

Full Field Non-Contact Investigation of Deformation Fields in Fillet and Plug Welds

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ABSTRACT

Fillet and plug weld are commonly used in structural applications in commercial heavy vehicles. This paper is primarily concerned with an investigation of the full field deformations fields in fillet and plug welds using three dimensional digital image correlation (3D-DIC). Two identical vehicle parts are constructed using a fillet weld for one specimen, and a plug weld for the other. The specimens are loaded under quasi-static conditions with simultaneous measurement of load, displacements and strain gage measurements. Strain gage locations are selected based on the results of a finite element analysis model. 3D-DIC measurements are constructed using a two camera setup. Thus, 3D-DIC measurements are compared to strain gage measurements and finite element predictions. The effectiveness of the non-contact full field method is evaluated for application to studying the weld details considered and potential for fatigue damage and durability.

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INTRODUCTION

Three Dimensional Digital Image Correlation (3D-DIC) is an optical method that uses two coupled charged array (CCD) cameras for image capture and employs tracking and image registration techniques for measurements of displacement and strain [1, 2, 3, 4]. This technique is able to reconstruct displacements with subpixel accuracy depending on various factors such as image quality, noise, and the correlation algorithm [5, 6]. The data obtained from tracking and image registration of speckle patterns is processed to determine contours, displacement and strains over the entire viewing area. A random, and optically recognizable pattern, must be applied to the surface of the material with spray paint, or, sometimes, vinyl coatings can be applied to the surface of the specimen [7]. In this method, the reference image is captured before load application, and intermittently during, load application. Correlation methods are subsequently employed to track the migration of facets (a collection of pixels) between images. Sutton et al. [8] provided practical considerations for accurate measurements with DIC including best practices with speckle patterning. Gothekear [9] provided

a standard for validation of the DIC technique using the stress strain curve in steel specimens using 2D-DIC results and extensometer measurements. Tang et al. [10] proposed an improved coarse search method, for measurement of large deformations with a 3D-DIC set-up. The experimental results validate the accuracy of 3D-DIC for high tensile deformation (i.e. up to 450%) with less accuracy at smaller displacements and strains.

Limited research has been reported on the application of 3D-DIC to the study of welds in structural assemblies typically used in commercial vehicles. Lagattu et al. [11] reported the experimental results of strain localization around a hole in a composite coupon with the one camera approach using a 2D-DIC method. Indirectly, the experimental results verified the ability of the DIC system to accurately measure the stress/strain behavior around a stress concentration (i.e. the hole). Reynolds et al. [12] verified the use of DIC to analyze the microstructural regions of a friction-stir weld, subjected to transverse loading, in a 3.9-mm thick sheet of 5454 aluminum alloy (the base and weld material were of the same alloy). The study also concluded that there was "no uncertainty" about the weld material since stress/strain

behavior was captured in real-time. In contrast, weld simulations make assumptions about the composition of the weld material.

In this study, we investigate the behavior of plug and fillet welds in a structural automotive part. More specifically, it is composed of square tubed pipe located in the engine compartment of a bus. Its primary function is for attaching hoses and the air cleaner. Strains as a function of weld type, are investigated for the likelihood of fatigue failure near regions of high concentrations in this design. We shall refer to this part in this manuscript as the “Attachment Module” (Figure 1). In this part two pieces of square tubing were welded together with a brace. For the first design, a fillet weld was applied on the bottom piece in a linear manner along the ends of the top piece. In the second design, the plug welds were applied by cutting a sufficiently large hole in the brace followed by applying the welding metal between the brace and the two square tubed pieces. Furthermore, five plug welds were applied on the 90-degree bend in a linear manner (Figure 2).

This study focuses on a comparative analysis of the 3D-DIC results of two different types of welds (plug and fillet), and the potential ability of this method to aid in design. The plug weld and fillet weld being analyzed are not flush with the structural surface as like a friction- stir weld from Reynolds et al. [12]. The method is used to study the behavior in the non-uniform surface topography of the fillet weld and plug weld. Test results are evaluated for their ability to accurately predict the localized strain distribution measurements with 3D-DIC.

DEVELOPMENT OF FINITE ELEMENT MODEL

Stress concentration measurements near the weld were verified by constructing a 3D finite element model. The model was run under linear analysis using the nonlinear solver (Abaqus 6.10; Dassault Systemes Simulia Corp., Vélizy-Villacoublay, France) The purpose of the finite element model is to verify the results of the non-contact 3D-DIC at, and near, the stress concentration area and for correlation to the strain gage measurements. Due to physical limitations, it is difficult to measure strain with strain gages at high stress regions and due to large discontinuities in the weld zone. The finite element model allows for filling in the details where strain gage measurements are not present. The base material, square tubing and bracket, is made of STKR 490 steel (Table 1). Tetrahedral elements (Element type: C3D10) were used for the model. The mesh size of sample A (fillet weld) consisted of 32,034 elements and 60,730 nodes. The mesh of sample B (plug weld) used 47,574 elements and 93,144 nodes.

EXPERIMENTAL METHOD

Calibration and Sample Preparation

In order to ensure optimal results with DIC for investigating stress concentrations of a sample with fillet welds and a sample with plug welds, a series of tests on coupons were conducted. The focus of the coupon tests was to ensure that speckle pattern was optimized for the automotive structural samples. The coupons also investigated the optical parameters needed for the region of interest, speckle size optimization as a function of lens distance from the coupon, load rate, image acquisition rate, lighting, shutter speed, grid size, facet size and smoothing settings.

Following the coupon testing, both automotive structural samples were prepared in the same manner. One strain gage was adhered near the fillet weld toe on the first sample (Figure 1). Another strain gage was adhered in the same location, essentially a superimposition, on the second sample containing plug welds. The strain gages used in this study are 5mm gage length and a 350 Ω resistance (KFG-5-350-C1-11L10M3R; Kyowa Corporation, Japan). The strain gages were installed using a cyanoacrylate base strain gage cement. Subsequent layers of an acrylic, white, matte spray-paint (Montana Gold) were applied to create a base layer for the speckle pattern. An acrylic, black, matte spray-paint (Montana Gold) was applied to create the black speckle pattern.

Prior to testing, the positioning of the cameras, relative to the sample, and the region of interest, were set. A 15 mm calibration target plate, rotated at various angles was used for calibration of the 3D-DIC setup. The system interface displays, in real-time, the tracking of target markers, and automatically acquires a series of eight images of this calibration target positioned at different angles. Calibration is used for determination of the imaging parameters (intrinsic and extrinsic) of each of the cameras in addition to the position of the cameras relative to the overall coordinate system. An output signal from the loading system is synchronized with the image correlation system. This ensures that each frame correlates with the actual load that is being applied to the sample. Both automotive structures were placed in the tensile tester in an analogous manner (Figure 2). The top grip of the tensile tester was attached and secured to the loading plate. However, the sample, relative to the top grip, was loaded in an offset manner (Figure 3). An image was recorded every two seconds during the loading process, when testing the samples (approximately 49 images were recorded during each session).

Strain gage, load, and displacement measurements were collected with a USB connected data acquisition system (Lab View NI9236; National Instruments, Austin, Texas, USA). The measurements were synchronized with the DIC system by reading the analog load signals simultaneously with the image measurement device. The experiments were performed in a displacement controlled mode, at a rate of 0.05 in/min,