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DOI
10.1002/stco.201710042

Publication date
2017

Document Version
Final published version

Published in
Steel Construction - Design and Research

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The RFCS project SIROCO (2014–17) included research on the further development and optimization of double shear connections with injection bolts to achieve slip- and creep-resistant bolted connections considering various influencing parameters. The type of resin, the curing condition of the resin, the geometrical and mechanical characteristics of the connection and the type of loading were studied. Results showed, for example, that of the five epoxy resins investigated, only RenGel SW404 + HY2404 (Araldite) fulfils the requirements given in Eurocode 3. A bearing stress of 175 MPa is safely allowable in the long-term without exceeding imposed deformation limits.

1 Introduction

Injection bolts may be used in shear connections as an alternative to fitted bolts, rivets or preloaded high-strength friction bolts. Injection bolts are bolts in which the cavity produced by the clearance between the bolt and the wall of the hole is completely filled with a two-component resin. Filling of the clearance is carried out through a small hole in the head of the bolt.

After injection and complete curing of the resin, the connection is slip-resistant. Load transfer may occur through shear and bearing (non-preloaded injection bolts) or through shear and bearing plus friction (preloaded injection bolts). In over 50 years of applications, injection bolted connections have performed well. There are no known cases of bad experience. Continuing research and the development of design rules and rules for execution in the Eurocodes have contributed to an increase in the numbers of applications. Recent publications including experimental and numerical research [7], [8], [9] have recommended modifying the current European regulations with respect to connections with injection bolts. The RFCS project SIROCO (2014–17) [11] included research on the further development and optimization of connections with injection bolts to achieve slip- and creep-resistant bolted connections while considering various influencing parameters. This paper describes the state of the art regarding regulations and recent research on injected bolts carried out before the SIROCO project started. Following an overview of the test programme for double shear connections with injection bolts, including all relevant test parameters as performed within the SIROCO project, a preliminary analysis of the test results will be presented.

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2 State of the art regarding regulations and research on injection bolts

The current regulations regarding injection bolts are laid down in EN 1993-1-8 [2] and EN 1090-2 [3]. The former discusses the calculation rules for the design resistance of a connection with injected bolts, whereas the latter provides execution information on the detailing of the bolt and the bolt hole itself.

2.1 Connection components

In principle, all fasteners of steel grades 8.8 and 10.9 allowed for preloaded and non-preloaded connections may be used in resin-injected bolted connections. Such fasteners are laid down in EN 14399 [4] and EN 15048 [5] respectively. In order to be able to inject the bolted assembly with resin, a hole is included in the head of the bolt, as indicated in Fig. 1 (for hole dimensions see Annex K of EN 1090-2). Where the bolts are designed to be preloaded, tightening should be carried out before injecting the resin.

The use of special washers under both head and nut is prescribed for resin-injected bolted connections. The washers must fulfil the requirements of EN 1090-2, Annex K. The washer under the head of the bolt promotes easy ingress of resin into the open space between bolt and plate package, whereas the washer under the nut includes a groove through which the air can escape during the injection of the resin.

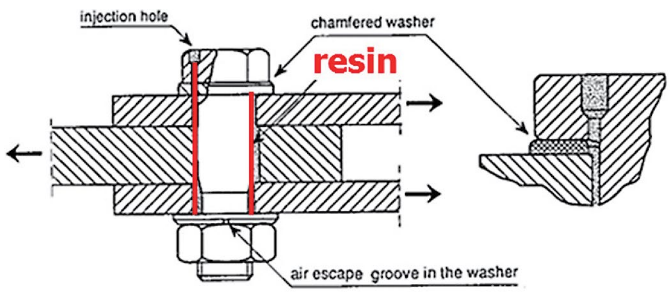


Fig. 1. Injection bolt in a double lap joint

The provisions regarding the hole diameter for injected assemblies are the same as for regular bolted assemblies and are laid down in Table 11 of EN 1090-2. The nominal diameter of the holes in the clamping package must be 3 mm larger than the nominal bolt diameter. An exception applies to bolts smaller than M27; in this case the minimum nominal hole diameter may be reduced to 2 mm larger than the nominal bolt diameter.

EN 1090-2, Annex K, prescribes that a two-component epoxy resin with a pot life of at least 15 min should be used to inject the bolted assembly. The type of resin itself is not further defined; however, end result specifications apply: The resin should fill all cavities in the connection and stop flowing after removal of the injection pressure. Current practice is the two-component epoxy resin Araldite SW404 with HY2404 hardener, now available as RenGel SW404 with RenHY2404 [7].

