Residual Stresses in GLARE Laminates due to the Cold Expansion Process

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ABSTRACT

Improvements to fatigue strength of fastener holes in metallic structures can be achieved by applying a cold expansion process to the hole prior to fastener installation. Similar improvements have been observed in fibre metal laminates; however, the influence of the fibre layers on the residual stress distribution in the metallic layers is not well understood. In response to this, a 3-dimensional finite element investigation has been performed. Using the commercial non-linear FEA code LS-DYNA, the split-sleeve cold expansion process of non-countersunk fastener holes is simulated in monolithic aluminum sheet and GLARE (GLAss REinforced aluminum) laminates. A simplified delamination model has also been included to study the influence of small delaminations typical in cold expanded GLARE holes. Results demonstrated that shear stresses resulting from the elastic expansion of the fibre layer act in parallel with interface pressure from the mandrel to expand the aluminum layers, and that their relative contributions are non-uniform through the thickness of the laminate.

INTRODUCTION

Fibre-metal laminates (FMLs) have gained interest in the aerospace industry for their ability to combine many of the benefits of monolithic metallic sheet and fibre-reinforced composites. Specifically, the combination of sheet metal fabrication and repair capabilities with the fatigue crack growth benefits of fibre reinforced composites provides a new damage tolerant material that can integrate into current metallic aircraft design practices. Currently, an aluminum-glass fibre variant known as GLARE (GLAss REinforced aluminum laminate) has been gaining acceptance as a viable alternative to monolithic 2024-T3 sheet in aircraft fuselages and will see its first application in the Airbus A380.

The primary feature of GLARE responsible for its improved damage tolerance is the fibre bridging mechanism. As cracks form in the aluminum layers, crack opening is resisted by adjacent fibre layers transferring the applied load over the crack. The resulting reduction in crack tip stress intensity factor leads to lower crack growth rates and in some cases impedes further crack growth [1-6]. In addition to improved damage tolerance, the fibre bridging mechanism results in a superior overall fatigue life compared to monolithic aluminum.

Despite the improvements to overall fatigue life, GLARE laminates exhibit a shorter fatigue crack initiation (FCI) period than comparable monolithic aluminum sheet. The lower stiffness of the fibre layers compared to the aluminum layers and unfavourable
residual stresses resulting from curing promote FCI in GLARE. Furthermore, the fibre bridging mechanism only becomes effective once fatigue cracks have grown to sufficient length (≥2mm) [2]. Thus the early fatigue crack growth performance of GLARE will also suffer from the higher stresses in the aluminum layers, further reducing its advantage over monolithic aluminum. Relying on the damage tolerant benefits of GLARE to make up for these deficiencies should not be sufficient. Indeed, structures should be damage resistant in addition to being damage tolerant.

Design considerations related to improving FCI life are not new in the aerospace industry. One method that is becoming common practice for postponing FCI is the introduction of residual compressive stresses in fatigue sensitive areas. The cold expansion of fastener holes is commonly used to achieve this end in mechanically fastened metallic structures.

Several techniques for achieving cold expansion of fastener holes exist; however most are variations of the basic process of passing an oversized object through a fastener hole [7-11]. One method that has gained wide acceptance in the aerospace industry is the split-sleeve method marketed by Fatigue Technology Inc. (FTI). This method has the added feature of a lubricated split-sleeve which is inserted into the fastener hole prior to expanding it using a tapered mandrel. The split-sleeve is used to prevent damage to the hole surface, which can occur when in direct contact with the moving pin.

The potential for applying such a technique to GLARE is evident. The introduction of residual compressive stresses into the metallic layers could postpone FCI and improve the overall fatigue advantage of GLARE. Experimental investigations carried out by van der Kuip [11] demonstrated that indeed such improvements are possible. Fatigue tests of split-sleeve and split mandrel cold expansion techniques revealed a 2-fold increase in crack free life for some of the aluminum layers. Distinct variations in crack initiation and growth behaviour between the various aluminum layers and the formation of delamination damage, however, were also observed indicating a need for further study of the influence of the fibre layer and delamination formation on the residual stress distribution.

A number of methods have been used to study the formation and distribution of residual stresses due to cold expansion. Analytical models based on a uniform expansion process have been applied to both plane strain and plane stress conditions in monolithic materials [12-15]. Application of such two-dimensional models to GLARE, however, is limited as they are not capable of predicting thickness variations in residual stress or handling thickness variations in material properties. More recently, finite element analysis (FEA) has been used to investigate cold expansion. The simulations permitted studies of through-thickness variations in residual stresses as well as the effects of non-uniformities in practical cold expansion techniques [8, 9, 16-19]. Such methods currently provide the best means for studying the effects of cold expansion on GLARE.

