Application of digital image correlation for the study of strain concentrations due to change in geometry in weld beads: parent interface of structural steel welds

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The paper aims to characterise the strain concentration of welded junctions subjected to elastic loads using digital image correlation (DIC). When measuring such small strains and heterogeneous strains fields with DIC, a compromise between noise and accuracy arises where a suitable choice of the image processing settings becomes crucial to obtain accurate results. An extensive study of the influence of the different processing parameters was carried out to ensure the best trade-off between accuracy and noise. A practical application was later performed with the found optimal settings; welded specimens were subjected to uniaxial and biaxial loads to assess possible influence of the strain state on the strain concentration. Results show a great variability of the strain concentration along the weld bead base, evidencing a significant influence of local geometrical characteristics. On the other hand, the strain state influence was found to be moderate, or almost inexistent for lower strain concentrations.

Keywords: Strain concentration, Digital image correlation, Welded junction

Introduction

For many years, a lot of different welding techniques have been employed as a joining process for structures. Nevertheless, industry standards and requirements have become more rigorous in the last years, demanding more resistant and light-weighted designs.

In addition, it is well known that the structural failure is most likely originated at the strain concentrations located in the vicinity of the weld bead. Consequently, a profound understanding of the strain concentration behaviour of welded joints becomes crucial for optimised structural designs.

With the purpose of extending the knowledge of the strain concentration behaviour in welded junctions, various approaches have been proposed using different measuring technologies. The most extended is the use of strain gauges, usually installed at controlled distances from the weld bead toe to measure strain values at these locations and determining the hot spot strain by means of extrapolation formulae. Gho and Gao,¹ for example, proposed a series of parametric equations for predicting the stress concentration factor in overlapped tubular K(N) joints. Ye *et al.*² also employed strain gauges to evaluate the stress concentration on welded steel bridge T-joints.

Although this measuring technique has been used for many years, it entails some limitations due to the structure of the gauge itself. They cannot be installed at geometrical discontinuities, thus compelling to perform parametric approximations to estimate the hot spot strain at the weld toe. Also, as it will be verified later, the strain concentration on welded junctions strongly depends on local geometric characteristics of the weld bead (i.e. the weld shape or the weld toe radius), and the exact location of these zones is usually unknown in advance. Erroneous positioning of the strain gauges would lead to strain underestimations and therefore to non-conservative results.

Full field measuring tools present a powerful alternative to overcome these limitations. A complete description of the different optical techniques available in experimental mechanics is shown by Patterson *et al.*³ including electronic speckle pattern interferometry, grating interferometry, image correlation,⁴ moiré, photoelasticity, shearography and thermoelasticity. In this regard, Orteu⁵ reported the potential of 3D DIC.

The present paper focuses on measuring the strain concentrations on steel welded junctions subjected to elastic strain fields with DIC. Measuring in these conditions becomes challenging due to three main reasons:

- *Highly heterogeneous strain fields:* crucial importance of achieving high spatial resolution to avoid smoothing the strain measurements at the concentration zone.
- *Small strains, i.e. below the yield point:* noise may become significant. A noise improvement usually

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requires data averaging and thus smoothing, establishing a compromise between this characteristic and the previous one.

- *Irregular shape*: complicating the camera lens focusing and specimen lighting operations during the setup of the experiment.

Although there have been various approaches to assess DIC performance when measuring heterogeneous strain fields and strain concentrations,^{6–8} they are usually limited to 2D DIC, and in many occasions deformed images are obtained virtually (i.e. neglecting image acquisition noise). There is no evidence of quantitatively assessing the capabilities of 3D DIC on strain fields generated by welded junctions.

The paper is structured in four main sections. After a brief introduction to the DIC technique, the first part of the study will present an assessment of the error induced when lowering the spatial resolution for the specific case of strain concentrations in welded junctions. For that, displacement data obtained from finite element method (FEM) models of different butt welded profiles was utilised to calculate the strains using equivalent methods as applied in DIC codes. Afterwards, the error was calculated as the difference between FEM model and DIC peak strains for each weld profile and spatial resolution.

