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Non-preloaded and preloaded connections with injection bolts

Experimental and numerical investigations

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ABSTRACT

Slip-resistant connections can be realized with fitted bolts, high strength friction grip bolts and injection bolts. By filling the clearance of the bolt with curing resin, injection bolts offer advantages in terms of execution and design. Normative requirements for the design and execution of injection bolts are essentially available in EN 1993-1-8, EN 1993-1-9 and EN 1090-2. Various factors influencing the load-deformation behaviour of non-preloaded and preloaded injection bolts were investigated within the presented research project to complement these regulations. The epoxy resins Rengel, Biresin and MM1018 showed promising bearing resistances and were determined as suitable resins for the application in connections with injection bolts. Boundary conditions close to reality – such as thermal extremes, humidity and long-term effects – led to no significant reduction of the bearing capacity. The interaction between the bearing of the resin and friction in the case of a preloaded application was considered in experimental and numerical investigations. In addition, fatigue failure of the resin could be precluded and the given detail categories confirmed independently of the resin.

Keywords: bolted connections, injection bolts, epoxy resin

1 INTRODUCTION

For the (replacement) building of new bridges as well as the maintenance and strengthening of existing bridge structures, the joining of individual structural components is necessary. Due to dynamic traffic loads, these joints have to be designed slip-resistant. Slip-resistant connections can be realized with fitted bolts, high strength friction grip (HSFG) bolts and injection bolts. By filling the clearance of the bolt with resin (see Fig. 1), the need for reaming the holes for fitted bolts or the surface treatment – including blasting and coating – for HSFG bolts can be omitted for injection bolts. A preloaded application combines the bearing capacity of the resin and the slip resistance arising from the preload. This type of connection therefore offers advantages in terms of execution and design.

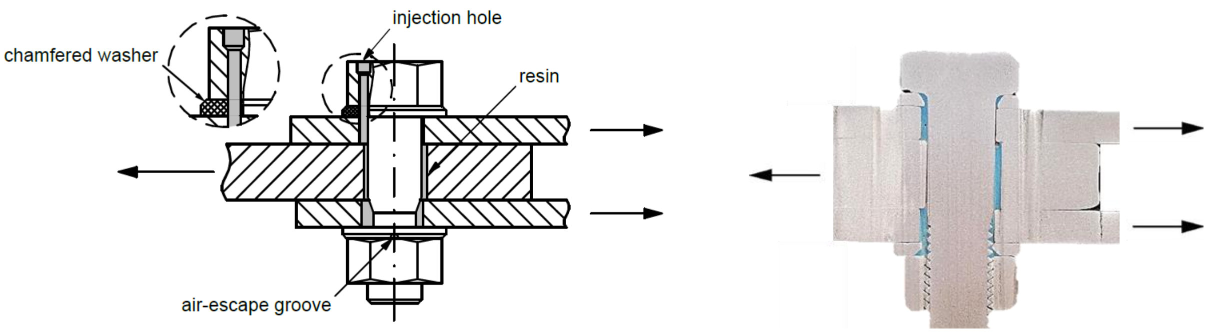

Fig. 1. Section through a double shear connection with injection bolt according to EN 1090-2, Annex J (left) and as a waterjet cut through a test specimen with blue injection resin (right)

The design of connections with non-preloaded and preloaded injection bolts is essentially regulated in EN 1993-1-8 and EN 1993-1-9, requirements for the execution are defined in EN 1090-2, Annex J. However, due to open issues regarding material criteria of the resin and execution, injection bolts are classified as special fasteners according to EN 1090-2. This currently limits the user-friendliness and number of successful application cases, despite the mentioned advantages of the connection type.

Experimental and numerical investigations were carried out within the framework of the research project IGF-No. 21369 N to answer open issues. First, selection criteria for suitable resins were defined. Varying curing temperatures and ambient temperatures as well as humidity conditions were considered as realistic boundary conditions for the application in steel structures. By changing the bearing strength of the resin and the friction coefficient of the surface – the relevant parameters for the individual load-bearing resistances – the stiffness dependent load-deformation behaviour could be investigated. The current results of non-preloaded and preloaded connections with injection bolts will be presented within the paper.

2 EXECUTION AND DESIGN OF INJECTION BOLTS

2.1 Recommendations according to ECCS No. 79

Fundamental research on the design and execution of connections with injection bolts was carried out by TU Delft in the 1970s and 1980s and published in the European Recommendations for Bolted Connections with Injection Bolts in ECCS No. 79 (1) in 1994. These recommendations include application examples, design and execution specifications as well as test procedures for the determination of the bearing resistance of the resin. The investigations of TU Delft are essentially based on the epoxy resin Rengel® SW404/HY2404 (formerly Araldit®), but the regulations for design and execution were defined independently of the resin. The main specifications compiled in the ECCS recommendations have been adopted almost unchanged in EN 1993-1-8, EN 1993-1-9 and EN 1090-2. Some aspects such as temperature and fatigue were considered more extensively, individual criteria of the test programs also differ in some instances. However, it is remarked that EN 1090-2 still refers to ECCS No. 79 for further information.

