IOP Conf. Series: Materials Science and Engineering **280** (2017) 012016 doi:10.1088/1757-899X/280/1/012016

Numerical Analysis of Thermal Stresses around Fasteners in Composite Metal Foils

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Abstract. The process of composite metal foil manufacturing (CMFM) has reduced a number of limitations associated with commercial additive manufacturing (AM) methods. The existing metal AM machines are restricted by their build envelope and there is a growing market for the manufacture of large parts using AM. These parts are subsequently manufactured in fragments and are fastened together. This paper analyses the thermal stresses around cylindrical fasteners for three layered metal composite parts consisting of aluminium foil, brazing paste and copper foil layers. The investigation aims to examine the mechanical integrity of the metallurgically bonded aluminium/copper foils of 100 micron thickness manufactured in a disc shape. A cylindrical fastener set at an elevated temperature of 100 °C is fitted in the middle of the disc which results in a steady-state thermal distribution. Radial and shear stresses are computed using finite element method which shows that non-zero shear stresses developed by the copper layer inhibit the axial slippage of the fastener and thereby establishing the suitability of rivet joints for CMFM parts.

Symbols

a radius of fastener	t_t thickness of top (aluminium) layer
b outer radius of composite	t_m thickness of middle (brazing) layer
ϑ Poisson's ratio	t_b thickness of bottom (copper) layer
α Coefficient of Thermal Expansion	σ_r radial stress
E Elastic Modulus	σ_θ tangential stress
T Increase in Fastener Temperature	E_{al} Elastic Modulus of aluminium
α_{al} Coefficient of Expansion of aluminium	E_{br} Elastic Modulus of brazing
α_{br} Coefficient of Expansion of brazing	E_{co} Elastic Modulus of copper
α_{co} Coefficient of Expansion of copper	r distance from centre of composite

Notations

CalculiX CrunchiX: CCX	CalculiX GraphiX: CGX
Composite Metal: CM	Coefficient of Thermal Expansion: CTE
Composite Metal Foil: CMF	Composite Metal Foil Manufacturing: CMFM
Finite Element: FE	Finite Volume: FV

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1. Introduction

Additive Manufacturing (AM) has been receiving unprecedented attention from the academia, mainstream media, investment and national governments around the world. A number of commercial systems exist based on AM technologies for the manufacture of products using a wide variety of materials such as plastic, photopolymers, metal, ceramics etc. These processes are capable of manufacturing products with good mechanical properties and are used widely in industries such as automotive, aerospace and medical. The most important product from these technologies is made out of metal powder, as metal parts can be used directly in industrial applications. The list of reasons for using AM for the manufacture of metal parts is long but the most important one is perhaps its ability to provide design freedom. Complex and intricate geometries that are very difficult and time consuming or sometimes impossible to manufacture using conventional methods can be easily produced by AM technologies. Although methods such as Direct Metal Laser Sintering (DMLS) and Electron beam Melting (EBM) are capable of manufacturing high quality metal parts, there are a number of limitations associated with them. The biggest issue is the cost of manufacture and the pre/post processing, which takes up a lot of time and resources. Composite Metal Foil Manufacturing (CMFM) has been introduced as a cost-effective alternative to these processes and has shown consistent results for certain mechanical properties [1]. It works by combining Laminated Object Manufacturing and brazing technologies. CMFM can join similar as well as dissimilar metal foils for the production of high quality metal and composite products at a fraction of the cost, and does not require extensive pre/post processing to improve properties or aesthetics [2]. The salient feature of CMFM process is that various metals of different grades can be combined to produce composites tailored to an application. The process has only been used to produce parts for testing of properties such as tensile strength, peel strength and shear strength. It has also produced some products of everyday use such as spanners manufactured with multiple layered aluminium alloy foil and a composite from alternate layers of copper and aluminium as shown in Figure 1.