The second part of the paper focuses on processing virtually deformed images with prescribed displacements obtained from FEM models. This part of the study aims to assess the influence and find the best combination of various DIC processing settings: subset size, step size and shape function. A description of the procedure to deform images numerically can be found on the work reported by Wang *et al.*⁹

The third part will evaluate the noise introduced in the system in real tests, presenting a methodology to help choosing the strain window value (SW) that presents the best compromise between strain error and noise.

The last part will present real test images processed with the configurations found in the previous sections. Different specimens were produced to study uniaxial and biaxial load cases to assess whether the strain state might have any significant influence on the strain concentrations.

DIC strain calculation procedure: overview

DIC can be defined as a non-contact optical method that acquires, stores and performs image analysis in order to extract full field shape, displacements and deformations. Summarised descriptions of the displacement extraction process can be found in Lava *et al.*¹⁰ and Perez *et al.*¹¹ The strain calculation is a post-processing operation from the obtained displacements. It is shown schematically in Fig. 1.

The general calculation process of the strains at a specific point consists of the determination of the deformation gradient (F), from which different strain expressions can be derived. For the present study, Euler–Almansi strain tensor expression is used, which reads as:

$$\varepsilon_{(x,y)}^{lnEA} = \ln(F_{(x,y)} - F_{(x,y)}^T)^{0.5} \quad (1)$$

In order to obtain the expression of the deformation gradient at a point, the displacement field obtained from the DIC process is first fitted in a square area around this point called the ‘strain window’ (SW). The SW is defined by the user and consists of a $N \times N$ displacement data points as shown in Fig. 1. Fit function can be first ($n = 1$) or second order ($n = 2$) depending on whether it is constructed using bilinear or biquadratic Lagrange polynomials, respectively. Since the procedure to obtain fit functions for u and v displacements is analogous,

1 DIC strain calculation process

only the expressions for u displacements will be shown for simplicity.

$$u_{FIT(x,y)} = \sum_{i=0}^n \sum_{j=0}^n a_{ij} x^i y^j \quad (2)$$

A Gauss–Newton algorithm is used to obtain the parameters values ' a_{ij} ' minimising the least square differences between actual and fitted displacement values.

$$S_{(x,y)} = \sum_{i=0}^{N^2} (u_{DIC} - u_{FIT})^2 \quad (3)$$

According to equation (2), the number of unknown parameters is $(n+1)^2$, so at least the same number of equations is needed to obtain unique solution. Therefore, it is important to ensure that the number of unknowns is equal or less than the number of data points in the SW:

$$(n+1)^2 \leq N^2 \quad (4)$$

Once obtained the fit displacement functions, the deformation gradient is determined by differentiation of these functions for u and v displacements at a specific point as follows:

$$F = \begin{bmatrix} 1 + \frac{\partial u_{FIT}}{\partial x} & \frac{\partial u_{FIT}}{\partial y} \\ \frac{\partial v_{FIT}}{\partial x} & \frac{\partial v_{FIT}}{\partial y} \end{bmatrix} \quad (5)$$

It can be deduced from the calculation process that the larger the SW area is, less noisy strain fields will be obtained. On the other hand, since the displacement surface fit is limited to a second order polynomial, it will not be able to adapt correctly to heterogeneous displacement fields within the SW area. More precisely, displacements fit function will not be capable to adapt to the displacement field if its third derivative within the SW is non-zero, resulting on smoothed results in this SW area.

Based on the schema of Fig. 1, it is easy to determine the so-called virtual strain gauge (VSG) which is the side length of the square over which the strains are calculated by the process previously described:

$$VSG \text{ (mm)} = [(SW - 1)Ss + 1]Ps \quad (6)$$

where 'Ss' is the step size, or the number of pixel skipped between data points, and 'Ps' is the pixel size in mm.

As can be noticed from the expression, the only variable that is set before the image processing and cannot be changed once the test has been set up is the pixel size. Achieving a small pixel size allows to increase the SW and Ss keeping the VSG size constant, hence reducing the noise level with no influence in the smoothing effect. Special attention for this parameter is required during the experimental setup when measuring heterogeneous strain fields.

Theoretical approach of the smoothing error

With the aim of quantifying the strain underestimation due to the smoothing error, the described strain calculation process will be implemented over displacement profiles obtained with FEM models of different butt welded profiles. This allows eliminating any other source of noise, isolating the smoothing error.

