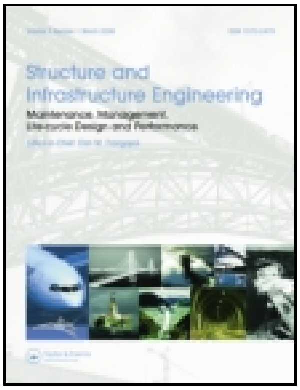

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Assessment of structural integrity and remaining life are essential tools for the management of ageing infrastructures, especially bridges. Compared to bolted or welded structures, little attention has been devoted to the fatigue assessment of riveted details. To fill this gap, extensive experiments are conducted on a short-span two-lane riveted steel-girder railway bridge near Sacile, Italy. In service since 1918, it was dismantled in 2006 and moved to a structural laboratory. Within a fatigue assessment framework, first physical and physical–chemical tests were performed, characterising the material properties; then, static, cyclic and fatigue full-scale tests were carried out. The experimental investigation allowed to test in particular the safe condition of the short riveted diaphragm connections of the bridge, and to compare the current fatigue design curves with experimental results. Moreover, the current practice to equate the fatigue behaviour of rivets to that of non-preloaded bolts proved to be a safe comparison.

Keywords: bridge; railway; fatigue; rivet; steel; safety assessment

1. Introduction

In developed countries, road and railway administrations have to make a decision of whether to demolish or retrofit old bridges still in use, while being aware that transported goods are on the increase. Among these, railway riveted steel girders represent a relevant structural typology, owing to their numbers and strategic positions. Most of the steel railway bridges still in service, around the world and in Italy, are riveted (Sustainable Bridges 2006). Mainly constructed during the second half of the 19th and the beginning of the 20th century, they have sustained almost one century of continuously increasing loads and train speeds. Even if wrought iron and older steels were mainly used, many of these bridges are still in service and appear able to cope with current and future loading demands. Due to the greater variability of the load compared to self-weight, a fatigue endurance check analysis in railway bridges is of crucial importance. Hence, the estimation of the remaining fatigue life is an essential ongoing procedure for railway management, see, for instance, an Integrated Research Project 'Assessment for future traffic demands and longer lives' funded by the European Commission in the 6th Program Sustainable Bridges (2006). Furthermore, literature relevant to riveted structures indicates that some fatigue failure reported is related to connected elements, rather than to the rivets themselves (Di Battista *et al*. 1998). Other authors, such as Brühwiler *et al*. (1990), suggested that rivet failures could also be probable in those cases in which riveted connections were designed according to the dimensions of the elements in the connection, rather than designed using allowable stress. More specifically, the remaining fatigue life is a reflection of features such as the diameter of the hole in relation to the plate thickness, the prestressing of the rivet, the net cross section of the plate/profile, the quality of connected material, the corrosion state and the average damage accumulated by the material. In this paper, physical and physical–chemical tests were performed on a dismantled short-span railway bridge in order to characterise its material properties, to develop static and cyclic full-scale tests, and to perform bending laboratory fatigue tests on half a girder and on short diaphragm riveted shear connections. It was ascertained that the critical fatigue detail was located in the shear rivets' resistance of the short diaphragm sustaining the rails, since they had been subjected to a much larger number of cycles and stress variations with respect to other members. For this reason, static and

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laboratory-fatigue tests were performed on this structural detail. Test results were compared to European standards. More specifically, it was shown that the shear Category 100 of Eurocode 3 EN 1993-1-9 (2005) is on the safe side, and that the equivalence between riveted shear splices and splices connected with non-preloaded bolts, as suggested by Di Battista and Kulak. (1997), applies and leads to conservative estimates. Current EN codes are for contemporary design and materials and are, in principle, not relevant and not applicable to existing structures, in particular, for materials such as early steels and riveted details. All comparisons with current EN codes are thus at the most only informative.

2. Assessment of current fatigue model and current practice

The fatigue behaviour of structural details is generally described by the *S-N* line in a Wohler diagram, which can be expressed as:

$$N(\Delta\sigma)^m = k, \tag{1}$$

where N is the number of cycles to failure; $\Delta\sigma$ indicates the constant amplitude stress range; k is a constant relevant to the critical detail; and m is the design curve slope of the investigated fatigue detail. If shear stresses are verified, Equation (1) is easily extended by replacing the axial stress range $\Delta\sigma$ with the constant shear stress range $\Delta\tau$.

Since only strains could be experimentally measured, stresses can be obtained by using Young's modulus. The technical literature provides some information on the fatigue behaviour of riveted members and details. There is a lot of literature concerning the bending data, and the main references are shown in Table 1. More specifically, compared to the amount of fatigue bending test data, those regarding shear failure are very scarce. Results in which rivets fail and are considered in this work are those provided by Stadelmann (1984) and Brühwiler *et al*. (1990). In order to assess bending details for riveted connections, comparison between the literature data concerning fatigue failure and specific detail categories adopted by Eurocode 3 EN 1993-1-9 (CEN 2005) are presented in Figure 1. In particular, the bending detail category $C = 63$ seems to be a safe category for riveted elements under bending. Category $C = 63$ has been suggested by Sustainable Bridges (2006) for bending detail, but a more detailed investigation on this topic can be found in Taras and Greiner (2007), in which several fatigue strength categories for bending fatigue, depending on various relevant parameters, have been identified.

With respect to shear fatigue data, it has been decided to perform full-scale tests, which are reported in the following sections.

3. A case study: the Meschio bridge

Experimental tests have been carried out on the Meschio railway bridge, a 12.40 m net span, riveted bridge built in 1918 and taken out of service in 2006. It was in service on the Mestre–Cormons line, in the northeast of Italy. After dismantling, the main beams were moved to the Structural Laboratory of Padua University.

The main horizontal structure was composed of an open deck and of twinned riveted composite flanged girders, 865 mm wide and 838 mm in height. The thickness of the plates was 11 mm. The web was reinforced by shear stiffeners 1 m apart, the flanges with 11 mm thick plates and increasing in number from the abutment to the mid-span. As illustrated in Figures 2 and 3, transverse bracing frames connected the twinned girders.

The track was made up of wooden beams recessed between the coupled girders, and each twinned girder supported the wooden elements that held one single rail; hence, the load is directly applied to the short transverse profile between the longitudinal plate girders.

Connections were made by double angles riveted both to webs and to transversal short diaphragms.

4. Experimental tests

The knowledge of material properties of existing metal bridges is essential for the assessment of their resistance and remaining fatigue life (ORE 1986, Liechti *et al*. 1997, ICOM 2001, ECCS 2005, Sustainable Bridges 2006). Material parameters are usually not available for bridges built between 1870 and 1940, owing to the lack of regulations, the non-standardised production and the construction processes. At the same time, the precise requirements of normalised materials according to EN 10025 (CEN 2004) are not usually fulfilled. Hence, physical, chemical and mechanical tests were carried out on samples, mainly on the base material, extracted from structural elements in order to obtain information on the constituent materials in view of the characterisation of both the fatigue structural behaviour and the evaluation of the residual life. Then, static and laboratory fatigue tests were carried out on the entire structure and on critical fatigue details. The complete description of tests and results is reported in Pipinato (2008).

