Three Dimensional Stress Analysis of Contact in Pin-Loaded Joints
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Abstract.
Pin-loaded joints are widely used in structural applications in the aerospace and civil industries. Two dimensional models traditionally used in analysing stress fields can lead to inaccuracies in predicting safe loads due to three-dimensional stress gradients. A novel approach is adopted herein where the embedded strain gauge technique is applied to a pin-loaded lug, facilitating direct measurement of internal, sub-surface contact strains in three-dimensions for multiple pin-lug clearance levels, friction co-efficients and different loading scenarios. Results have shown that the dry friction case gives a lower hoop strain at the centre of the contact than the lubricated case and the unloading behaviour does not match the loading behaviour due to the history dependent nature of the friction at the contact interface. Differences are found in the axial strains through the thickness of the lug along the lug ligament for the case of loading by a steel pin, indicating a requirement to model the three-dimensional behaviour of the lug.

Introduction
The pin-loaded lug is commonly used to transmit loads. The straight-shanked, round-ended lug is the most commonly used, and is the geometry adopted herein. Though various authors have reported that through-thickness effects may be significant due to pin bending, there exist few studies to quantify this effect [1, 2]. In such situations, it is insufficient to analyse the lug behaviour with a 2D model. Research surrounding the 3D lug problem is limited, and is mostly based on numerical work without experimental validation. For this work, an experimental analysis using embedded strain gauge models [3] is conducted in parallel with a numerical analysis using the finite element method. Though not as popular as surface strain gauging, embedded strain gauging is an established technique for the experimental measurement of internal strains, and its use in contact analysis has been demonstrated for the case of a sphere in contact with a flat plate [4]. A further advantage of the technique is that embedded strain gauge models may be tested non-destructively. For the above problem, the influence of varying parameters such as clearance and friction may each be quantified experimentally using a single experimental model.

Experimental Work
Three experimental models were manufactured to measure internal strains. Miniature strain rosettes were embedded 8mm from the contact surface of the first model at three angular locations with respect to the hole and at three depths through the model thickness, as shown in Figure 1 (a). In total, strains were measured from 15 internal gauges and 28 surface gauges. The other two models manufactured had gauges to measure strains in three orthogonal directions at a radial distance of 6mm from the contact surface. The models were manufactured from an epoxy (CT1200/HT907) using a specialist casting process. The carrier technique of Little [3] was used in model manufacture. Strain gauges were applied to a CT1200/HT907 carrier (Figure 1 (b)) and a square peg was machined on the underside of this to allow for accurate assembly to the base of a steel mould (Figure 1 (c)). The casting was poured, cured and subject to a post-curing cycle to ensure it was fully cross-linked and stable. It was then machined to its final dimensions.

Figure 1: Model manufacture and experimental testing
A bearing load was applied to the model using a Tinius-Olsen tensile testing machine (Figure 1 (d) and (e)). Test fixtures were designed to apply a quasi-static load to the pin ends. A load cell measured the force
applied and a knife-edge element ensured equal distribution of load across the two pin ends. Strain readings were continuously recorded during loading and unloading of the model. Repeatability and reproducibility of the setup were also verified. A finite element model of the test setup was developed in ABAQUS Standard version 6.10 using Python script. Use of Python script allowed for efficient updating of model properties to include geometry, clearance, materials, friction and load. Element type, mesh properties and contact definitions were also controlled.

**Typical Results**

A sample of the results obtained is presented. These results are for loading by a mild steel pin. As a first approximation a co-efficient of friction of 0.2 was used in the finite element simulation. The measured hoop strains are plotted along a circumferential path in Figure 2. This is for a 2kN load and the strain gauges are at a radial distance of 8mm from the contact surface. Experimental strains are shown at three depths (Planes B (8mm), C (30mm) and D (52mm)) through the lug thickness. A comparison of these experimentally-measured strains shows consistency to within a few microstrain, demonstrating the ability of the model developed in measuring behaviour at internal points.

The effects of friction are shown in Figure 3 at the top of the contact. The lubricated test result is close to the frictionless finite element solution. The dry contact gives a lower magnitude of hoop strain and a large hysteresis in unloading due to the history-dependent nature of the stick-slip frictional contact.

Another typical result shows the strains along the lug sides for a clearance fit of 0.17% (Figure 4). These measured strains are in the direction through the thickness of the model, parallel with the axis of the hole. A clear difference is noted between the strains on the centre plane (Plane C) and the strains on the other two internal planes (Planes B and D).  

**Conclusions**

The technique has successfully been applied to the thick pin-loaded lug, facilitating the measurement of internal strains local to the contact surface. A clear difference is measured at the centre of the contact (0° angle) between the lubricated and dry friction tests. A reduction in the hoop strain is found for the higher friction case and a history dependancy is found during unloading of the lug. Both the experimental and finite element results along the lug ligament demonstrate a variation in the axial strain through the thickness of the lug confirming the need to consider the 3D effect for thick lugs.

**References**