2 FEM models and displacements extraction zone

The FEM models were constructed in steel material with $E = 2e^{11} \text{ Pa}$, $\nu = 0.3$ and assumed linear behaviour, since the study is focused on strains under the yield point. The model was meshed using quadratic shell elements, with mesh refinement over strain concentration zone to ensure the existence of at least three elements along the weld toe radius.¹² Force was applied at one end of the specimen, and displacements in the force direction were restricted in the other.

Since the strain concentration level strongly depends on the geometry of the weld bead, a total of 120 different weld profiles were studied changing the geometrical parameters presented in Fig. 2 in order to achieve a complete approach.

It should be noted that the maximum strain values obtained in the FEM models in relation to the geometrical characteristics of the weld bead may differ from the reality despite the fine mesh used at the concentration zones. Nevertheless, it is important to remember that this study aims to evaluate the DIC capacity to adapt to sharp displacement changes, and to relate the smoothing error to the different levels of strain concentrations.

Figure 3 shows the strain concentration factor (SCF, i.e. ratio between the maximum strain and the nominal strain out of the concentration area) values obtained by FE simulations in relation to the different weld bead geometry configurations. Greater influence of the weld toe radii is observed over the weld bead angle. SCF values oscillate between 2.15 and 4.18 depending on the configuration. It should be mentioned again that these results should be only taken as an theoretical approximation.

In order to study the smoothing error in a consistent manner, it is important to keep the same pixel size (in our case, distance between data points or nodes), so that the VSG is also constant along the profile. This mimics the unrealistic situation of a single CCD camera always perpendicularly aligned to the weld profile. To do so, the displacement profile was not extracted directly from FEM results, but obtained by discrete integration of the FEM strain profile given a constant position increment in the direction perpendicular to the weld bead $\Delta x = 0.1 \text{ mm}$ (equation (7)), which is the actual distance between nodes.

$$\begin{aligned} \varepsilon_{xx} &= \frac{\partial u_x}{\partial x} \rightarrow u_x = \int_0^L \varepsilon_{xx} \partial x \rightarrow \text{discrete data} \\ \rightarrow u_x &= \sum_{i=0}^L \varepsilon_{xx(i)} x_i \end{aligned} \quad (7)$$

3 Theoretical SCF obtained with FE simulations

After all the displacement profiles were obtained, the described post-processing process was applied to calculate the strains using VSG sizes from 0.1 to 2.3 mm for each profile: first equations (2) and (3) were employed to make the displacement fit, then equation (5) was used to calculate the deformation gradient, and finally, the strains are calculated using equation (1). The relative smoothing error was afterwards obtained as the difference between peak strains obtained from the FEM model and from the theoretical calculations.

$$\text{Relative error}(\%) = \frac{\max(\epsilon_{\text{FEM}}) - \max(\epsilon_{\text{CAL}})}{\max(\epsilon_{\text{FEM}})} \quad (8)$$

The results obtained are shown in Fig. 4. The graph presents vertical groups of 120 blue dots for every VSG size studied, each dot belonging to a different FEM model. The red line displays the mean error, and the black one at both sides the mean error plus/minus one standard deviation.

As expected from the theoretical considerations, the smoothing error increases when increasing the VSG size. The maximum error remains negligible for VSG under approximately 0.3 mm regardless the weld shape. As will be seen in the following sections, this VSG sizes implies reaching a pixel size under $5 \mu\text{m}$ to obtain acceptable results, which is difficult to achieve with ordinary DIC equipment. It can be concluded that it will be complicated to avoid the smoothing error when measuring strain concentrations in welds with common DIC equipments.

Nevertheless, deviations do not increase dramatically with the VSG, keeping the mean error around 15% for a VSG size of 2 mm, not very difficult to achieve in normal conditions.

Finally, it can be observed that the relative error increasingly scatters with increasing VSG, evidencing more significant influence of the weld bead geometry for larger VSG sizes.

Theory validation: virtually deformed images

In the previous section, smoothing error in relation to the VSG size was determined for different predefined displacement profiles obtained from FEM calculations, thus, not considering possible error and noise sources from the calculation process of these displacements (i.e. image correlation process). An evaluation of the influence of the different processing settings process becomes necessary to obtain optimal results. More specifically, influence of subset size, step size and shape function on the smoothing error and noise will be assessed in this section.