Table 1. Experimental results from literature on riveted members and details (Pipinato 2008).

Author	Year	Experimental data	
Reemsnyder	1975	Type of test	Axial loading constant-amplitude test
		Specimens	Riveted gusset plate connections
		Structure	Ore unloading bridge
		Hot-spot detail	Tension chord at its connection to a gusset plate
		Note	Five test results have been obtained by newly fabricated specimens
Baker and Kulak	1982	Type of test	Bending and shear test
		Specimens	Built-up hanger members
		Structure	Highway bridge
		Hot-spot detail	Built-up hanger members
Out *et al.*	1984	Type of test	Flexural test
		Specimens	Stringers
		Structure	Railway stringers
		Hot-spot detail	Continuous riveted connection between the web and the flange angles
		Note	Results from corroded specimens not shown
Fischer *et al.*	1987	Type of test	Flexural test
		Specimens	Built-up hanger members
		Structure	Railway stringers
		Hot-spot detail	Web to flange connection
Brühwiler *et al.*	1990	Type of test	Flexural test
		Specimens	Built-up plate girders and lattice girders, wrought iron and rolled mild steel
ATLSS	1993	Type of test	Flexural test
		Specimens	Flanged angle to web
		Structure	Railway stringers
		Hot-spot detail	Web to flange connection
Adamson and Kulak	1995	Type of test	Flexural test
		Specimens	Stringers
		Structure	Built-up railway stringers
		Hot-spot detail	Horizontal bracing attachment riveted to the tension flange
Di Battista and Kulak	1997	Type of test	Axial tension
		Specimens	Diagonals
		Structure	Railway truss bridge
		Hot-spot detail	Riveted connection of the outstanding legs of these angles to gusset plates
Akesson and Edlund	1996	Type of test	Flexural test
		Specimens	Flange angles riveted to web plate
		Structure	Built-up railway stringers
		Hot-spot detail	Angle to web connection
Helmerich *et al.*	1997	Type of test	Bending and axial test
		Specimens	Truss members
		Structure	–
		Hot-spot detail	Built-up plate girders
Matar and Greiner	2006	Type of test	Flexural test
		Specimens	Secondary members
		Structure	Railway bridge
		Hot-spot detail	Flange to web connection
		Note	Only non-corroded specimens were tested
Pipinato	2008	Type of test	Flexural test (no failure in bending)
		Specimens	Full-scale girders and short diaphragm connection
		Structure	Railway bridge
		Hot-spot detail	Short diaphragm connection
		Note	Only non-corroded specimens were tested

5. Base material tests

5.1. *Metallurgic and quantometric tests on the base material*

Metallurgic and quantometric tests on the base material were performed with a spectrometer and a microscope, and showed a homogeneous grain distribution between ferrite and perlite, with 10–30 μm grain size. In addition, a high sulphur and low carbon content was detected. The steel sulphur content was about twice the maximum value adopted in commonly commercial steel (CEN 2004). As a result, it is possible

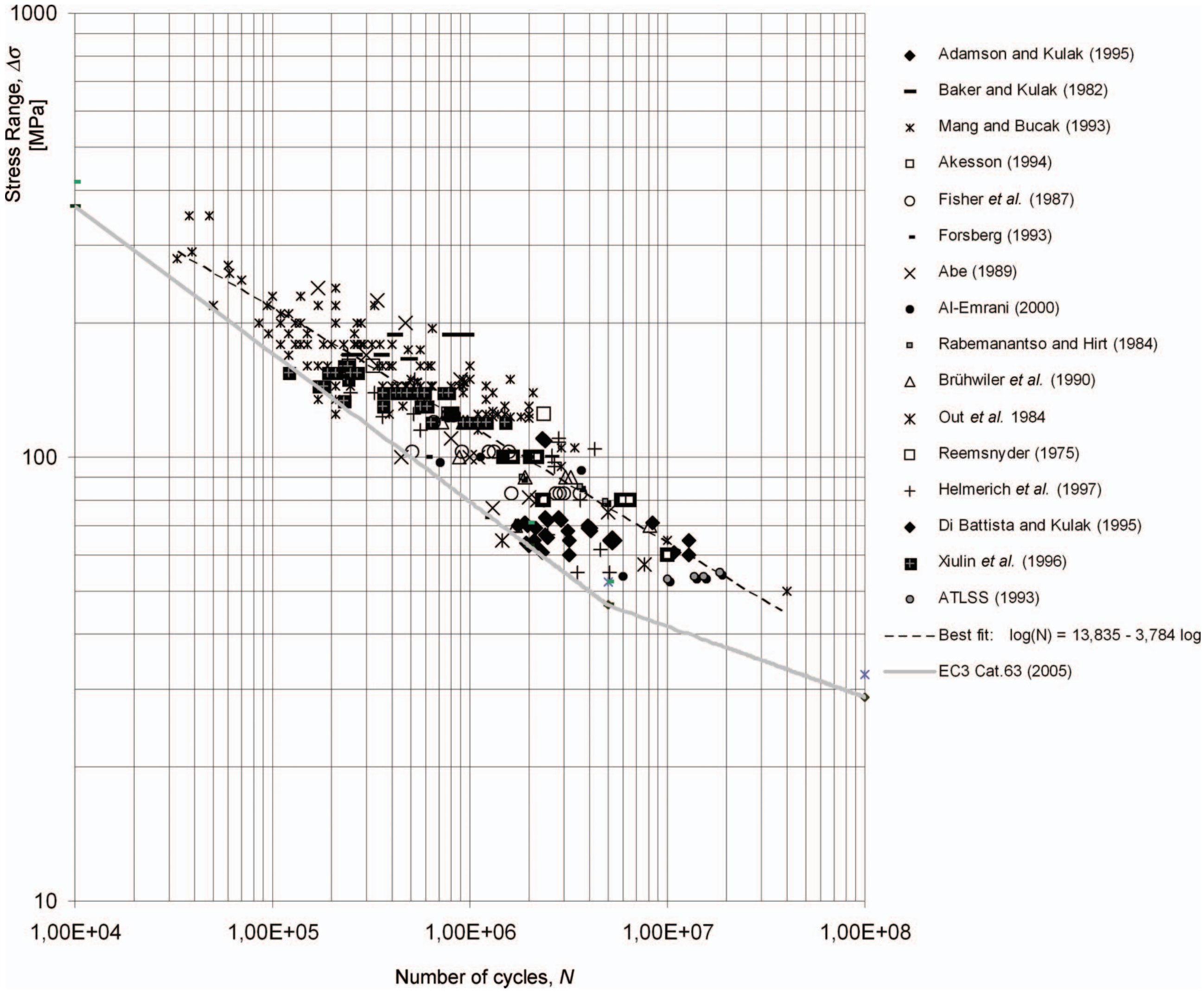


Figure 1. Results of literature fatigue bending tests *versus* EN 1993-1-9 (CEN 2005) bending fatigue category $C = 63$ design curves.