2.2 Execution according to EN 1090-2

The execution of injection bolts is regulated in EN 1090-2 (2), Annex J. Injection bolts can be applied with or without preload, in the case of a preloaded application the bolts must be tightened before the injection. For a successful injection a special machined bolt assembly is required, 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 as shown in Figure 1. A two-component system – usually epoxy resin – should be used for injection. To enable a successful filling of the bolt clearance, the resin should have an appropriate viscosity and pot life, exact selection criteria are not defined. The corresponding design bearing strength of the resin stress should be determined by tests according to EN 1090-2, Annex G, which results in the same test procedure as for the determination of the slip factor for HSFG bolts. This test procedure is described in more detail in 3.1 and 3.2.

2.3 Design according to EN 1993-1-8 and EN 1993-1-9

Injection bolts according to EN 1993-1-8 (3) are assigned to bolted connections loaded in shear, thus category A, B and C depending on the bolt preload. Each category specifies the design method, an additional load-bearing capacity results from the design bearing resistance of the resin $F_{b,Rd,resin}$, which is defined as follows:

$$F_{b,Rd,resin} = \frac{k_t \cdot k_s \cdot d \cdot t_{b,resin} \cdot \beta \cdot f_{b,resin}}{\gamma_{M4}} \qquad Eq.\ (1)$$

The factor k_t takes into account the limit state (1,0 for SLS and 1,2 for ULS) and therefore the load duration and k_s the bolt clearance (1,0 for holes with normal clearance, $(1{,}0 - 0{,}1 \cdot m)$ for oversized holes with m as the difference between the normal and oversized hole dimension). d is the bolt diameter, $t_{b,resin}$ the effective bearing thickness and β a factor that considers the thickness ratio of the plates. The bearing strength of the resin $f_{b,resin}$ has to be determined according to EN 1090-2, Annex J. The partial safety factor γ_{M4} is recommended as 1,0 because a sudden collapse of a structure with injection bolts due to failure of the resin cannot occur. The input parameters mainly depend on the geometry of the connection and the bearing strength of the resin. The exact parameters and design equations can be found in EN 1993-1-8. The design methods corresponding to the category of bolted connection are compiled in Table 1. In the case of a preloaded connection in category B or C the bearing resistance of the resin $F_{b,Rd,resin}$ can be added to the slip resistance $F_{s,Rd}$ at serviceability limit state or ultimate limit state. In the revision of the Eurocodes an unchanged adaption of this design approach is intended (4).

Table 1. Verification at 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	$F_{v,Ed} \leq F_{v,Rd}$ $F_{v,Ed} \leq F_{s,Rd} + F_{b,Rd,resin}$	–

Note: Design method is adopted unchanged in prEN 1993-1-8.

The fatigue strength of connections with injection bolts is regulated in EN 1993-1-9 (5), the detail categories are listed in Table 2. In terms of fatigue, connections with non-preloaded injection bolts are equated with fitted bolts and connections with preloaded injection bolts with HSFG bolts. The given detail categories in EN 1993-1-9 as well as in the current revision prEN 1993-1-9 (6) do not contain any information regarding the fatigue strength of the injection resin itself. It is noted that the ECCS recommendations included some remarks regarding additional fatigue tests with evaluation of the relative displacement.

Table 2. Detail categories for bolted connections according to EN 1993-1-9

	fitted bolts	injection bolts without preload	slip resistant connections	injection bolts with preload
single shear	80	80	90	90
double shear	90	90	112	112

Note: Detail categories are adopted unchanged in prEN 1993-1-9, adjustment of the parameter m and stress range Δσ with stress concentration factor is intended.

3 EXPERIMENTAL INVESTIGATIONS

3.1 Test specimen and materials

Different material tests have been carried out on resin samples as well as static and cyclic tests on double shear connections with injection bolts. Hardness and compression tests were performed to characterize selected resins first. Shore hardness Type D, compressive strength and compressive modulus of a certain magnitude proved to be suitable and comparable selection criteria. The epoxy resins Rengel® SW404 with hardener HY2404 (initially suggested in the ECCS recommendations), SikaBiresin® G33 and Diamant® MM1018 FL were selected for further investigations. Additional tests with plexiglas tubes demonstrated a good applicability and filling capacity of each resin.