2.2 Design resistance

Static resistance

The static design resistance of a resin-injected bolted connection depends on the connection category. In the case of a non-loaded injected shear connection (cat. A), the design resistance of a bolt is the smallest value of the design shear resistance $F_{v,Rd,A}$ of the bolt (Eq. (1)) and the design bearing resistance $F_{b,Rd,resin}$ of the resin (Eq. (2)):

$$F_{Rd,A} = \min\left(F_{b,Rd,resin,}F_{v,Rd}\right) \quad (1)$$

$$F_{b,Rd,resin} = (k_t \cdot k_s \cdot d \cdot t_{b,resin} \cdot \beta \cdot f_{b,resin})/\gamma_{M4} \quad (2)$$

where:

k_t = 1.0 for SLS (long duration) or 1.2 for ULS

k_s = 1.0 for holes with normal clearances or 1.0–0.1m for oversized holes

m difference (in mm) between normal and oversized hole dimensions (for short slotted holes, m is half of the difference between slot length and width [1])

d bolt diameter

$t_{b,resin}$ length over which the resin is considered to be effective ($t_{b,resin}$ and β have a value as a function of ratio t_1/t_2 in double shear connections)

$F_{b,resin}$ bearing strength of the resin, to be determined using Annex G of EN 1090-2

In the case of a preloaded injected shear connection (cat. B/C), the design resistance is the sum of the design slip resistance $F_{s,Rd}$ due to the clamping force and the design bearing resistance $F_{b,Rd,resin}$ of the resin. In the case of category B and C connections, the design ultimate shear load of a bolt may not exceed either the bolt design shear resistance $F_{v,Rd}$ or the design bearing resistance $F_{b,Rd,B/C}$ (Eq. (3)):

$$F_{Rd,B/C} = \min(F_{s,Rd} + F_{b,Rd,resin,}F_{v,Rd}, F_{b,Rd}) \quad (3)$$

According to the 1994 ECCS recommendations [1], the bearing stress $f_{b,resin}$ for the commonly used epoxy resin RenGel SW404 with RenHY2404 is about 130 MPa. Recent research carried out by Gresnigt & Beg [7] have shown that for this specific resin, the long-duration bearing stress can be taken as $f_{b,resin,LT}$ = 200 MPa and the short-term stress as $f_{b,resin,ST}$ = 280 MPa.

Table 1. Fatigue detail category according to EN 1993-1-9

Connection type	Non-preloaded		Preloaded	
	Double lap	Single lap	Double lap	Single lap
Non-injected	50	50	112	90
Injected	90	80	112	90

Fatigue

The structural resistance against failure due to fatigue is governed by EN 1993-1-9 [6]. Resin-injected bolted double lap connections are detail category 90, unless the bolts are also preloaded, in which case the detail category may be assumed to be 112. In the case of single lap connections without preloaded bolts, the detail category is 80 and is raised to category 90 when the bolts are also preloaded. The detail category per connection type is summarized in Table 1.

Although EN 1993-1-9 does not distinguish between preloaded and preloaded resin-injected connections, experimental research by De Jesus et al. [8] on connections taken from existing bridges has indicated that in the case of the latter, the fatigue strength is considerably reduced. However, more recent numerical experiments carried out by Correia et al. [9] indicate that resin-injecting a preloaded connection has a beneficial effect on its fatigue strength [9].

3 Test programme of RFCS project SIROCO

3.1 Experimental parameters

In order to achieve the research objectives, a well-thought-out experimental plan was carried out with different influencing parameters such as type of resin, the curing condition of the resin, the geometrical and mechanical characteristics of the connection and type of loading. The main parameters considered in the experiments are listed in Table 2.

Owing to the many influencing parameters, the experimental plan was divided into several stages and some of those subdivided into several further steps. Each of the stages or steps concern only a few influencing parameters.

4 Selection of resin materials

4.1 Short-duration tests – force for 0.15 mm slip criterion

Five resins were selected as candidates for use in injection bolts to examine the feasibility and effectiveness of the injection. RenGel SW404/HY2404 (Araldite) is the initial resin recommended in ECCS publication No. 79 [1] and the possible alternative resins are Edilon Dex-R2k, Edilon Dex-G20, Sikadur 30 and Sika Injection 451. The curing temperature under ambient conditions was approx. 24 °C and the curing time was 72 h. After curing, short-term tests were performed on standard specimens with M20 bolts, according to the guidelines in EN 1090, Annex K [2], to determine the tensile force needed to achieve a displacement of 0.15 mm at the centre of the bolt group (CBG).

Table 2. Experimental parameters for double shear connections with injection bolts

Bolt	Type Size Hole and clearance Shank	Non-preloaded/Preloaded M20/M36 Normal round hole 2 mm/3 mm/Slotted hole 4 mm/6 mm 40 mm/80 mm/100 mm
Resin type	Initial Alternative	RenGel SW404 + HY2404 (Araldite) Edilon Dex-R2K/Edilon Dex-G20/Sikadur 30/Sika Injection 451
Curing	Time Temperature	6/24/48/>72 h 8/16/24 °C/ambient temperature (~20 °C)
Test load	Short duration Long duration Fatigue load	Constant/Step load Constant/Step load Constant amplitude with different load level

