Experimental characterization of the strain concentration factor in welded junctions of rectangular tube beam using digital image correlation

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Abstract

The most common cause of failure in bus structures is fatigue, and it is generally located at strain concentration zones that appear in the welded junctions of these structures. Therefore, measurement and characterization of these regions becomes crucial in structural analysis and design of bus structures.

In bus structural analysis, simplified finite element models (FEM) are generally used, since they enable to examine different variables with low computational cost. Nevertheless, by utilizing these models, it is impossible to reproduce the structure junction geometry in detail, which impedes the calculation of strain in the concentration areas.

In the present paper, measure and characterization of the strain concentration factor (SCF) of welded junctions typically present in bus structure has been carried out. For this purpose, 10 'T' welded junctions were tested, disposed in two different configurations. Every junction was subjected to two types of load, and to 10 different load levels for each load type. A DIC equipment was used to obtain the deformations close to the weld bead. Once processed all the measured data, and calculated the SCF, it was characterized as function of load type and level.

The results presented in this article make possible to know the actual strain experienced by the tested junctions in simplified FEM models, allowing a more precise structural design without computational cost increase. Additionally, an alternative methodology for the calculation of SCF based on the DIC techniques has been presented.

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1. Introduction

Increasingly in the last years, the industry of large passenger transport vehicles (LPTVs) demand ever lighter, longer-lasting, better equipped buses at minimum cost, that requires ever more efficient design and manufacture process. Recently, notable design improvements have been attained due to the development of the Finite Element Method (FEM), a tool that enables reproducing the behavior of the analyzed structure, and thus, evaluate and optimize it.

A wide range of design and optimization of bus structure have been carried out with the aid of FEM. Hu, Yang, & Wang, 2012, for instance, developed a methodology for validating FEM models of bus structures based on modal correlation with experimental results. On the other hand, Ruiz, Ramirez, Jacobo, & Schouwenaars, 2012, also based on FEM models construct an iterative method of bus structure optimization. Also, Manokruang, & Butdee, 2009, propose a methodology for bus body frame lightweight based on the elimination of considered as unnecessary elements. These are some examples of the wide range of possibilities that FEM based calculations offer in relation to LPTVs structures. All of the aforementioned authors, as well as many others, have carried out simplified FEM modeling of LPTVs structures using beam type elements (Adams, & Vince, 1999). This type of element is commonly used in large tubular structures since they permit examining a wide variety of variables with low computational cost, therefore allowing designers to perform complex and detailed simulations.

Although the utilization of this element type has a wide spread acceptance, it has some significant limitations due to its simplicity in geometry modelling and formulation (Alcalá, Badea, Martín, & Aparicio, 2013). One important limitation is the impossibility of modeling the structure junction’s geometry in detail. This limitation impedes the calculation of local strain increases due to steep geometrical changes, since they are impossible to be modelled with beam elements.

Most of the LPTV’s junctions are performed through welding processes, which tends to locate strain concentrations at the weld bead toe. The most utilized parameter to evaluate the strain concentration is the strain concentration factor (SCF), defined as the ratio between the maximum local strain measured and the nominal strain, which not consider the local geometry discontinuities. The most commonly used technique for the determination of the SCF is using strain gauges located at controlled distances from the strain concentration zone and posterior application of extrapolation algorithms with the measured values. Ye, Ni, & Ko, 2012, for example, carried out an experimental assessment of the SCF of ‘T’ junctions with the aid of strain gauges, also Gho, & Gao, 2004, used this technique to develop a parametric formulae of the SCF in overlapped tubular joints.

Calculating the SFC with the aid of strain gauges has some limitations due to the structure of the gauge itself that makes impossible precise strain measurements at material discontinuities, therefore compelling to perform an extrapolation process. Besides, in the case of welded junctions, the exact shape of the weld bead geometry is not accurately known, and consequently, the maximum strain concentration zone is not well located. Erroneous positioning of the gauges leads to underestimation of the maximum SCF in the welded junctions and therefore, to a non-conservative estimations.

