PULL-THROUGH FAILURE PREDICTION FOR COMPOSITE BOLTED JOINTS USING ONSET THEORY

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Abstract
This paper presents a failure analysis based on Onset Theory which has been implemented in the MSC.Marc finite element program and applied to predict the pull-through failure of bolted joints in unidirectional carbon fibre composite laminates. Failure prediction is coupled with a progressive failure analysis to predict the growth of matrix cracking and delamination. It has been shown that Onset Theory can reasonably predict the initiation of pull-through failure including all failure mechanisms although improved material data is for future studies. Failure progression was also well captured but was limited by the intrinsic difficulties of using simple damage mechanics to model discrete damage phenomena.

1 Introduction
Composite laminates are highly susceptible to the localised failure induced by geometric discontinuities and concentrated loads, even more so than metallic structures. Consequently, bolted joints in composite structures play a critical role in overall structural performance. The importance of bolted joints has led many authors to investigate failure of bolted joints both experimentally and numerically. The majority of these studies have considered only in-plane failure modes, such as bearing, shear-out and net-tension.

Transverse loading induced in fasteners is generally avoided because composite joints are very weak in this direction. Failures due to pull-through or pull-out loads are dominated by through-thickness laminate failure mechanisms such as transverse shear cracking and delamination. These mechanisms are controlled by the composite resin and as a result the critical failure loads are generally an order of magnitude lower than the in-plane failure modes [1, 2]. Despite this vulnerability, pull-through failure of composite joints has not been given much attention in the scientific literature because it has generally been considered that transverse joint loads can be minimised by smart joint design.

Current design trends toward thin skinned post-buckling structures have invigorated interest in fastener pull-out. Under post-buckling conditions, bolted joints must carry significant tensile loads. It has also been shown that structures subjected to impact loads exhibit critical pull-through loads in fasteners [3].

To minimise the requirement for costly experimental test programs and accelerate the design phase for composite structures, it is critical that validated numerical models of composite joint pull-through failure are developed. This paper presents a full 3D modelling approach for composite joints. Failure is predicted using Onset Theory and a progressive failure algorithm is used to model the progression of damage within the joint.

2 Summary of Experimental Results

Banbury and Kelly [1, 4] have conducted the most comprehensive study of fastener pull-through failure available in the open literature. Other experimental and numerical studies have been conducted by the Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) in conjunction with the German Aerospace Centre (DLR) [2, 3, 5-8]. These tests span a decade of research and predate the ASTM standard for pull-through loading of composite bolted joints, ASTM D 7332 [9], although very similar test fixtures were used. A schematic representation of the pull-through test fixtures is shown in Figure 1, highlighting the two major variants used in the literature.

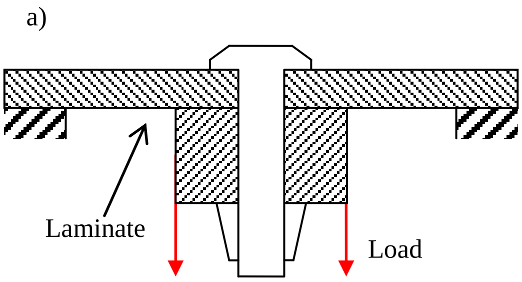

Figure 1. Pull-through test fixture schematic view showing a) simply supported edges and b) clamped edges

2.1 Failure Load

A typical load-deflection curve for a pull-through specimen is shown in Figure 2. The specimen response is linear (except for rig slack), followed by a sharp load drop in which matrix damage spreads throughout the specimen. After the initial load drop, the specimen maintains load carrying capacity up until a second failure point, which is not shown below. The specimen results presented in Figure 2 are for a T650/F584 UD tape specimen of 2.4mm nominal thickness and layup $[0,90,+45,-45]_{2s}$.

