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Load-deformation behavior of injection bolts for maintenance of steel structures under dynamic loads

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Abstract

Connections of steel-structures under dynamic loads need to be slip-resistant according to EN 1993-2. Bolted connections without slip can be realized with fitted bolts, preloaded high strength friction grip (HSFG) bolts or injection bolts. Injection bolts are particularly advantageous because the increased effort required for reaming the holes for fitted bolts or for special surface preparation for HSFG bolts can be avoided. The paper focuses on the experimental analysis of connections with non-preloaded and preloaded injection bolts according to EN 1090-2. Different resins and curing conditions are considered, as well as different surface treatments or friction coefficients. Thus, the interaction between the slip resistance and the bearing resistance of preloaded injection bolts is investigated more detailed.

Keywords

bolted connections, injection bolts, maintenance, fatigue, epoxy resin

1 Introduction

A major part of existing steel bridges in Germany was built at the end of the 19th century and the beginning of the 20th century. Characteristic for these structures are rivets as a fastening technique and material heterogeneities. This results in currently required maintenance and strengthening measures, including not only the renewal of the corrosion protection but also the replacement of riveted joints on non-weldable steel structures. Rivets can be replaced by fitted bolts, preloaded high strength friction grip (HSFG) bolts or injection bolts.

Not only for this case the application of injection bolts particularly is advantageous, because the increased effort required for reaming the holes for fitted bolts or for special surface preparation for HSFG bolts can be avoided. By filling the gap between the shank of the bolt and the wall of the hole with injection resin (see Figure 1), injection bolts provide a slip-resistant connection with sufficient clearance for an easy assembly.

Normative requirements for the design and application of injection bolts are essentially available in EN 1993-1-8 [1], EN 1993-1-9 [2] and EN 1090-2 [3]. However, the application of injection bolts for steel bridges is currently not possible in Germany without a special technical approval. There is a lack of extensive knowledge of the exact load-deformation behavior of the connection, especially for different influencing factors. The present research project [4] therefore deals with open issues from a German point of view. How do temperature and vibrations influence the curing process and strength of the resin? How do the bearing resistance of the resin and the slip resistance interact in a preloaded application of injection bolts? And what is the fatigue resistance of the connection and the resin itself? The current results of the national research project IGF-No. 21369 N provide answers to some of these essential questions.

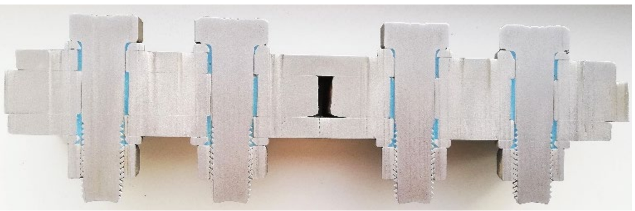

Figure 1 Waterjet cut through a standard specimen with injection bolts according to EN 1090-2, Annex G and J with Rengel (blue)

2 Execution and design of injection bolts

2.1 Regulations according to ECCS recommendation No. 79

Fundamental design and execution regulations are based on extensive research carried out in the 1970s and 1980s at TU Delft in the Netherlands. These research results were compiled in the *European Recommendations for Bolted Connections with Injection Bolts* [5] in ECCS No. 79 (1994). The main specifications have been incorporated almost unchanged in EN 1090-2 and EN 1993.

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2.2 Execution according to EN 1090-2

According to the informative Annex J in EN 1090-2, injection bolts can be used as non-preloaded or preloaded bolts. A special machined bolt assembly is required for a successful injection, including an injection hole in the head of the bolt, a chamfered washer under the bolt head and an air escape groove in the washer under the nut. Figure 2 shows a sectional drawing of an assembled and injected bolt. In the case of preloaded injection bolts, the bolt must be tightened before the injection.

