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Structural Analysis of Historical Metal Bridges in Italy

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Abstract In this paper different studies on the structural analysis, the fatigue assessment and the damage evaluation of metal bridges are reported. These work examples are related to a widespread amount of works conducted since the first of 2000 in the research area of bridge design and assessment. The most part of these researches are related to railway bridges and historical metal bridges, because of their particular vulnerability to damage decay during their life. The main research topics are presented and discussed.

Keywords: Steel bridge; fatigue; remaining life; monitoring.

Introduction

Increasing of traffic and speeds on infrastructures, has lead to the consequent increase of cargos and speeds in railway bridges, strategic node of an historical national net in some case at the limit of the traffic capacity. Managing authorities are more and more aware of this relevant consistency of old bridges, and they are interrogating on multiple aspects, that goes from the appraisal of the residual life, to the possibilities offered by programmed maintenance operations, until the extreme solution of the substitution of the complete structure. In order to bridge the gap of a minor attention on historical metal bridges, a deep analysis is herein reported on different studies performed on bridge historical structures. These studies have been conducted in partnership with different bridge owners, such as RFI-Rete Ferroviaria Italiana (the Italian national railway authority) and others.

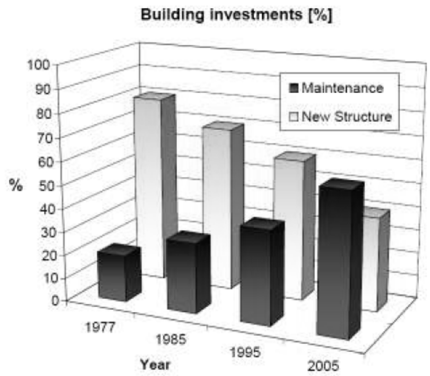

Figure 1: Building investments on maintenance and new structures (Sustainable bridges 2006)

Lifelines and Damage

Lifelines are those systems that are vital for the continued operating of communities in an industrialized society. They include also transportation systems. Even without an earthquake, the disruption of any one of these systems, even for a day, would constitute a major disaster. In the aftermath of a damaging earthquake, many of these systems play a critical role for the emergency response community and the community in general to save lives and prevent additional damage to property (Schiff and Buckle 1995). In particular in transport systems, bridges represents nodes of lifelines in which cyclic or exceptional damage phenomena could lead to the closure or in other case to a sudden collapse of the structure. Research studies are needed, in particular in order to prevent

major disaster to the lifelines served by single bridges. In particular from the structural point of view, damage could influence the dynamic response of a structure and, at the same time, changes in its behavior may be associated with the decay of the system's mechanical properties (Salawu 1997). Based on these considerations, various papers have examined the use of measured variations in dynamic behavior to detect structural damage. Particular attention has been focused on the use of frequencies only, on account of the simplicity of measuring them and, therefore, their experimental reliability (Ostachowicz and Krawczuk 1991). Moreover, the estimation of the remaining fatigue life is an essential ongoing general procedure particularly important for railway bridge management (Sustainable Bridges 2006, Assessment of Existing Steel Structures 2008). Fatigue behaviour of riveted connections has been overly studied during these last decades both with experimental and numerical approaches (Al-Emrani 2005, Al-Emrani and Kliger 2003, DiBattista et al. 1997, DiBattista et al. 1998, Imam et al. 2007, Kulak 1996, Kulak 2000, Matar 2007, Matar and Greiner 2006, Pipinato et al. 2009a, Pipinato et al. 2009b, Righiniotis and Timothy 2008). Some existing studies related to riveted structures indicates that some fatigue failures are related to connected elements, rather than to the rivets themselves (Righiniotis and Timothy 2008). Other authors, such as Bruhwiler et al. (Bruhwiler and Smith (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. With regard to fatigue assessment of riveted historical metal bridges, many factors have found to play an important role, as documented by several studies (DiBattista, et al. 1997, Matar and Greiner 2006, Pipinato et al. 2009a, Pipinato et al. 2009b) and an accurate estimation of the stress variation by means of a detailed experimental approach or proper numerical analyses of the critical details is of key importance for a reliable estimation of the remaining fatigue life of the structure. As shown in (Bruhwiler and Smith 1990), the fatigue life of riveted railway bridges is often governed by particular critical structural details since they undergo a much larger number of loading fluctuations and stress variations with respect to other members. In short and medium span riveted bridges, and in particular in twinned beam bridges short diaphragm riveted connections were found to be the governing fatigue details. Dynamic identification could help in preliminary evaluation of the structural integrity of the whole bridge, as developed in the following.