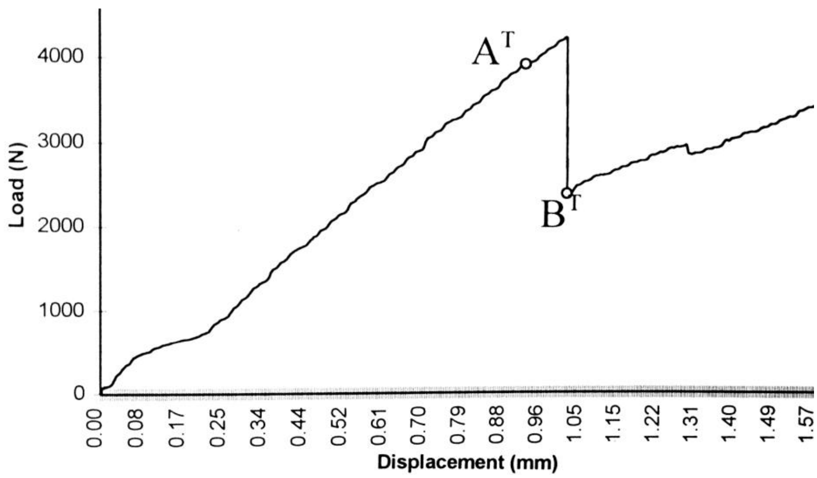

Figure 2. Load-deflection curve for thick unidirectional tape specimen [10]

2.2 Failure Modes

When loaded to a load prior to the large load drop, specimens did not exhibit internal damage for an indentation of the top surface at the edge of the bolt hole and some tensile matrix failure in the lower most +-45 plies [10]. After initial failure, significant internal damage was observed, characterised by through thickness shear cracking and radiating delaminations, as shown in Figure 3. The left of each image is toward the bolt hole and the dashed line in represents the radius of the bolt head from central axis of the specimen.

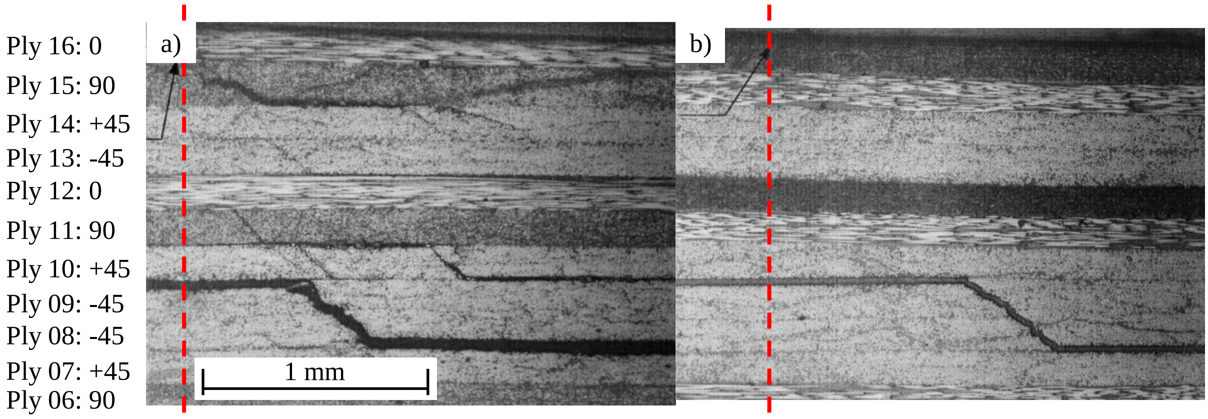

Figure 3. Micrograph of specimen loaded to point B (see Figure 2) showing sections a) parallel to 0° plane and b) parallel to 90° plane [10]

3 Onset Theory

Onset Theory, also known as Strain Invariant Failure Theory (SIFT), was first proposed by Gosse and Christensen [11] and a closely related companion paper by Hart-Smith [12]. The key hypothesis of Onset Theory is that failure of composite materials at the micro-mechanical level can only occur via a small set of constituent failure mechanisms. For the composite matrix there are only two failure mechanisms; failure due to volume change (*dilatation*) and failure due to dilation-free angle change (*distortion*). Mechanistically, dilatation failure corresponds to crazing and micro-cavitation while distortion failure corresponds to shear-yielding. Fibre failure can be controlled by any preferred mechanism, however investigations by Hart-Smith [12] and Buchanan et al. [13] suggest compatible fibre failure mechanisms. This paper will only be concerned with matrix failure.