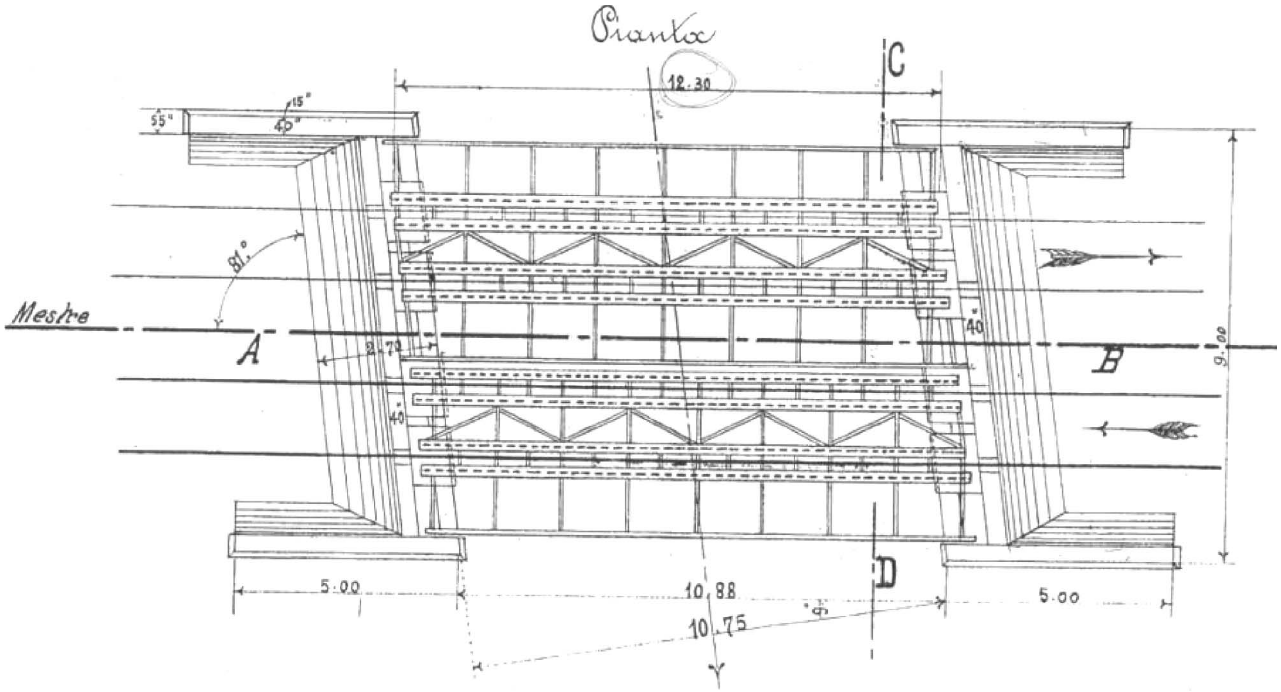
to state that this old steel is not equivalent to a modern mild steel, because its high sulphur content reduces both corrosion resistance and metal toughness and, in turn, the fatigue endurance (Ray *et al*. 1985, Nisha and Fatemi 2009).

5.2. *Tensile tests on the base material*

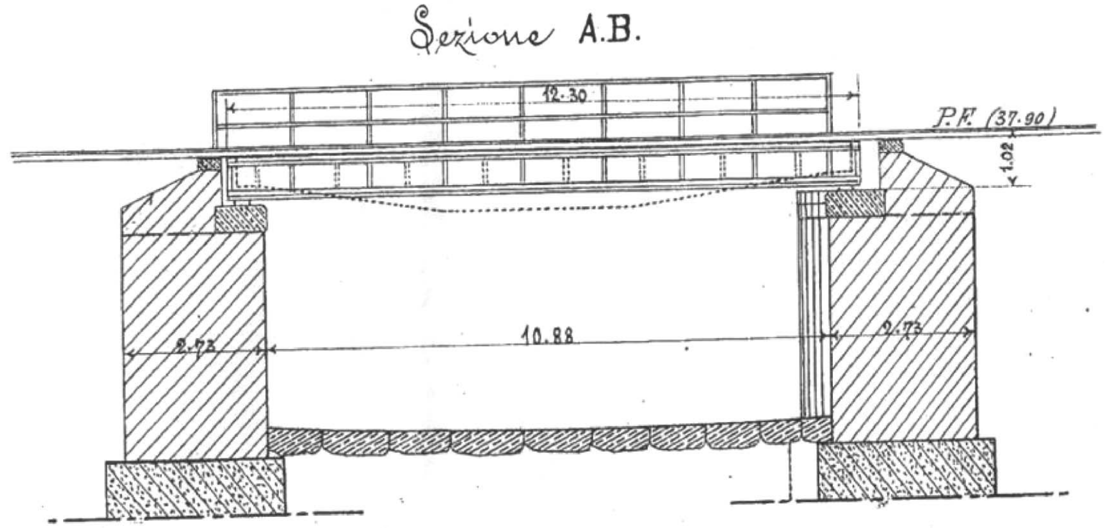
Steel specimens were extracted from beam webs in order to determine their mechanical properties according to the UNI EN 10002-1 (CEN 2004) procedure. Samples were taken from the web after removing the lateral pedestrian part. The constituent material exhibited a mechanical strength within the range of S275 and S355 steel (CEN 2004), with a mean yield strength $f_{y,m} = 322$ MPa and a mean ultimate strength $f_{u,m} = 421$ MPa. The comparison between these data with those reported in Sustainable Bridges (2006) implies that they appear consistent with a mild steel.

5.3. *Impact tests on the base material*

Although impact strength tests are uncommon for riveted structures, they were developed with the aim of giving an additional reference on the material. They were performed on six specimens with a cross section of 10×10 mm and a V-notch, at the controlled temperature of 20°C and with a nominal energy of 300 J. The average Charpy energy level, CVN, was about 11.5 J, much lower than the reference value of 27 J required for modern steel in EN 10025-2 (CEN 2004). Consequently, the base material steel is apparently more brittle than modern steel and presents a shorter fatigue resistance.



(a)



(b)

Figure 2. (a) Original plant and (b) lateral view of the 1918 Meschio bridge (dimensions are in metres).

5.4. Hardness tests on the rivets

The limited dimensions of the rivets made it necessary to estimate the tensile strength by means of correlations with surface hardness. With this aim, four Vickers tests were carried out on the head of the rivet. They showed an average value equal to HV145 at a load level of 294 N. Thus, an ultimate tensile strength f_u of about 500 MPa was estimated in line with the requirements of the Italian Railway Authority (RFI 2000). It must also be stated that the hot formed rivet head can have a different hardness with respect to the rivet shaft transferring the shear forces.