In order to evaluate these parameters isolated from other possible noise sources related to the test setup and image acquisition, an in-house software¹⁰ was employed to numerically deform a speckled image according to the displacement profiles obtained as described in section 'Theoretical approach of the smoothing error'. The speckled image utilized for the numerical deformation is

4 Relative smoothing error

5 Displacements in 'y' direction imposed

shown in Fig. 5, where the displacement profile was imposed on each pixel row of the image. The sharpest weld profile ($\alpha = 60^\circ$ and $r = 0.5$) was used to study the worst case scenario.

It must be kept in mind that the displacement profiles imposed here do not correspond to reality, since first, the weld bead has a non-planar shape (stereo DIC would be required for retrieving correct results), and second, a uniaxial load case would imply some deformation (i.e. contraction) in 'x' direction due to Poisson modulus. Nevertheless, this approach is appropriate to study the capability of DIC to adapt to the sharp strain profiles perpendicular to the weld bead.

Table 1 lists the different values employed for parameters studied, giving a total of 18 different combinations. Strain calculation was performed with a SW = 35 pixels, and biquadratic Lagrange polynomials for displacements interpolation. The pixels size was 20 μm , similar size to the majority of the test images of sections 'From virtual to real test images: study of noise influence' and 'Real test examples'. The resulting VSG sizes are 0.7, 1.38 and 2.06 mm for step sizes of 1, 2 and 3 respectively, according to equation (6).

After processing all different parameter combinations, a post-processing operation was followed in order to perform an evaluation metric for the smoothing error and the strain noise. First, the average strain profile was determined as the mean strain value for each row, that is, for an image with 'm' rows by 'n' columns:

$$\varepsilon_i = \frac{1}{n} \sum_{j=1}^n \varepsilon_j \quad \left. \vphantom{\varepsilon_i} \right\} i = (1, 2, \dots, m) \quad (9)$$

The relative smoothing error was calculated according to equation 8, using the average strain profile ' ε_i ' instead ' ε_{CAL} '. For noise evaluation, the mean of the standard

deviations for each row was obtained as follows:

$$\bar{\sigma} = \frac{1}{m} \sum_{i=1}^m \sqrt{\frac{1}{n} \sum_{j=1}^n (\varepsilon_{ij} - \bar{\varepsilon}_i)^2} \quad (10)$$

The obtained results of the relative smoothing error for the different parameters are shown in Fig. 6. These parameters have been grouped in pairs in order to study possible joint effects. The step size is found to have greatest influence, in accordance with the direct influence of this parameter on the VSG size and thus on the smoothing error. Regarding the shape function, quadratic shows a slight error decrease for Ss = 1, this effect disappears for Ss = 2 and Ss = 3. Similarly, a smaller subset size shows a little error decrease for Ss = 1, but this difference also disappears for Ss = 2 and Ss = 3.

Maximum and minimum errors shown in the surface fit of Fig. 6c are 15.2 and 17.1%, respectively, evidencing the smallest influence of subset size and shape function on the smoothing error.

Finally, it can be noticed that the errors obtained in this section are consistent with the ones obtained in the previous section, obviously adding the source of variability from the DIC process.

On the other hand, similar graphs have been constructed to study the effect of these parameters on the strain noise (Fig. 7). A significant noise increase can be observed for smaller step size values, again confirming the compromise between results noise and accuracy. It can also be discerned a negative effect of smaller subset sizes on the strain noise, especially for quadratic shape function (c) and Ss = 1 (b). Also, a noise increase is noticed using quadratic transformation function, more pronounced for smaller step (a) and subset (c) sizes. Finally, the notable noise improvement using affine shape function and subset size of 27 pixels ($\sigma_N = 0.09$) with respect to quadratic transformation function and subset size of 15 pixels ($\sigma_N = 0.48$) should be mentioned.

It can be concluded from the observed results that subset size and shape function have little effect on the smoothing error, but greater influence on the strain noise. Therefore, affine transformation function and subset = 27 pixels will be used in the following tests over real welded specimens, assuming the 2% of smoothing error

Table 1 DIC processing settings studied

Parameter	Cases studied
Step size	1, 2, 3
Subset size	15, 21, 27
Shape function	Affine, quadratic

6 Influence of different DIC processing settings on the relative strain error

7 Influence of different DIC processing settings on the normalised strain noise

increase previously mentioned, in benefit of a notable noise reduction.