In this paper, the results of a numerical study into the residual stress field surrounding cold expanded holes in thin GLARE laminates are presented. The split-sleeve cold expansion process in GLARE3-2/1-0.3 and 2024-T3 is simulated using the non-linear
finite element (FE) code LS-DYNA. Results from the simulations are compared to
determine the influence of the fibre layer on the formation and distribution of residual
stresses in GLARE, including the effects of delamination resulting from the cold
expansion process.

**FINITE ELEMENT SIMULATIONS**

**Finite Element Model**

The explicit finite element code LS-DYNA was used to model the split-sleeve cold
expansion process (FTI process specification 8101D). For modelling purposes, the
following simplifications to this process were made: the lubricated split-sleeve was
removed and the mandrel was assumed to be rigid. To compensate for the lack of the
split-sleeve, its thickness was added to the radius of the mandrel and a frictionless contact
interface was used between the plate and the mandrel. Additionally, the final reaming
step to enlarge the cold expanded hole to nominal dimensions was not considered in this
analysis.

A schematic of the FE model is shown in Figure 1, consisting of a rigid mandrel, rigid
backing plate and deformable plate. The mandrel and backing plate were represented as
rigid surface meshes while the plate consisted of eight-node single-point integration brick
elements. Details regarding the mesh are given in Table 1 and Figure 2. As a
consequence of using single-point integration solid elements, zero-energy deformation
modes (hourglassing modes) needed to be resisted through artificial stabilization
(hourglass control) [20, 21]. The stiffness based type 6 hourglass control in LS-DYNA
was used for this purpose. Time scaling was also invoked to reduce the computational
time and take advantage of the low inertial effects (quasi-static nature) of the cold
expansion process.

Quarter symmetry was utilized during the simulations with symmetry boundary
conditions prescribed along the two symmetry planes and along the periphery of the
plate. Axial motion of the plate was constrained through frictionless contact with the
fixed backing plate and through nodal constraints applied to the exit-face nodes on the
periphery of the plate. Motion of the mandrel was constrained to the axial direction. The
mandrel was translated through the plate at a constant feed rate starting from a position of
initial contact with the plate until contact was broken. Subsequent to this, the backing
plate was removed and the plate allowed to come to rest.

Simulations were performed for both 2024-T3 and GLARE3-2/1-0.3 plates with nominal
thicknesses of 1.0mm and 0.86mm respectively. The hole radius R was set to 1.45mm
corresponding to the FTI process specification for starting hole radius for a 3.2mm
diameter fastener hole. Similarly, major and minor mandrel radii were set to 1.52mm and
1.37mm respectively. Plate dimensions of 25.4mm long by 25.4mm wide were used for
both materials.

A power-law plasticity model with isotropic hardening was used for the aluminum plate
and aluminum layers in the GLARE laminate while an orthotropic elastic material model
was used for the prepreg layers (unidirectional preimpregnated glass-fibre layers that form each cross-ply fibre layer). A summary of the material properties required by these models is provided in Table 2 [22, 23].

**Delamination Modelling**

The presence of delamination damage after applying various cold expansion process to GLARE was noted in experimental investigations by van der Kuip [11]. Although the extent of these delaminations was typically below 20% of the original hole radius, they allows unrestrained elastic springback of the fibre layer in the delaminated area following cold expansion. Thus it was deemed important to investigate the influence of delaminations on the residual stress state in cold expanded GLARE.

Two possible cases were considered. In the first case (Case A), delamination was not considered and the interface between the various layers was defined as a tied contact interface. This interface fixes nodes on adjacent faces of the interface together so that deformation of the interface is possible, but relative deformation at the interface faces is not. In the second case (Case B), delamination along the aluminum-prepreg interfaces was modelled using a tied interface with the addition of a shear stress and normal stress failure criterion known as a tiebreak contact interface [20]. This failure criterion is suitable for predicting delamination initiation but the rigid nature of the tied interface results in stress concentrations along the delamination front that cause over-predictions in delamination growth and size. Thus, the extent of the delamination was limited by predefining an allowable delamination size with the tiebreak interface and surrounding it with a tied interface. Modelling delamination in this manner, although highly simplified, avoided the need to model the dynamics of delamination propagation and permitted the continued use of quasi-static assumptions in the simulations. Alternate interface failure models that included limited plasticity of the interface were also attempted; however, requirements to accurately model delamination propagation conflicted with the mesh refinement requirements for accurate residual stress distributions, making computational times unfeasible.