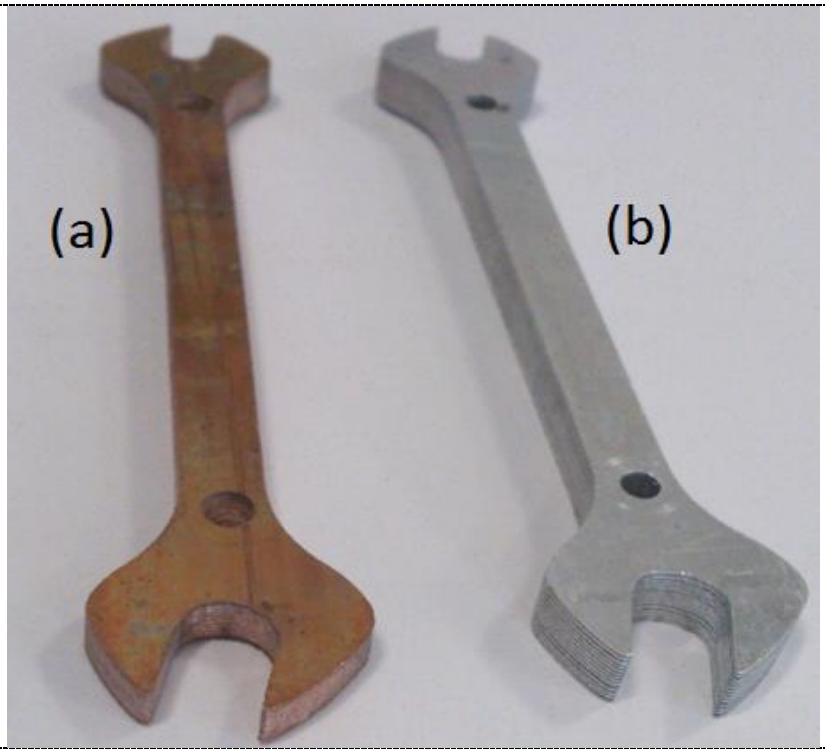

Figure 1. CMFM based composites made of layered (a) copper-aluminium (b) aluminium.

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There are a number of applications where large metal parts are produced in fragments (due to constraints on build envelope) and are fastened together with rivets for aerospace, automotive and marine structures. A smart way is the use of composite structures, as they can provide better performance as compared to using single material metal parts. This approach has its issues as well because often mechanical failures occur due to variation in thermal expansion of the two joined materials if poorly designed. CMFM can provide design freedom which will help in making complex shapes and it has already demonstrated higher fracture values for its composite products (copper/aluminium) compared to the parent alloys used [3]. This process, however, has not been tested rigorously for thermal expansion of its joining materials. Therefore, this paper will analyse the stresses induced in the composites made by CMFM due to thermal expansion mismatch between steel fasteners. This knowledge is needed to extend the applications of CMFM process, particularly for allowable stress limits around cylindrical fasteners. There are few studies on stresses in composites but most of them focus on homogeneous materials [4]. However, there are none on CMFM parts and this paper will aim to investigate such effects.

2. Thermal stresses around cylindrical fasteners

The general equations for stress gradients developed in reference [5] for a plate due to a hot-spot is directly relevant to this work. Figure 2 shows the cross-section of a circular plate (radius, b) with a hot-spot (radius, a) at temperature T.

