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Observation of failure scenarios in riveted assemblies: an innovative experimental strategy

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Abstract

Hot riveting was largely used as method of assembly in France during the appearing and expansion of the railway network (1840-1940). Present in wrought iron and steel constructions, riveted connections are commonly found in the French railway heritage.

Conceived as a permanent assembly, these connections work by the shearing of the rivets and the friction between the plates, such friction is caused by the clamping force due to the cooling of the rivet after forging. The mechanical behavior of the assembly will depend on the many parameters involved in the process. However, three main failure modes have been identified: tension on the plates, shearing of the rivet and bearing in the plates (pressure of rivet on the rivet hole).

To understand the influence of friction in the global behavior of the assembly, a comparison between two types of S235 steel specimens is proposed. The first was a set of several hot riveted specimens and in the second one, the rivet was replaced by a martensitic stainless steel axis with a high yield stress that kept the pieces of the connection in place (no clamping force was thus present this time). The behavior of both types of specimens was then studied in tension using 3D Digital Image Correlation to analyze local and global displacements.

The comparison between the relative displacements of the connected plates of the two types of specimens allows identifying the influence of friction in the global behavior. To complete this kinematics investigation, failure scenarios are described through longitudinal cross sections analysis.

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Keywords:
riveted assemblies, digital image correlation, static loadings, steel.

1. Introduction

In order to estimate the remaining service life of ancient railway bridges, the understanding of the mechanical behaviour of riveted assemblies is a necessary prerequisite. Many research teams have then investigated the fatigue behavior of riveted connections and materials used in the field of bridge engineering [1–6]. However, static loadings can give preliminary results on the potentials influence of parameters which are not yet fully elucidated. So far, few static loadings analysis have been performed on riveted joints [7].

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The objective of this study is to propose an experimental procedure able to give information on the friction strength induced by the clamping force due to the cooling of the rivet. This strength is indeed important in order to perform relevant fatigue tests (considering that cyclic loadings must be applied in the friction domain) and then to propose an appropriate numerical model dedicated to high cycle fatigue. The friction strength limit is indeed the strength from which the applied load is transferred to the plates through other concurrent mechanisms: the plates bearing (pressure of the rivet shank on the rivet hole) and the rivet shearing.

For this task, a set of several hot riveted specimens was specially manufactured with the support and expertise of the reparation team of metallic structures of the SNCF. Double lap joint and single riveted specimens were chosen for this study in order to have a symmetrical behavior of the connection (i.e. no induced bending moment and out-of-plane displacements). Even if riveted assemblies of metallic bridges were made in wrought iron (particularly in the second half of the 19th century), it was decided to manufacture these specimens in steel in order to overcome the material effect. Wrought irons have indeed a known and scattered mechanical behavior due to the presence of non-metallic inclusions [4], [8] and [9]. A S235 grade steel was chosen as plate material (8mm thick). 18mm diameter rivets (S355 grade steel) used in metallic reparation were driven. Pinned specimens made with the same S235 steel were also manufactured to be able to observe the influence of the clamping force in the riveted connections.

Nomenclature

SNCF	National Society of French Railways
RPM	Reparation team of metallic structures (SNCF)
LBMS	Brest Laboratory of Mechanics and Systems
UBO	University of Brest, France
DIC	Digital Image Correlation
ROI	Region Of Interest
U_{rel}	Relative displacement (mm)

2. Experimental set-up

The design of the riveted specimens is based on the geometry characteristics described in French literature at the end of the 19th century which can give examples, for instance, of plates thickness to use for a given rivet diameter d[10], [11] and also later in [12]. For a 18mm rivet, the thickness of a steel plate must be close to 8mm. The edge distance was chosen equal to $1,5d$ (i.e. 27mm) and the rivet lap equal to $2d$ (i.e. 36mm) which are also in line with the literature and allows to show all potential failure scenarios (plate tension, rivet shearing and plate bearing). The layout of the riveted specimens is presented in the Figure 1. The rivet length was chosen with the NF E 27-156 French standards and verified with preliminary tests.

The pinned specimens were assembled using a high yield stress axis (950MPa) with a threaded end. The corresponding nut was manually tighten until it just contacts the plate. The locational clearance fit was less than 0.05mm in that case.

One plate material and one rivet material were used for this study. The chemical composition of these materials are given in Table 1.

Table 1. Chemical composition of the materials used (plates and rivets).

