FATIGUE BEHAVIOUR OF RESIN-INJECTED BOLTS: AN EXPERIMENTAL APPROACH

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ABSTRACT

Resin-injected bolts have been used in reparation of existing bridges. This technology is used in shear connections as an alternative to rivets, fitted bolts or preloaded high strength friction grip bolts. The use of resign-injected bolts allows similar behaviour as fitted bolts, but with lower costs, since it only requires a standard preparation of the holes. The use of resin injected bolts improves the slip resistance of the joint. In rehabilitation of old riveted bridges, resin-injected bolts may be used to replace faulty rivets, preserving null sleep, as the original rivet. However, creep may occur if bearing stresses on resin are excessive. The performance of resin-injected bolts has been essentially demonstrated by quasi-static or creep tests. Very few studies concerning the assessment of the fatigue behaviour of resin-injected bolts can be found in literature. This paper presents the results of an experimental program aiming the evaluation of the fatigue behaviour of two types of joints (single and double shear) with preloaded resin-injected bolts. Results are compared with test data obtained with standard preloaded bolts, revealing a systematic fatigue strength reduction.

KEY WORDS: bolted connections, resin-injected bolts, fatigue behaviour, experimental analysis

1. INTRODUCTION

Repairing and strengthening operations of old riveted steel bridges may use alternative fastening techniques, such as rivets, welding, high strength friction grip bolts, fitted bolts and resin-injected bolts, also known as injection bolts. Riveting is usually preferred in order to preserve the original architecture of the bridge. However, riveting is not attractive either, because of the difficulties to find good equipment and skilled riveters. The use of welding may be impossible due to the poor weldability properties of the old steel. The used of high strength friction grip bolts is not a good option, because of the very uneven surfaces of corroded plates as well the presence of paint layers, leading to low friction coefficients. Fitted bolts are attractive, but expensive solutions. Therefore, resin injected bolts appears as a good solution that have been applied in reparation of old bridges, both in Portugal (e.g. reparation of the bridge in Figueira da Foz [1], over Mondego river) and abroad (e.g. reparation of the bridge in Oranienburg, linking Netherlands to Germany [2]). Injection bolts are bolts in which the cavity produced by the clearance between the bolt and the wall of the hole is completely filled up with a resin. Filling of the clearance of an injection bolt is carried out through a small hole in the head of the bolt. After injection and full curing of the resin, the connection is slip resistant. Shear load is transferred through bearing and shear of the bolt. Injection bolts can be manufactured from normal standard structural bolts, representing an inexpensive solution. The bolts and washers are adapted to enable the injection of the resin. Figure 1 represents schematically a resin-injected bolt.

The mechanical performance of resin-injected bolts has been demonstrated essentially based on quasi-static tests, cyclic tests representing seismic loading and creep tests [1-3]. The resin-injected bolts provide a low slip factor and good bearing resistance. Also, it allows a good corrosion resistance. The epoxy resins have been proved to be a best solution for resin-injected bolts [1].

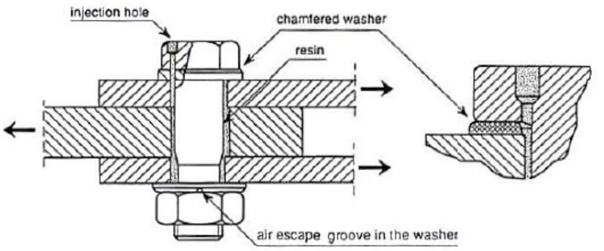

Figure 1. Injection bolt in a double lap joint [3].

High-cycle fatigue tests of resin-injected bolts are very rare. Eurocode 3 [4] suggests the same fatigue detail category for preloaded high strength bolts and preloaded injection bolts (class 110 for double covered symmetrical joints and class 90 for one sided connections). The same detail category is also proposed for fitted bolts and non-preloaded injection bolts (class 90 for double covered joints and class 80 for one sided connection).

This paper presents the results of an experimental program, consisted of fatigue tests on both bolted and resin-injected bolted connections. Two types of connections were investigated, using materials from two distinct bridges, namely the Fão (double shear connection) and Trezói (single shear connection) bridges. A total of four series of specimens were tested. The results showed that, for the same initial preload applied to the standard and resin-injected bolts, a systematic fatigue strength reduction is observed in resin-injected bolts, thus contradicting the Eurocode 3 recommendations, which suggests the same fatigue strength for both types of fastening techniques.