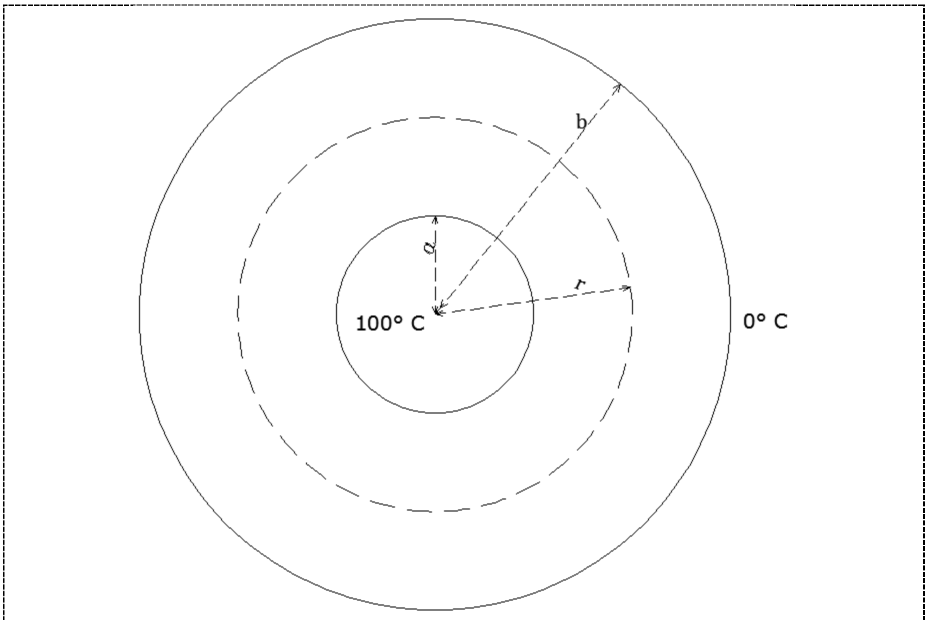

Figure 2. Schematic of circular plate with a hot-spot.

The temperature (∅) of plate varies in radial direction according to equation (1):

$$\emptyset = T \log \frac{\left(\frac{b}{r}\right)}{\log(\frac{b}{a})} \tag{1}$$

The non-dimensional radial stress can be expressed according to equation (2):

$$\frac{\sigma_r}{E\propto T} = \frac{1}{2\log\left(\frac{b}{a}\right)}\left[\frac{\left\{1-(1-v)(1-t)\log\left(\frac{b}{a}\right)\right\}\{(b^2/r^2)-1\}}{\{(1+v)+(1-v)t\}\left\{\frac{b^2}{a^2}\right\}+(1-v)(1-t)} - \log(b/r)\right] \quad (2)$$

Similarly, the normalised shear stress which is the difference between radial and tangential components can be expressed according to equation (3):

$$\frac{\sigma_r-\sigma_\theta}{E\propto T} = \frac{1}{2\log\left(\frac{b}{a}\right)}\left[\frac{\left\{1-(1-v)(1-t)\log\left(\frac{b}{a}\right)\right\}(2b^2/r^2)}{\{(1+v)+(1-v)t\}\left\{\frac{b^2}{a^2}\right\}+(1-v)(1-t)} - 1\right] \quad (3)$$

Both radial and tangential stresses in the neighbourhood of the hot-spot converge to a value of 0.5EαT for a large plate i.e., b/a$\rightarrow\infty$. Composites are made of at least two or more layers with distinct material properties for each. Analytical equations for two layered systems are relatively simple. However, as the number of layers increase such equations become more complex. No closed form solutions exist for composites of various different layers and hence in this work, FE methods were used. CMFM part investigated here is a composite made of three layers. The top and bottom layers are aluminium and copper foils respectively that are sandwiching a layer of brazing paste. All three layers have different parameters for E, α& ϑ.

3. Experimental Methodology

FE models of a fastener were built with three layered composite consisting of aluminium foil, brazing paste and copper foil. A benchmark study was initially conducted with analytical models available for isotropic structure. Afterwards, full FE analyses were conducted by assigning material data described in Table I for the composite layers and fastener. The variations in radial and tangential stresses for various configurations of models were computed. Parametric investigations were conducted by varying thicknesses of each layer of composite.

Table I. Properties of Fastener, Metal Foils and Brazing Paste Layer.

Properties	Fastener	Aluminium 1050 H14 ½ hard temper	99% Copper	80% Zinc 20% Aluminium Brazing Paste
E (GPa)	205	70.0	115.0	52
ϑ	0.3	0.3	0.3	0.35
α (μm/m .°K)	12.0	23.0	17.0	21.8

3.1. Assumptions

1. There is no clearance between fastener and surrounding composite material.
2. Fasteners are of same thickness as that of composite with no end bolt or head.
3. There is no interference friction between fastener and composite.
4. The increase in fastener temperature was 100℃.
5. Temperature of inner and outer faces of composite was at 100 & 0℃ respectively, radially varying according to equation (1).
6. Faces in the thickness direction were considered to be insulated. The heat entering into the composite via fastener at the inner face leaves at the outer face.

