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Abstract

The fatigue strength improvement of materials and structures has always been the subject of studies, as a consequence of the rapid development of technologies and strict safety requirements. In the railway field the fatigue resistance problem is thoroughly studied due to high transportation safety standard. Fatigue cracking is a major issue, in particular at rail-end-bolt holes. Cold Expansion is a common technique to induce beneficial residual compressive stresses around the holes, with the aim to improve the fatigue life of the rail. This paper is the first of a two part-series dealing with the study of the residual stress-strain field induced by the cold expansion process around rail-end-bolt holes. In Part I of this series, a contribution to better understanding the whole strain field distribution arising around rail-end-bolt holes during and after cold expansion is presented. Strains were experimentally measured using both electrical strain gauges and 2D-Digital Image Correlation. Contrary to common literature, strain-time history during the entire cold expansion process was investigated, in order to capture the highly non-linear elasto-plastic response of the material; the results of this study has been used in Part II of this series for the validation of the finite element model described there. The cold expansion process was applied to three rail holes, having equal nominal diameter. At first, the experimental results concerning each expanded hole are analysed. Then, all the results are compared, in order to evaluate the repeatability: - of the measurements; - of the Cold Expansion process; - of the adopted experimental technique, and, above all, to extrapolate the distribution of the hoop and radial residual strains as a function of the distance from the hole edge. At the end, results obtained by strain gauges and 2D-Digital Image Correlation are compared: a good agreement is found on the central flat surface of the rail web, which guarantees the availability of a robust and valuable highly non-linear reference result that has been used for the validation of the finite element model presented in Part II of this series.

Keywords: Cold Expansion; Residual Stresses; Strain Gauge; Digital Image Correlation; Fatigue life; Fatigue Crack Growth; Experimental Analysis

1. Introduction

The attempt to improve the fatigue strength of materials and structures has always been subject of studies by researchers, because of the rapid development of industries and technologies. In the railway field the fatigue problem is particularly studied, due to high transportation safety standard required for both trains and superstructure...
components. Fatigue cracking originating at rail-end-bolt holes of rail joints, for example, is a critical problem encountered in the railway superstructure (Zerbst et al. 2009; Cannon et al. 2003).

Rail joints may be classified as non-insulated or insulated (Carolan, Jeong, and Perlman 2014); while the former are currently employed to join two rail segments of unequal size and for temporary repairs (Talamini, Jeong, and Gordon 2007), insulated rail joints (IRJs) are necessary components to guarantee railway safety (Esveld 2001), being used for signalling purposes (Himebaugh, Plaut, and Dillard 2008) and for broken rails detection (Jeong, Bruzek, and Tajaddini 2014). However, both the high impact forces transmitted by the wheels to the railway superstructure during the train run (Talamini, Jeong, and Gordon 2007; Mandal, Dhanasekar, and Sun 2016) – sometimes amplified by weak ballast conditions (Pucillo et al. 2018; De Iorio et al. 2016) – and lower bending stiffness compared to normal rails, along with stress concentration effects at the rail-end-bolt holes, make IRJs susceptible to severe loading conditions (Kerr and Cox 1999), and onset fatigue cracks at the hole surface (Mayville and Stringfellow 1995).

To reduce this drawback, various techniques have been proposed in the literature. Pad coining, ball expansion, direct mandrel expansion, split-sleeve cold expansion, and interference-fit fasteners, for example, are typical techniques adopted in the aerospace industry to prestress the holes by a residual compressive stresses field around the edge of the hole, with the aim to reduce the total stress and, as a consequence, to improve the fatigue life of such components (Fu et al. 2015).