	C	Si	Mn	P	S	Cu	Ni	Cr	Al	Fe
Plates (S235)	0.195	0.24	0.98	0.01	0.024	0.06	-	-	-	bal.
Rivets (S355)	0.17	0.013	0.48	0.021	0.012	0.036	0.017	0.028	0.036	bal.

The experiments were performed with an Instron® 5585 tensile device equipped with two hydraulics grips; the displacement speed was set at 0.5 mm/min. As riveted assemblies behave with friction and potential clearances between

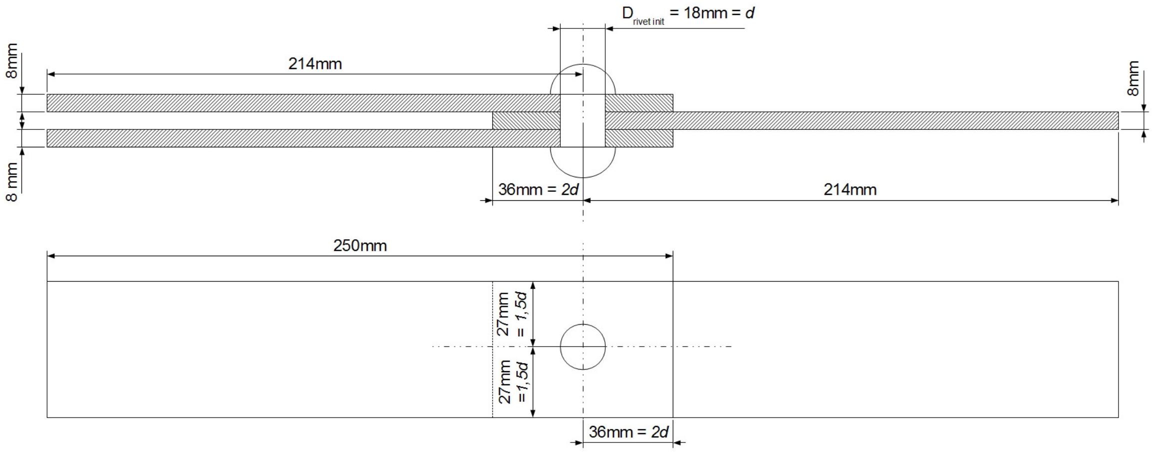

Fig. 1. Elevation and plan views of the riveted specimens.

the rivet shank and the rim of the hole can be observed in the studied connections, global and local displacements were analyzed. An image analysis system based on Digital Image Correlation (ARAMIS, GOM) was used. This enabled to analyse the behaviour of each plate separately, see Figure 2.

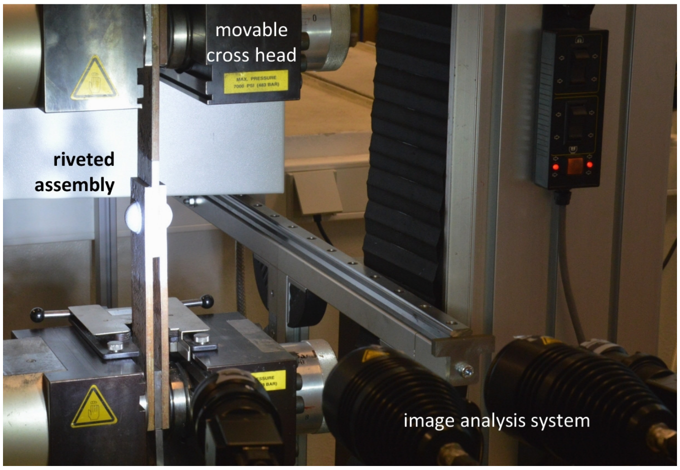

Fig. 2. Riveted joint set-up into the tensile machine with the DIC (GOM) equipment.

In order to study the relative displacement between the outer plates (fixed to the stationary cross head) and the middle plate on which the load is applied, several analysis regions were chosen in the main ROI. In these boxes, the average displacement was measured. The ROI, the chosen regions, the speckle pattern used for the DIC and the loading direction are presented in the Figure 3. The same regions were analyzed for pinned assemblies. Blue zones presented in Figure 3 are used to analyze the displacement of the middle plate far enough from the stress concentrator (rivet hole). Red zones were chosen for the determination of the relative displacement of middle plate.

Tests were displacement controlled.