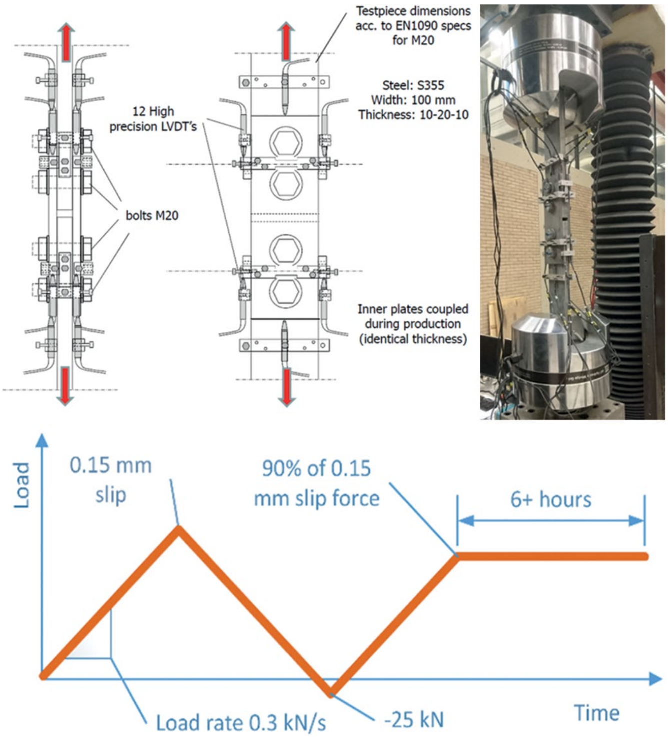


Fig. 2. Specimen with instrumentation, test machine and test procedure

This specimen had a top and bottom connection with two non-preloaded M20×80 injection bolts per connection. The bolts were placed in a normal hole of 22 mm dia. The specimen including instrumentation, test machine and test procedure are shown in Fig. 2.

During injection of the specimens and the short-term tests, the following results were obtained:

- Except Sika Injection 451, the three other alternative resins selected (Edilon Dex-R2k, Edilon Dex-G20 and Sikadur 30, used separately) all show good performance regarding resin injection. For the Sika injection 451, the cavity in the bolt hole was not filled properly and most of the resin ran out of the connection and between the steel plates. The viscosity appeared to be very low. Therefore, Sika Injection 451 was not included in the further research.
- As shown in Fig. 3, RenGel (Araldite), the initial resin recommended in ECCS publication No. 79 [1], achieved the highest tensile force value at the slip value of 0.15 mm, i.e. 215 kN at CBG, and was also shown to have the best time-dependent behaviour of all of the resins tested.
- Edilon Dex-R2K takes second place behind RenGel (Araldite); for this resin the tensile force value at the slip value of 0.15 mm at CBG is 183 kN, and its creep behaviour in the short-term test is not so large.
- For Edilon Dex-G20, the tensile force value at the slip value of 0.15 mm at CBG is 170 kN, and for Sikadur 30, the same type of force value is 171 kN, but both of them exhibited significant creep behaviour.

4.2 Short-duration tests – influence of curing temperature and overload behaviour

The strength and stiffness properties under different temperature conditions (8, 16 and 24 °C) were investigated in step 2. The curing time in all tests was 48 h. In addition to the EN 1090-2 load procedure, an additional overload step with increased load rate was applied up to the maximum load of the test setup (see Fig. 4a). The following results were obtained and decisions taken:

- When the curing temperature falls in the range 8–24 °C, the very slight temperature dependency can be neglected for both the RenGel and the Edilon Dex-R2K resins (see Figs. 4b and 4c).
- The Edilon Dex-G20 and Sikadur 30 resins cannot be used as alternatives due to their low strength values and large creep behaviour, so these resins were not be considered in the subsequent tests.
- The benchmark value of 0.15 mm slip at CBG can be taken as 200 kN for the RenGel resin and 160 kN for the Edilon Dex-R2K resin.
- In order to reduce the effects of the friction between plates in subsequent tests, a torque value of 30 Nm was used for pretightening.
- The overload behaviour of the RenGel and the Edilon Dex-R2k connections remain quasi-linear far beyond the 0.15 mm slip criterion of EN 1090 (see Fig. 4d).

4.3 Short-duration tests – creep behaviour for at least 90 h

The strength and stiffness properties under a constant load applied for at least 90 h were investigated in step 3 for the two resins remaining after step 2. The curing time was 6 or 24 h and the two types of loading were used as shown in Fig. 5. The F value in this figure stands for the benchmark