In particular, the split-sleeve cold expansion process was developed by Boing in the late 1960s and marketed by Fatigue Technology Incorporated (Restis and Reid 2002; Fatigue Technology Inc 2016; 2017). Using this technique, an oversized tapered mandrel is pulled through the hole, causing yielding of an annular area surrounding the hole; when the mandrel is removed, the surrounding material, which has been elastically deformed, tries to return to its original state and contracts the yielded annular area, producing compressive hoop stresses near the hole edge. The presence of the lubricated split sleeve guarantees the reduction of the force required for mandrel extraction, protects the hole surface from detrimental frictional forces, and can eliminate surface roughness and imperfection due to machining on the hole surface (Chakherlou and Vogwell 2003).

It is important to highlight that, even if the fatigue strength improvement due to cold expansion is commonly accepted by industries, there is still no shared method for choosing the optimum percentage of cold expansion as a function of the specific application. In many cases, the optimum cold expansion percentage is chosen on the basis of fatigue tests carried out with two or more percentage of cold expansion (Chakherlou and Vogwell 2003; Chakherlou, Taghizadeh, and Aghdam 2013; Ball and Lowry 1998), which is not a fully satisfactory results at the design stage of a structural component, mainly if the damage tolerant approach is chosen as design philosophy (Carpinteri 1993; Carpinteri, Brighenti, and Vantadori 2006; Carpinteri and Vantadori 2009; De Iorio et al. 2012; Pucillo, Esposito, and Leonetti 2019a; 2019b) and a crack growth prediction model is adopted to schedule maintenance intervals (Zerbst, Schödel, and Heyder 2009; Zerbst et al. 2009; Zerbst and Beretta 2011). Indeed, damage tolerant design requires the knowledge of the actual value of the stresses for stress intensity factor calculation (Carpinteri 1994; Brighenti and Carpinteri 2013; Carpinteri, Ronchei, and Vantadori 2013), which in turn needs the a priori evaluation of the residual stress-, and/or strain-, field generated by cold expansion.

Many efforts have been made to obtain experimentally the residual stresses induced by cold expansion. X-ray (Ball and Lowry 1998; Pina et al. 2005; Shao et al. 2007; Shuai et al. 2019; Priest et al. 1995; Zhao et al. 2013; Cook and Holdway 1993; de Matos et al. 2004; Stefanescu, Edwards, and Fitzpatrick 2002; Stefanescu et al. 2003) and neutron diffraction techniques (Luzin et al. 2004; Stefanescu et al. 2003), the modified Sachs method (Özdemir and Edwards 1996), and the Garcia-Sachs method (Garcia-Granada et al. 1999; Garcia-Granada, Smith, and Pavier 2000), are typical experimental techniques used to measure residual stresses. Unfortunately, all these methods are affected by some limitations: - the X-ray method is limited to surface measurement (Cook and Holdway 1993) and does not guarantee good accuracy in regions of high stress gradients; the measurement procedure of the neutron diffraction method is very complex; - the Sachs method is characterized by approximate formulation. An innovative extension of the rectilinear groove method associated with the integral method calculation procedure has been proposed in (Zuccarello and Di Franco 2013) to detect the variation of residual stresses with depth, but, being a semi-destructive technique, it is not suitable if the specimens/components must subsequently be submitted to fatigue tests, as is the practice.

Moreover, since the cold expansion process is mainly adopted in the aeronautical field, almost all the studies were focused on drilled plates in aluminium alloys with or without cold expansion (Shao et al. 2007; Shuai et al. 2019; Garcia-Granada et al. 1999; Lacarac et al. 2000; Priest et al. 1995; Zuccarello and Di Franco 2013; Cook and Holdway 2013).
1993; Amrouche et al. 2003; Ball and Lowry 1998; Pina et al. 2005; Gopalakrishna et al. 2010; de Matos et al. 2004; Ozelton and Coyle 1986; Stefanescu, Edwards, and Fitzpatrick 2002; Stefanescu et al. 2003), being them well representative of real aircraft structures connected by rivets or bolts. Only in few cases the experimental investigations have been carried out on steel parts (Lindh, Taylor, and Rose 1980; Zhao et al. 2013), but none of them concerned railway components, and in particular rail-end-bolt holes.