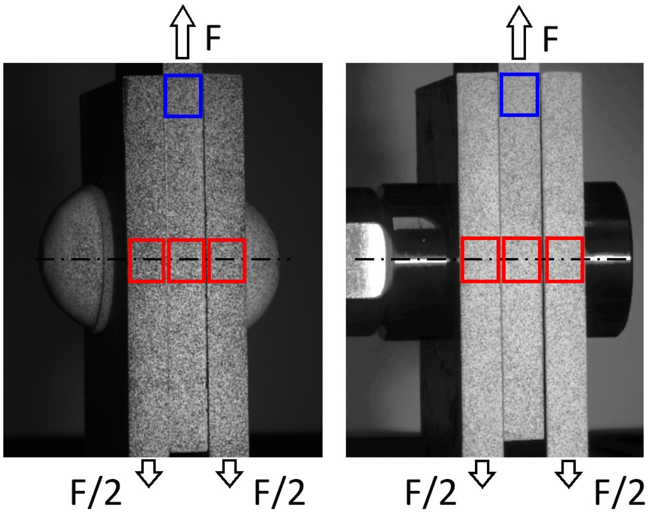

Fig. 3. Example of the ROI including the DIC speckle pattern, analysis zones and loading direction on a riveted specimen (left) and a pinned specimen (right).

3. Results and analysis

Shear tests on three riveted specimen were carried out. Since the potential scatter obtained with pinned specimen should be significantly lower (no effect of the hot riveting process), pinned specimen behavior was tested only twice. As expected, the behavior of pinned specimens seems to be repeatable. For all tested specimens, the middle plate failed in tension.

The shear behavior of three riveted specimens and two pinned specimens is presented in Figure 4. These curves correspond to the relation between the applied load and the measured displacement of the middle plate (blue boxes presented in Figure 3).

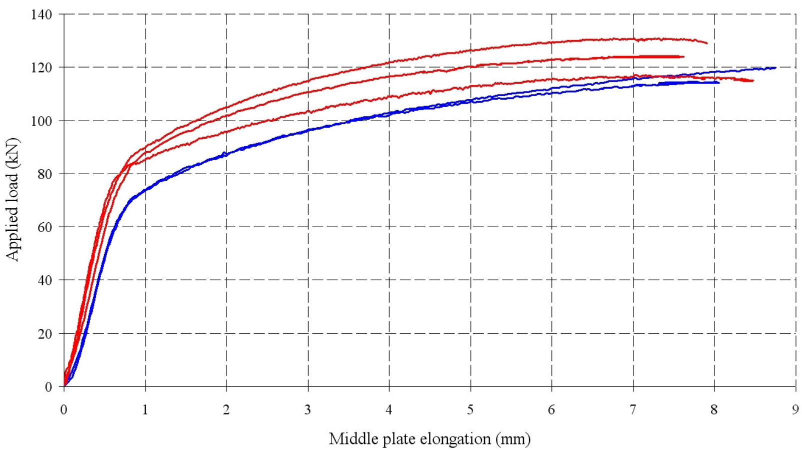

Fig. 4. Set of load-elongation curves of the riveted specimens (red) and pinned specimens (blue).

Every riveted specimen behavior follow the same trend. When comparing riveted and pinned specimens, it appears that the prestress induced by the clamping force due to the cooling of the rivet seems to "delay" the yielding of the middle plate of the connection. The corresponding strength is increased by *ca.* 10%.

Moreover, the stiffness measured on the middle plate also increased with the prestressed state. The stiffness is indeed increased by *ca.* 20%. This observation might be related to the prestress considering that stiffnesses of the rivet (S355) and the axis (martensitic stainless steel) are close. Considering that the steels used are homogeneous, the observed scatter in the riveted specimens set of curves can be attributed mainly to the hot riveted process and its induced parameters: driving temperature and driving pressure for instance.

The friction caused by the clamping force is then studied by measuring the relative displacement between the middle plate and the outer ones.

3.1. Relative displacement between inner and outer plates

Red regions (Figure 3) were studied to analyse the relative displacement U_{rel}. It corresponds to the averaged displacement (along the load direction) measured on the middle plate compared with the mean displacement of the outer ones (along the load direction as well). Considering that the influence of the clamping force, and therefore of the friction between the plates, was previously shown, U_{rel} is only analysed during the first 100 seconds of test (about 50kN), see Figure 5. Since results on pinned specimens proved to be very repeatable, only one curve is proposed for comparison in this diagram.