2. EXPERIMENTAL DETAILS

The experimental program consisted of fatigue tests of both standard bolted connections and resin-injected bolted connections. In addition, two distinct geometries and materials were tested, namely:

- a double shear connection made of puddle iron, extracted from the Fão riveted road bridge (see Figure 1a);
- single shear connection made of construction steel from the Trezoi riveted railway bridge (see Figure 1b).

The Fão bridge was inaugurated in 1892 and was built in Puddle iron, which is a material with many heterogeneities, responsible for significant scatter in material properties. The Trezói bridge was inaugurated in 1956 and was built using construction steel similar to the current steels.

In all connections (standard and injection bolts), bolts were preloaded using a torque of 80 N.m. Bolts with diameter equal to 22 mm were inserted into holes drilled with a diameter equal to 24 mm, resulting a radial clearance of 1 mm. The same type of bolts was used in both standard joints and resin-injected bolts. A hole was drilled in the standard nuts and a channel was machined in the washer to allow resin injection. Figure 2a) illustrates the procedure to inject the resin that can be summarized as follows:

- Preparation of the nuts and washers;
- Surfaces cleaning;
- Preloading of bolts;
- Application of the resin using a syringe;
- Cure of the resin.

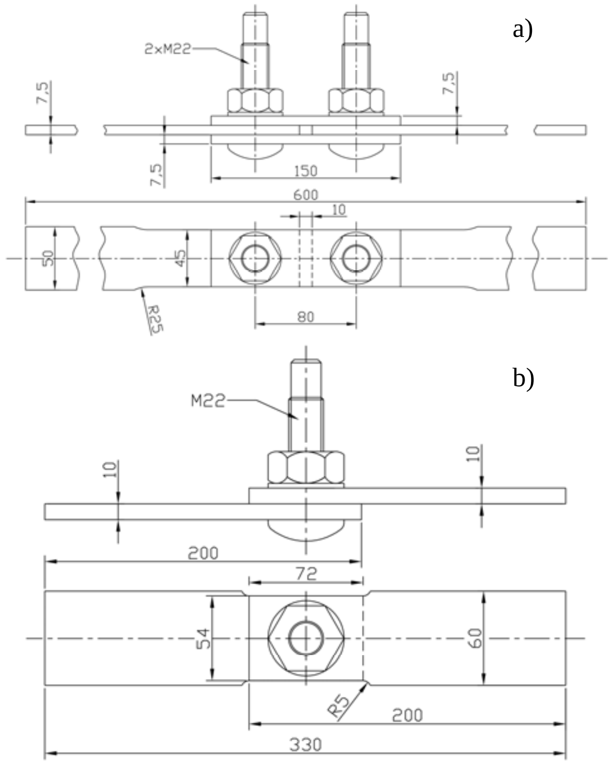

Figure 1. Geometry of the bolted joints considered in this study: a) double shear connection; b) single shear connection (dimensions in mm)

Figure 2b) shows injection bolts with the respective nuts removed. The figure shows that the clearance was filled by the resin as expected. Besides Figure 2b) was obtained after fatigue failure, it shows an apparently undamaged adhesive. It was not easy to remove the bolts from the connection. Only using a hammer or other loading device was possible to extract the bolts.

The resin used in the preparation of the injection bolts was a commercial epoxy, available as SIKADUR 30®. Table 1 summarizes the evolution of the mechanical strength properties of the adhesive, with the cure time, from the manufacturer. The Young modulus of the adhesive is equal to 12800 N/mm^2. All resin-injected bolts were subjected to a cure time of at least 8 days, which resulted near maximum strength properties.

The double shear connections were tested on a INSTRON 8801 servohydraulic machine rated to 100 kN. The single shear connections were tested on a MTS 321.21 servohydraulic machine rated to 250 kN. All fatigue tests were carried out under stress control with a stress R-Ratio equal to 0, for the double shear connection, and a stress R-Ratio equal to 0.1, for the single shear connection. The fatigue failures were considered to be the break of the resisting sections of the specimens.