For this reason, the present paper, which is the first of a two-part series on the application of cold expansion to rail-end-bolt holes, tries to offer a contribution to better understanding, by mean of two experimental techniques, the whole strain field induced during and after cold-expansion around rail-end-bolt holes that is not present in the current literature. In Part II, the experimental measurements have been used to validate a finite element model that simulates the cold expansion process on rail-end-bolt holes.

The experimental measurements have been done by means of both electrical strain gauges (ER) and Digital Image Correlation (DIC). In literature, it is possible to found experimental studies on expanded holes carried out by using ER (Gopalakrishna et al. 2010), but none of them concerns rail steels. A typical drawback of strain gauges highlighted by several authors is that the measurements refer to the mean value of the strains acting in the area covered by the grid of the strain gauges. However, being the strain variation well approximated by a linear function in the zones of the rail near the holes and instrumented with ER, as preliminary finite element simulations carried out in Part II (Pucillo et al. 2020) revealed, the measured strains are equal to the strains acting at the centre of the strain gauges (Ajovalasit 2015), and consequently the error is zero and the strain gauge technique may be conveniently used without uncertainties.

Digital Image Correlation has the great advantage to provide data in full-field conditions in terms of displacements and, by mean of derivative operations, to retrieve both normal and shear strain field in the domain of interest (Pan et al. 2009; Pan 2018). DIC technique has been used both in the past and recently to analyse the cold expansion mechanism, but, once again, most of the studies deal with aluminium sheets having single or multiple fastener holes (Backman et al. 2008; Backman, Cowal, and Patterson 2010). Other full-field experimental techniques used on this topic are the Moiré photography (Cloud 1980), the Moiré interferometry (Link and Sanford 1990), and the grid method (Ball and Lowry 1998); however, their main disadvantage is due to the high level of strains, which in many cases damages or distorts the grids, causing difficulties in extracting the fringe pattern.

To have an experimental test setup that was representative of the real case, cold expansion has been applied to three rail holes having the same diameter of insulated rail joints, namely 32 mm. Contrary to what detectable in the literature, the strains have been acquired with strain gauges during the entire cold expansion process, in order to capture the highly non-linear elasto-plastic response of the material and to give fundamental reference results for the validation of the finite element model developed in Part II. The experimental results concerning each expanded hole have been compared in order to evaluate the repeatability: - of the measurements; - of the CE process; - of the adopted experimental technique, and, above all, to extrapolate the distribution of the hoop and radial residual strains as a function of the distance from the hole edge. At the end, results obtained by strain gauges and 2D-DIC are compared, in order to give a robust and valuable highly non-linear reference result for the validation of the finite element model presented in Part II of this series.

2. Experimental campaign

To evaluate both the strain field during the process and the residual strain field after mandrel removal, a rail segment was considered, having six holes of the same diameter of real railway joints, 32 mm. As shown in Fig. 1, before expanding the holes, part of the rail foot and of the rail head have been removed, with the aim to create the gripping areas of the specimens that will be extracted from the expanded and not expanded drilled rails, and that will be submitted to fatigue tests. In (Pucillo 2019), finite element analyses have demonstrated that the removal of part of the foot and of the head does not modify the residual stress distribution due to cold expansion compared to that obtained with the full rail section, so the modified rail was assumed to be representative of the real drilled rail.