3.1 Invariants

Matrix failure is governed by two strain invariant measures. The first invariant corresponds to dilatation of a unit cell and is given by the first strain invariant, J_1,

$$\begin{aligned} J_1 &= \varepsilon_x + \varepsilon_y + \varepsilon_z \\ &= \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \\ \varepsilon_{dil} &= J_1 \end{aligned} \qquad \ldots(1)$$

where ε_{dil} is the dilatational strain invariant, $\varepsilon_{x\text{-}z}$ are the strains in any orthogonal coordinate system and $\varepsilon_{1\text{-}3}$ are the principal strains.

The second invariant corresponds to dilatation-free distortion of a unit cell and is given by the square-root of the modified second strain invariant, J_2',

$$J_2' = \frac{1}{6}\left[\left(\varepsilon_x-\varepsilon_y\right)^2+\left(\varepsilon_y-\varepsilon_z\right)^2+\left(\varepsilon_z-\varepsilon_x\right)^2\right]+\frac{1}{4}\left(\gamma_{xy}{}^2+\gamma_{yz}{}^2+\gamma_{zx}{}^2\right)$$
$$= \frac{1}{6}\left[\left(\varepsilon_1-\varepsilon_2\right)^2+\left(\varepsilon_2-\varepsilon_3\right)^2+\left(\varepsilon_3-\varepsilon_1\right)^2\right] \quad \ldots(2)$$
$$\varepsilon_{dis} = \sqrt{J_2'}$$

where ε_{dis} is the distortional strain invariant.

Two corresponding critical strain invariants are defined as material properties. Failure occurs when either of the two invariants reaches the critical value. A failure index, F, is defined as,

$$F = \max\left(\frac{\varepsilon_{dil}}{\varepsilon_{dilcr}}, \frac{\varepsilon_{dis}}{\varepsilon_{discr}}\right) = 1 \quad \ldots(3)$$

3.2 Micromechanical Enhancement

Onset Theory only describes constituent level failure mechanisms. There is currently no computationally feasible way to accurately determine the constituent strain state for a given global strain state for a realistic heterogeneous composite structure.

To approximate the strain state in a heterogeneous composite material, a micromechanical modelling approach is adopted, known as *Micromechanical Enhancement* (MME). MME involves modelling representative unit cells including the fibre and matrix material as separate phases and constructing a relationship between the macroscopically applied strains and the microscopic strains in the constituents. A detailed description of this technique can be found in Buchanan et al. [13]. The MME technique yields two matrices which modify the homogeneous global strain tensor to approximate the heterogeneous local strain tensor at a range of points within the representative unit cell,

$$\hat{\boldsymbol{\varepsilon}}^k = \mathbf{M}^k\boldsymbol{\varepsilon} + \mathbf{A}^k\Delta T \quad \ldots(4)$$

where; $\hat{\boldsymbol{\varepsilon}}$ is the elastic strain tensor defined at a location, k, within the representative unit cell, **M** is the micromechanical enhancement matrix, ε is the elastic homogeneous strain state applied to the unit cell, **A** is the thermal enhancement matrix and ΔT is the temperature difference between the matrix strain-free temperature and the test temperature.

This MME approach requires that a free thermal contraction analysis is conducted prior to the mechanical simulation in order to determine the residual strains that are present due to thermal expansion mismatch between the plies of the laminate.

4 Model Generation

A model was generated to simulate the pull-through failure of a unidirectional tape specimen from Banbury [1, 10], discussed in §2. The simulation was conducted using MSC.Marc with user defined failure subroutines. Two planes of symmetry were utilised to reduce run-time, although the laminate was not truly symmetric due to the presence of the ±45 plies. Penalty based contact was used to simulate the structural interactions between components.

The model utilised 8-node 3D solid elements as shown in Figure 4. A total of 32 elements were utilised through the thickness of the 16-ply part. Reduced integration elements were used for regions of the mesh with large aspect ratios that resulted from the fine through-thickness mesh on the laminate part.