3.2. Material properties

Material tests were conducted for the grade of copper, aluminium and brazing in CMFM parts. Properties summarised in Table I were assigned for metal alloys and brazing paste in composite. The properties of steel in reference [6] were assigned to the fastener.

4. Finite element analysis

The CalculiX [7] is an open source non-linear FE code that is compatible with operating systems such as Linux, Windows, Mac and Android. It is divided into two independent codes (viz: Calculix GraphiX and Calculix CrunchiX). The Calculix GraphiX, also referred to as CGX, handles pre-processing to define a geometry, mesh, loads, and boundary conditions; it has both command and interactive modes. The CGX has an interactive 3D-environment that uses libraries in the openGL API for post-processing results. The Calculix CrunchiX also referred as CCX is a solver code that can do both linear and non-linear calculations. It can solve using, FE and FV methods. The CCX code is capable of performing many types of analyses including static, dynamic, fluid and thermal. FE models of the fastener and composite were built from scratch. An API script was coded with definitions of the geometry and mesh. This was done to facilitate parametric studies, it was easier to define/update model details with script. Commands were described in a script that is read by CGX. An auxiliary python code was used to update script with parameters to define geometry and meshing. In this way, FE model generation and meshing was automated. A section cut of disc equal to 1/16 of full model was built to reduce computational cost i.e., a wedge shaped sector equal to 22.5° arc cut out of a full cylinder. An illustration of the FE model is shown in Figure 3. Solid continuum elements were used for discretization; 8-noded elements (type C3D8) were used to represent both fastener and composite. Analysis was repeated with both linear and quadratic elements. The nodes of the fastener and composite were tied for their radial displacements. Constraints to specific nodes were assigned with the "*EQUATION" keyword. A finer mesh was used for the composite in the neighbourhood fastener. The radial dimension of elements were increased away from the zone of interest. An illustration of fine and coarse meshes used are shown in Figure 4. Particular attention was given for stress distribution around the fastener.