The experimental results presented in this work concern the cold expansion process applied on holes #2, #5, and #6. To achieve a 2.0% of cold expansion (see (Pucillo et al. 2020), Section 1), an FTI RTS 32-0 mandrel, and a RTS32-0 self-lubricated split-sleeve, the sleeve having a thickness of 0.3 mm, were used (see Fig. 2).
2.1. Specimen instrumentation and preparation

Strain gauges were installed on the rail web surface in order to allow the measurement of both hoop and radial strains during and after the cold expansion process. The three holes were differently equipped and a total of twenty-six foil strain gauges were installed on a single side of the rail web, that is the mandrel entry side. The mandrel exit side was not instrumented because of the contact between the rail web surface and the nose cap assembly of the puller. Strain gauges arrangement for holes #2, #5, and #6 is shown in Fig. 3, Fig. 4, and Fig. 5, respectively. For clarity of exposition, the angular coordinate $\theta$ is introduced, that is the angle between the rail longitudinal axis and the radial direction in the cylindrical coordinate system centred on the hole.
To obtain useful experimental data for the validation of the FE model described in Part II, strain gauges were mounted in a manner to measure the strain distribution as a function of the radial distance from the hole edge. In particular, the measurement of cold-expansion-induced hoop residual strains along the directions at $\theta = \pm 45^\circ$ is crucial, being these the critical directions for crack initiation and propagation at not expanded rail-end-bolt holes (Mayville and Stringfellow 1995; Zerbst et al. 2009; Cannon et al. 2003). Considering that the stress-strain field was expected to be symmetrical with respect to the vertical plane passing through the axis of the hole, to increase the spatial resolution of the hoop strain measurement along the critical directions ($\theta = +45^\circ$ and $\theta = -45^\circ$), additional strain gauges were installed along symmetrical angular locations ($\theta = +135^\circ$ and $\theta = -135^\circ$, resp.) but not at the same distance from
the hole edge. For example, as shown in Fig. 3 (hole #2) and Fig. 5 (hole #6), strain gauges at the angular location $\theta = +135^\circ$ were mounted farther from the hole edge than strain gauges at $\theta = +45^\circ$. From the practical point of view, it would have been impossible to install two strain gauges at the same angular locations at 9 mm (see ER at $\theta = +45^\circ$ and $R = 25$ on hole #2 and #6) and 11 mm (see ER at $\theta = +135^\circ$ and $R = 27$ on hole #2 and #6) from the hole edge, or at 3.5 mm and 5 mm (see ER at $\theta = +45^\circ$ and $R = 19.5$, and ER at $\theta = +135^\circ$ and $R = 21$, respectively, on hole #6), because of the strain gauge matrix width. Similarly, on hole #6 (see Fig. 5), the strain gauge at $\theta = -135^\circ$ (ER at $R = 21$) was mounted closer to the hole edge than that at $\theta = -45^\circ$ (ER at $R = 25$).

Moreover, considering a fatigue testing campaign to be performed on specimens to be extracted from the drilled rail, the numerical prediction of hoop residual stresses acting along the rail longitudinal axis, which identify the minimum transversal section of the specimen, is essential. For this reason, it is appropriate to compare the FEM results with the experimental data along the rail longitudinal axis, and for this purpose some strain gauges were also mounted at $\theta = 0^\circ$, at an increasing distance from the hole edge, as shown in Fig. 3, Fig. 4, and Fig. 5.

Because the expected residual stress-strain field is not axisymmetric, strain gauges installed around the same hole at an equal radial distance from the hole edge were mounted at different angular locations, with the aim to appreciate the strain field dependency on the angular coordinate $\theta$. For example, it was possible to compare both the hoop strains (Fig. 3) and the radial strains (Fig. 5) measured at $+90^\circ$ with those at $-90^\circ$, as well as the hoop strains at $+45^\circ$ and $-45^\circ$ (Fig. 3), and the hoop strains at $+135^\circ$ and $-135^\circ$ (Fig. 5).

Since the rail web surface doesn’t exhibit a natural texture, the speckle pattern was artificially made on the mandrel entry side of the rail web by spraying black and white matte paints. The rail web surface was coated with white paint first, in several very light coats, then, the speckles were applied. Before painting, the rail web surface was sanded to guarantee a good adhesion of the white coating to the metal and avoid detachment during cold expansion process. A rectangular speckle pattern big enough to include strain gauges footprint was made around the three holes. Steps of speckle pattern preparation are shown in Fig. 6.