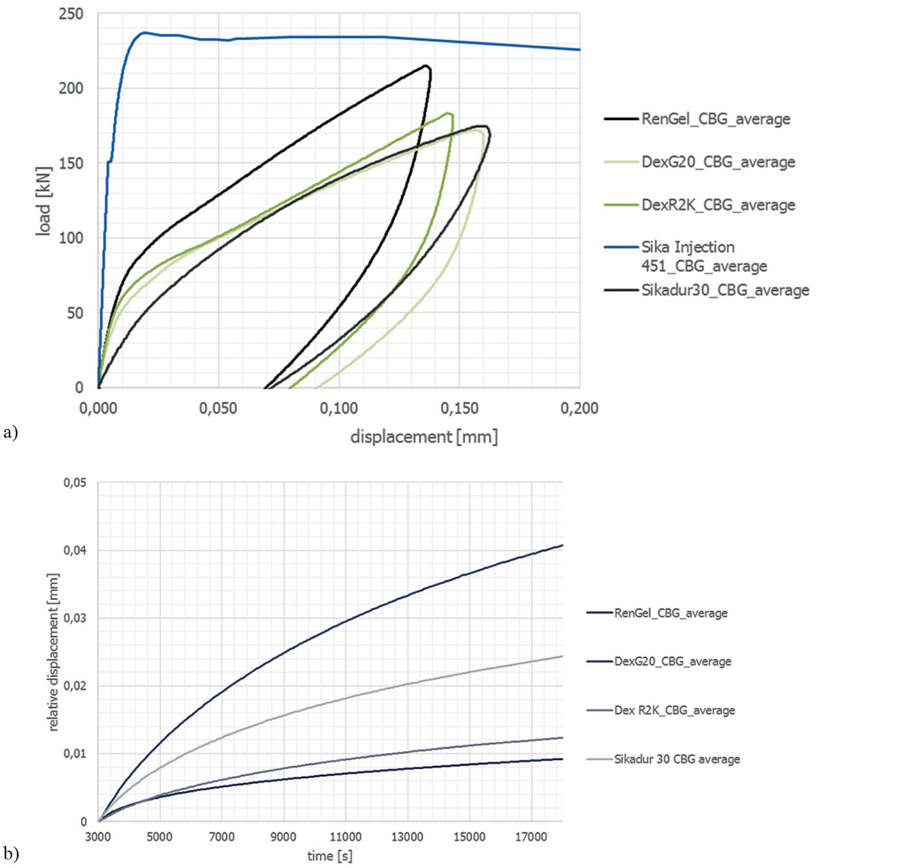


Fig. 3. Initial test results: a) load-displacement curves, b) displacement-time curves

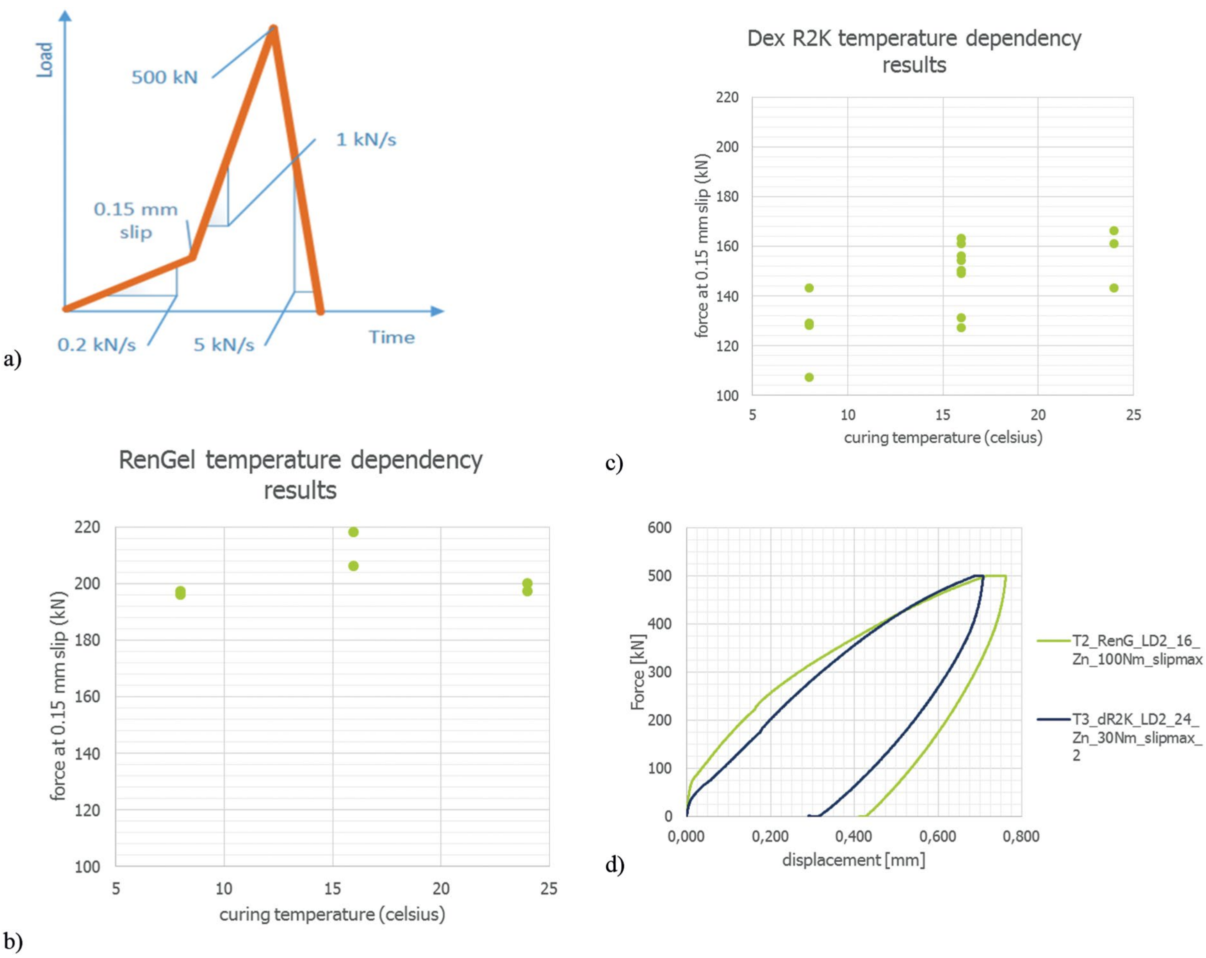
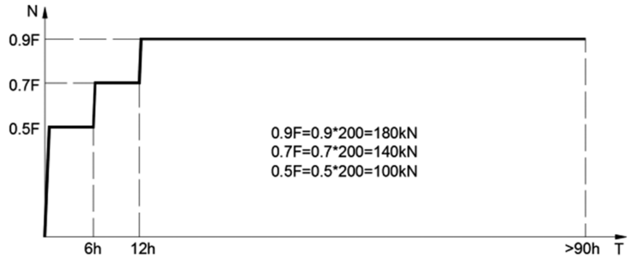
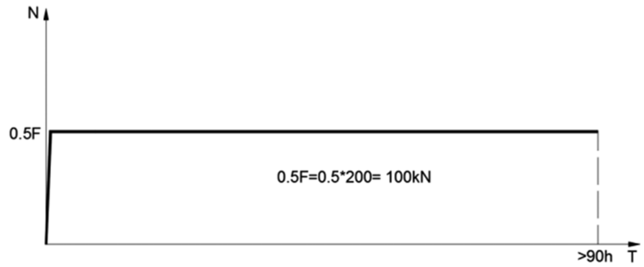