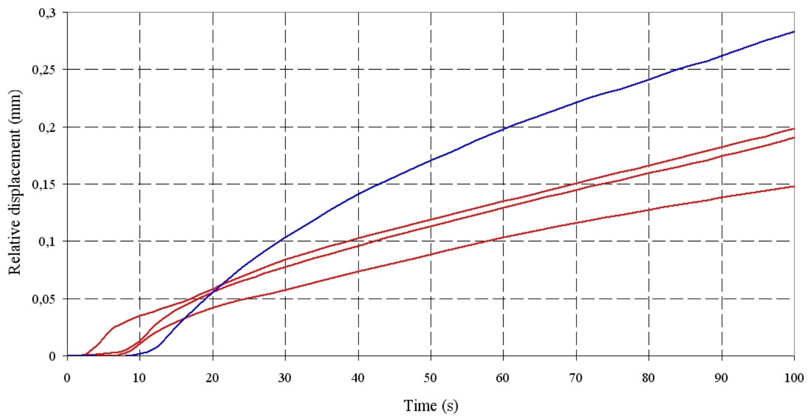

Fig. 5. Evolution of the relative displacement in riveted assemblies (red) and in a pinned specimen (blue).

The result shows that U_{rel} is rapidly influenced by the friction between the plates in riveted assemblies. Indeed, the corresponding speed of a pinned specimen (with a low friction strength) is higher than those of riveted specimens.

This confirms the previous observation where the stiffness measurement of the assembly can be related to the friction strength induced by the rivet driving operation.

3.2. Riveted connections cross sections

In order to better understand the failure scenario that occurs in the studied riveted assemblies, cross sections analysis were also performed. Two types of specimens were cut along the longitudinal axis of the rivet then polished with silicon carbide paper: the tensile tested ones and three others which were not tested (they were manufactured to this purpose). For the latter, the clearances between the rivet shank and of the rivet hole (along the rivet shank) are small and are due to the rivet driving process.

The comparison of two different cross-sections is proposed in the Figure 6. It highlights the different clearances present in a hot riveted joint: clearances due to the driving process (Figure 6 left), and those due to the plastic deformation in the vicinity of the stress concentration (Figure 6 right). The cross section corresponding to the tested specimen illustrates the bearing of the outer plates while the middle one is under permanent deformation.

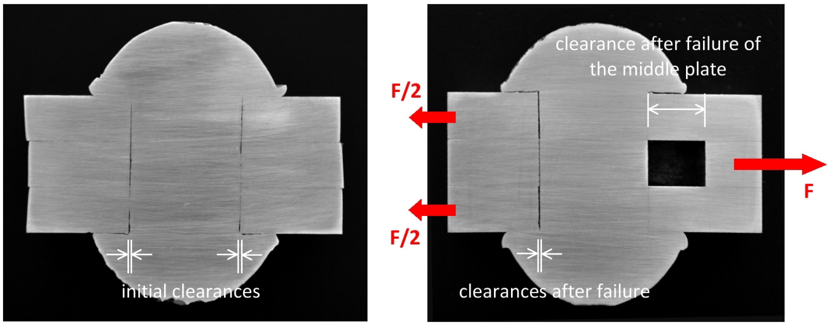

Fig. 6. Comparison of clearances observed on a non-tested (left) and a tested riveted (right) specimen.

This comparison allows us to better understand the behaviour of the tested riveted connections through experimental investigations. No slipping was measured during the increasing of the progressive shear loading; it means that the transition from the friction-type to the bearing-type behaviour is smooth. This is corroborated by the very small clearances observed in longitudinal cross-sections of the riveted assemblies. Once bearing behaviour begins,the applied load is transferred to the plates through two concurrent mechanisms: this pressure of the rivet shank and the rivet shearing. Considering the involved shear loadings, and the high mechanical properties of the S355 grade steel, no shear deformation of the rivet was expected nor observed.

Two main failure mechanisms were thus observed during this experimental campaign: the tensile failure mode (primary) and the plate bearing (secondary).

4. Conclusions

Tensile tests were performed on steel riveted and pinned assemblies in order to identify the contribution of the clamping force on the global behaviour of a hot riveted joint. An image analysis system was used to identify the potential frictional strength through stiffness analysis. This investigation shows that a DIC system is able to give information of the friction strength induced by hot riveting. This study is thus able to provide important results for modelling riveted connections, failure scenarios are indeed frictional strength dependant. The next step is to extend this study to connections subjected to cyclic loadings. In addition, an examination of longitudinal cross sections of riveted joints makes it possible to describe the different failure modes involved during shear loadings.

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