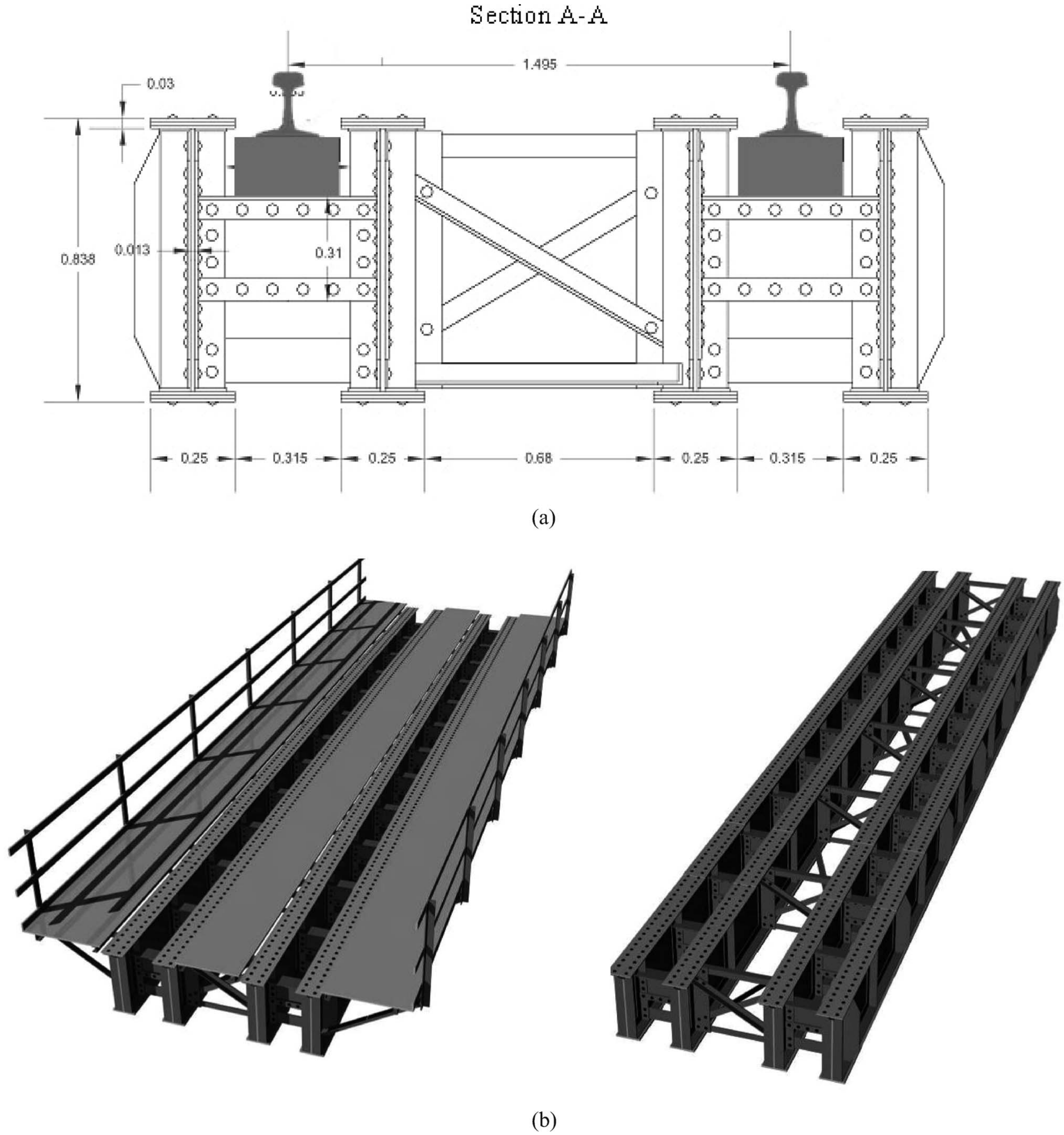


Figure 3. Twinned girder of the Meschio bridge: (a) mid-span vertical section and (b) three-dimensional view of girders, including short diaphragm riveted shear connections (dimensions are in metres).

6. Full-scale static tests

6.1. *Bending test*

In order to characterise the structure in bending and to verify its structural integrity, full-scale bending tests were performed on a girder at the Material Testing Laboratory of the University of Padua. In the first test, BLC1, a three-point bending scheme and 5.0 m of free span were considered, as shown in Figures 4 and 5. The load was applied by means of a hydraulic jack approximately at the centre of the specimen. Out-of-plane buckling of the panel web was observed at a