To overcome these limitations, Digital Image Correlation (DIC) technique has shown as a very valuable tool, since it enables measuring strain in a full area of interest, including, therefore, the strain concentration zones (Sutton, Orteu, & Schreier, 2009). This technique ensures to measure the maximum strain suffered by the welded junction, avoiding the extrapolation process.

The present paper proposes a methodology for experimental strain concentration factor characterization based on DIC strain measurements. For this purpose, 10 ‘T’ welded junctions disposed in two different configurations were tested. Every junction was subjected to two types of load, and to 10 load levels for each load type. The DIC equipment was used in each test to measure the maximum strain supported by the junction. Once processed all the measured data, a characterization of the relation between load level, load direction and SFC has been carried out and is discussed in the last section of the presented paper.

The characterization performed enables the calculation of the actual maximum strain suffered by the welded junction in simplified FEM models of LPTV structures, therefore, making possible a more precise structural design and optimization without computational cost increase.
2. Welded junctions description

As stated in the previous section, a total of 10 ‘T’ welded junctions typically present on LPTV structures were fabricated. The cross section dimensions of the welded rectangular tubes are 60x40x3mm, and the material of all the specimens is S275JR. All the welds have been performed using MIG welding technology, with filler metal recommended for this type of steel according to standard UNE-EN 13479. Two ‘T’ weld configuration of the junctions were used as shown in Fig. 1, fabricating 5 specimens of each. The dimensions of the specimens were duly chosen so the tests could be performed appropriately (all measurements in mm).

3. Test procedure description

The test carried out to measure maximum strains in the welded junctions consist of the specimen installation, followed by the DIC equipment set up and measurement acquisition. Subsections below, describe each of these steps with further detail.

3.1. Specimen installation

Described welded junctions were subjected to different load levels in directions ‘Z’ and ‘Y’, according to coordinate system of Fig. 1. A hydraulic cylinder was used to apply controlled loads. As it can be seen in Fig. 2, solicitations in ‘Z’ direction were directly applied by the cylinder. For ‘Y’ direction was necessary the installation of a pulley in order to change load direction.

The point of application of the load is situated at a distance of 840 mm from the closest face of the junction to the cylinder. Load was applied in the form of displacement of the specimen at the point of load application, ranged -12.5 mm to +12.5 mm, with incremental load steps of 2.5mm.
In the case of ‘Y’ load direction, the metal cable that connects the hydraulic cylinder to the specimen stretches as the cylinder moves, and consequently, there will be relative displacement between them. For that reason it was installed an extra wire sensor to measure the displacement of the specimen at the point of load application. Displacement constraints were applied at controlled distances from the welded junctions as shown in Fig. 3. This configuration will be applied to both load directions.

3.2. Strain measurements with DIC

The Digital Image Correlation equipment utilized for strain measurements was installed as shown in Fig. 4. The cameras of the equipment focus the corner of the closest weld bead toe to the point of load application, which is the location where the maximum strains will occur. It was randomly chosen the corner to be measured for each specimen due to the impossibility to measure more than one in the same test with DIC.
As stated before, DIC allows strain distribution measurements over a full area of interest. By way of example, Fig. 5 shows the strain distributions obtained for one specimen of each junction type subjected to a displacement of 12.5mm in ‘Z’ direction. The figure also shows, for all the specimens, the strain over a line that starts at the points of maximum strain, and extends perpendicularly to the weld bead.

Once obtained the strain distribution of each specimen and for each load level and direction, the maximum strains registered were gathered in the following graphs (Fig. 6). As expected, an increasing maximum strain with increasing displacement is observed. Higher strains are registered when applying load in ‘Y’ direction, since the specimen’s inertial moment is higher in this direction. It can also be observed symmetric behavior of the junctions...
since no significance difference is appreciated between maximum strains when displacement is applied in positive or negative direction.