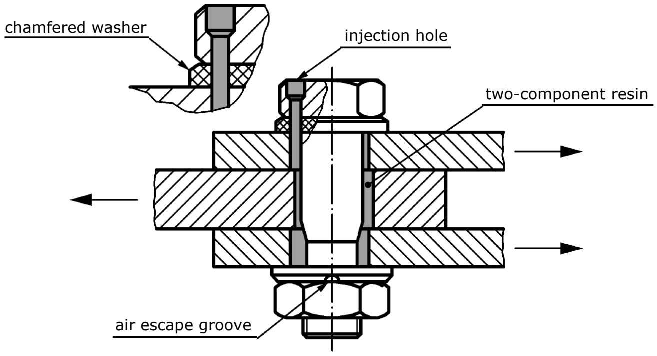

Figure 2 Injection bolt in a double shear connection according to EN 1090-2, Annex J

A two-component resin – usually epoxy resin – should be used for injection and the corresponding design bearing stress should be determined by tests according to EN 1090-2, Annex G. This results in the same test procedure as for the determination of the slip factor for HSFG bolts. This test procedure is used and described for static tests in 3.2 and 3.3.

2.3 Design according to EN 1993

Injection bolts can be used in bolted connections subjected to shear, thus in category A, B and C depending on the bolt preload. In addition to the known design procedures for each category, the design bearing resistance of the resin has to be verified. The bearing resistance of the resin is defined in EN 1993-1-8 as follows:

$$F_{b,Rd,resin} = \frac{k_t \cdot k_s \cdot d \cdot t_{b,resin} \cdot \beta \cdot f_{b,resin}}{\gamma_{m4}} \qquad (1)$$

The factor β considers the thickness ratio of the plates, d is the bolt diameter, $f_{b,resin}$ is the bearing strength of the resin, $t_{b,resin}$ is the effective bearing thickness, k_t depends on the limit state and k_s on the bolt clearance. The input parameters therefore significantly depend on the geometry of the connection – such as d and $t_{b,resin}$ – and the bearing strength of the resin $f_{b,resin}$. For the exact parameters and design equations, reference is made to EN 1993-1-8. The design procedures that have to be carried out corresponding to the category of the bolted connection are compiled in Table 1. According to EN 1993-1-8, the bearing resistance of the resin $F_{b,Rd,resin}$ can be added to the slip resistance $F_{s,Rd}$ in the case of a preloaded connection with injection bolts. The revision of the Eurocodes currently intends an unchanged adaption of this design approach [6].

Table 1 Verification of ultimate and serviceability limit state (ULS and SLS) for connections with injection bolts according to EN 1993-1-8

	ULS	SLS
A	$F_{v,Ed} \leq F_{v,Rd}$ $F_{v,Ed} \leq F_{b.Rd,resin}$ $F_{v,Ed} \leq F_{b,Rd}$	–
B	$F_{v,Ed} \leq F_{v,Rd}$ $F_{v,Ed} \leq F_{b.Rd}$	$F_{v,Ed,ser} \leq F_{s,Rd,ser} + F_{b,Rd,resin}$
C	$F_{v,Ed} \leq F_{v,Rd}$ $F_{v,Ed} \leq F_{s,Rd} + F_{b.Rd,resin}$	–

Beside the static load bearing capacity, the fatigue strength of connections with injection bolts is already regulated in EN 1993-1-9. The detail category of connections with non-preloaded injection bolts is equated with the detail category of fitted bolts and that of connections with preloaded injection bolts with the detail category of HSFG bolts. This results in detail category 90 for double shear connections with non-preloaded and 112 for preloaded injection bolts. However, the given detail categories in EN 1993-1-9 and prEN 1993-1-9 [7] do not include any information regarding the fatigue strength of the injection resin itself. According to ECCS No. 79, additional fatigue tests must be carried out.