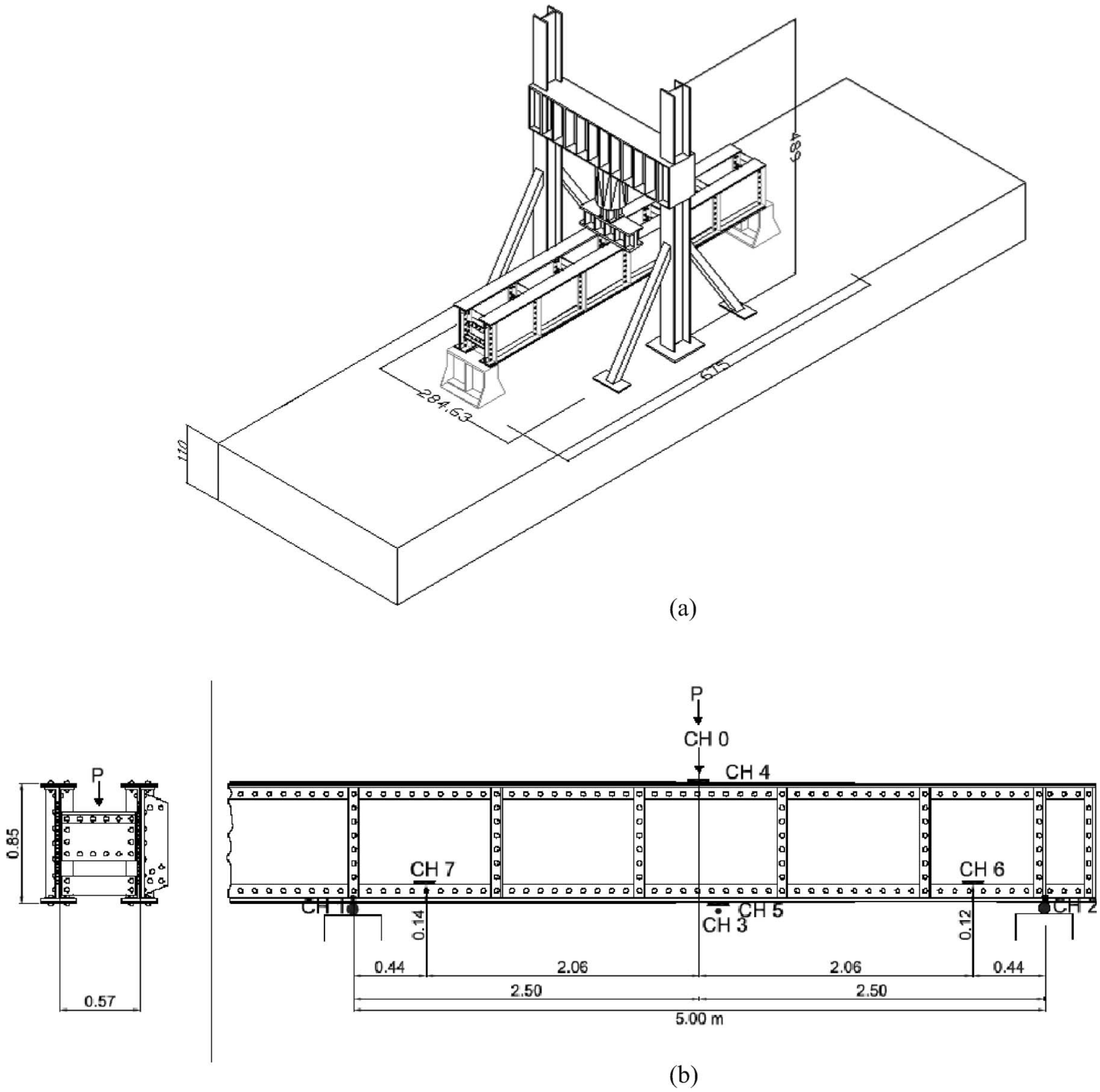


Figure 4. (a) Bending test BLC1: specimen and set-up and (b) sensor distributions for loads (CH 0), displacements (CH 1–3) and strains (CH 4–7) (dimensions are in metres).

value of 2600 kN. In the second test, BLC2, the load was applied above the shear stiffener, and the test set-up is illustrated in Figure 6. The beam was cyclically loaded by increasing the maximum load up to 3000 kN. The onset of plastic behaviour occurred at 2600 kN. The deflection increased linearly up to 2900 kN and the irreversible value of the displacement at the mid-span was about 1.4 mm. The peeling paint can be observed in Figure 7.

It must be stated that static load tests resulting in failure are not realistic for comparison with the real use of the structure (3000 kN means five 600 kN lorries concentrated on one point), but these tests had the unique aim of investigating the structural behaviour until failure of the considered substructures.

6.2. Shear test

In order to characterise the detail category of the shear riveted connection between the transverse panels and the twinned beams, i.e. of the short diaphragm connections, a twinned girder was split up into several specimens, approximately 1 m long. The SLC static shear tests (Figure 8) were carried out at the Material Testing Laboratory of the University of Padua.

Figure 5. Overall view of the BLC1 test.

Monotonic test data highlighted a quasi-linear behaviour up to 900 kN and a failure load of 1060 kN. Failure occurred in the middle of the shank of rivets located at the second and third rows (see Figure 9) corresponding to a shear stress value of about 470 MPa. No significant damage was detected in the base material.

7. Full-scale laboratory fatigue tests

7.1. Bending tests

The full-scale laboratory fatigue test was performed at the Material Testing Laboratory of the University of Padua with the aim of checking the remaining fatigue life of the whole girder. The beam was fixed at each end to two vertical supports, and also secured to a

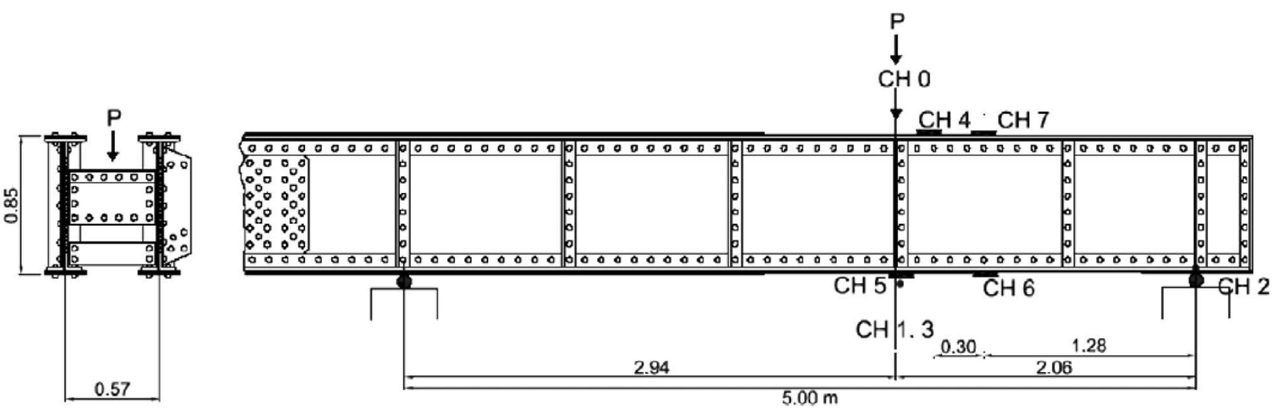
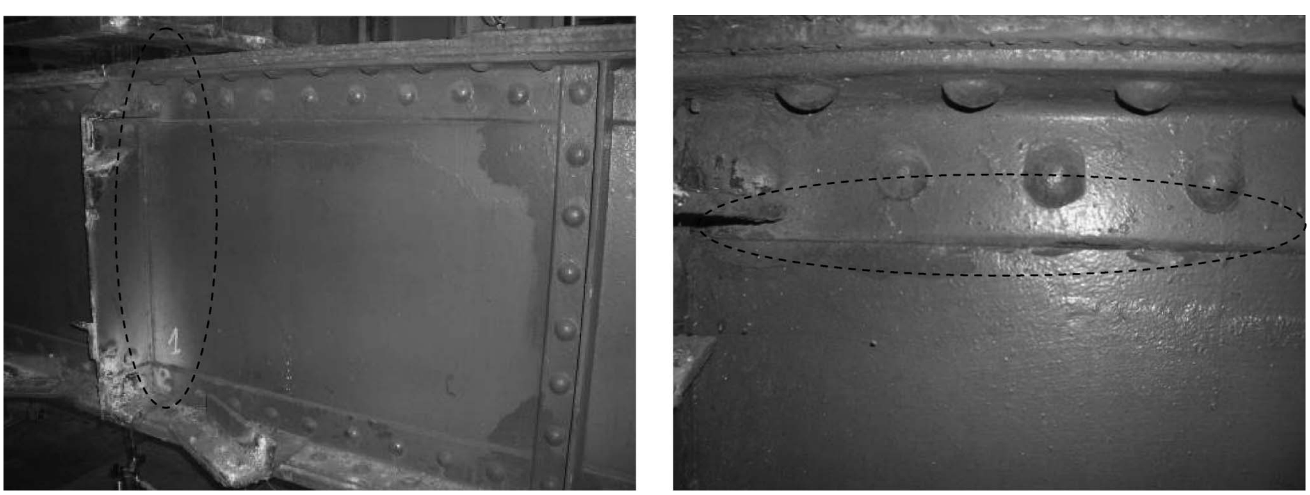


Figure 6. Bending test BLC2: specimen and sensor distributions for load (CH 0), displacements (CH 1–3) and strains (CH 4–7) (dimensions are in metres).