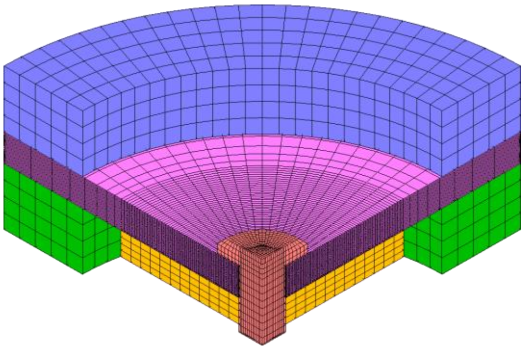

Figure 4. Bolted joint assembly

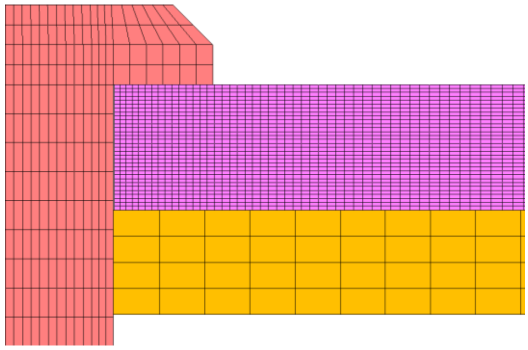

Figure 5. Detailed mesh cross-section (0° plane)

All metallic structure including the bolt, bushing and grips were modelled using linear elastic isotropic material properties as no yielding was expected. The laminate was modelled using linear elastic orthotropic properties with both thermal expansion and damage effects included. The elastic material properties for T650-F584 were taken from [14]. The critical strain invariants for this material were not measured directly as no test data was available. Instead, they were estimated from similar material data for Cycom970. A progressive failure algorithm was used in Marc to reduce the stiffness of elements that reached a failure index, F, of 1. The progressive failure algorithm was highly simplified for this initial research and simply reduced all stiffness terms to 1% of their pristine values immediately after failure was predicted.

The simulation consisted of two load steps. An initial pre-step was used to model the initial thermal condition simulating the temperature difference between curing and the test temperature. During this pre-step, an *overclosure* constraint linkage was also used to apply a pre-displacement to the bolt to simulate the tightening torque. The experiment was simulated with a second step, in which a displacement controlled load was applied to the specimen grips while the bolt bushing was held fixed. A total displacement of 1.2 mm was applied to the part quasi-statically.

5 Results

The model was compared with the results presented in Banbury [10]. The predicted failure load is shown below in Figure 6. A small offset to the experimental displacement has been added to remove the effect of slack in the experimental rig.

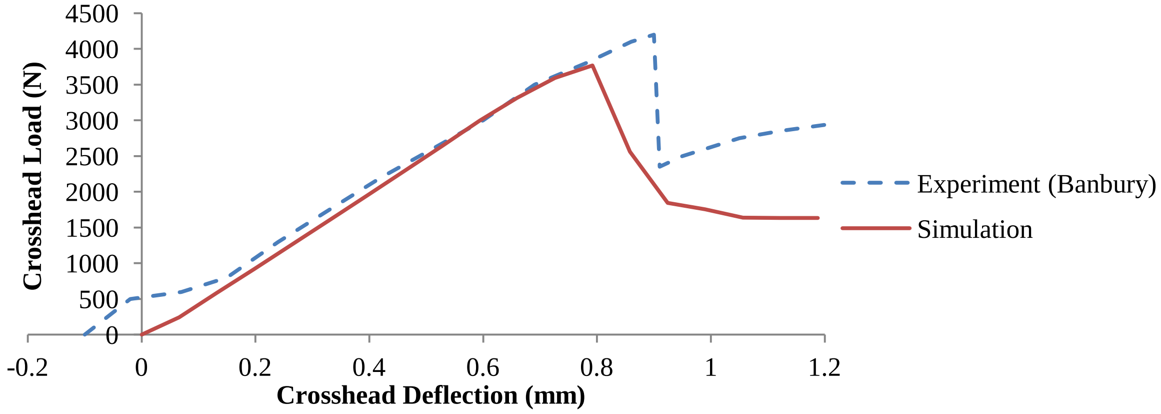

Figure 6. Predicted load-deflection curve compared with experimental result

Damage progression was predicted in the specimen using the progressive failure algorithm. The damage prior to initial failure is shown in Figure 7. Damage was predicted at the edge of the whole and in the lower +-45° plies, which agrees extremely well with the description given by Banbury.