Failure of the tiebreak interface was simplified in this application to neglect normal interface stresses, and a maximum shear stress of 43 MPa was defined [24]. The predefined delamination size was set to 20% of the hole radius based on observations made by van der Kuip [11]. The same delamination size was defined for both aluminum-prepreg interfaces, and no delamination was permitted between the two prepreg layers. Subsequent to failure, the tiebreak interface acted as a standard surface-to-surface contact interface.

**Finite Element Results**

Residual radial and tangential stress distributions for 2024-T3 and GLARE3-2/1-0.3 plate were obtained from the finite element simulations. For presentation purposes, in-plane and thickness positions within the plate are given in the undeformed state and are normalized using the hole radius and plate thickness respectively. Stress results are also normalized using the yield stress $\sigma_y$ of the 2024-T3 aluminum plate/GLARE layers. For
brevity, results for the GLARE simulations are presented along the xz-plane only (Figure 1) unless otherwise stated.

Figure 3 and Figure 4 compare the residual radial and tangential stress distributions at various thickness locations from the 2024-T3 and GLARE simulations. Although none of the previous finite element studies examined the same plate/hole/mandrel geometry, general trends and residual stress magnitudes agree well with the 2024-T3 results [16, 18, 19]. Further agreement was found when comparing the 2024-T3 mid-plane results to various analytical models (Figure 5) [3, 12].

The results from the GLARE simulations exhibit similar trends as the 2024-T3 simulations; however, a larger radius of plastic deformation indicated by the location of the peak in tensile tangential stress is clearly evident in GLARE (Figure 4b). This behaviour can be attributed to the apparent strain hardening behaviour of the fibre layers. As the aluminum layers begin to yield, their stiffness drops and load is redistributed through the elastic fibre layers, producing a stiffer yield response than monolithic aluminum (Figure 6). In a strain driven process such as cold expansion, this results in a larger applied load producing the larger region of plastic flow. This dependence on strain hardening is also predicted by analytical models [12].

Variations in the radius of plastic deformation at the mid-plane and in the residual stresses at the hole edge between Al1 and Al2 are also evident in Figure 4 and Figure 7. As the cold-expansion process is not achieved in a uniform matter, the through-thickness anisotropy of the GLARE laminate affects the matter in which Al1 and Al2 are each expanded. As the mandrel is pulled through the laminate, it first encounters and expands Al1. Due to the plasticity of Al1, this initial expansion is achieved through localized plastic deformation near the hole edge. As the mandrel travels further through the laminate, elastic expansion of the fibre layer further expands Al1 and begins to expand Al2 through shear. This shear driven expansion results in more uniform expansion of the aluminum layers and increases the radius of the yield zone as described above. Once the mandrel reaches Al2, this layer has been nearly fully expanded through shear stresses from the fibre layer, and does not receive the same localized plastic deformation near the hole edge as does Al1. The shear dominated expansion of Al2 results in a larger yield zone but generates smaller residual compressive tangential stresses near the hole edge (Figure 7) due to the lower degree of plastic deformation in this region compared to Al1.

The influence of in-plane anisotropy of material properties on the residual tangential stress distribution in GLARE is shown in Figure 8. Near symmetry of the results about $\theta = 45^\circ$ indicates that the residual stresses are more strongly dependant on the overall fibre layer (the $0^\circ$ and $90^\circ$ unidirectional cross-ply layer) rather than the adjacent most unidirectional prepreg layer. The lower stiffness of the fibre layer along $\theta = 45^\circ$ results in a lesser degree of shear driven expansion and smaller plastic region than along the stiffer $\theta = 0^\circ$ and $90^\circ$ planes.
DISCUSSION

Non-Uniform Expansion

The FE simulations showed that different residual stress distributions occur in the two aluminum layers in GLARE (Figure 4b), which was attributed to the relative contribution to their expansion from direct contact with the mandrel and from shear stresses resulting from the elastic expansion of the fibre layers. This contribution is likely linked to the relative amount of expansion of adjacent layers during the cold expansion process, indicating a sensitivity to mandrel geometry. For instance, a more gradual taper in the mandrel would produce a larger expansion in the fibre layer before Al1 was fully expanded, increasing the degree of shear driven expansion of Al1 by the fibre layer. Likewise, a less gradual taper would decrease the influence of the fibre layer on the expansion of Al1.

Influence of Delamination

In the FE simulations not including the delamination model, the interface between the fibre and aluminum layers remains intact causing the aluminum layers to resist the elastic springback of the fibre layer. This resistance results in further contraction of the aluminum layers and increased residual compressive tangential stresses at the hole edge. Away from the free edge of the hole, large tensile radial stresses develop, reducing the compressive tangential stresses creating the clear hump visible in Figure 4b. Introduction of the delamination model allows unrestrained springback of the delaminated portion of the fibre layer, thus reducing the radial tensile stresses (and associated strain energy) within the aluminum layers. Similarly, a reduction in the compressive tangential stresses at the hole edge also occurs.