Finally, it should be pointed that a complete approach to establish this compromise requires knowledge of the real noise values existing in images taken and processed in actual test conditions. In the next section this issue will be studied in greater detail.

From virtual to real test images: study of noise influence

Two main aspects determine the strain noise in DIC measurements. First, the test setup conditions, which includes

specimen lighting, focus or speckle pattern quality. Second, the processing settings were chosen to calculate the strains. Both sources need to be taken into account for a complete noise assessment, so actual test conditions become necessary to fully assess the strain noise.

The noise study was performed using an uniaxial test image. The test setup, the image with the area of interest and the subset are shown in Fig. 8. Stereo vision was used since the welded specimen shape is not planar, and the pixel size was $19.3 \mu\text{m}$. For the noise evaluation mean strain and standard deviation was determined over an homogeneous deformation region ($\bar{\epsilon}_h, \sigma_h$), and over the strain concentration area, i.e. the weld toe ($\bar{\epsilon}_c, \sigma_c$).

8 Uniaxial test setup and captured image

Table 2 Different configurations studied for image processing and the resulting VSG size

Case number	1	2	3	4	5	6	7	8	9	10	11	12
Step size	1	1	1	2	2	2	2	3	3	3	3	3
Strain window	27	41	53	23	27	33	41	23	25	31	37	41
VSG size (mm)	0.52	0.79	1.02	0.87	1.03	1.26	1.56	1.30	1.41	1.76	2.11	2.34

All images were processed using a subset size of 27 pixels and affine shape function in accordance with the findings of previous section. The different combinations of step size and SW used to ensure a wide range of VSG sizes are summarised in Table 2.

Once processed all cases shown in Table 2, mean and standard deviation in relation to the VSG was determined (Fig. 9). Results over the homogeneous strain region are shown in Fig. 9a. It can be seen that the average strain converges to a nominal value (1050 μm approx.) from VSG sizes of about 1 mm. Below this value, the noise level completely biases the results. From a VSG of 1 mm the standard deviation shows a significant decreasing tendency: lowering from 350 μm for a VSG of 1 mm to 200 μm for a VSG of 1.4 mm. This tendency becomes less significant for larger VSG size values.

As shown in Fig. 9b, the mean strains over the weld toe continuously decreases instead of converging to a constant value as in the case of homogeneous deformation region. This decrease is due to the smoothing effect for VSG sizes above 1 mm. For smaller VSG sizes, both smoothing error and noise have an effect on the mean strain. The strain decrease from a VSG of 1 mm to a VSG of 2 mm is 11.9% (from 2180 to 1920 μm), and the smoothing error increase calculated in section 'DIC strain calculation procedure: overview' for the same VSG sizes is 10% (from 6 to 16%), evidencing good agreement between theoretical and experimental results.

After the data analysis, it is verified that it is going to be necessary to deal with some smoothing effect. A VSG range from 1.3 to 1.5 mm is considered to be a balanced compromise which would lead to an approximate smoothing error of 10%, and a strain noise close to 200 μm . This will be the VSG objective range in the test image processing of next section.

It is important to point out that the results presented in this section have been obtained with a pixels size of 19.3 μm . Decreasing this pixel size would enable using a

smaller VSG for the same noise level, or analogously, decreasing the strain noise maintaining the same VSG size. Finally, it is also important to note that a change in the test conditions may also have significant influence on the strain noise.

Real test examples

In this section, the findings of the previous ones are applied to a real case study. Two sets of three specimens were constructed and subjected to uniaxial and biaxial loadings, respectively, with the aim of evaluating possible differences in the strain concentration behaviour due to the load type. The three rectangular specimens were subjected to uniaxial load in a Zwick tensile machine as shown in Fig. 8. The three circular specimens were tested under biaxial loading using a disc inflation test setup (Fig. 10b). All loads were applied to ensure elastic deformation of the specimens. A total of twenty images were taken of each specimen when loaded in order to check the stability of the image processing and results.