3 Experimental analysis

3.1 Test specimen and materials

Material tests have been performed on different resins as well as static and cyclic tests on connections with non-preloaded and preloaded injection bolts. To characterize suitable resins first, hardness tests according to EN ISO 868 [8] and compression tests according to EN ISO 604 [9] were carried out on resin samples. In addition to the injection material Rengel SW404 with hardener HY2404 – which is initially recommended in ECCS No. 79 – the epoxy resins Biresin G33, Diamant MM1018 FL and Icosit KC 220/60 TX were selected for injection. The determined material parameters are summarized in Table 2 and can be seen as a selection criterion for other resins. Further, the applicability and filling capacity within the connection can be assessed by means of tests with plexiglass tubes.

Table 2 Material properties of the examined injection resins

resin	shore hardness Type D*	compressive strength $\boldsymbol{f_c}$* in N/mm²	compressive modulus $\boldsymbol{E_c}$* in N/mm²
Rengel	85-90 (87,6)	110-125 (130,2)	(8.412)
Biresin	90 (83,7)	120 (111,6)	(7.472)
MM1018	89 (85,7)	161	10.000
Icosit	(84,5)	–	–

* manufacturer specifications from the product data sheets, (…) test results according to EN ISO 868 and EN ISO 604 after 1 week of curing at room temperature (average of 5 test specimens)

The standard specimen according to EN 1090-2, Annex G and J for M20 bolts with steel plates S355 was used to determine the static and fatigue load bearing capacity of the connection. The steel surfaces were blasted to a preparation grade Sa 2 ½ on the one hand with round and on the other hand with angular blasting shots. The corresponding friction coefficients were determined in 3.3.

3.2 Static tests on connections with non-preloaded injection bolts

The static tests were performed according to EN 1090-2, Annex G and J. The tests comprise short-term tests, regular creep tests for the general assessment of the creep behavior and if necessary extended creep tests.

The short-term static load capacity of connections with non-preloaded injection bolts and thus the bearing resistance of the resin was determined with regard to a limit displacement of 0,15 mm according to EN 1090-2, Annex G. Therefore, the relative displacement of the outer and inner plates in the centre of the bolt group was evaluated. Exemplary load-deformation curves and the averaged test results for the bearing resistance of the different resins are shown in Figure 3. The specimens cured for about 24 h at room temperature (RT) before testing.

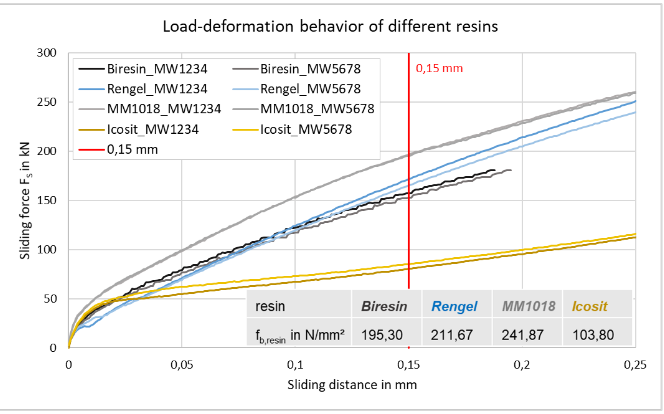

Figure 3 Comparison of the load-deformation behavior of injection bolts with different resins and mean bearing resistance related to a limit displacement of 0,15 mm according to EN 1090-2, Annex G

It can be evaluated that the resins Biresin and Rengel have nearly the same bearing resistance $f_{b,resin}$ of 195,3 N/mm² and 211,67 N/mm². The bearing resistance of the resin MM1018 with 241,87 N/mm² is even greater, which was already to be expected due to the increased compressive strength and compressive modulus. Despite almost the same Shore hardness, the resistance of Icosit with 103,80 N/mm² is significantly smaller and therefore no longer considered to be relevant for the application in injection bolts. In addition, this shows that only hardness is not suitable as a selection criterion for the resin.