Case Studies

Meschio Bridge The dismantling of a twin beam bridge of the 1918 of RFI pertaining to the Mestre-Cormons line, has been the reason in order to consider the opportunity to analyze the structure with laboratory tests. The bridge has been in line near Sacile (Pordenone) until the second half of 2006. The bridge is characterized by one single span of 12,30 m, with the typology of twinned-beams, with independent lane for every direction: every double composite twinned-beam, measure in width section 85 cm, for 95 cm of height. The thickness of the web is constant along the beam and measure 11 mm, while the flanges and the cantonal measure 11-22-33 mm, with reinforcing increasing towards the half span of the structure. The bridge has been divided in the middle in two parts of 6,15 meters each one.

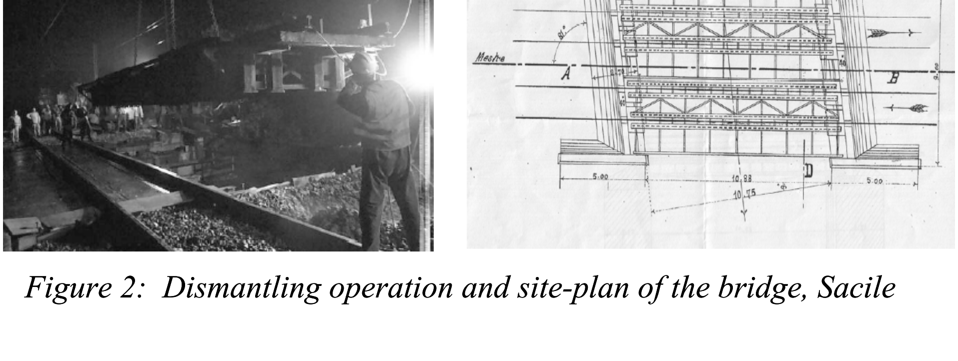

Figure 2: Dismantling operation and site-plan of the bridge, Sacile

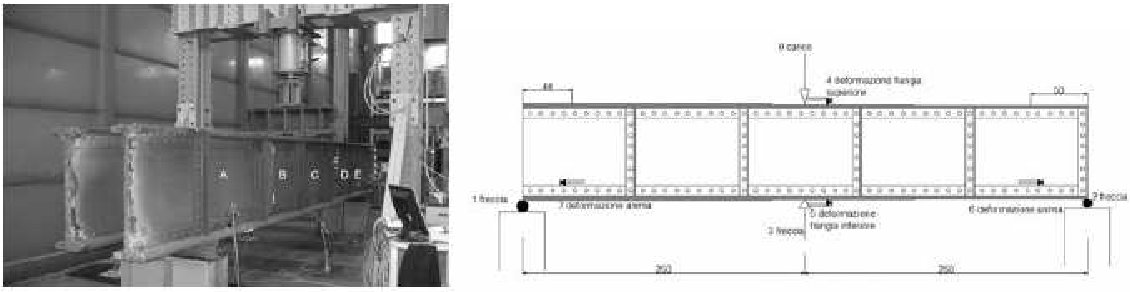

Figure 3: Experimental testing of bridge members

The bridge has been completely dismantled and subdivided in more parts, in order to perform static and high cycle fatigue testing, both bending and shear. Results of the research performed are reported for e.g. in (Pipinato et al. 2009a, Pipinato et al. 2009b).