From the obtained results, and with the identified smoothing error, it is possible to estimate the actual maximum strain at the weld toe by adding the expected smoothing error to the maximum strain obtained. Given that the DIC strain results (ϵ_{DIC}) and smoothing error (S_{E}) for a specific VSG size each follow normal distributions, the predicted actual strain at any location 'x' will be also a normal distribution resulting from the addition of both, with mean and variance the sum of mean and variances of both terms (equation (12)). The variance of the strains calculated by DIC at each 'x' position over all the 20 images can be obtained from equation (11).

$$\sigma_{(x)} = \sqrt{\frac{1}{20} \sum_{i=1}^{20} (\epsilon_i - \bar{\epsilon})^2} \quad (11)$$

9 Smoothing error and noise evolution for a homogeneous deformation area **a** and along the weld toe **b**

10 Test specimens a and test setup for biaxial load case b

$$\left. \begin{aligned} \varepsilon_{DIC(x)} &\sim N(\varepsilon_{(x)}, \sigma_{(x)}^2) \\ S_{E(VSG)} &\sim N(\mu_{VSG}, \sigma_{VSG}^2) \end{aligned} \right\} \varepsilon_{actual} \sim N(\varepsilon_{(x)} + \mu_{VSG}, \sigma_{(x)}^2 + \sigma_{VSG}^2) \quad (12)$$

Considering that the cumulative probability of a normal distribution is $P = 0.954$ for two standard deviations, the actual maximum strain will be within the following interval with a 95.4% of confidence.

$$\varepsilon_{actual} = (\varepsilon_{(x)} + \mu_{VSG}) \pm 2(\sigma_{(x)}^2 + \sigma_{VSG}^2)^{0.5} \quad (13)$$

The strain concentration characterisation was carried out using the SCF, written as the ratio between the actual maximum strain predicted, and the nominal strain obtained as the average strain value over the homogeneous deformation region:

$$K_\varepsilon = \frac{\varepsilon_{actual}}{\varepsilon_{nominal}} = \frac{(\varepsilon_{(x)} + \mu_{VSG}) \pm 2(\sigma_{(x)}^2 + \sigma_{VSG}^2)^{0.5}}{\bar{\varepsilon}_h} \quad (14)$$

Both sides of the weld bead toe were measured for each specimen, so a total of 12 sets of images were processed. In

order to perform the SCF calculation in an automated manner, the position, displacement and strain results were exported to a text file and treated employing the commercial software 'Matlab.'

It should be noted that strain concentrations are expected in the direction where the geometrical change is present, i.e. perpendicular to the weld shape. Nevertheless, due to the irregular shape of the weld bead, the perpendicular direction might not be always aligned with 'Y' direction of the specimens, resulting in strain concentrations with an 'X' component at these zones. To account for the resulting SCF, von Mises equivalent strain was utilised. Although the orientation of the weld bead might vary, the strain profile perpendicular to it in each point should follow the same shape studied in previous sections, so the smoothing underestimation accounted in equation (14) to calculate the SCF is still valid. By way of example, the equivalent von Mises strain fields obtained from an image processed from a uniaxial test and from a biaxial one are shown in Fig. 11, where clear strain concentrations can be observed along the weld bead toe. The gaps observed belong to data with a poor correlation coefficient (below 0.85), discarded to ensure accurate results.

11 Strain fields obtained for uniaxial and biaxial tests

12 SCF along weld bead profiles for uniaxial and biaxial load cases

The resulting von Mises strain was calculated at each data point, and the evolution of SCF confidence interval along the weld toe was obtained by means of equation (14). Figure 12 shows these results for the strain fields of Fig. 11. In accordance with the strain fields, a higher strain concentration tendency is present in the uniaxial test image. Also a significant variation of the SCF can be observed depending on the point measured. SCF_{Std} values refer to the standard deviation of the mean SCF along the weld toe.

The obtained results of the SCF_{Mean} and SCF_{Std} for all the images are summarised in Tables 3 and 4 for uniaxial and biaxial tests, respectively. Data of specimen 3 in the biaxial test were not considered in the study due to high noise values observed, probably caused during image acquisition. Once discarded all data with low correlation coefficient, a total of 965 SCF were calculated for the uniaxial load case, and 1182 for the biaxial one.