In order to evaluate the influence of different curing temperatures and ambient temperatures after curing, further tests – limited to injection bolts with Rengel – were carried out. The minimum curing temperature was set to +5-7°C and the limit component temperatures to -20 and +70°C in accordance with EN 1991-1-5 [10] for steel bridges. The static test results are summarized in Table 3.

Table 3 Static bearing resistance of non-preloaded injection bolts with Rengel under different curing and ambient temperatures

test condition	$f_{b,resin}$* in N/mm²	percentage of $f_{b,resin,RT}$*
curing for 24h at 5-7°C	219,23	103,6%
curing for 48h at 5-7°C	238,48	112,7%
storage at -20°C after curing for 5d at RT	236,51	111,7%
storage at +70°C after curing for 5d at RT	225,82	106,7%

* mean values related to a limit displacement of 0,15 mm according to EN 1090-2, Annex G (1 specimen per test condition)

Consequently, the tested curing and ambient temperatures do not result in any reduction of the bearing resistance. Low temperatures can result in an increase of the stiffness of epoxy resins and high temperatures – of course below the decomposition temperature – can lead to post-curing, which is confirmed by these test results.

Since epoxy resins as a polymer tend to creep, the regular creep test according to EN 1090-2, Annex G could not be observed for each resin. This test prescribes a limit value for the increase in deformation of 0,002 mm for the period between 5 min and 3 h after the load application of 90% of the short-term resistance. Therefore, extended creep tests at different load levels were carried out in order to assess the long-term deformation. The limit displacement regarding the service life of 50 or 100 years is specified as 0,3 mm.

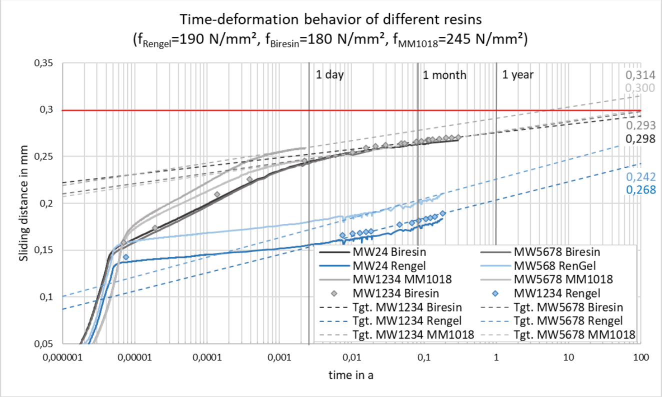

Figure 4 Comparison of the time creep behavior of non-preloaded injection bolts according to EN 1090-2, Annex G (black - Biresin, blue – Rengel, grey – MM1018)

Figure 4 shows the time-creep behavior of Biresin, Rengel and MM1018 at different bearing stresses. Due to the different bearing resistances, different utilization rates of the short-term resistance result. The tested stress levels vary between 90% and 100% of the bearing resistance of the resin. Extrapolated in a double-logarithmic scale, the limit displacement of 0,3 mm is observed for almost all tested resins and stress levels. For Biresin a bearing resistance of at least 180 N/mm² (92% $f_{b,resin}$) and for Rengel of 190 N/mm² (90% $f_{b,resin}$) can be assumed. Since the increase in deformation decreases with time, MM1018 with a bearing stress of 245 N/mm² (101% $f_{b,resin}$) would also have been successfully tested with longer test duration.

3.3 Static tests on connections with preloaded injection bolts

For the static tests on connections with preloaded injection bolts, only the injection resins Biresin and Rengel were considered. MM1018 was added to the test program later, the tests are still outstanding. The short-term static load capacity of the preloaded connections was also determined according to EN 1090-2, Annex G. The focus of the test evaluation was on the interaction of the bearing resistance of the resin and the slip resistance due to preloading. As already described in 2.3, EN 1993-1-8 allows an addition of both load bearing components. Therefore, for the verification of connections with injection bolts in category B and C the following applies:

$$F_{Rd,preload+resin} = F_{s,Rd} + F_{b,Rd,resin} \qquad (2)$$

The averaged test curves for preloaded connections with Biresin and Rengel as injection resin and different surface treatments are shown in Figure 5 and 6. For comparison, the load-deformation curves of non-preloaded injection bolts and HSFG bolts are also plotted. The mean values of the short-term bearing resistance related to a limit displacement of 0,15 mm are summarized in Table 4 and 5.