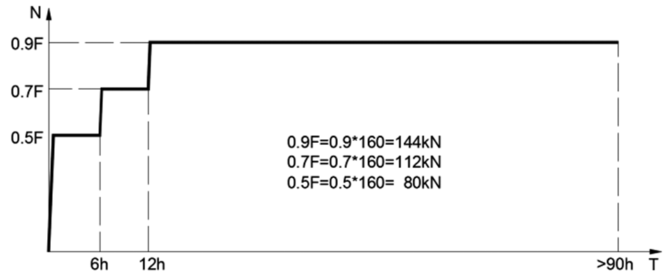
Fig. 4. Step 2: a) load procedure, b) & c) curing temperature results, d) overload behaviour



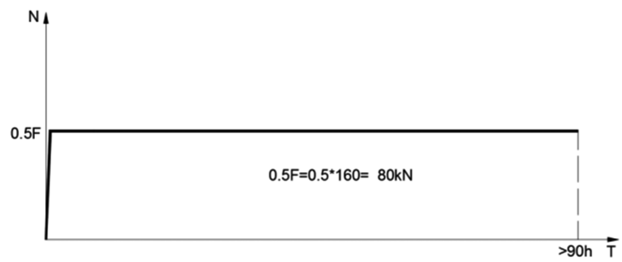
a) Step loading procedure – RenGel (Araldite)



b) Constant loading procedure – RenGel (Araldite)



c) Step loading procedure – Edilon Dex-R2K



d) Constant loading Procedure – Edilon Dex-R2K

Fig. 5. Step 3: loading procedures for Edilon Dex-R2K and RenGel (Araldite)

force value at the slip value of 0.15 mm at CBG obtained in step 2. The following results were obtained:

– RenGel (Araldite) exhibited a good, stable bearing capacity during a loading period of at least 135 h. The resin showed only a very slight creep behaviour, which occurred during the first several hours of loading.
– The curing time of RenGel (Araldite) and Edilon Dex-R2K, 6 and 24 h respectively, did not affect the creep behaviour.
– The potential alternative resin Edilon Dex-R2K exhibited an unstable bearing capacity.

Considerable difference was found between the different specimens and even between the two connections of the same specimens. For one of the specimens, the slip exceeded 0.3 mm. The load level was only 50 % of the benchmark force value of 0.15 mm slip at CBG of the plates as obtained in step 2. Edilon Dex-R2K may be used an alternative to RenGel (Araldite), but this kind of resin has a larger displacement.

4.4 Long-duration tests – effect of using slotted holes

Based on the results obtained in the short-term tests, two types of resin were selected for the long-term tests: RenGel (Araldite) and Edilon Dex-R2k. A standard specimen with M20 bolts was adopted. This specimen has a top and bottom connection with one non-preloaded M20 injection bolt per connection. The bolts were placed in a normal 22 mm dia. round hole or a 24 or 26 mm slotted hole. The specimens were loaded in four strings, each including four specimens. In each string, two specimens had the normal round holes with 2 mm clearance, one specimen had the slotted holes with 4 mm clearance and one specimen had the slotted holes with 6 mm clearance. The loading procedures applied are shown in Fig. 6. The F value stands for the 0.15 mm connection slip for both resins as obtained in the short-duration tests. For the specimens with one connection, the F value is 100 kN for the RenGel specimens and 80 kN for the Edilon Dex-R2K specimens.