![Speckle pattern preparation](image)

**Fig. 6. Speckle pattern preparation.**

### 2.2. Experimental setup

To avoid any undesirable motion during the cold expansion process, the rail was fixed using two steel L brackets and three clamps, as shown in Fig. 7-a. The part of the rail that has been obtained by cutting the rail foot was placed face down, while the part that has been obtained by cutting the rail head was turned upward.

Strain gauges were connected to a data acquisition system composed by an HBM QuantumX MX1615B amplifier and a computer laptop (see Fig. 7-b). The Catman data acquisition software was used for data visualization, analysis
and storage during the measurement. To capture the strain-time history during the entire cold expansion process, the sample rate was set to 50 Hz. The sensor mode was quarter bridge 3-wire for all the strain gauges.

The optical image acquisition system was composed by a CCD camera and a computer laptop (see Fig. 7-b). A Photron Fastcam SA3 was used, equipped with a Nikon AF Nikkor 50mm f/1.8D Lens. The camera, connected to the computer laptop via ethernet cable, was placed so that the sensor was parallel to the flat area of the rail web surface. To control the Photron camera from the computer the Photron Fastcam Viewer (PFV) software was used; operations such as setting camera options, shooting, and saving recorded data to the computer were accomplished with PFV. The frame rate was set to 125 frame per second (fps) and the spatial resolution to 1024 x 1024 pixels; camera recording time was 21.5 s, which was long enough to shoot the cold expansion process. Images from the mandrel entry side of the rail web (see Fig. 7-d) were acquired during the cold expansion of each hole.

![Fig. 7. (a) Fixing system; (b) setup for ER and DIC measurement; (c) exit side of the mandrel; (d) entry side of the mandrel.](image)

3. Results

The results are reported both in terms of strain-time history for each ER, and as residual strain field around cold-expanded holes (DIC results). Considering that in the railway field the dimensional tolerance on hole diameter is very strict, an almost equal percentage of cold expansion for each hole was expected.

For this reason, at first the experimental results obtained by strain gauges on each expanded hole will be analysed and compared, in order to evaluate the repeatability: - of the measurements; - of the cold expansion process; - and of the adopted experimental technique. Subsequently, all the strain gauges results will be considered together, as if all had been acquired during the expansion of a single hole, to extrapolate the distribution of the hoop strain as a function of the distance from the hole edge along the directions of interest.

At the end, results obtained by 2D-DIC will be shown.

3.1. Strain gauges data

In this subsection, cold-expansion-induced strains are shown as a function of time for each hole. As mentioned previously, this is not present in the current literature.

For this purpose, and for clarity in the exposition of the strain-time histories reported in the following diagrams, each strain gauge signal was identified using the nomenclature:

\[#N_D\theta_dfh_CE_X,#\]

where \(N\) is the hole number around which strain gauges data are acquired, \(D\) indicates the active direction of the ER (\(D = R\) in case of radial strain, \(D = T\) in case of hoop strain), \(\theta\) and \(dfh\) are, respectively, the angular location and the installation distance from the hole edge, and \(X\) indicates the cold expanded hole number.
3.1.1. Cold expansion of hole #5