Comparison of the overall behaviour of the strain concentration is shown in Fig. 13. Histograms on the left hand show similar distributions of the SCF for both load cases. These histograms illustrate the scatter behaviour of the SCF. The right panel shows the cumulative probability with the limits of the confidence interval according to equation (14). Similarities of both load cases are more clearly observed in this diagram, specially for smaller SCF values (probability under 0.7). A slight tendency to concentrate higher strains is observed for the biaxial load when increasing the SCF value, showing differences of about 0.26 for cumulative probabilities close to 0.9. These differences are in any case well under the confidence margins of both load cases.

Table 3 SCF_{Mean} and SCF_{Std} for all the images of uniaxial test

Profile number	1	2	3	4	5	6
SCF_{Mean}	1.91	2.99	1.93	2.74	1.99	2.44
SCF_{Std}	0.40	0.24	0.27	0.61	0.41	0.63

Table 4 SCF_{Mean} and SCF_{Std} for all the images of biaxial test

Profile number	1	2	3	4	5	6
SCF_{Mean}	2.54	2.26	X	1.94	1.95	1.88
SCF_{Std}	0.89	0.39	X	0.26	0.38	0.35

Discussion and conclusions

The article presents a profound evaluation of DIC capabilities for measuring strain concentrations on steel welded junctions subjected to elastic deformations. Additionally, practical application has been demonstrated by characterising of the SCF of different butt welded junctions subjected to uniaxial and biaxial loads.

The potential of DIC techniques to measure strain concentrations on steel welded junctions deformed within the elastic range has been demonstrated. Nevertheless, the specific characteristics of the deformation field on these type of junctions requires special attention to the spatial resolution during the image processing in order to avoid significant strain underestimation.

The theoretical approach to the smoothing error induced for different VSG shows that the strain underestimation due to data smoothing is negligible for a pixel size less than 5 μm . This value, however, is very difficult to achieve with common DIC equipments. Also, such pixel size would introduce other variables that can bias the results, such as the small speckle needed for the specimen surface or the increasing sensitivity to any noise source. In any case, the smoothing error has been shown to increase moderately with the size of the VSG. Additionally, this error always tends underestimate the strains, which permits the implementation of corrections on actual test images based on the theoretical characterisation.

Results obtained from virtually deformed images evidence a compromise between noise and smoothing error. Both shape function and subset size were found to have smaller influence on the smoothing error than in the noise level. Step size showed great influence both in noise and smoothing error, this influence was proved to be consequence of its direct relation with the VSG size, as shown in Fig. 9, were different combination of step size and SW that achieve the same VSG size lead to the same results. It is important to point that the computational cost increases quadratically with the step size decrease. Therefore, it is recommended to use the highest step size possible for a target VSG size.

In order to assess the influence of the VSG size on the strain noise and the smoothing error, it is necessary to process images acquired in actual test conditions. This enables accounting for any possible noise source that may arise from the test setup. For the 19.3 μm pixel size achieved in this study, noise was found to completely

13 Statistical comparison of the SCF behaviour for both load cases studied

bias the results for a VSG size less than 1 mm. In theory, this limit would decrease linearly by decreasing the pixels size. For VSG between 1 and 1.5 mm, the noise decrease is pronounced, becoming less significant for higher VSG sizes. On the other hand, the smoothing error was observed to increase moderately while increasing the VSG, and shows good agreement with the theoretical results. It was concluded from the results that a target VSG between 1.3 and 1.5 meets a good compromise, since the noise oscillates from 250 to 180 μm , and the mean smooth error keeps under 10%.

It should be noticed that the noise study presented in the article can be used as long as the test conditions are similar. When test conditions differ, it is recommended to perform an analogous study since significant differences in the noise levels may be found.

Practical application was performed in the last section of the paper, processing test images subjected to uniaxial and biaxial load cases. An error metric was adopted to predict the confidence interval limits for the actual maximum strains. Results show significant variation of the SCF along the weld toe, which evidences the importance of the weld geometry. On the contrary, the influence of the load case in the SCF was found to be almost negligible.

The overall mean and standard deviation of the SCF obtained was 2.33 and 0.43, respectively, for the uniaxial specimens, and 2.11 and 0.45 for the biaxial ones. This characterisation was carried out over more than 2000 different weld toe points and supposes itself a powerful tool from the structural design point of view in welded structures.

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