The following results have been obtained so far:

– RenGel (Araldite) has shown a good and stable bearing capacity during a loading period of 70 days at a maximum load level of 70 % of the benchmark force value of 0.15 mm slip at CBG of the plate as obtained in step 2. The displacements of the specimens with a normal

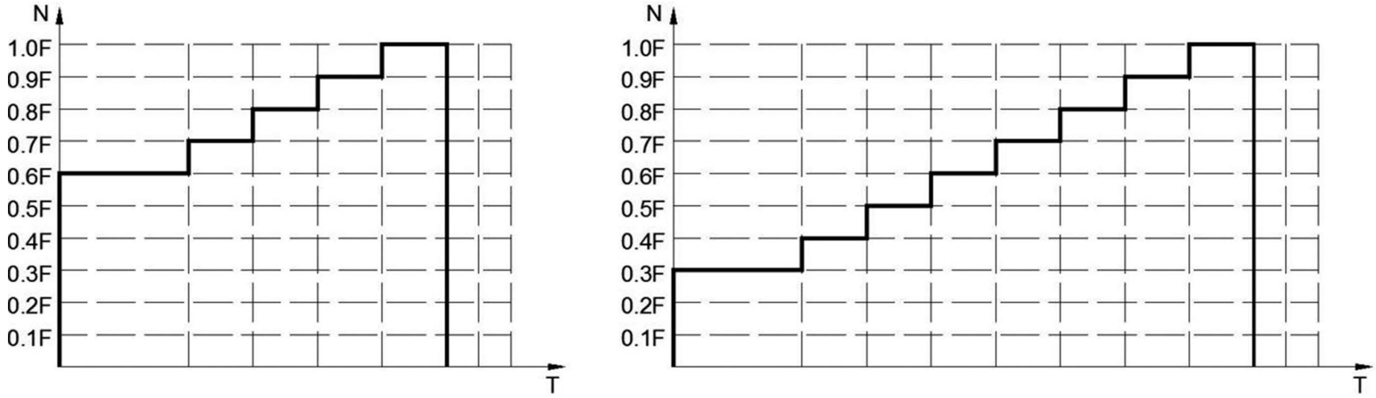


Fig. 6. Loading procedures for stage 2: long-duration tests – effect of using slotted holes

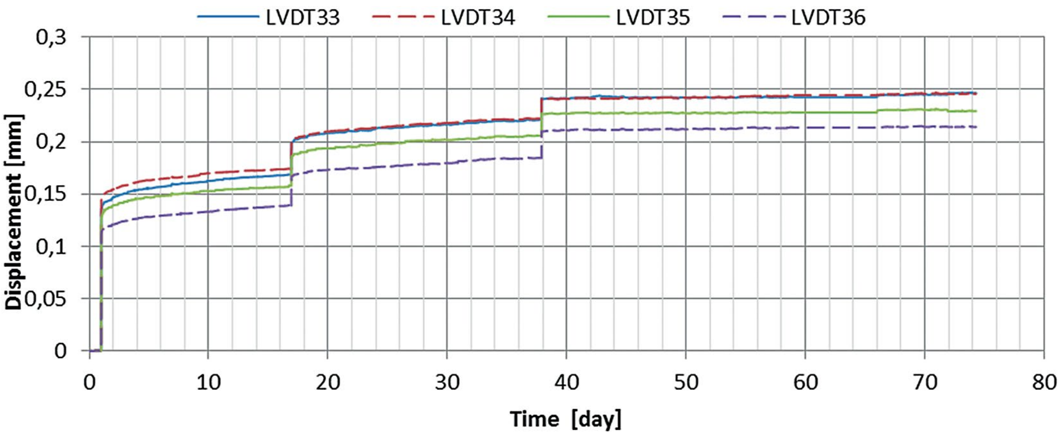


Fig. 7. Long-term test results for a RenGel specimen with slotted holes with 6 mm clearance – F_{max} = 70 kN