For the determination of the static and cyclic load bearing capacity of the s standard specimen according to EN 1090-2, Annex G and J with steel plates S355 (static and cyclic tests) and S460 (only static tests) were used. The plate surfaces were blasted to a preparation grade Sa 2 ½ with round and angular blasting shots to achieve different surface conditions. Further details can be found in 3.3. The bolts M20, 10.9 were snug-tightened with 30 Nm or tightened to the nominal minimum preloading force $F_{p,C}$ using a calibrated torque method (60/325/475 Nm).

3.2 Static tests on non-preloaded connections with injection bolts

After material characterization, static tests were performed according to EN 1090-2, Annex G and J to determine the bearing strength of the resins. The test procedure comprises four short-term tests, one regular creep test for the general assessment of creep behaviour and if ascertained at least three extended creep tests. The load-deformation behaviour as well as the time-deformation behaviour have to be evaluated. The upper connection (MW1234) and lower connection (MW5678) of each test specimen have to be considered separately, therefore the relative displacement of the outer and inner plates in the centre of the bolt group has to be determined. Full details of the specimens, used measurement and test procedure can be found in (7).

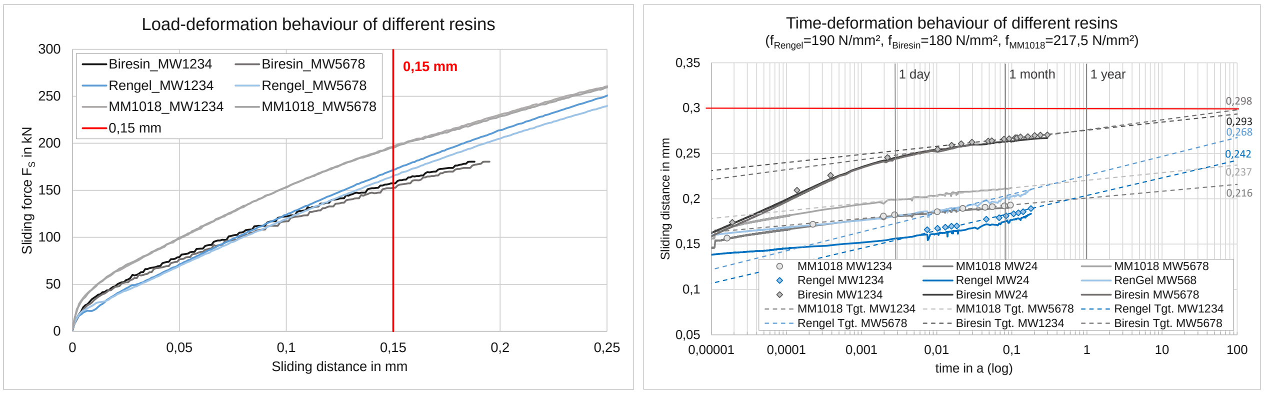

Fig. 2. Comparison of the load-deformation behaviour (left) and comparison of the time-deformation behaviour (right) of non-preloaded injection bolts with different resins according to EN 1090-2, Annex G

The short-term static load capacity was determined with regard to a limit displacement of 0,15 mm according to EN 1090-2, Annex G. The specimens were snug-tightened before injection and cured for about 24 h at room temperature. Exemplary load-deformation curves of Rengel, Biresin and MM1018 are shown in Figure 2 (left) and the resulting bearing strength of the resins are listed in Table 3.

Table 3. Results of static tests on non-preloaded connections with injection bolts

Resin	$F_{b,resin,m}$ in kN	$f_{b,resin,m}$ [1)] in N/mm²	$f_{b,resin}$ [2)] in N/mm²
Rengel	169,34	211,7	190,0 (90%)
Biresin	156,03	195,0	180,0 (92%)
MM1018	193,50	241,9	217,5 (90%)

1) mean values related to a limit displacement of 0,15mm acc. to EN 1090-2, Annex G (4 specimens per resin)
2) since extended creep testing was required, the nominal bearing strength is the value demonstrated to satisfy the specified creep limit

Since epoxy resins are polymers and tend to creep, creep tests are decisive. The regular creep test, which 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, could not be observed for all resins. Therefore, extended creep tests were necessary to consider long-term effects. According to EN 1090-2, Annex G a limit displacement regarding the service life of 50 or 100 years is specified as 0,3 mm. Exemplary time-deformation curves of Rengel, Biresin and MM1018 are shown in Figure 2 (right). The limit displacement of 0,3 mm is observed for all tested resins. The maximum tested stress levels vary between 90% and 92% of the static bearing resistance of the resin and define the nominal bearing strength $f_{b,resin}$ (see Tab. 3).