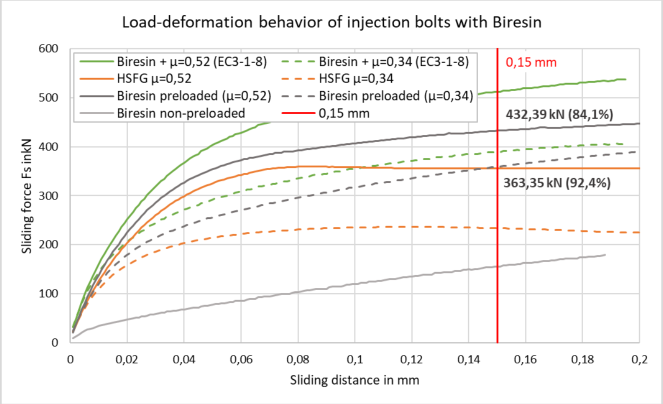

Figure 5 Load-deformation behavior of non-preloaded and preloaded injection bolts with Biresin (green - summation of slip resistance and bearing resistance, orange – slip resistance, grey - Biresin)

Table 4 Bearing resistance of preloaded injection bolts with Biresin in comparison to the individual load bearing due to preload and resin

Biresin	F_s* in kN	$F_{b,resin}$* in kN	$F_{p,resin}$* in kN
µ=0,34	237,15	156,24	363,35 (92,4%)
µ=0,52	357,70	156,24	432,39 (84,1%)

* mean values of 3 test specimens related to a limit displacement of 0,15 mm according to EN 1090-2, Annex G (F_s – slip resistance, $F_{b,resin}$ – bearing resistance of the resin, $F_{p,resin}$ – bearing resistance of the preloaded injection bolt)

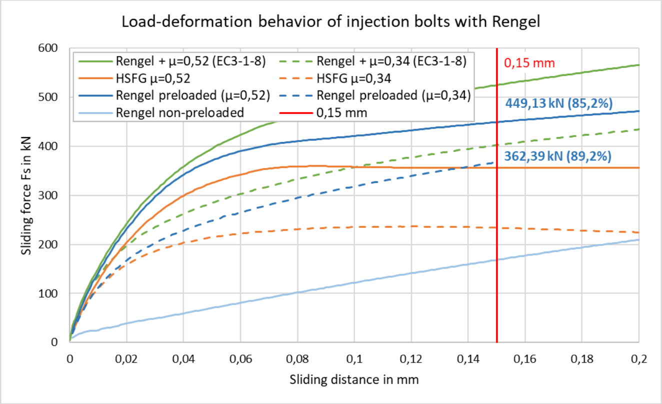

Figure 6 Load-deformation behavior of non-preloaded and preloaded injection bolts with Rengel (green - summation of slip resistance and bearing resistance, orange – slip resistance, blue - Rengel)

Table 5 Bearing resistance of preloaded injection bolts with Rengel in comparison to the individual load bearing due to preload and resin

Rengel	F_s* in kN	$F_{b,resin}$* in kN	$F_{p,resin}$* in kN
µ=0,34	237,15	169,34	363,85 (89,5%)
µ=0,52	357,70	169,34	449,13 (85,2%)

* mean values of 3 test specimens related to a limit displacement of 0,15 mm according to EN 1090-2, Annex G (F_s – slip resistance, $F_{b,resin}$ – bearing resistance of the resin, $F_{p,resin}$ – bearing resistance of the preloaded injection bolt)