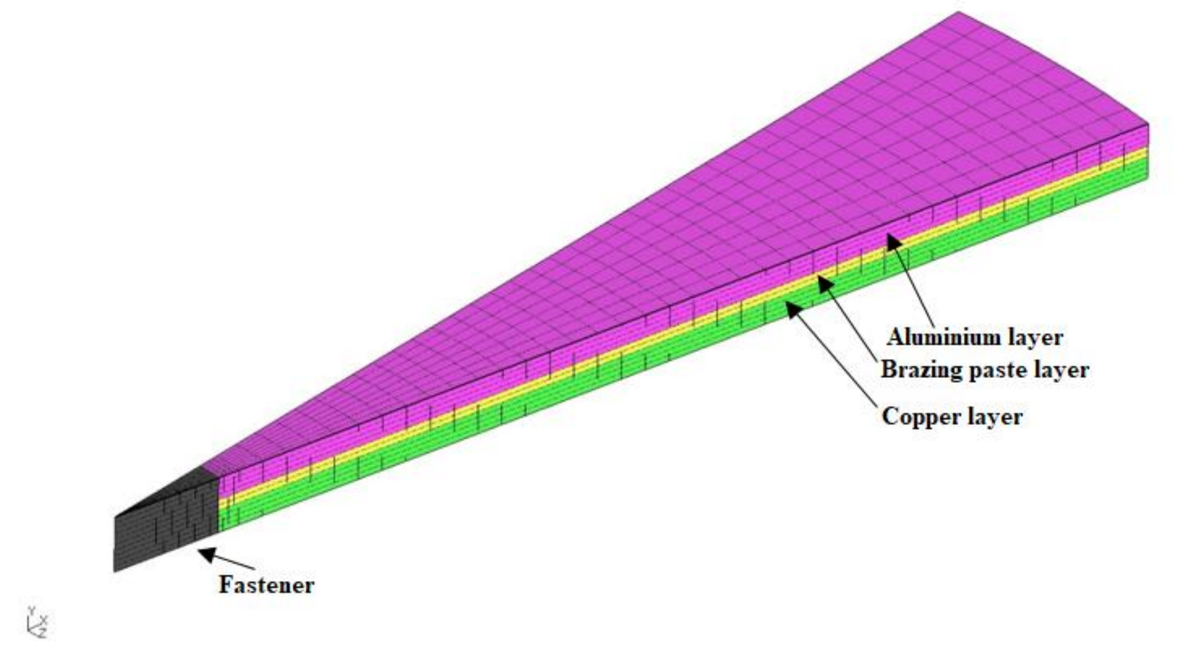

Figure 3. FE model of fastener surrounded by 3-layered composite.

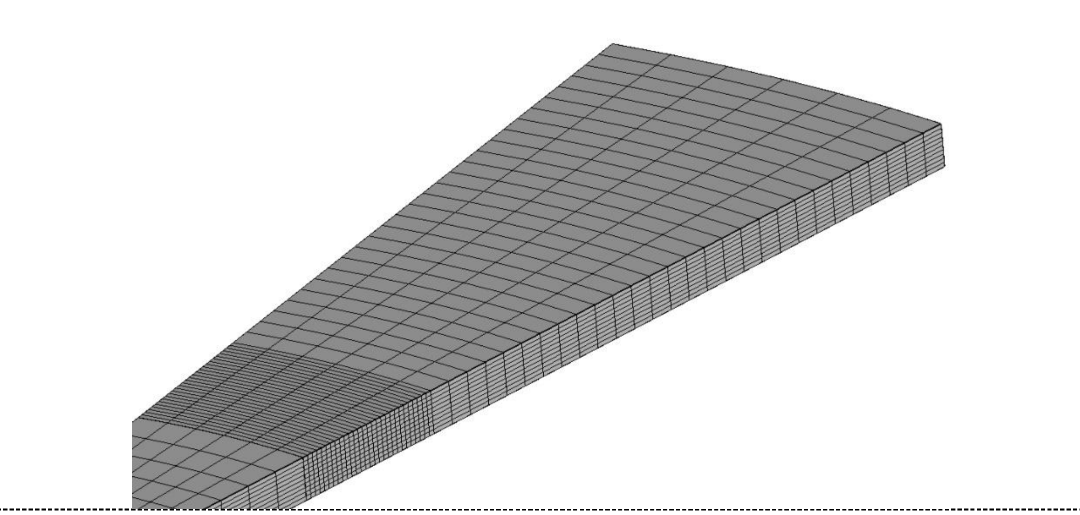

Figure 4. Coarse and fine Mesh.

5. Model validation

The fastener and all three layers of the composite were assigned with identical elastic modulus, Poisson's ratio and CTE. For simplicity, material data [8] for the FE model was assigned with CTE=10^{-05}, E=10^{05} and ϑ=0.3. The model is analogous to a homogeneous plate with a local hot-spot. Thermal stresses predicted by the FE model were compared with closed-form solutions (equations 2 and 3). The fastener was subjected to a 100℃ temperature increase and stresses developed at the interface between the fastener and surrounding materials were examined. The radial and tangential stresses becomes 0.5EαT if the extent of surrounding material is large compared to the fastener. The outer radius of the plate was increased successively up to 15 times that of fastener. The FE model results were within 2% of analytical results. Comparisons of FE and analytical results are shown in Figure 5 and Figure 6 for b/a=2.