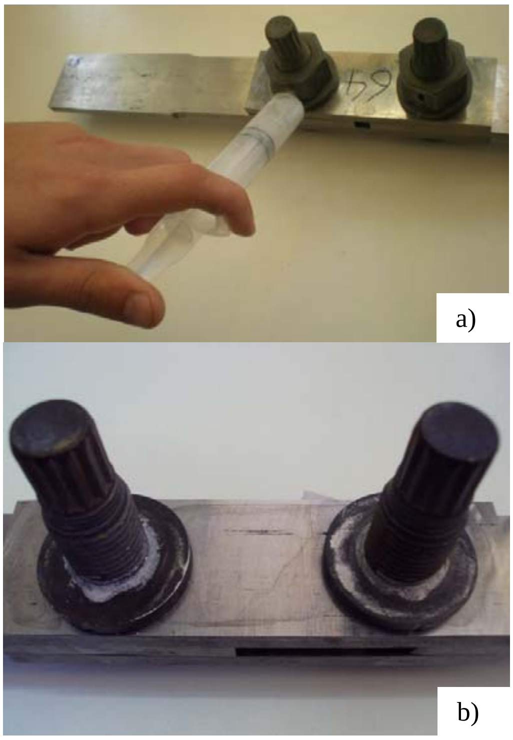

Figure 2. Resin-injection bolts: a) injection of resin; b) injection bolts with nuts removed, showing the filled clearance.

Table 1. Cure properties of the SIKADUR 30 adhesive.

Cure time	Compressive strength (+10ºC)	Shear strength (+15ºC)	Tensile strength (+15ºC)
1 day	50-60 N/mm^2	3-5 N/mm^2	18-21 N/mm^2
3 days	65-75 N/mm^2	13-16 N/mm^2	21-24 N/mm^2
7 days	70-80 N/mm^2	14-17 N/mm^2	24-27 N/mm^2
14 days	-	15-18 N/mm^2	25-28 N/mm^2

3. RESULTS AND DISCUSSION

Tables 2 and 3 summarize the fatigue test results obtained for the four test series. Regarding the double shear connection, from the Fão bridge, 7 specimens were tested with resin-injected bolts and 7 were tested with standard bolts. The test frequencies ranged from 2.5 to 10 Hz. The specimens with resin-injected bolts were tested always with the same net stress range (355.5 MPa). A huge scatter was observed in the fatigue lives for this series. The specimens with the standard bolts were tested with net stress ranges from 355.5 MPa to 398.6 MPa, with two specimens being tested for the stress range of 355.5 MPa. One of these specimens was a run-out. Taking into account the run-out life, results an average life of 2 394 976 cycles for the joints with standard bolts, under a stress range of 355.5 MPa. It is interesting to note that the average life obtained for the joints with resin-injected bolts was 333 548 cycles, which is significantly lower than observed for the connections with standard bolts. Also, none of the specimens with resin-injected bolts failed for a life higher than the lowest life obtained for the specimens with standard bolts.

Two series of single shear connections composed, respectively, of 4 connections with resin-injected bolts and 3 connections with standard bolts, made of steel from the Trezói bridge, were fatigue tested. Two stress levels were defined, namely: net stress ranges about 271 MPa (lower stress range) and about 362 MPa (higher stress range). Tests for the higher stress range were conducted at a frequency of 4 Hz; tests for the lower stress range were conducted according to a frequency of 6 Hz. Despite the reduced number of tests, a relative small scatter is observed in the fatigue results, for these connections made with the steel from the Trezói bridge.

Table 2. Fatigue data from the double shear connection made of material from the Fão bridge.

	$\Delta\sigma$ [MPa]	R	f [Hz]	N_f [cycles]
Resin-Injected Bolts	355.5	0.0	5.0	376856
	355.5	0.0	5.0	102854
	355.5	0.0	5.0	166294
	355.5	0.0	5.0	52949
	355.5	0.0	8.0	1321738
	355.5	0.0	8.0	183212
	355.5	0.0	8.0	130935
Standard Bolts	355.5	0.0	8.0	3245417→
	377.0	0.0	10.0	428551
	377.0	0.0	5.0	556452
	398.6	0.0	5.0	72355
	398.5	0.0	2.5	666412
	398.5	0.0	2.5	417582
	355.5	0.0	2.5	1544535

Table 3. Fatigue data from the single shear connection made of material from the Trezói bridge.

	$\Delta\sigma$ [MPa]	R	f [Hz]	N_f [cycles]
Resin-injected bolts	361.8	0.1	4	91993
	362.6	0.1	4	120808
	271.5	0.1	6	325865
	271.9	0.1	6	235780
Standard bolts	362.2	0.1	4	297700
	271.3	0.1	6	827824
	271.4	0.1	6	765606

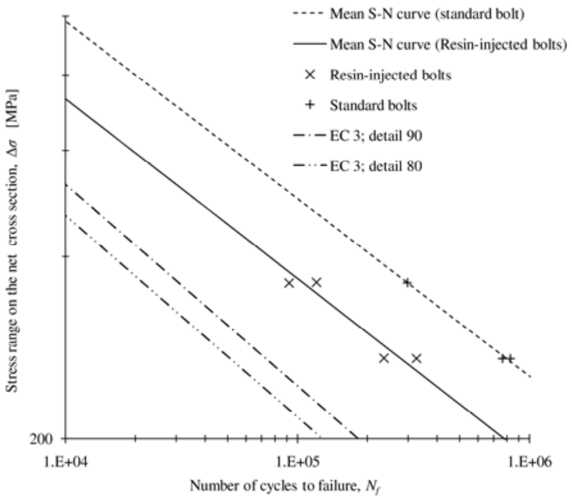

Figure 3. Comparison of S-N fatigue data from the single shear connections made of the material from the Trezói bridge.