It can be seen that the summed load bearing capacity of the resins and the preloading is not reached at a relative displacement of 0,15 mm. For a friction coefficient of 0,34 about 92,4% of the summed load capacity is achieved with Biresin and about 89,5% with Rengel. With increasing friction coefficient and in result increasing slip resistance, the proportion of the added bearing capacity decreases. For a friction coefficient of 0,52 only about 84,1% of the total bearing capacity remains with Biresin and about 85,2% with Rengel. Therefore, the design approach according to EN 1993-1-8 should be adjusted considering the individual load-deformation behavior of the connections. Suggested is a reduction of the slip resistance according to equation (3). Since a determination of k is not yet possible due to the small number of tests, it is conservatively recommended to set $k = 0{,}75$.

$$F_{Rd} = k \cdot F_{s,Rd} + F_{b,Rd,resin} \quad \text{with} \quad k = f(\mu\,; f_{b,resin}) \qquad (3)$$

In addition, the creep behavior according to EN 1090-2, Annex G was considered. Regular creep tests showed a greater creep tendency for Biresin than for Rengel. The preloaded connections with Rengel complied with the limit displacement of 0,002 mm. From the extended creep tests at 90% of the short-term bearing resistance and a friction coefficient of 0,34, the creep deformations are lower than with the non-preloaded injection bolts. The limit displacement of 0,3 mm is observed for both resins with an extrapolated displacement of 0,241 mm for the standard specimen with Biresin and 0,157 mm for the specimen with Rengel. Further investigations on different load levels and surface treatments are still outstanding.

3.4 Fatigue tests on connections with non-preloaded injection bolts

The major unknown in dynamically loaded connections with injection bolts is the fatigue behavior of the resin and its influence on the fatigue strength of the connection. Therefore, some aspects – such as the fatigue behavior – were included in the test program on injection bolts as part of the SIROCO project [11] in 2014. However, due to other test parameters, the fatigue tests were eliminated from the test program later. Thus, fatigue tests were carried out within the framework of the research project IGF-No. 21369 N.

As described in 2.3, the detail categories according to EN 1993-1-9 are defined for connections with non-preloaded and preloaded injection bolts. For non-preloaded injection bolts in double shear connections results detail category 90. First, the fatigue tests were used to confirm this category and secondly to determine the fatigue strength of the resins. The tests were performed with a stress ratio R=0,1 and at a frequency between 5 Hz and 10 Hz. From 5 million load cycles onwards, the tests were evaluated as fatigue-tested specimen without rupture. They were then tested at a higher stress level again, in ideal circumstances until failure.

When considering the six specimens tested with Biresin, only a maximum stress of 95% of the static bearing resistance of the resin led to fatigue failure of the connection at 3,4 million load cycles. Maximum stresses of 100% and 120% showed no failure after 5 million cycles. With Rengel, three of six tested specimens failed at a maximum stress of 90% (5,2 million cycles), 95% (2,2 million cycles) and 100% (3,2 million cycles) of the static bearing resistance. The test results are shown in the fatigue resistance curve in Figure 7.

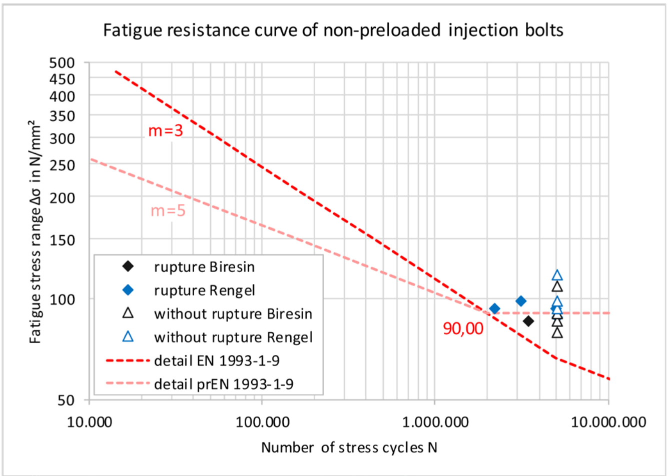

Figure 7 Fatigue test results of non-preloaded injection bolts with Biresin (black) and Rengel (blue) compared to the fatigue resistance curve according to EN 1993-1-9 and prEN 1993-1-9