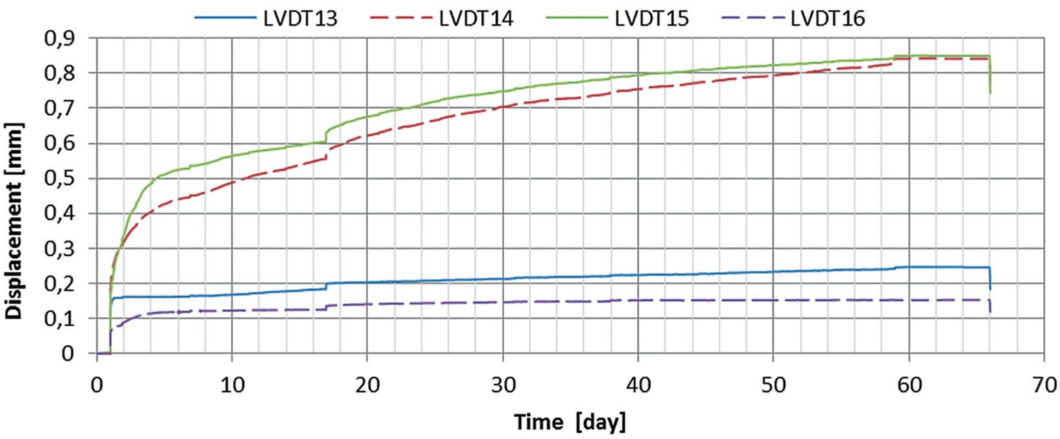


Fig.8 Long-term test results for a Dex-R2K specimen with normal round holes with 2 mm clearance – F_{max} = 56 kN

round hole with 2 mm clearance appeared to be about 0.15 mm. The displacements of the specimens with a slotted hole with 4 or 6 mm clearance showed a higher value, 0.20 mm and 0.25 mm respectively. The two different loading procedures did affect these values.

– As shown in Fig. 8, the potential alternative resin Edilon Dex-R2K showed an unstable bearing capacity. Considerable difference was even found between the two connections of the same specimens. For some specimens, the slip exceeded 0.3 mm at a load level that was only 50 % of the benchmark force value of 0.15 mm slip at CBG of the plates as obtained in step 2. Owing to the large scatter of the results, the effect of slotted holes could not be distinguished.

5 Large bolt tests

The effect of the size of the bolt was investigated by testing specimens with non-preloaded M36 injection bolts in a normal round hole with 3 mm clearance. This specimen had a top and bottom connection with two non-preloaded M36 injection bolts. The thickness of the plates in the double shear connection was the same as the specimens in the M20 bolt tests. The other plate dimensions were adjusted in line with the increase in the bolt size. RenGel resin was used in this test series. After curing for at least 24 h, short-term tensile testing according to the guidelines in EN 1090, Annex K, was performed to determine the tensile force needed to achieve a displacement of 0.15 mm at the centre of the bolt group (CBG). The following results were obtained:

– The slip load was found to be approximately the same for the M36 and M20 specimens (see Fig. 9a).
– The bearing stress of the connection with the M36 bolts appeared to be 40 % lower than that of the connection with M20 bolts (see Fig. 9b).

6 Long bolt tests

In the case of relatively long bolts (diameter of bolt small in comparison to thickness of plates), the bending deformation of the bolt may cause a very uneven bearing stress distribution. These uneven bearing stresses will result in additional creep deformation. The design rules for the bearing resistance of the resin in EN 1993-1-8 are only valid for bolts with $L/D \leq 3$ (L = total thickness of plates, D = diameter of bolt). For longer bolts, only the bearing resistance for L = 3D may be taken into account.

Tests were carried out on connections with L/D = 3 and 4 using RenGel resin; M20 bolts were used and the plate package length was 60 and 80 mm respectively. The loading procedure according to EN 1090-2 was applied (see Fig. 10a) and the following results were obtained (see Fig. 10c):

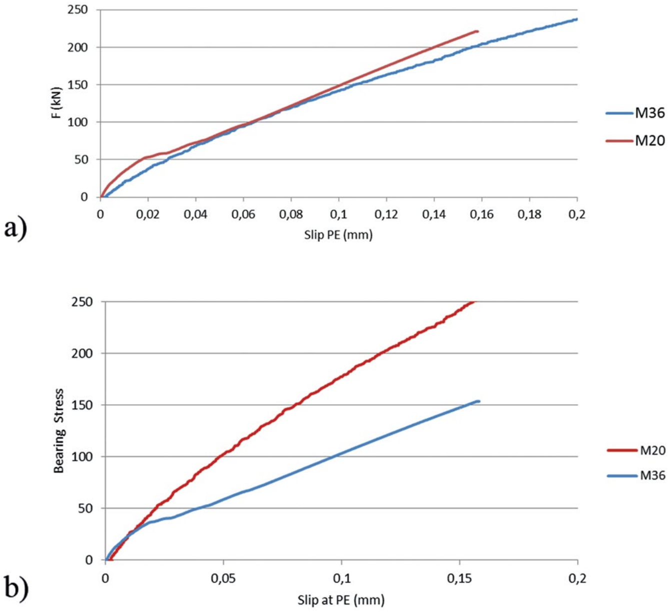


Fig. 9. Large bolt test results: a) load-displacement curves, b) stress-displacement curves

– The first series of tests indicates additional capacity beyond L/D = 3. This was not the case i n the second series of tests. More research on this bolt length effect is necessary to evaluate the effective width method of EN 1993-1-8.