In addition to these static tests with resins cured under room temperature, different boundary conditions for further static tests were considered. The influence of low curing temperatures (5-7°C), temperature extremes (-20°C and +70°C), humidity (80-100% rH) and outdoor exposure (2 weathering periods) were investigated on non-preloaded connections. The resulting bearing strength of the resins Rengel, Biresin and MM1018 in relation to the bearing strength at room temperature are summarized in Table 4. The tested curing and ambient temperatures as well as humidity and weathering conditions do not result in any significant reduction of the bearing resistances. An extended curing time is recommended for connections with Biresin and MM1018 at curing temperatures below 10°C. In general, low temperatures can result in an increase of the stiffness of epoxy resins and high temperatures can lead to post-curing, which can be seen as confirmed by these test results.

Table 4. Results of static tests on non-preloaded connections with injection bolts under different boundary conditions

Resin	Test conditions	$f_{b,resin}$ 1) in N/mm²	Percentage of $f_{b,resin,RT}$ 2)
Rengel	curing for 24h at 5-7°C	219,2	103,5%
	curing for 48h at 5-7°C	238,5	112,7%
	storage at -20°C after curing for 5d at RT	236,5	111,7%
	storage at +70°C after curing for 5d at RT	225,8	106,7%
	weathering for 1 1/2 years (-10/+40°C, 40-100% rH) after curing at RT	234,2*	110,6%
	storage and curing for 42h under cold and wet conditions (5-10°C, 80-100% rH) 3)	266,4*	125,8%
Biresin	curing for 24h at 5-7°C	86,8	44,5%
	curing for 48h at 5-7°C	215,6	110,6%
	storage at -20°C after curing for 5d at RT	204,4	104,8%
	storage at +70°C after curing for 5d at RT	205,1	105,2%
	weathering for 1 1/2 years (-10/+40°C, 40-100% rH) after curing at RT 3)	237,3*	121,7%
MM1018	curing for 24h at 5-7°C	49,2	20,3%
	curing for 48h at 5-7°C	215,3	89,0%
	storage at -20°C after curing for 5d at RT	235,8	97,5%
	storage at +70°C after curing for 5d at RT	206,8	85,5%

1) mean values related to a limit displacement of 0,15mm acc. to EN 1090-2, Annex G (1 specimen per test condition, *) 2 specimens per test condition)
2) static bearing strength of the resin under room temperature (RT), see Tab. 3
3) tightened with 60 Nm acc. to DASt 024 (8) instead of 30 Nm acc. to ECCS No. 79

3.3 Static tests on preloaded connections with injection bolts

Static tests on preloaded connections with three different resins leading to different bearing strengths $f_{b,resin}$ and two different surface treatments resulting in two different slip factors μ were carried out to investigate the interaction of the bearing resistance of the resin and the slip resistance due to preloading. Focus of the test evaluation was on the design specifications according to EN 1993-1-8, which imply an addition of both load bearing components for category B and C connections. Exemplary load-deformation curves for preloaded connections with Rengel and Biresin are shown in

Figure 3, for comparison the load-deformation curves of non-preloaded injection bolts and HSFG bolts are also plotted.

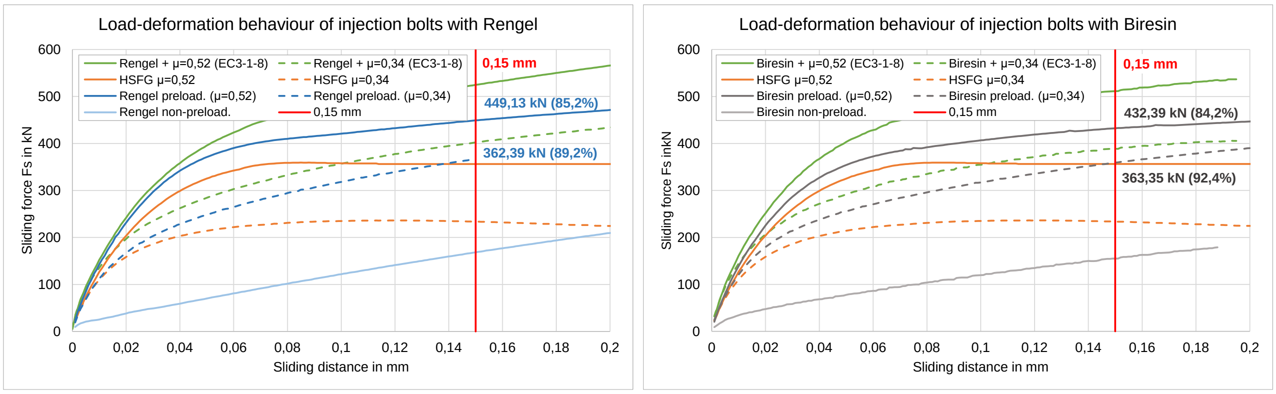

Fig. 3. Load-deformation behaviour of non-preloaded and preloaded injection bolts with Rengel (left) and Biresin (right), green – summation of slip resistance and bearing resistance, orange – slip resistance, blue/grey – resin