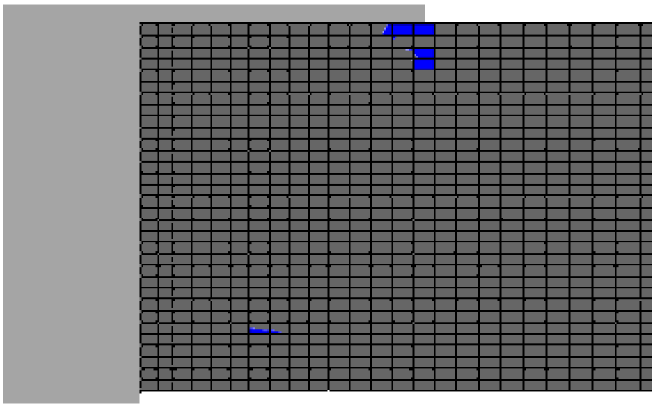

Figure 7. Damage regions (dark blue) predicted at the 0° plane prior to initial failure

The damage prediction after the initial failure relied both on the failure criteria and also the damage progression algorithm. The predicted damage on the is compared with the Banbury experimental micrographs in Figure 8. External failure at the edge of the bolt head and internal delamination and shear cracking was well predicted, except for a major crack in the central -45° plies which was not observed at the 0° plane. Closer inspection revealed that the central crack and delamination did initiate in the expected location but did not propagate to the surface of the model, as shown in Figure 9.

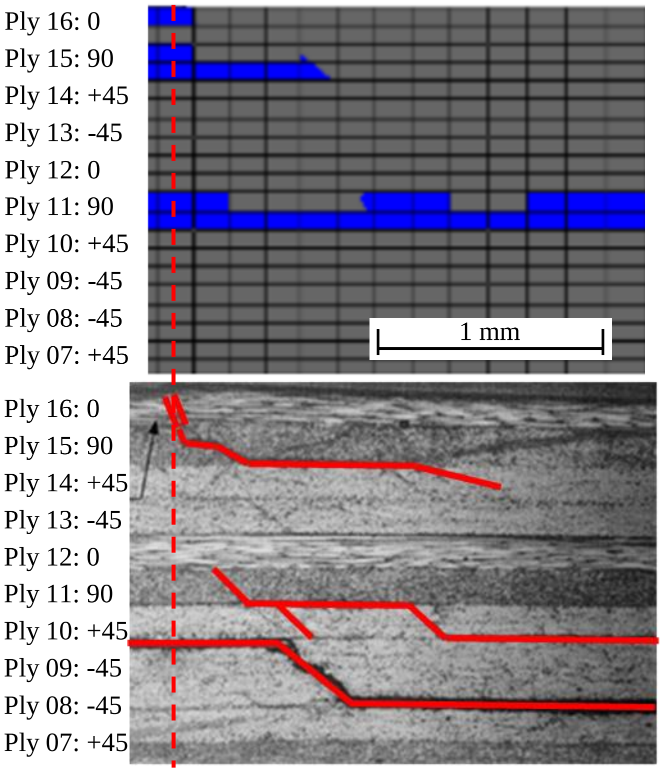

Figure 8. Damage regions (dark blue) predicted at the 0° plane after initial failure