Due to the relatively large number of fatigue-tested specimens without rupture, a statistical evaluation of $\Delta\sigma_c$ as the value for 2 million load cycles for a 75% confidence level of 95% probability of survival is not appropriate. As a result, the detail category according to EN 1993-1-9 is confirmed by the tests. It is noted that the preliminary draft prEN 1993-1-9 provides an adjustment of the slope parameter from m=3 to m=5 and a consideration of the stress distribution in the net cross section of the steel plates. The tests results are than all located above the adjusted fatigue resistance curve.

Furthermore, the fatigue failure of the resin was defined at a relative displacement of 0,3 mm at the center of the bolt group, in accordance to the extended creep tests. For the maximum stress a stress range of 90% to 120% of the short-term bearing resistance of the resin was tested. Since no significant increase in displacement occurred after 1 million load cycles, no fatigue failure appeared over several million load cycles. Exceeding the limit displacement of 0,3 mm was only possible due to the creep behavior of the resins. Therefore, no fatigue strength of the resins can be defined, creep deformation is decisive.

3.5 Fatigue tests on connections with preloaded injection bolts

The fatigue tests on connections with preloaded injection bolts were used to confirm the detail category 112 according to EN 1993-1-9. One test specimen per resin was tested at a maximum stress level of 100% of the static bearing resistance of the resins. No fatigue failure occurred for over 5 million load cycles. An increase of the maximum stress to 130% led to fatigue failure of the preloaded connection with Biresin at 866.130 cycles and for Rengel at 822.630 cycles. As the standard specimen according to EN 1090-2, Annex G is not really suitable for fatigue tests, the steel plate width was reduced from 100 mm to 80 mm for further tests to increase the stress range. The test specimen with Rengel at a maximum stress level of 100% of the static bearing resistance failed at about 3,1 million load cycles, Biresin could be evaluated as a fatigue-tested specimen without rupture again. The results are presented in Figure 8.

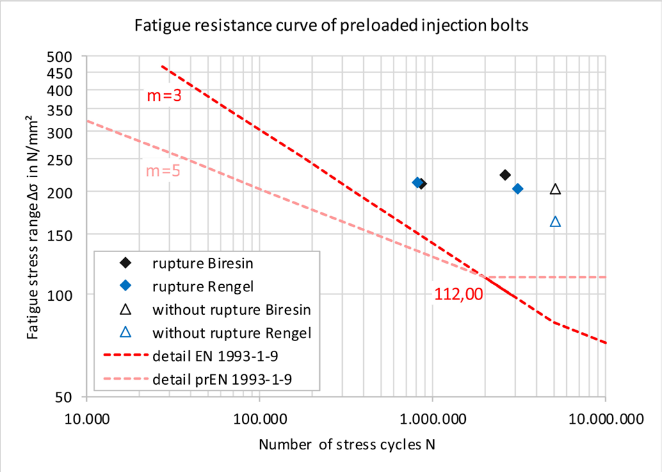

Figure 8 Fatigue test results of preloaded injection bolts with Biresin (black) and Rengel (blue) compared to the fatigue resistance curve according to EN 1993-1-9 and prEN 1993-1-9

Here as well, prEN 1993-1-9 provides an adjustment of the slope parameter from m=3 to m=5. The fatigue stresses are still to be evaluated in the gross section. Irrespective of this, the test results on preloaded connections with injection bolts are all located above the fatigue strength curve. Detail category 112 is therefore confirmed.