Table 5 contains the mean values of the short-term bearing resistance related to a limit displacement of 0,15 mm. The summed load bearing capacity of the resin and the preload is not reached, the proportional values vary between 84,2% and 92,4%. It can be seen that with increasing slip factor and corresponding slip resistance the percentage $F_{0,15,m}/F_{sum}$ decreases.

Table 5. Results of static tests on preloaded connections with injection bolts

Resin	μ	F_{Sm} in kN	$F_{b,resin,m}$ in kN	$F_{0,15,m}$ in kN	F_{sum} in kN	Percentage $F_{0,15,m}/F_{sum}$
Rengel	0,34	237,15	169,34	362,39	406,49	89,2%
	0,52	357,70		449,13*	527,04	85,2%
Biresin	0,34	237,15	156,03	363,35	393,18	92,4%
	0,52	357,70		432,39*	513,73	84,2%
MM1018	0,34	237,15	193,5	381,79	430,65	88,7%
	0,58	417,35*		515,65*	610,85	84,4%

Note: mean values related to a limit displacement of 0,15mm acc. to EN 1090-2, Annex G (at least 3 specimens per test condition, *) 1 or 2 specimens per configuration)

The tests were evaluated regarding the interaction of the load bearing components for a design approach considering the individual load-deformation behaviour of the different connection types. As there is a reduced value of the total load bearing components, the following options for including a reduction factor are considered:

$$F_{Rd} = k_1 \cdot (F_{s,Rd} + F_{b,Rd,resin}) \quad \text{with} \quad k_1 = f(\mu\,; f_{b,resin}) \qquad \text{Eq. (2)}$$

$$F_{Rd} = k_2 \cdot F_{s,Rd} + F_{b,Rd,resin} \quad \text{with} \quad k_2 = f(\mu\,; f_{b,resin}) \qquad \text{Eq. (3)}$$

$$F_{Rd} = F_{s,Rd} + k_3 \cdot F_{b,Rd,resin} \quad \text{with} \quad k_3 = f(\mu\,; f_{b,resin}) \qquad \text{Eq. (4)}$$

The factors k_1, k_2 and k_3 were first recalculated in accordance with the test results and then approximated using different (stiffness related) approaches. These suggested approaches partly take into account the decisive influencing factors $f_{b,resin}$ and μ or rather $F_{b,Rd,resin}$ and $F_{s,Rd}$. The values determined are listed in Table 6.

Table 6. Different approaches for possible reduction factors k_1, k_2 and k_3

Resin	μ	$k_{1,test}$	$k_{2,test}$	$k_{3,test}$	$k_1 = \left(\frac{F_S}{F_S+F_{b,resin}}\right)^{0,1}$	k_2 = fixed value	$k_3 = F_S/F_{b,resin}$
Rengel	0,34	0,892	0,814	0,740	0,877 (98,4%)	0,80 (99,1%)	0,714 (98,8%)
	0,52	0,852	0,782	0,540	0,843 (99,0%)	0,80 (101,4%)	0,473 (97,5%)
Biresin	0,34	0,924	0,794	0,747	0,871 (94,3%)	0,80 (95,2%)	0,659 (103,5%)
	0,52	0,841	0,772	0,508	0,836 (99,4%)	0,80 (102,3%)	0,437 (98,3%)
MM1018	0,34	0,887	0,873	0,808	0,887 (100 %)	0,80 (100,4%)	0,816 (93,6%)
	0,58	0,844	0,772	0,478	0,842 (99,7%)	0,80 (102,3%)	0,464 (98,5%)
mean		0,873	0,801	0,637	98,5%	100,1%	98,4%
CV		3,42%	4,41%	20,6%	1,98%	2,46%	2,93%

Note: Values for k are determined with mean values related to a limit displacement of 0,15mm, see Tab. 5. Conformance with the test results is specified by the values in brackets (…).

However, it should be noted that the design specifications according to EN 1993-1-8 do not directly imply a limit displacement of 0,15 mm, which is only specified in EN 1090-2, Annex G. The summed load bearing capacity will be achieved with larger relative displacements, failure will not occur in this order of magnitude. Additionally, it should be considered that all evaluated bearing resistances are at mean level, variances and characteristic values are not yet included. Characteristic values might lead to different factors and ratios. An extensive evaluation can be found in (7).