(a) (b)

Figure 7. Test BLC2: (a) vertical stiffener and L-bracings at the point of load application and (b) paint raisings at the end of the test.

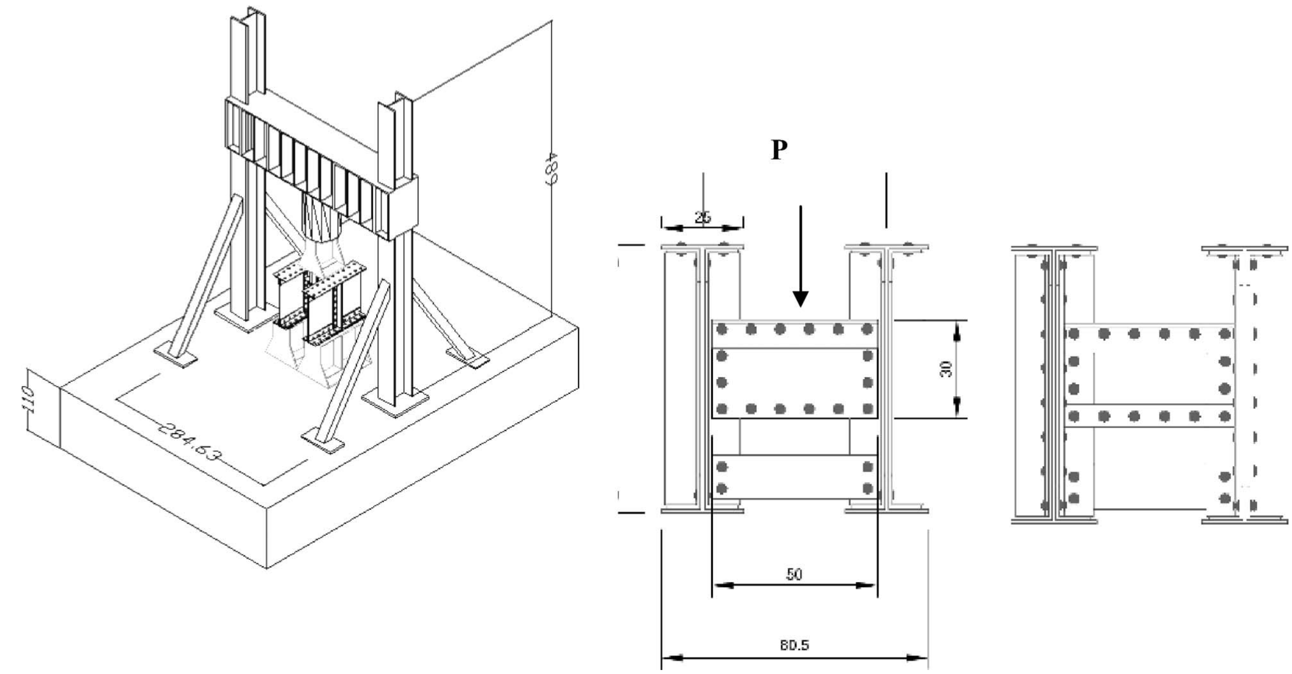


Figure 8. Shear test SLC on short diaphragm riveted shear connections, test set-up and specimen dimensions (in cm): front and rear views.

Figure 9. A failed rivet of the SLC test on short-diaphragm riveted shear connections.

reinforced concrete massive floor by means of four threaded vertical bars, leaving a free span of 5.60 m, while a vertical upward force was applied at the mid-span. The test set-up is depicted in Figure 10. In detail, supports were provided by two HEB 220 coupled by $500 \times 500 \times 50$ mm steel plates; threaded bars of 47 mm in diameter and 3100 mm in length were employed. The test was suspended, without reaching any failure, after 2,500,000 load cycles, with a load variation $\Delta P = 285$ kN in the range 15–300 kN. The test, performed at the frequency of 1 Hz, required 28 days; both continuous and periodic acquisition of loads and displacements were performed.

7.2. *Shear tests*

In railway bridges, members with a shorter influence length usually undergo the largest number of load cycles, since they are directly loaded and undergo a much larger number of cycles and of stress variations with respect to other members. The short diaphragm riveted connection under shear is the critical fatigue detail of the bridge, as a result of simple calculations, the literature and previous tests. Hence four specimens, obtained by splitting up the twinned girder (see Figure 11) were tested in the Laboratory for Structural and Material Testing at the University of Trento, in agreement with the test set-up reported in Figure 12. In view of the high force level and the high loading frequency, the specimen was fixed to the reaction floor by means of threaded high-resistance bars, thus preventing any displacement. Similarly, the end swivel of the actuator was tightened to the upper flange of the transverse connection plate. Due to the limited dimension of the transverse diaphragm, the bending moment effect need not have been considered and simple shear forces were considered to be applied to the rivets.