Although delamination damage is often regarded as undesirable, it is a critical element of the damage tolerant behaviour of GLARE. The formation and growth of a delamination between a cracked aluminum layer and adjacent fibre layer increases the length over which the fibre layer is elongated due to crack opening displacements. As a result, overstraining is prevented and the fibre layer remains intact. The growth of this delamination is balanced by a reduction in interface shear which also results from the reduction in local strain of the fibre layer.

Similarly, the formation of a delamination due to cold expansion is also beneficial; however in this case the driving force is the cold expansion displacement (or more accurately, the retained expansion of the aluminum layers) rather than crack opening displacement. Reductions in residual stresses in the fibre layer and interface shear stresses between the fibre and aluminum layers (Figure 7) will help preserve the integrity of the fibre layer and reduce the driving force for further delamination growth. Furthermore, the aluminum layers also benefit from the delamination through a reduction in residual tensile radial stress which could facilitate fatigue crack initiation (Figure 3b).
Limitations of Delamination Model

The results of this study need to be viewed within the limitations of the delamination model that was used. Delamination was modelled as an initiation event with predefined delamination sizes. As a result, the influences of delamination propagation and size are not present in the results. Furthermore, the tied and tiebreak interfaces used to model adhesion between the aluminum and prepreg layers were rigid contact interfaces. As a result, stress concentrations that would be reduced by limited plasticity of the adhesive layer were generated along the edge of the delamination. For this reason, results for the GLARE simulations were presented along the mid-plane of the aluminum layers away from the stress concentration at the adhesive interface.

CONCLUSIONS

A 3D finite element analysis has been carried out to investigate the effect of the fibre layer in a GLARE3-2/1-0.3 laminate on the residual stress distribution resulting from the split-sleeve cold expansion process. A simplified delamination model that initializes a predefined delamination based on a maximum shear stress criterion was incorporated into the model to investigate the influence of small delaminations observed in experimental work conducted by other researchers [11]. Parallel studies in 2024-T3 plate were completed, which provided good agreement with analytical models [3, 12] and finite element studies conducted by other researchers [8, 9, 16-19].

Based on the results of the finite element simulations, the following conclusions can be made:

1. Cold expansion of GLARE3-2/1-0.3 results in a larger region of plastic flow (characterized by the location of the peak tensile tangential stress) than in 2024-T3 plate. This is attributed to the apparent strain hardening behaviour produced by redistribution of load by the fibre layer under yielding conditions.

2. Expansion of the aluminum layers in GLARE occurs by two mechanisms: direct expansion through radial pressure between the aluminum layer and mandrel, and shear driven expansion resulting from the elastic expansion of the fibre layer.

3. Formation of a delamination during the cold expansion process permits unrestrained elastic springback of the delaminated portion of the fibre layer. The dissipation of strain energy in the fibre layer is complemented in the aluminum layers by a reduction in tensile radial stresses and compressive tangential stresses near the hole edge. The reduction in fibre layer residual stress serves to protect the integrity of the fibre layer under superimposed loading in a manner analogous to delamination resulting from the fibre bridging mechanism.

Overall, the mechanisms observed in this study reinforce the suitability of GLARE for the application of the cold expansion process. Further investigation into the effects of delaminations, however, is still required. Specifically, the effect of the delaminations on stress distributions under superimposed loads, and the influence of delamination size and variations in size through the laminate thickness are still unknown.
REFERENCES:


Figure 1: Schematic of FE model.
Figure 2: Finite element mesh for GLARE3-2/1-0.3 simulations.

Figure 3: Comparison of residual radial stress distributions: (a) monolithic 2024-T3, (b) GLARE3-2/1-0.3.
Figure 4: Comparison of residual tangential stress distributions: (a) monolithic 2024-T3, (b) GLARE3-2/1-0.3.

Figure 5: Comparison of 2024-T3 FE mid-plane results to analytical models.
Figure 6: Schematic of 2024-T3 and GLARE stress-strain curves.

Figure 7: Residual tangential stress variation through plate thickness at hole edge (along xz-plane for GLARE).
Figure 8: Comparison of GLARE aluminum layer mid-plane residual tangential stress distributions: (a) Case A – Al1, (b) Case A – Al2, (c) Case B – Al1, (d) Case B – Al2.
Table 1: Deformable plate mesh details.

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Table 2: Material properties [22, 23].

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