Fig. 6. Welded junctions maximum strains.

4. Characterization of the SCF

According to the graphs showed in Fig. 5 of the previous section, the SCF can be expressed as the relation between the maximum strain measured, and the nominal strain at this location, determined by theoretical calculation:

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SCF = \frac{\sigma_{\text{max}}}{\sigma_{\text{nom}}} \quad (1)
\]

Utilizing the relation of Ec.1 in each welded junctions, and for each of the test performed, it is possible to establish a relation between the SCF and the nominal strain. Since symmetric behavior has been appreciated in the test results, absolute value of the displacements have been used to calculate this correlation.

Fig. 7 below shows maximum strain measured in regards to calculated nominal strain, over which second grade polynomial regression have been developed from mean values of strain at each load level. In all cases great agreement is appreciated, with R-squared values over 0.9.

It is also observed a general trend of the welded junctions to maintain constant the SCF in relation to the rest of the weld of the same type, that is, if one junction, and for a specific load presents a high value of the SCF, it will also present high values for the rest of the load cases. It is likely due to the variability of the weld geometry characteristics which have direct influence over the SFC.

Generally, small changes in the SCF are appreciated over the tests load range. Nevertheless, it can be observed a SCF slight decreasing tendency up to a nominal strain level of about 6e-4 for Type-A junctions and about 7.5e-4; from this strain values, the SCF begin to slowly increase. These nominal strain values correspond to local maximum strains close to the material proportional limit.
In order to perform a comparison between load direction, junction type, and the SCF, calculated values by the polynomial regressions for various nominal strain levels are gathered in Table 1 and Fig. 8. For ‘Z’ load direction, only values of SCF up to a nominal strain of 0.0009 have been processed, since lack of data from that strain level can result in erroneous outcomes. For the same reason, SCF is calculated from nominal strain values of 0.0002 in the case of ‘Y’ load direction.
Significant agreement of the SCF can be noticed from the test result for both junction and load configurations; likewise, little variation of the SCF is present over the tested strain range. All the junctions and load configurations show SCF values between 2 and 2.5, with the exception of junction type ‘A’, for ‘Y’ load direction, that present values over 2.5 for nominal strains over 0.001.

Results exhibit slight difference between junction type and load direction, nevertheless, junction type ‘A’ with ‘Z’ load direction, shows minimum SCF values up to nominal strains of 0.007, from this point, minimum values are present in junction type ‘B’, regardless of the load direction. The most unfavorable configuration, though with little difference from the rest, is shown by the junction type ‘A’ with ‘Y’ load direction, presenting the highest values of SCF over the strain range of the tests performed.

5. Conclusions

In the presented work, an experimental characterization of welded junction typically present on LPTV has been carried out, based on full field strain measurement with the aid of digital image correlation.

Advantages of using DIC techniques instead classical strain gauges have been evidenced in the test procedure described, avoiding any type of extrapolation calculation, as well as ensuring the measurement of the maximum strain in the weld junction regardless of location changes from one junction to another.

The SCF calculation developed in this paper is limited to the welded junctions configuration tested; however, the methodology followed is valid for any type of junction of the structure of the LPTV.

From the structural design point of view, no significant differences of the SCF are noticed between junction typology. Nonetheless, notable influence of the weld bead geometry is observed in view of the considerable variability shown by the SCF obtained for the same junction configuration and load state. Hence, a proper welding process could decrease the SCF significantly, allowing structural design optimizations.

Additionally, the results obtained demonstrate the non-conservative error made by developing tensional calculations based on simplified models of LPTVs structures constructed using beam elements. Nonetheless, this
limitation can be overcome by using the regression formulae proposed for the tested junctions, leading to much more accurate results.

It is therefore author’s opinion that the results provided in this paper represent a valuable tool for LPTV structural design, making possible to know the actual strain experienced by the tested junctions in simplified FEM models. This makes possible a more precise structural design without computational cost increase.

6. References