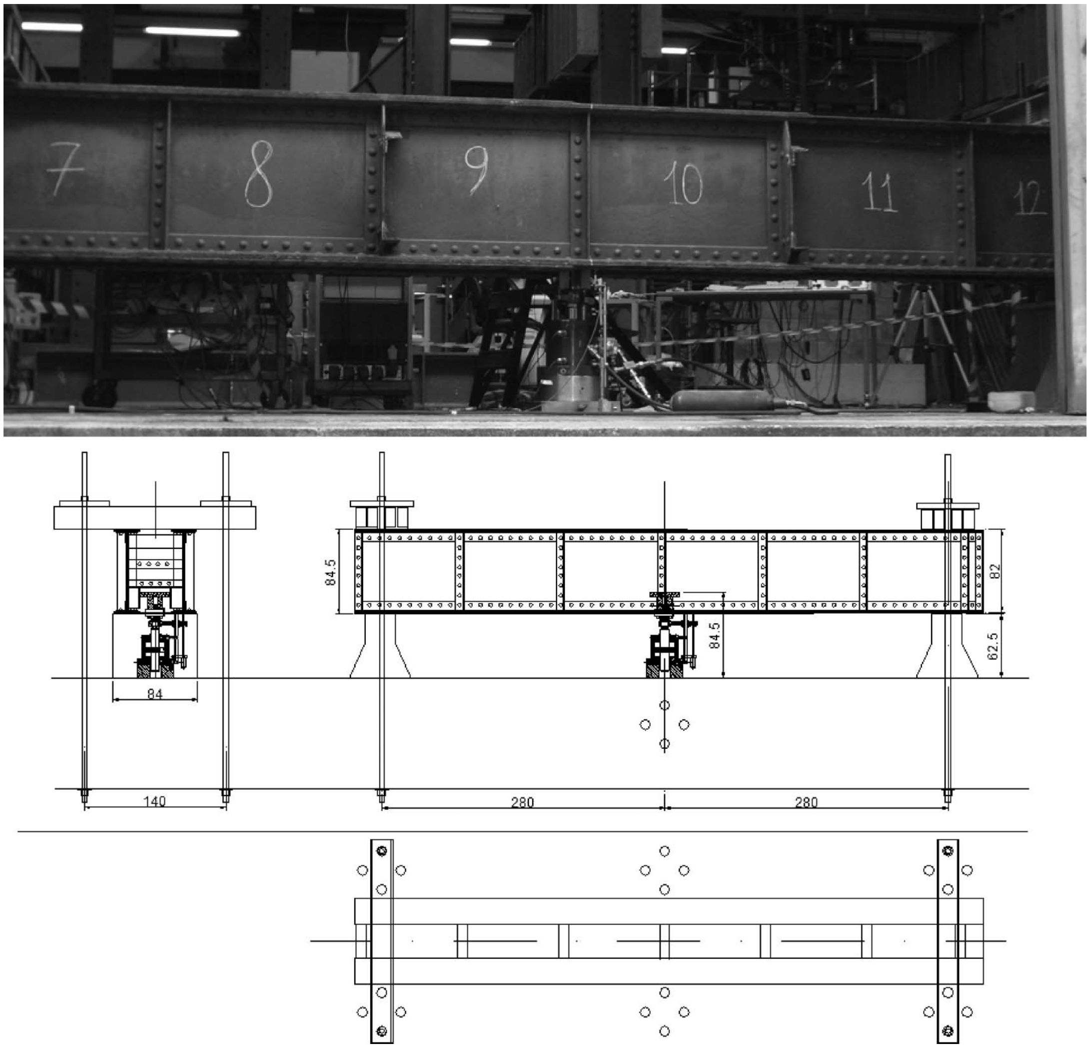


Figure 10. Full-scale fatigue test BHC and set-up (dimensions in cm).

In order to reduce the test duration, the widest load range resulting in an elastic stress state was applied. With this aim, a 1000 kN actuator endowed with a 850 litre/minute oil flow servo-valve was employed, operating a force control at a frequency between 5 and 8 Hz; some days were required to reach rivet failure. Based on the maximum resistance of about 1060 kN, observed in the static test without any significant plastic deformation, upper load levels in the range 700–900 kN were applied. According to the actual loading, only compressive forces were applied, and the minimum load of 100 kN was always maintained, preventing the specimen decompression and any gaps. The test protocol and main results are summarised in Table 2. In detail, the first specimen was loaded in the range 100–900 kN and failed at 184,000 cycles; the second in the range 100–800 kN and failed at 560,000 cycles; the third in the range 100–850kN and failed at 208,850 cycles; the fourth in the range 100–700 kN and failure was reached after 504,500 cycles. All results conservatively neglect cycles deriving from the previous service life because these cycles produced stress variation significantly lower than those obtained during the test. In all tests, failure occurred in rivets and resulted in the head popping off; after the first failure of a rivet, the other ones rapidly reached collapse owing to the increased shear stresses. *S–N* results are summarised in the Wohler diagram of Figure 13 with the literature data of Stadelmann (1984) and Brühwiler *et al.* (1990). Moreover, all data are compared to the EC 1993-1-9 (CEN 2005) fatigue line corresponding to the detail Category $C = 100$, see §2, based on the analogy between rivets and non-preloaded bolts suggested by Di Battista *et al.* (1997). The actual fatigue resistance appears to be greater than values

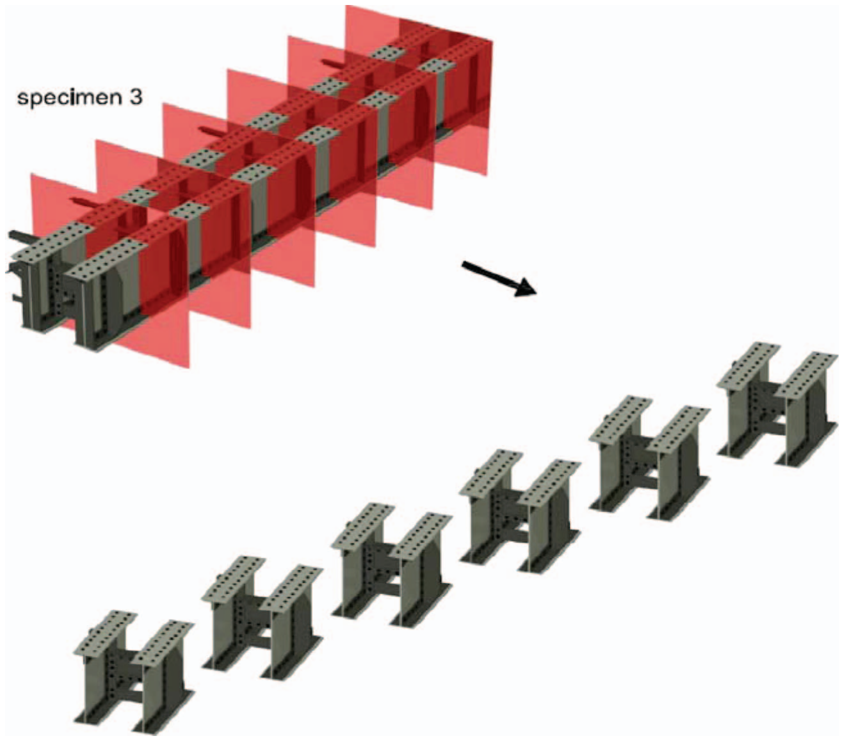
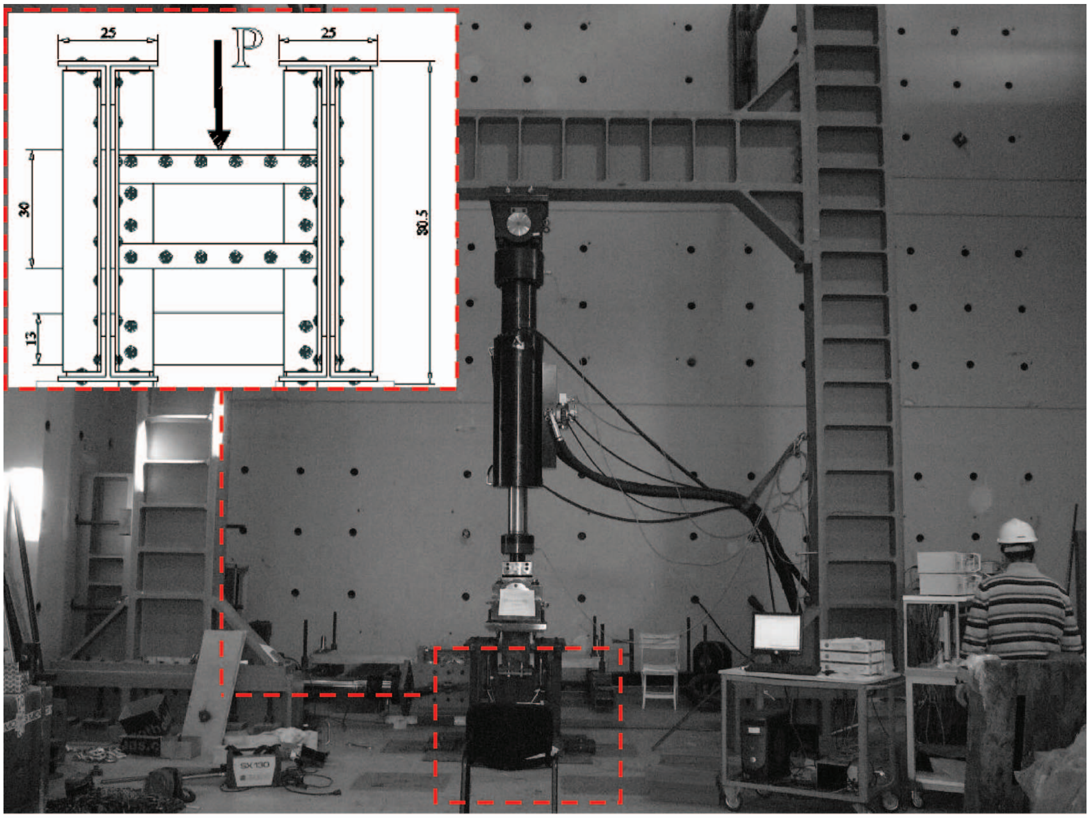