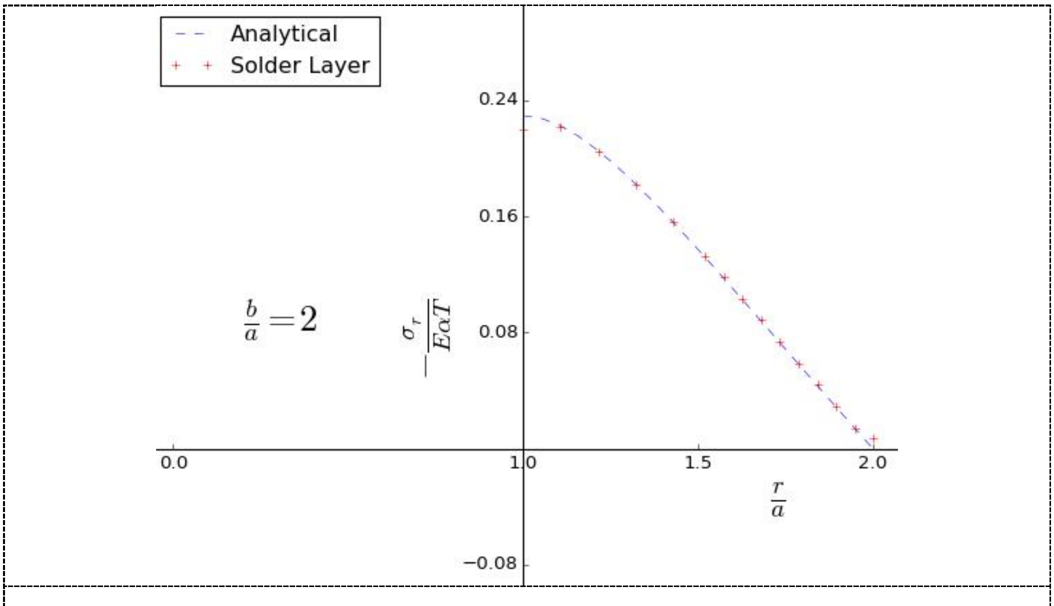

Figure 5. Variation in radial stresses for b/a=2.

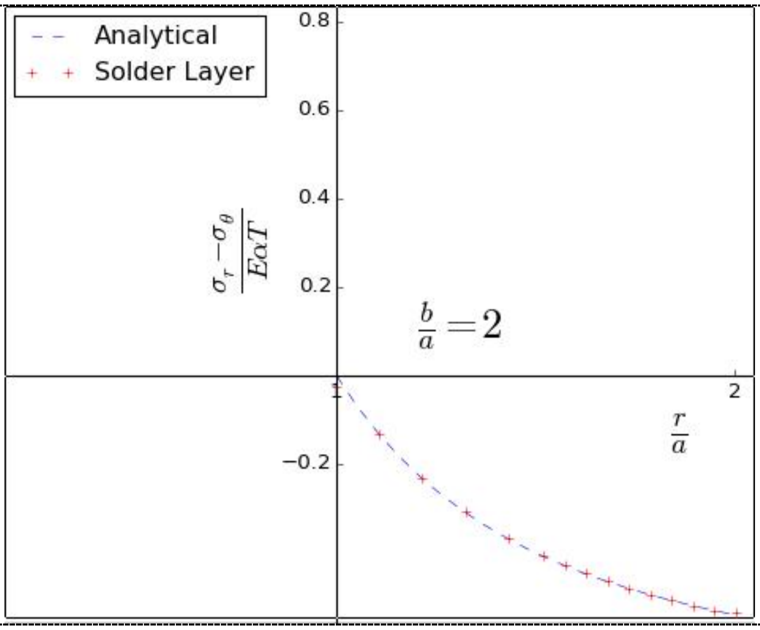

Figure 6. Variation in shear stresses for b/a=2.

6. Results and Discussion

All post-processing images were generated in CGX. Plots for the variations of radial (σ_r) and shear stresses ($\sigma_r - \sigma_\theta$) as a function of position from centre were generated for each layer of composite. Plots for b/a ratios 2 and 3 are presented in Figure 7 and Figure 8. It can be seen that stresses in aluminium and brazing layers is analogous to analytical works. However, shear stresses are non-zero in the neighbourhood of the fastener for the copper layer. The FE stress contours for tangential stresses for b/a ratio 3 are shown in Figure 9.