7 Concluding remarks

The SIROCO research on the behaviour of double shear connections with injection bolts allows the following main conclusions to be drawn:

a) The injection procedure is the most important aspect for successful applications. Pot life and viscosity are the most important parameters of a resin.
b) The resin mechanical properties show poor correlation with the performance for injected bolted connections.
c) Edilon Dex G 20, Sika 30 and Sika injection 451 are unsuitable resins for injected bolted connections.
d) Edilon Dex R2K can be used successfully but suffers from scatter of results and lower strength values in comparison to RenGel SW404/HY2404.
e) The curing temperature of the resin was not a factor for RenGel SW404/HY2404, but was a factor for Edilon Dex R2K.
f) From analytical modelling, an L/D ratio of 3 is identified as a maximum capacity for injected bolted connections.
g) Experimental results show a constant or slightly increasing capacity for L/D ratios between 3 and 4.
h) A bearing stress of 175 MPa is safely allowable for the long-term without exceeding imposed deformation limits.
i) The long-term tests also showed that 60 % of the initial slip is due to deformation mechanisms other than compression of the resin.

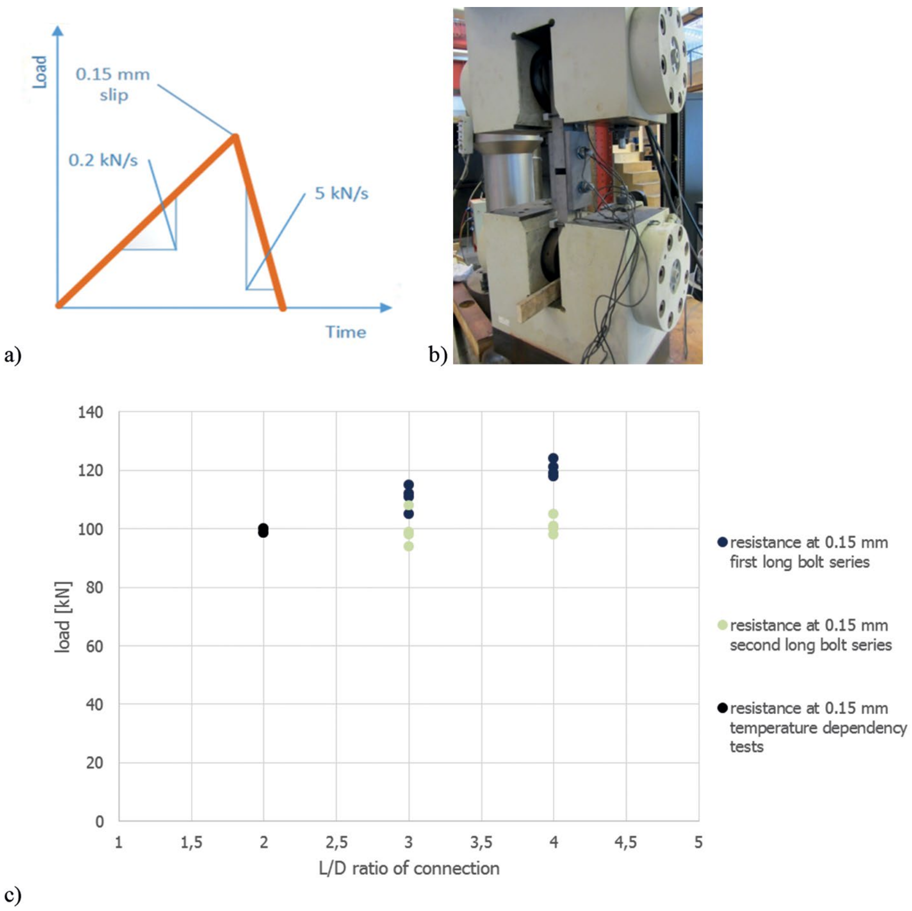


Fig. 10. Long bolt tests: a) loading procedure, b) specimen in test rig, c) test results

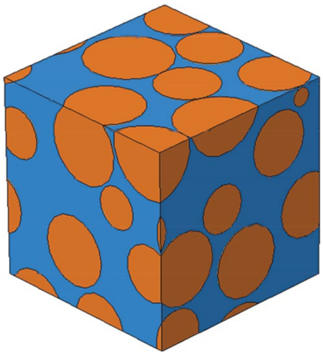


Fig. 10. Reinforced resin using spherical steel particles

j) The use of oversized holes reduces the allowable bearing stress as a result of lower initial stiffness and increased slip as a result of a longer creep length.
k) Connections with M36 bolts have the same initial stiffness as M20 connections and a reduced creep deformation at equal loads as a result of a lower bearing stress.

A recent innovation at TU Delft is *reinforced resin* [12]. Reinforcing the resin is achieved by inserting spherical steel shots into the connection prior to injecting conventional epoxy resin. The steel skeleton provides a stiff load bearing path, resulting in an increased connection stiffness (+71 %) and decreased creep deformation (–35 %) as achieved in a laboratory case study. Preliminary investigation has shown that the Young's modulus of the reinforced resin is in the range 20–25 GPa, whereas for the resin itself this is 4.2 GPa. The connection stiffness does not increase in the same rate as the Young's modulus, because other deformation mechanisms (e.g. bolt bending) also have a significant influence on connection slip. Although the particle skeleton has advantages, the connection must be injected with resin.

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Keywords: double shear connections; injection bolts; resin; creep behaviour; bearing resistance

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