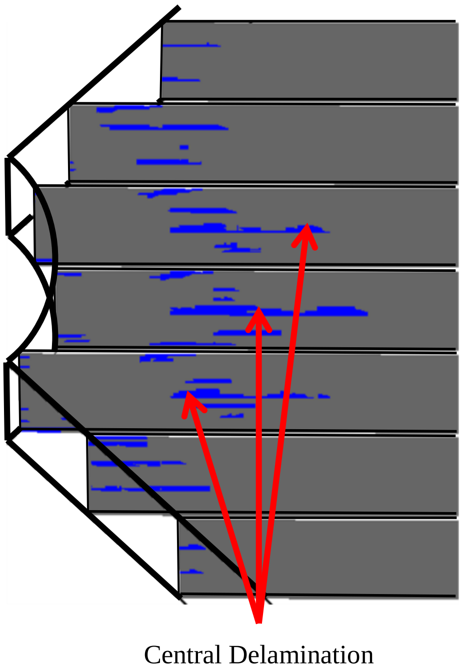

Figure 9. Damage regions predicted after initial failure showing internal central delamination after initiation in the -45° ply

6 Discussion and Conclusion

Prediction of transverse matrix failures and delamination is one of the most challenging problems faced when predicting failure of complex composite structures such as bolted joints. It has been shown in this and other research that Onset Theory is an excellent tool for predicting matrix failures in composite laminates.

This research presents initial attempts to apply Onset Theory in conjunction with a progressive damage problem. Experimental comparison for this research was challenging. Onset Theory requires material characterisation that is not provided by traditionally reported material data sheets, including thermal expansion properties of the composite and constituents. Many assumptions were made about the material and constituent behaviour based on different sources found in literature. Despite the challenges, comparison with experimental results has shown that the simulation methodology has tremendous potential. The failure load of the part was slightly under-predicted but the damage initiation sites and failure progression were very well predicted. Further research is still needed, especially in the areas of material characterisation and damage progression algorithms.

7 Future Direction

7.1 Further Pull-through Testing with Unidirectional Composite Material

There are a lack of pull-through experimental results for joints made from unidirectional composite material. Consequently the failure mechanisms are not as well understood as for fabrics and there is limited ability to conduct validation of simulations across large data sets. A parametric study of pull-through failure in unidirectional composite laminates will be conducted to expand this important area of knowledge. The modelling approach used in this paper can then be directly applied to a larger sample of experimental results.

7.2 Extension of Onset Theory to Fabrics

Much of the experimental work conducted into the failure of bolted joints, especially the pull-through failure, has been using fabric composite laminates. Fabric composites cannot readily be analysed using constituent based failure theories because the meso-architecture of the fabric is not accounted for. Extension to fabric architectures will greatly expand the range of applicable problems for Onset Theory. A current study is underway to extend the MME approach discussed in §3.2 to include the effect of the fabric architecture. Fabric meso-models, as illustrated in Figure 10, will be used to determine the strain enhancement due to the fabric structure.

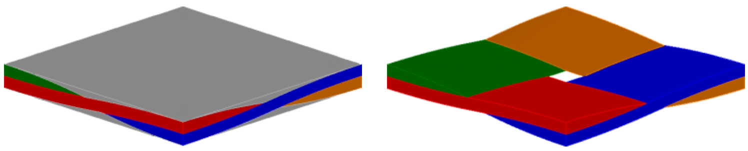

Figure 10. Mesomechanical model for plain-weave fabric composite

The strain tensor within the fabric, $\hat{\boldsymbol{\varepsilon}}$, at a location, l, inside the mesomechanical model and at a location, k, inside the micromechanical model is then given by

$$\hat{\boldsymbol{\varepsilon}}^{k,l} = \mathbf{N}^l \mathbf{M}^k \boldsymbol{\varepsilon} + \mathbf{B}^l \mathbf{A}^k \Delta T \qquad \ldots(5)$$

where **N** is the mesomechanical enhancement matrix, **M** is the micromechanical enhancement matrix, ε is the homogeneous strain state applied to the unit cell, **B** is the meso- thermal enhancement matrix, **A** is the micro- thermal enhancement matrix and ΔT is the temperature difference between the matrix strain-free temperature and the test temperature.

7.3 Improving the Progressive Failure Algorithm

The progressive damage algorithm used in this paper was very limited. Work is currently underway to develop algorithms based on continuum damage mechanics that use the dilatational and distortional strain invariants as strain measures to degrade only matrix dominated stiffness terms. Fibre failure will also be included.

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