4 Conclusion and remarks

With the tests considered in the presented research project IGF-No. 21369 N, some open issues regarding the application of injection bolts were answered. The hardness, compressive strength and compressive modulus of the resins can be used as relevant selection criteria for other resins, in addition to the well-known epoxy system Rengel SW404 with hardener HY2404. The epoxy resins Sika Biresin G33 and Diamant MM1018 FL have proven to be suitable as well for the use in injection bolts. It is shown that different curing and ambient temperatures – that have to be expected on the structure – do not lead to a reduction of the bearing resistance of the resin Rengel.

In the case of preloaded connections with injection bolts, it became clear that the interaction of the bearing resistance of the resin and the slip resistance must be considered more detailed. The summation of both load-bearing components was not reached in the tests carried out. The utilization varies according to the bearing strength of the resin and the friction coefficient of the steel surfaces. An optimization of the design resistance therefore is part of the research project IGF-No. 21369 N.

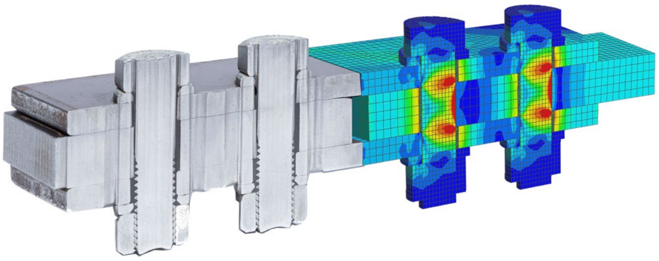

Figure 9 Section through a standard specimen with injection bolts in the experimental analysis (left) and the numerical simulation (right)

With the fatigue tests, the detail categories of the non-preloaded and preloaded connections with injection bolts according to EN 1993-1-9 could be confirmed. Since no fatigue failure of the resin occurred, no detail category could be determined for the resin. Several million load cycles only led to a small increase in relative displacements, creep deformations are therefore always decisive for long-term considerations. For further test results and numerical simulations of the experimentally tested connections (see Figure 9), reference is made to the research project IGF-No. 21369 N.

5 Acknowledgement

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References

[1] EN 1993-1-8 (2009) *Design of steel structures – Part 1-8: Design of joints*. CEN/TC 250, European Committee for Standardization, Brussels.

[2] EN 1993-1-9 (2009) *Design of steel structures – Part 1-9: Fatigue*. CEN/TC 250, European Committee for Standardization, Brussels.

[3] EN 1090-2 (2018) *Execution of steel structures and aluminium structures - Part 2: Technical requirements for steel structures*. CEN/TC 135, European Committee for Standardization, Brussels.

[4] Ungermann, D.; Kröger, L. (expected 2024) *Anwendung von Injektionsschrauben bei der Instandsetzung von dynamisch beanspruchten Stahlkonstruktionen*. DASt IGF-No. 21369 N, Düsseldorf.

[5] ECCS No. 79 (1994) *European Recommendations for Bolted Connections with Injection Bolts*. European Convention for Constructional Steelwork, Brussels.

[6] prEN 1993-1-8 (2021) *Design of steel structures – Part 1-8: Design of joints*. CEN/TC 250, European Committee for Standardization, Brussels.

[7] prEN 1993-1-9 (2023) *Design of steel structures – Part 1-9: Fatigue*. CEN/TC 250, European Committee for Standardization, Brussels.

[8] EN ISO 868 (2003) *Plastics and ebonite – Determination of indentation hardness by means of a durometer (Shore hardness)*. CEN/TC 249, European Committee for Standardization, Brussels.

[9] EN ISO 604 (2003) *Plastics – Determination of compressive properties*. CEN/TC 249, European Committee for Standardization, Brussels.

[10] EN 1991-1-5 (2009) *Actions on structures – Part 1-5: General actions – Thermal actions*. CEN/TC 250, European Committee for Standardization, Brussels.

[11] SIROCO (2019) *Execution and reliability of slip resistant connections for steel structures using CS and SS*. Research Fund for Coal and Steel (RFCS), Grant No. RFSR-CT-2014-00024, Duisburg-Essen.