Casaratta Bridge The bridge is characterized by one single span of 12.30m, and is made up by two twinned-beams, with independent lane for every direction. Each double composite twinned-beam, is 85cm large, and 95cm height. The thickness of the web is constant along the beam and measure 11mm, whereas the flanges increase throughout the span with 11-22-33mm thicknesses. Wood beams are located between the coupled beams. Transverse short shear diaphragms riveted with double angles to both webs carries the rails. Each twinned beam supported the wood elements of a single rail.

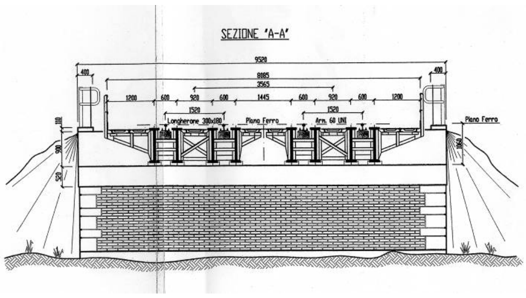

Figure 4: Elevation design of the Casaratta bridge

Short diaphragm riveted connections have been a common source of fatigue damage in some typical riveted railway bridges with short span. Hence the fatigue life of riveted railway bridges is often governed by this structural details since they undergo a much larger number of loading fluctuations and stress variations with respect to other members. For this kind of connection an accurate numerical analysis, taking into account material non linearities due to plasticization of materials and contact phenomena between the rivets and the plate and the plates themselves, is developed to obtain some indications on the failure mode of the critical fatigue details and accurate stress variations for the estimation of the residual fatigue life. The numerical results well fit the experimental results in terms of maximum shear load of the connection. The numerical analysis showed that, for typical this connection, the damage is generated by high stress levels concentrated in central rivets. As a result, rivet failure due to shear stress concentration, together with possible rivet's loss or diffused corrosion, was found to be the one of the major mechanism related to fatigue cracking for this type of railway bridges.

Rosolina Bridge The Rosolina bridge, built in 1960 in the Rovigo province, is a medium span open truss metal riveted railway bridge. It is composed by three span, skewed up to the Po river. The total span is approximately 100m, subdivided in 36-32-36 m. The deck is 5.1m large, measured between the axis of the lateral reticular structure. The three spans are simple supported. Two towers for the bridge opening operation lies on the lateral span, but they are completely abandoned since the construction and were never put into operation. The reticular structure has been built as a Warren system. Triangular gusset plate connect the various members of the bridge.


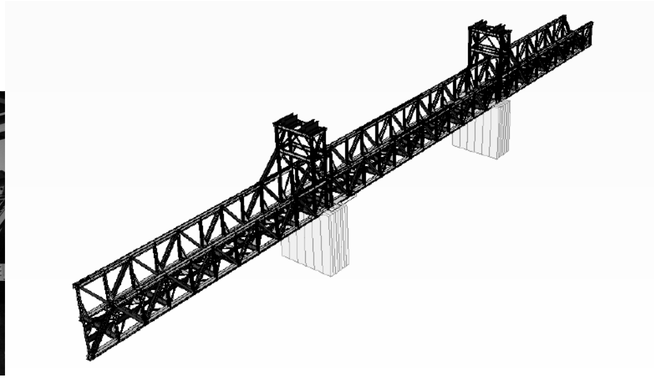

Figure 5: Lateral view of the bridge (on the left), and Fem model (on the right). Rovigo