3.4 Fatigue tests on connections with injection bolts

Fatigue tests were performed on standard specimens in accordance with EN 1090-2, Annex G (S355, M20, 10.9) to investigate the fatigue strength of (preloaded) connections with injection bolts. The tests were carried out with the resins Rengel and Biresin, test data for MM1018 is not yet available. The stress ratio was set to R=0,1 and the test frequency ranged between 5 Hz and 10 Hz. The maximum load was set to 90% to 130% of the static bearing capacity. The test results were evaluated according to the detail categories specified in EN 1993-1-9 and prEN 1993-1-9, as presented in Table 2. From 5 million load cycles onwards, the tests were classified as fatigue-tested specimens without rupture and then tested at a higher stress level again. The results for non-preloaded and preloaded connections are shown in the fatigue resistance curves in Figure 4.

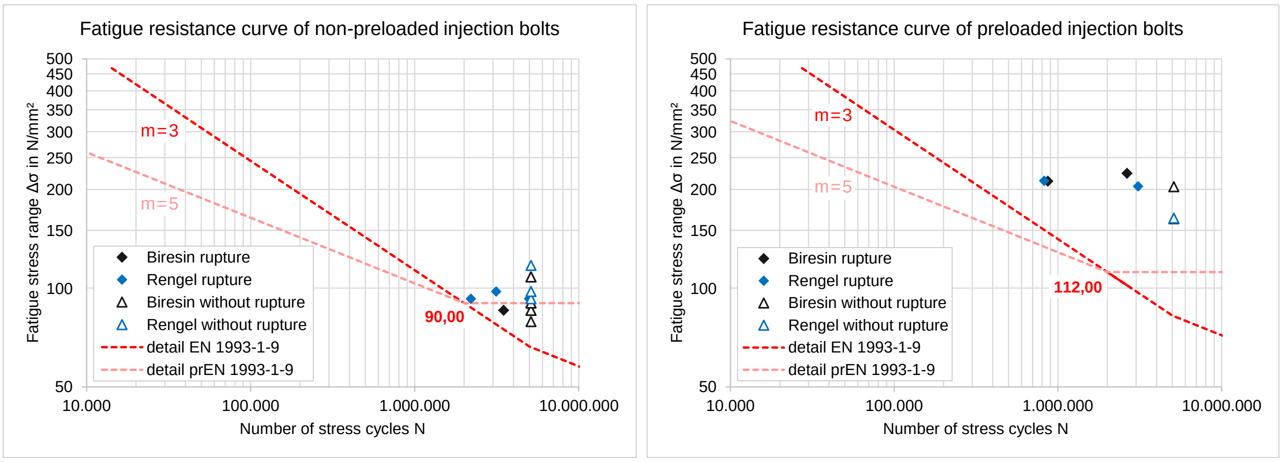

Fig. 4. Fatigue test results of non-preloaded injection bolts (left) and preloaded injection bolts (right) with Biresin (black) and Rengel (blue) compared to the fatigue resistance curves according to EN 1993-1-9 and prEN 1993-1-9

Despite large scattering of the test results combined with a low number of tests and a relatively large number of fatigue tested specimen without rupture, the detail categories could be confirmed independently of the injection resin. The amendments in prEN 1993-1-9 for non-preloaded connections with injection bolts will raise the tested stress ranges, as stress concentration factors will be taken into account. An adjustment of the slope parameter will have no effect on the classification of the presented test results.