During the cold expansion of hole #5, an electric power unit (see Fig. 2-c, on the left) was used at first but, while the mandrel was being pulled through the hole, the power unit had a breakdown and was replaced by the hydraulic one (see Fig. 2-c, on the right). Fig. 8 shows the measured strains on hole #5 before (Fig. 8-a/b) and after (Fig. 8-c) the replacement of the power unit. Looking at Fig. 8-a/b, at \( t \approx 225 \) s the signal of the strain gauge installed at 2.5 mm from the hole edge (#5_T0_2.5_CE_5) was interrupted during the first step of the cold expansion process, probably due to the strain gauge detachment as a consequence of the high induced strain level. At the end of the operations carried out with the first pooling equipment the signal intensity of strain gauges mounted at 16 mm and 44 mm from the hole edge remained unchanged for \( t \geq 233 \) s, which corresponds to mandrel locking at the end of the first step. As expected, the measured strains decrease with the distance from the hole edge: the strain measured by strain gauge glued at 16 mm (#5_T0_16_CE_5) was equal to about 3100 \( \mu \text{m/m} \), which is greater than that measured at 44 mm (#5_T0_44_CE_5), approximately equal to 820 \( \mu \text{m/m} \). Moreover, it is interesting to note that both strains decreased and then increased at \( t \approx 355 \) s (see the dotted ellipse in Fig. 8-a). This corresponds to the attempt to complete the mandrel stroke: before the mandrel passes through the hole, it is forced against the web of the rail, causing web bending and, similarly to what happens during metal forming, it induces compressive hoop strains, or strain decrease, because of Poisson's effect. In contrast, when the pulling action ceases (see also the dotted ellipse in Fig. 8-b), or when the mandrel passes through the hole at the completion of the cold expansion process (see the dotted ellipse in Fig. 8-c), increasing hoop strains are induced in the web of the rail.

![Fig. 8. Hoop strain measurement near hole #5 before (a, b) and after (c) the replacement of the power unit.](image)

Once the power unit was replaced, the mandrel was pulled through the hole to complete its stroke, causing a further increase of the strain field, as shown in Fig. 8-c for \( t \geq 29 \) s. The measured strains reached a maximum value (at \( t \approx 35 \) s) when the mandrel maximum diameter gets in contact with the hole surface. As expected, the value of the maximum strain recorded by each strain gauge depends on their distance from the hole edge: the strain gauge placed at 16 mm (#5_T0_16_CE_5) measured a maximum value of the hoop strains equal to 4780 \( \mu \text{m/m} \), whereas strain gauge glued at 44 mm (#5_T0_44_CE_5) recorded a value of about 1130 \( \mu \text{m/m} \).

Successively, when the mandrel gets out from the hole, the values of both strains reached a local minimum, as it is visible in the dotted ellipse in Fig. 8-c for \( t \approx 37 \) s. After this point, both the strains again showed a new increase (as a consequence of the web bending effect cancellation, as discussed previously), up to the final values, which are the residual strains at the end of the cold expansion process. The hoop residual strain close to the hole is positive, and its intensity decreases as the distance from the hole edge increases. In fact, a value of 2640 \( \mu \text{m/m} \) and 470 \( \mu \text{m/m} \) was recorded, respectively, by strain gauge placed at 16 mm and 44 mm from the hole edge.
3.1.2. Cold expansion of hole #2

Fig. 9 shows strain gauges data acquired during the cold expansion of hole #2. Data shown in Fig. 9-a refer to hoop strains measured by strain gauges installed at 0°. The strain trend is the same as those shown in Fig. 8-c (hole #5), therefore the same considerations exposed above for hole #5 are worth.

Fig. 9. Hoop (a, b, c) and radial (d) strain measured by strain gauges applied near the hole #2.

Fig. 9-b shows the hoop strains measured by the two strain gauges installed at +45° and by the one glued at +135°. As seen about the strain gauge installed at 2.5 mm from the edge of hole #5, the signal of the strain gauge at 3.5 mm was interrupted during the cold expansion process. Fig. 9-c refer to hoop strain measurements by strain gauges installed at +90° and -90°. Because of the different constraint effect exerted by the material belonging to the remaining part of the rail foot compared to that exerted by the remaining part of the rail head (remember that both the head and the foot were partially removed for this experiment, see Section 2), different residual strain values were measured by strain gauges glued at symmetric positions with respect to the rail longitudinal axis. In particular, it was found that the hoop residual strain at 90° is higher than that recorded at -90°:

$$\varepsilon_{\text{hoop, res}}(\pi/2) > \varepsilon_{\text{hoop, res}}(-\pi/2),$$

and this result agrees with the literature (Lowry 1991; Ball and Lowry 1998), where it is reported that lower magnitude of residual stresses are expected for short edge distance (see also Section 3 of (Pucillo et al. 2020) for more details). For completeness, Fig. 9-d shows the radial strain measured by the strain gauge installed along the longitudinal axis.
of the rail ($\theta = 180^\circ$) at 3.5 mm from the hole edge; in this case, the signal has gone out of the reading range of the amplifier during the maximum hole expansion, therefore it was not possible to acquire the maximum intensity, whereas at the mandrel exit the signal has returned into the reading range of the amplifier, so the acquired residual strain of approximately -15200 $\mu$m/m is correct.

3.1.3. Cold expansion of hole #6

Strain gauges data acquired during the cold expansions of hole #6 are shown in Fig. 10. Fig. 10-a shows the hoop strain measured by strain gauges installed at 0° (the strain trend is the same of those of Fig. 8-c (hole #5) and Fig. 9 (hole #2)), while Fig. 10-b refers to hoop strain measurement at $\pm 45^\circ$ and $+135^\circ$; even in this case, the signals of the strain gauges installed at 3.5 mm from hole edge (#6_T0_3.5_CE_6 and #6_T45_3.5_CE_6) were interrupted during the first step of the cold expansion process.

The comparison between the signals of strain gauges applied at the same radial distance (9 mm) from hole edge but installed at different angular locations (#6_T0_9_CE_6, #6_T45_9_CE_6, and #6_T-45_9_CE_6) reveals that the hoop residual strain at 0° is higher than the one at 45°, that is higher than the one at $-45^\circ$:

$$\varepsilon_{\text{hoop, res}} (0) > \varepsilon_{\text{hoop, res}} (\pi/4) > \varepsilon_{\text{hoop, res}} (-\pi/4).$$

Signals shown in Fig. 10-c refer to the radial strains measured by strain gauges installed at +90° and 180°. The strain trend is the same as in Fig. 9-d (hole #2), therefore the same considerations are worth.

3.1.4. Data comparison between strain gauges measurements around different holes and extrapolation of the strain trend as a function of the distance from hole edge

The comparison between residual strains measured by strain gauges installed around different holes but placed at the same positions is shown in Fig. 11. Residual strains are reported as a function of the distance from the hole edge and for different angular locations, with the aim to verify the actual repeatability of the cold expansion process, and at the same time to extrapolate the hoop residual strain distribution along the directions of interest.

Fig. 11-a shows the comparison between hoop residual strains along the direction at 0°. For all the holes, the residual strain decreases with the distance from hole edge and, because of the negligible differences between the cold expansion percentages (Section 3), strains are, as expected, almost the same. The percentage difference, calculated with respect to the smallest strain value of each set of experimental points referred to the same position, was also calculated, and is shown in the right vertical axis of the diagrams: a maximum value of 7.5% was found. In Fig. 11-b
the comparison between radial residual strains at 180° is shown: the percentage difference is 23%. As mentioned in Section 2.1 the strain trend along the directions at +45° and +135° was expected to be the same, therefore the hoop residual strain distribution was determined considering together the strain gauges installed at +45° and +135° around holes #2 and #6 (Fig. 11-c). Strains acquired at 9 mm from hole edge are the same (percentage variation is equal to 1%); at 11 mm, instead, a higher value of the percentage difference was calculated (60%). However, excluding the latter case, the trend is consistent, and the low percentage difference between the measurements is excellent, which gives a good level of confidence with the acquired data set, above all in view of the FE validation of Part II (Pucillo et al. 2020).

![Image](image.png)

Fig. 11. Hoop (a, c) and radial (b) residual strains measured by strain gauges after 2.0% of CE. Percent difference between ER measurements made on different holes and at the same location, and dependency of the residual strains on the distance of the hole edge.