A detailed FEM model of the entire bridge has been performed. No alternative model has been realized computing for material degradation , e.g., reducing transversal section, as the visual inspection performed has considered this problem not affecting the structure. As the aim of the bridge assessment is referred to the in-service conditions, all the elements are assumed elastic. Some characteristics related to the FEM model realized are: beam elements have been used for structural elements, except for gusset and joint plates in which plate elements have been introduced; all section geometries for each beam element have been shaped as the as built section. The model has been calibrated with the deformed configuration obtained by the in-situ test performed in 2010. A monitoring system has been introduced into the structure with the aim of calibrating the FEM model, but also to test in-field stress excursion, and to perform a dynamic identification. In particular and according to the analysis phase, the deformations in the "critical" elements were monitored by means of strain gauges, to evaluate the maximum strains and consequent stresses in occurrence of the passage of the trains. Different test setups were considered in the dynamic data acquisition, thus using a limited number of sensors to characterize the most part of the structure. Vibrations were recorded both in occurrence of the passage of the train, to evaluate the acceleration peaks, and just for ambient vibrations (mainly wind). Acquired data (output only method - OMA) were elaborated by using the FDD approach (Brincker et al. 2000), and the main frequencies of interest were defined.

Figure 6: Lateral view of the central span of the Adige bridge, Rovigo

Adige Bridge Simple truss spans are simply supported on the shoulders and on the central piles in the river-bed. The historical bridge was built in 1866, and after 40 years the second parallel track was realized: these bridges, were both destroyed during the II World War. The configuration of the bridge structure is presented in the above figure: the even-track, was built in 1946 and the other one in 1949. The bridge studied is the oldest in service (from 1946). The superstructure consists of riveted built up truss members. The bridge consists on a double three span (50.16m–60.648m–50.160m ≈ 161m) two-way truss girder, 5.06m wide (from the center of mass of the lower chords) and 7.2m high (from

lower chord to the upper one). Every bridge, consists of two longitudinal truss girders with transverse frame at the deck. The longitudinal truss beam is made up of 32 different cross-sections having slightly variable geometric dimensions. Lower and upper chords are composed by U-shaped sections. The deck is realized with longitudinal stringers, and transverse floor beams. Actually, wooden transverse beams have been totally replaced along the national railway lines with concrete ones, except in metal bridges in which they stand, to avoid induced failure or cracking related to vibrations. All structural elements are built-up members, connected by hot riveting. About boundary conditions, double fixed and movable bearings stands alternately on each side span as shown. The application of an assessment procedure to the Adige Bridge outlined some relevant issues:
- the materials used in this quite old railway bridge have shown mechanical and chemical properties (strength, chemical composition) comparable to those provided by actual Eurocodes;
- corrosion is a local phenomenon that does not necessarily play a relevant role on the global response of the bridge if section loss is less than 15%;
- fatigue cracks, not discovered in this first phase assessment;
- fatigue assessment concerning the remaining life could be performed using the Palmgren - Miner rule, accounting the possible traffic increase for the estimation of the residual lifetime: the result gives a reasonable and detailed estimation of safe exercise;
- monitoring should be an option when the "calculated" fatigue safety is insufficient.

The application of such a comprehensive procedure to the Adige Bridge, with a common scheme for railway bridges, showed that a detailed analysis and assessment can result in limiting the economical effort for retrofitting works to a small fraction of the costs needed for replacing the bridge.

Conclusions

In this paper some research case studies have been presented concerning the analysis and assessment of historical metal riveted railway bridges. Different analysis have been conducted and are herein summerized:

- concerning the Meschio bridge, static, quasi-static and high cycle fatigue experimental tests have been conducted on the dismantled bridge, in order to find out the more damaged sub-structure of the bridge; key results have been reported also in (Pipinato et al. 2009a, Pipinato et al. 2009b);
- the Casaratta bridge, is another similar short span metal bridge, as the Meschio one; it has been more investigated from the microstructural point of view, by comparing also some test results with advanced numerical FEM model; once calibrated these models, it has been confirmed the experimental behaviour of fatigue failure observed also in the Meschio bridge;
- about the Rosolina bridge, this study has been performed with the aim of investigating the remaining life of the existing structure; the bridge has been dynamically identified, and structural NDT tests have been performed; the remaining life has been calculated according to (Pipinato 2010);
- finally, concerning the Adige bridge, in this case the remaining life has been calculated according to advanced reliability assessment, also in accordance with the method reported in (Pipinato and Modena 2009).

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