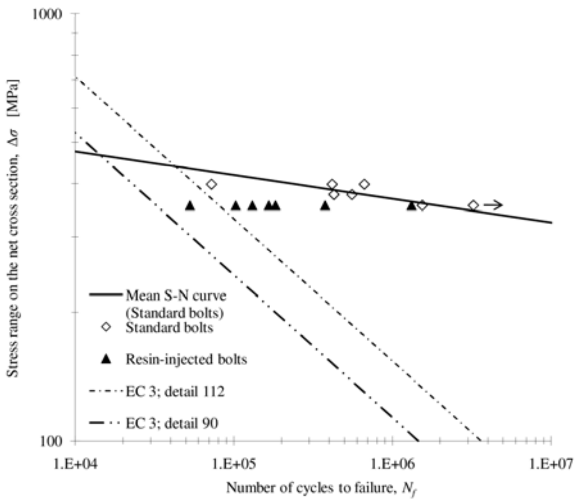

Figure 4. Comparison of S-N fatigue data from the double shear connections made of the material from the Fão bridge.

Test fatigue results from the single shear connections were also consistent with a fatigue life reduction with the use of resin-injected bolts.

Figures 3 and 4 plot the fatigue data obtained respectively for the single and double shear connections. The figures include mean S-N curves obtained using the experimental data, except for the double shear connection made of resin-injected bolts, since just one stress range level was tested for this latter series. Also, curves proposed in Eurocode 3 for double and single shear bolted connections, are included in the graphs. Two detail categories are plotted, the higher one being proposed for preloaded bolts, with or without injected resin; the lower detail category is proposed for fitted bolts and non preloaded injection bolts. The Eurocode S-N curves are conservative as expected. Only one data point exception is found for the single shear connection build with resin-injected bolts. Comparing the experimental mean S-N curves with the code-based S-N curves, it is interesting to note that S-N curves obtained for the single shear joints are approximately parallel to the code S-N curves. Also, the mean S-N curves for the resin-injected bolts and standard bolts are parallel. For the double shear connection, the experimental S-N curve is no longer parallel to the code-based S-N curve. This observation may be justified by the significant differences in the materials, being the material from Trezói bridge a construction steel similar to current ones. Its crack propagation properties should be very similar to the materials served as the basis for the definition of the S-N curves slopes (m=3).

The use of resin-injected bolts produced a consistent fatigue strength reduction in all test series. This is a surprising result, since Eurocode 3 does not distinguish the detail category between preload bolted connections and preload resin-injected bolted connections. This conclusion raises some concerns since resin-injected bolts are often used in rehabilitation of old structures.

A plausible explanation may be advanced, based on effects of preload (clamping stresses) applied to the bolts. The preload reduces the stress concentration around the holes, therefore increasing the fatigue strength. For high stress levels, responsible for some localized plastic strain, the initial preload on bolts may increase. On effect, the compressive contact stresses between the bolt and the hole increase the thickness of the plates, due to the Poisson effect, being responsible for a clamping stress increasing. Higher compressive stresses are obtained in standard bolts; the injected resin produces a redistribution of stress around the holes, reducing the magnitude of the compressive stresses, and the clamping stresses by consequence. This hypothesis must be verified by numerical simulation in future works.

4. CONCLUSIONS

This paper reported experimental research on fatigue behaviour of standard and resin-injected bolted connections. Two types of connections were tested, namely single and double shear connections. Each one of these connections were made of distinct materials, from the Fão and Trezói bridges. The main conclusion derived from the experimental data, was the fatigue strength reduction verified with the use o the resin-injected bolts. This conclusion was verified with two independent test configurations, which makes it stronger. This conclusion is somewhat surprising since the Eurocode 3 does not propose a lower detail category for resin-injected bolts. Also, it is common sense that the resin-injected bolts are a better fastening technique, than standard bolts.

This experimental investigation highlights the need for more research on fatigue behaviour of resin-injected bolts, including more testing and numerical modelling.

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