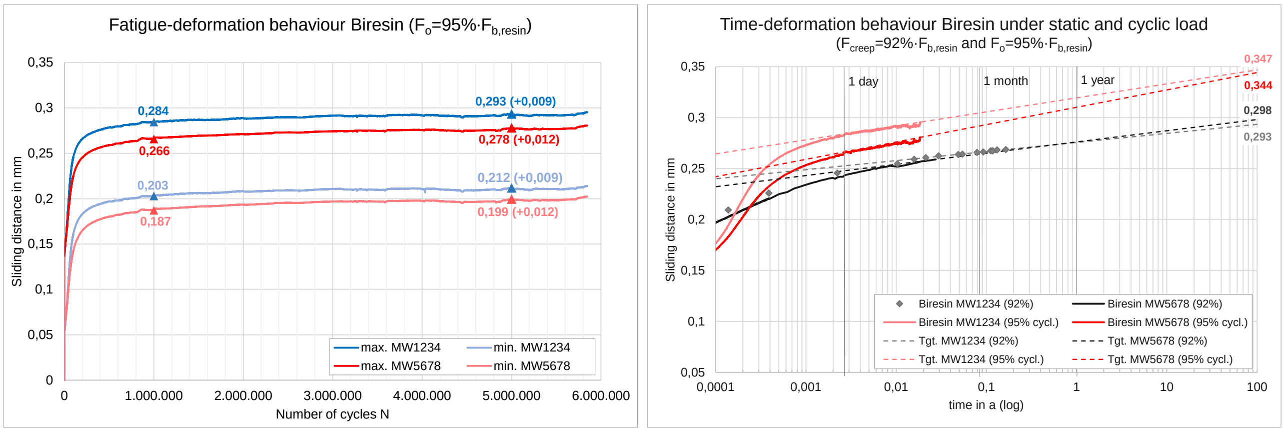

Fig. 5. Fatigue-deformation behaviour (left) and resulting time-deformation behaviour (right) of non-preloaded injection bolts with Biresin under a maximum load F_o=95%·$F_{b,resin}$ with a stress ratio R=0,1

In addition, the tests were used to determine the fatigue strength of the resin, which is not defined in ECCS No. 79 or EN 1993-1-9. Since no fatigue failure of the resins could be recognized after disassembly of exemplary specimens, fatigue failure was defined at a relative displacement of 0,3 mm at the centre of the bolt group, in accordance to the extended creep tests defined in EN 1090-2, Annex G. The non-preloaded connections showed no significant increase in displacement after 1 million load cycles (see Fig. 5, left), so no fatigue failure appeared over several million load cycles. Exceeding the limit displacement of 0,3 mm was only possible due to high load-deformations during the first load cycles or due to the creep behaviour of the resins. Thus, no fatigue strength of the resins can be defined, creep deformation is decisive. Figure 5 (right) shows the time-deformation behaviour under cyclic loads compared to the deformations in an extended creep test with nearly the same maximum load. It can therefore be stated that the maximum load of a fatigue action causes similar creep deformations as those resulting from static creep tests with constant loading.

4 NUMERICAL INVESTIGATIONS

4.1 Numerical model and input parameters

Numerical investigations were carried out to extend the results from the experimental tests. For this purpose, a numerical model was created using the simulation software ANSYS Workbench 2023 R1. For the numerical model the same specimen dimensions were selected as for the experimental investigations. To reduce the amount of data as well as computing time, the double symmetric specimen was reduced to one quarter. For the steel plates (S355) and the bolts (M20, 10.9) as well as the resin bilinear isotropic hardening was defined. Material parameters are based on manufacturer specifications or test results. The input parameters are summarized in Table 7.

Table 7. Input parameters for the selected material models

Material	Young's modulus in N/mm²	Poisson's ratio	Yield strength in N/mm²	Tangent modulus in N/mm²
Steel plates S355	210.000	0,3	355,0	10,0
M20, 10.9	210.000	0,3	900,0	10,0
Rengel	7.036,65	0,3	113,85	10,0
Biresin	6.512,06	0,3	107,98	10,0

Since the preloaded connection and even the non-preloaded connection due to snug-tightening have a bolt preload, the preload is defined in a separate load step. The ANSYS tool 'Contact Step Control' enables different contact types for these two load steps – preload and displacement-controlled loading – so that the preload results in no stresses for the resin. The bolts were modelled according to model class III in VDI 2230-2 (9). The friction coefficient of the surfaces was set to 0,2 for the non-preloaded connection. For the preloaded connections the friction coefficient was defined based on the test results on connections with HSFG bolts (see Tab. 5).

4.2 Validation of the numerical model

For validation of the numerical model, the tests on non-preloaded connections with Rengel and Biresin, the connections with HSFG bolts and the preloaded connections with Rengel and Biresin were modelled. Both experimentally determined slip factors were taken into account. For comparison with the experimental test results, the relative displacement of the outer and inner plates in the centre of the bolt group were evaluated. The numerical load-deformation curves in comparison to the experimental results are shown in Figure 6.

