varies. Similar to the difference of the quasi-static strength determined in [8], it is about 5 MPa higher for the Sikadur compared to DuploTEC.
- The fracture pattern under fatigue loads is similar to the one observed for static loads. Failure occurs as special cohesive failure in the adhesive layer at the pile.
- A waterjet cut of a tested, yet intact specimen indicates that no gradual, partial damage occurs prior to failure. This is further supported by the evaluation of hystereses recorded at different points in time of a fatigue test. Over the course of the test, no changes in the form of the hysteresis were detected.

Based on presented results, it can be concluded that the hybrid grouted joint offers a promising alternative to state-of-art joint types for the transfer of fatigue loads. This enables its use in various steel construction applications.

6 Acknowledgments

The presented research was conducted within the framework of the research project IGF-No. 19989 N/ FOSTA P 1307 of the Forschungsvereinigung Stahlanwendung e.V., Sohnstraße 65, 40237 Düsseldorf. This project was supported by the Federal Ministry of Economics & Energy through the German Federation of Industrial Research Associations (AiF) as part of the program for promoting industrial cooperative research. We thank our research partners Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM (Bremen, Germany).

7 References

[1] Radaj, D. (2007) *Ermüdungsfestigkeit. Grundlagen für Ingenieure.* 3., neubearbeitete und erweiterte Auflage. Berlin: Springer. 978-3-540-71458-3.

[2] DIN Deutsches Institut für Normung e.V., *DIN EN 1993-1-9:2010 Eurocode 3: Bemessung und Konstruktion von Stahlbauten – Teil 1-9: Ermüdung*.

[3] Albiez, M.; Vallée, T.; Fricke, H.; Ummenhofer, T. (2019) *Adhesively bonded steel tubes — Part I: Experimental investigations.* International Journal of Adhesion and Adhesives 90, pp. 199-210. DOI: 10.1016/j.ijadhadh.2018.02.005.

[4] Damm, J.; Albiez, M.; Ummenhofer, T.; Göddecke, J.; Meschut, G.; Kötz, F.; Matzenmiller, A. (2023) *Experimental and numerical investigation of the damping properties of adhesively bonded tubular steel joints.* The Journal of Adhesion, pp. 1-31. DOI: 10.1080/00218464.2023.2178909.

[5] Dallyn, P.; El-Hamalawi, A.; Palmeri, A.; Knight, R. (2015) *Experimental testing of grouted connections for offshore substructures: A critical review.* Structures 3, pp. 90-108. DOI: 10.1016/j.istruc.2015.03.005.

[6] Nayeb-Hashemi, H.; Rossettos, J. N.; Melo, A. P. (1997) *Multiaxial fatigue life evaluation of tubular adhesively bonded joints.* International Journal of Adhesion and Adhesives 17(1), pp. 55-63. DOI: 10.1016/S0143-7496(96)00023-1.

[7] Ummenhofer, T.; Albiez, M.; Boretzki, J.; Vallée, T.; Myslicki, S. (2021) *Hybride Grout-Verbindungen für Stahlbaukonstruktionen (HybridGrout). Forschungsprojekt FOSTA P 1307 / IGF-Nr. 19989 N, Final report*.

[8] Boretzki, J.; Albiez, M.; Myslicki, S.; Vallée, T.; Ummenhofer, T. (2023) *Hybrid grouted joints: Load bearing and failure behaviour under static, axial loading (submitted).* Construction and Building Materials.

[9] Dragoni, E.; Mauri, P. (2000) *Intrinsic static strength of friction interfaces augmented with anaerobic adhesives.* International Journal of Adhesion and Adhesives 20(4), pp. 315-321. DOI: 10.1016/S0143-7496(99)00062-7.

[10] DIN Deutsches Institut für Normung e.V., *DIN EN 10025-1:2005 Warmgewalzte Erzeugnisse aus Baustählen – Teil 1: Allgemeine technische Lieferbedingungen*.

[11] Deutscher Ausschuss für Stahlbeton e.V., *DAfStb Vergussbeton, Vergussmörtel:2019-07 DAfStb-Richtlinie - Herstellung und Verwendung von zementgebundenem Vergussbeton und Vergussmörtel*.

[12] Pagel Spezial-Beton GmbH & Co. KG (2021) *Super high strength grout C80/95 HF10.* Essen.

[13] DIN Deutsches Institut für Normung e.V., *DIN EN 196-1:2016 Methods of testing cement – Part 1: Determination of strength*.

[14] Myslicki, S.; Vallée, T.; Boretzki, J.; Albiez, M.; Ummenhofer, T. (2023) *Hybrid bonded joints combining organic and inorganic adhesives: Development and validation of an innovative joining technique (submitted).* Construction and Building Materials.

[15] DIN Deutsches Institut für Normung e.V., *DIN EN 1465:2009 Klebstoffe – Bestimmung der Zugscherfestigkeit von Überlappungsklebungen*.

[16] DIN Deutsches Institut für Normung e.V., *DIN EN ISO 527-2:2012 Kunststoffe – Bestimmung der Zugeigenschaften –Teil 2: Prüfbedingungen für Form- und Extrusionsmassen*.

[17] Rasche, M. (2012) *Handbuch Klebtechnik.* München: Hanser. 978-3-446-42402-9.

[18] Schijve, J. (1994) *Fatigue predictions and scatter.* Fatigue & Fracture of Engineering Materials and Structures 17(4), pp. 381-396. DOI: 10.1111/j.1460-2695.1994.tb00239.x.