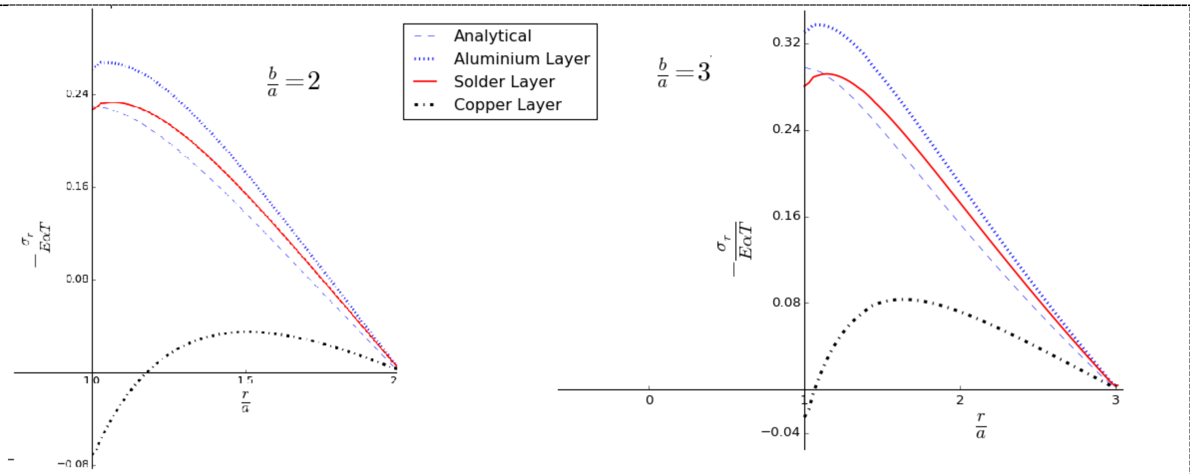

Figure 7. Radial stresses in composites.

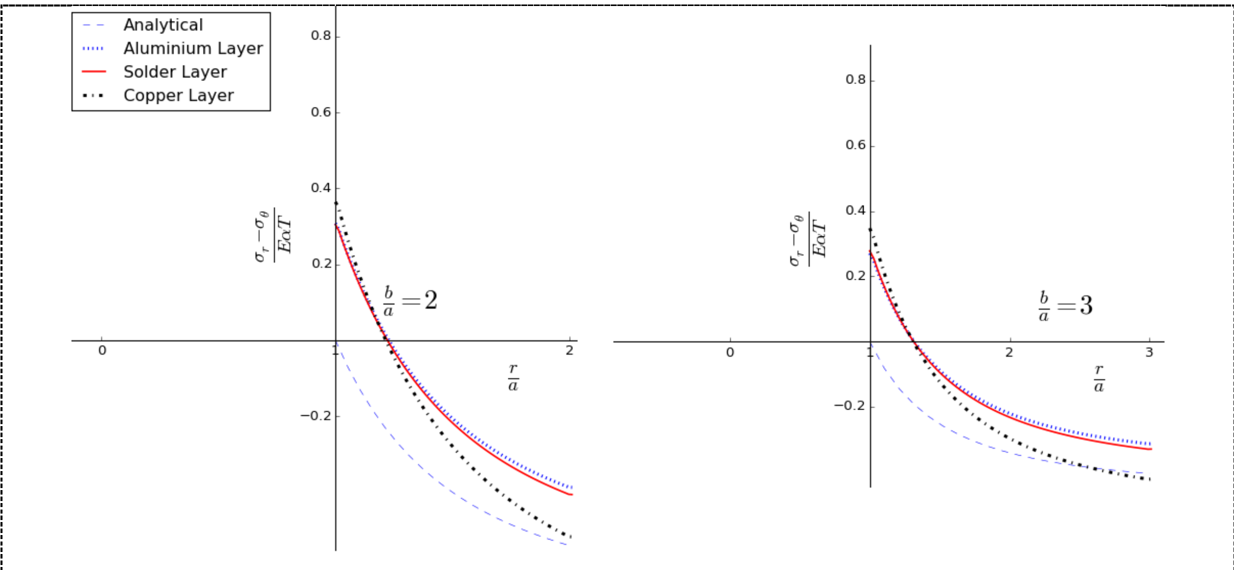

Figure 8. Shear stresses in composites.