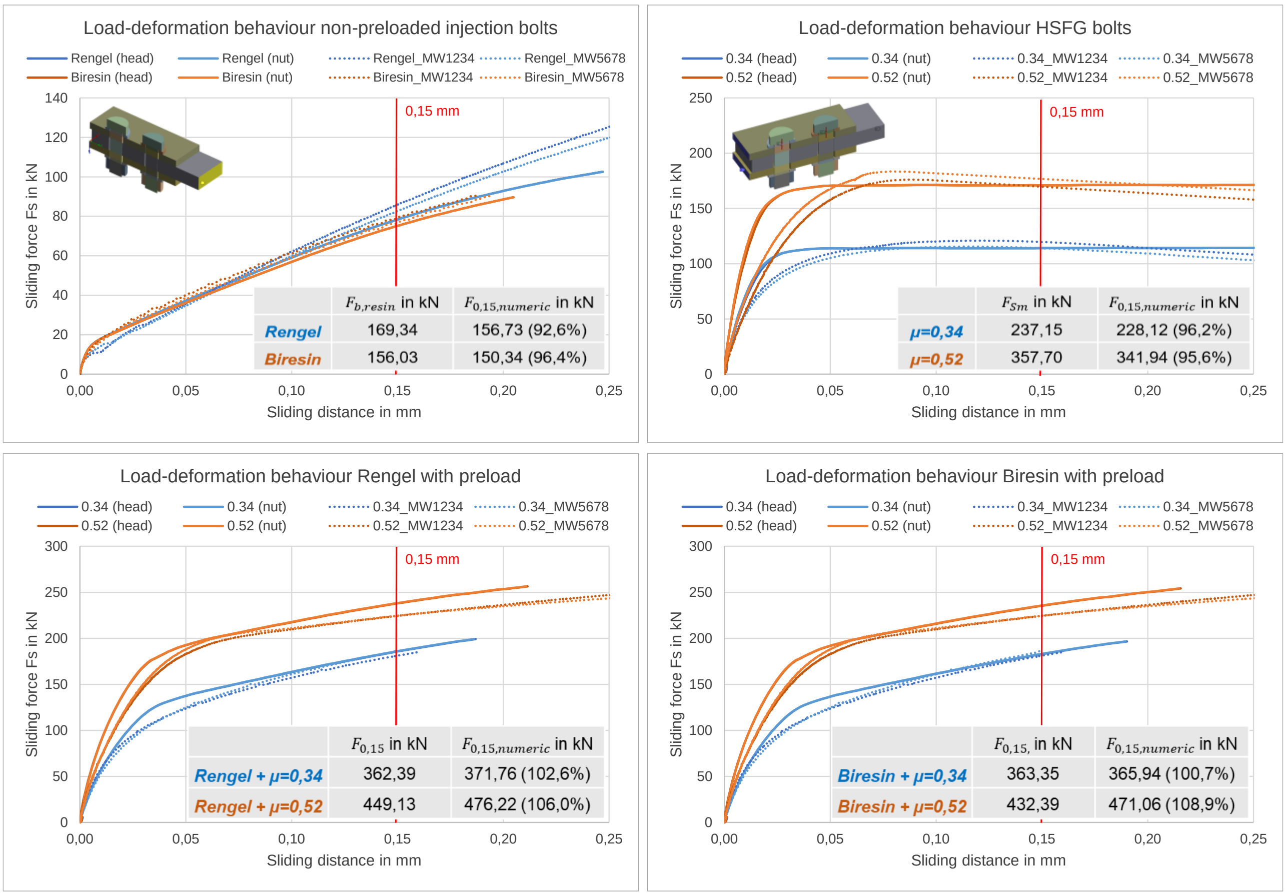

Fig. 6. Comparison of the load-deformation behaviour of non-preloaded injection bolts (top left), HSFG bolts (top right) and preloaded injections bolts with Rengel (bottom left) and Biresin (bottom right) in simulations and tests

The load-bearing capacity defined at a relative displacement of 0,15 mm is achieved with a sufficient accuracy, the values deviate by around ± 9%. In addition, the characteristic load-deformation behaviour is consistent with the experimental investigations. The stiffness of the non-preloaded connection with injection bolts appears to be lower, which could probably be compensated with a different material model that includes hardening in the case of confinement. At the same time, the modelled HSFG bolts seem to be stiffer at small displacements. This can maybe be justified with neglected aspects of the tribological systems. Preload losses and settling effects were not taken into account yet. This difference in stiffness also affects the preloaded-connections with injection bolts.

The difference between the numerical and experimental results increases with increasing slip factor or rather slip resistance. Nevertheless, the numerical model can be seen as validated and enables stress analysis and parameter studies. Geometric factors (resin thickness or clearance, bolt length etc.) and material parameters (Young's modulus, compressive strength, surface conditions etc.) are of major interest, particularly with regard to the design and execution specifications.

5 CONCLUSION

The presented investigations enable a deeper knowledge of the behaviour and the execution of injection bolts. As a research result the existing regulations for design and execution could be complemented and improved. The resins Rengel, Biresin and MM1018 were determined as suitable resins for the application in connections with injection bolts, tested under realistic boundary conditions. In the case of a preloaded application, the load-deformation behaviour can only be described stiffness related to the different load-bearing components. This can be investigated further using numerical simulations, a validated numerical model has been created. For further information, reference is made to the full research report in (7).

6 ACKNOWLEDGMENT

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