3.2. 2D-DIC data

Analysis of images was performed using Vic-2D software (Correlated Solutions Inc., Columbia, SC, USA). The first image was acquired before the mandrel was inserted into the hole and was set as the reference image. Correlation was run between the reference image and the last one of the test data.

One of the benefits of using a full-field optical technique, like image correlation, is the easy of strain separation, something that in other techniques, such as photoelasticity, can be quite difficult to perform. The contour plots of normal ($\varepsilon_{xx}$ and $\varepsilon_{yy}$) and shear ($\varepsilon_{xy}$) residual strains near the various holes are reported in Fig. 12. For the hole #2 and hole #6, the images were processed by setting a subset size of 17 pixels$^2$, a step size of 5 pixels, and a strain filter window of 15. For the hole #5, instead, images were processed by setting a subset size of 43 pixels$^2$, a step size of 7 pixels, and a strain filter window of 15.
4. Discussion - 2D-DIC vs. strain gauge data

In this Section, the experimental results obtained by strain gauges and by 2D-DIC are compared. Being the 2D-DIC technique limited to measurement of in-plane displacements and strains of a planar object surface, experimentally measured residual strains can be considered accurate only for the central (flat) part of the rail web surface. For this reason, DIC results are compared with those obtained by strain gauges only along the rail longitudinal axis, i.e. along the direction at 0°. The comparison between results concerning hole #6, hole #2, and hole #5 is shown in Fig. 13.

As it is shown in Fig. 13-a, DIC results referred to hole #6 are in very good agreement with strains measured by strain gauges, being the percentage difference between the strains measured by DIC and those measured by strain gauges of about 5%.

Concerning hole #2 (Fig. 13-b), a good agreement between the results obtained with the DIC and the strain gauges is observed in terms of trend of the residual strains as a function of the hole distance, even if a higher percentage difference (≈ 25 %) was found with respect to what observed previously for hole # 6. This can be due to some imperfection in the speckle pattern or, more probably, to out of plane displacements of the rail during the cold expansion process. In fact, as explained in Section 2.2, the rail was fixed on the worktable only by mean of brackets and clamps, which may not remove any undesirable movement of the rail during the process.

Concerning hole #5 (Fig. 13-c), the strain gauges and the DIC results appear almost not in good agreement. This disagreement could be attributed, as for hole #2, to the speckle and to out of plane displacements of the rail; moreover, during this experiment a non-parallelism between the CCD sensor and the rail web surface was observed, which strongly affects the results.
5. Conclusions

An experimental campaign has been carried out to investigate the effects of the cold expansion on rail-end-bolt holes. Two experimental techniques have been adopted: electrical strain gauges and 2D-DIC. Strain gauges were employed to acquire both radial and hoop strains during the cold expansion process, whereas 2D-DIC technique allowed to measure the residual strains in full-field conditions in the zone of the rail web in the proximity of the hole.

The novelty of the proposed work relies on the application of the CE on real railway component (rail-end-bolt holes), thus on different material and geometry compared to the previous works. Indeed, in this work the CE was applied on a standard rail, made of steel and characterised by a specific geometry, meanwhile all the available knowledge is based on experimental campaign carried out on test specimens made of aluminium.

Strain-time histories have been measured along different radial paths during the entire cold expansion process, including those along which fatigue crack paths are observed in bolt holes of Insulated Rail Joints, in order to capture the elasto-plastic response of the material during the cold expansion process. This is not present in the current literature, and represents a robust and valuable highly non-linear reference result that has been used for the validation of the finite element model presented in Part II of this series.

It is found that the application of the cold expansion to the holes of Insulated Rail Joints gives repeatable results, which is a very important result from the industrial point of view of the Railway Infrastructure Manager.

DIC and strain gauges results are almost consistent and comparable, and this further guarantees a valuable dataset in view of the validation phase of the finite element model.

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References