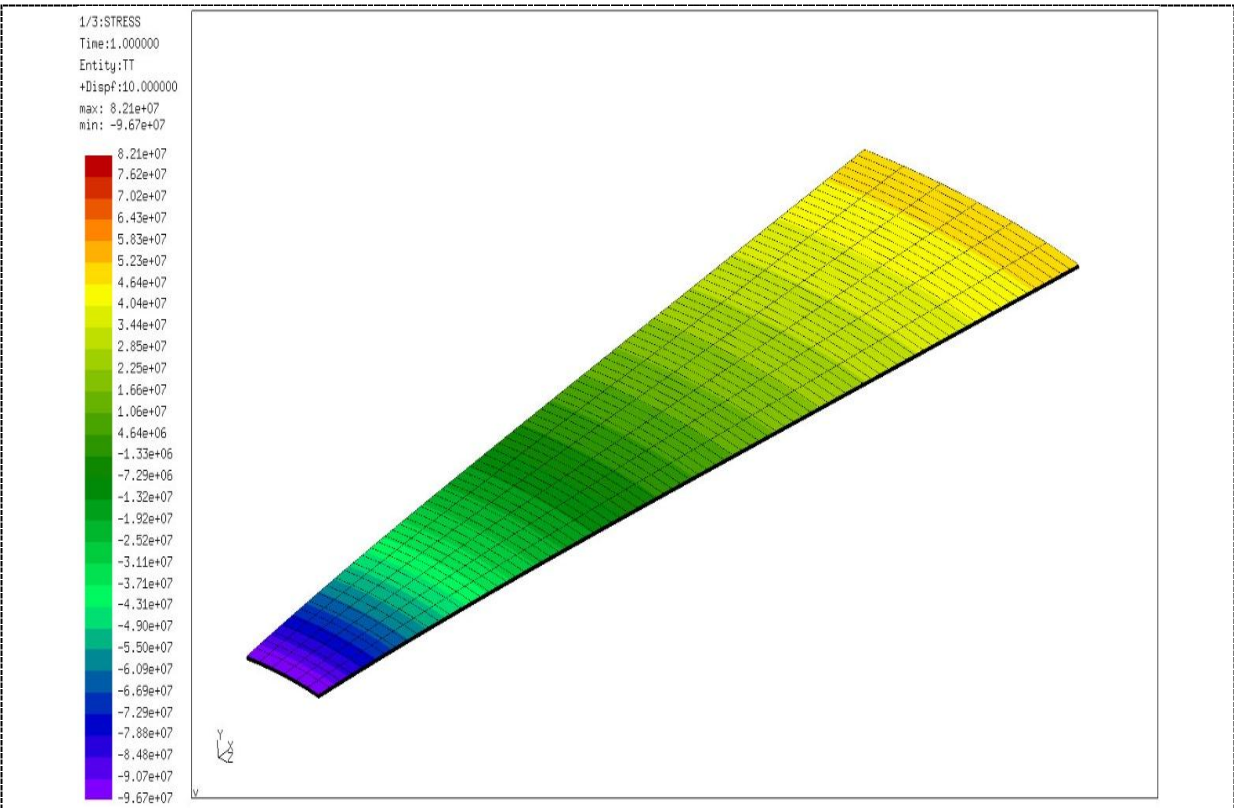

Figure 9. Tangential stresses in composites for b/a ratio of 3.

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7. Conclusions

Numerical investigations were carried out for thermal stresses around cylindrical fasteners in a CMFM composite made from thin foils (100 microns) of aluminium and copper. This study will support the fastening of large parts manufactured by CMFM. The obtained results enable the design of slip-free composite structures that can have bespoke characteristics and advantages. The shear stresses ($\sigma_r - \sigma_\theta$) are zero for homogeneous materials whereas they are always non-zero for Composite Metal Foil (CMF) under elevated temperatures. This is favourable as it will inhibit the fastener loosening axially which will provide a better support to the joint made between large parts. The numerical analysis of the aluminium/copper foil structure has shown the same trait where the copper layer is under compression and thus resulting in an even tighter fitting of the fastener. This added feature combined with the other advantages will make CMFM a very good option for joining large structures using fasteners.

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