Figure 11. Dismantling process of one girder of the Meschio bridge.

predicted by Category $C = 100$; this confirms results of the full-scale fatigue test and the fact that, differing from the use of bolts, the lack of thread roots and thread run-outs in rivets causes a positive influence of the fatigue endurance because of the absence of stress concentrations. Performing a 5% fractile regression and assuming a safety coefficient equal to 1.35, as suggested by EN 1993-1-9 (CEN 2005) for an assessment method related to safe life and high consequence of failure, a design fatigue category $C = 117$ could be suggested according to these results and those of Stadelmann (1984) and Brühwiler *et al.* (1990). The design fatigue category is related to these types of riveted connections, but a more extensive experimental research is needed to confirm or improve this result.

8. Conclusions

Static and laboratory fatigue tests on a riveted railway bridge are described and commented upon in this paper, with the aim of obtaining new insights on the fatigue behaviour of riveted railway bridges. The old steel constituting the twinned-girder of the Meschio bridge was characterised using metallographic, tensile and impact tests. As a result, it did not match EN 10025-2 (CEN 2004) standards, both from a mechanical and chemical point of view. In detail, a high sulphur and low carbon content was detected, thus reducing corrosion resistance and tenacity. In fact, a low CVN value equal to 11.5 J was detected. It was, however, associated with the rather high yielding and ultimate tensile stress, which are equal to 322 and 421 MPa, respectively. A Vickers hardness test was also performed on the rivets and, based on the literature, an ultimate failure tension close to that of a mild steel was found. Full-scale static, cyclic and laboratory fatigue bending tests did not show either crack propagation or failure for the in-service applied loads up to 2,500,000 cycles. With regards to the critical fatigue detail of the entire bridge, it was located in the riveted connection of the short-shear diaphragm to which the load was directly applied. Results of four laboratory shear fatigue tests allowed the determination of the failure in the rivet shanks and resulted in the head popping off. The recorded mean resistance was higher than the one predicted by EN 1993-1-9 (CEN 2005), category $C = 100$. With regards to the choice of the shear fatigue detail category, results confirm a safe analogy between rivets and non-preloaded bolts in shear connections. This extra safety could also be related to the lack of thread roots and thread run-outs in rivets, which reduce



(a)

(b)

Figure 12. Laboratory fatigue SHC test: (a) test set-up and (b) the shear diaphragm after the rivets failure (the dimensions are in $\times 10^{-2}$ m).

stress concentrations in rivets in comparison with non-preloaded bolts. Performing a 5% fractile regression and assuming a safety coefficient equal to 1.35, a design fatigue category $C = 117$ could be suggested. The design fatigue category is related to these types of riveted connections, but a more extensive

Table 2. Results of shear fatigue substructure tests.

Specimen	Maximum load (kN)	Minimum load (kN)	Number of cycles	Remarks
I	900	100	138,000	Paint cracks under loaded rivets
			150,000	Paint cracks under rivets loaded in rear part
			159,000	Visible rivet head deformation
			176,000	2–3 mm detachment rivet heads from central plate in rear left part
			184,000	Failure: front side, right rivets/2nd–3rd row
II	800	100	23,300	Paint cracks under loaded rivets
			188,400	1–2 mm detachment rivet heads from central plate in the rear left part
			560,000	Failure: rear side, right rivet/3rd row
III	850	100	203,850	Paint cracks under rivets loaded in the rear part
			208,850	Failure: rear side, right rivet/3rd row
IV	700	100	430,515	Paint cracks under rivets loaded in rear part
			504,515	Failure: rear side, right rivet/3rd row

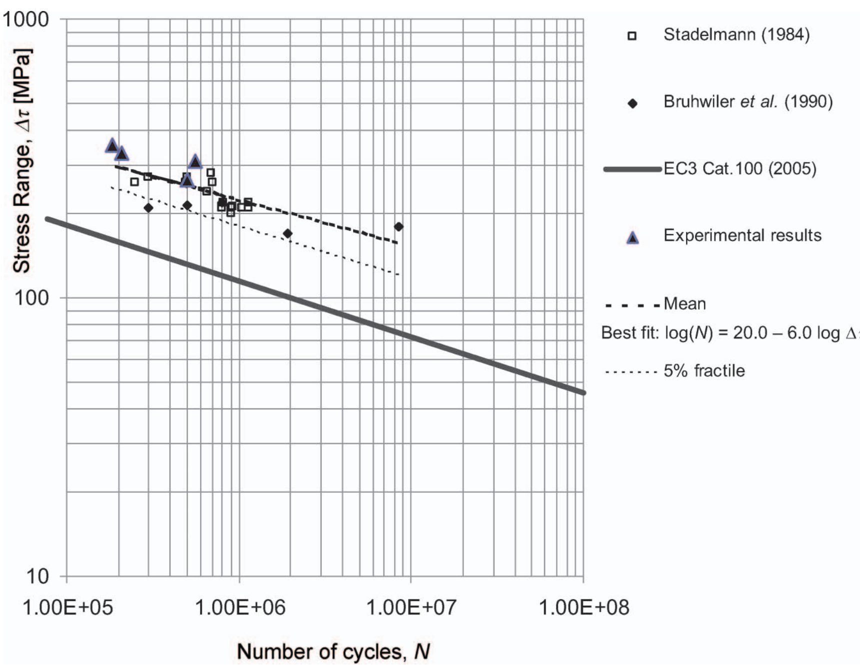


Figure 13. *S–N* curve with present shear fatigue test results, shear fatigue literature results and shear fatigue design and experimental curves.

experimental research is needed to confirm or improve this result.

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