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THE EFFECT OF THE THROUGH-THE-THICKNESS COMPRESSIVE STRESS ON MODE II INTERLAMINAR FRACTURE TOUGHNESS

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ABSTRACT

The effect of through-the-thickness compressive stress on the mode II interlaminar fracture toughness is investigated experimentally and replicated numerically. The modified Transverse Crack Tensile specimen recently proposed by the authors is used, together with an experimental device designed to apply a constant transverse compressive stress on the surface of the specimen.

Experiments are conducted using IM7/8552 specimens for different compressive stresses, ranging from 0 to 100 MPa, covering all the practical applications commonly encountered in the aeronautical industry (e.g., tightened filled holes or bolted joints).

It is shown that the mode II interlaminar fracture toughness increases with the applied compressive through-the-thickness stress. Finally, experiments are replicated using appropriate numerical models based on cohesive elements that take into account frictional effects. A good agreement between numerical predictions and experiments is found.

1 INTRODUCTION

Filled holes and bolted joints are well known examples of subcomponents where the applied compressive stress (due to the clamping of the bolt) has a beneficial effect on the strength of the subcomponent. The applied clamping pressure reduces the propagation of the cracks that develop under the washer and provides a through-the-thickness restraint (offered by the fastener) that is reflected in an increase of the subcomponent strength and in a change of the failure mode.

Accurate and physically-based strength prediction methods for filled holes or bolted joints consist of Finite Element-based numerical models where appropriate progressive damage models are implemented. The use of analytical and semi-analytical methods is limited to the case of two-dimensional stress field (e.g., open holes, pinned joints) and is inhibited here by the complex triaxiality of the stresses in the neighbourhood of the hole. Even though the point- or the average-stress method could be still applied, the determination of the "characteristic distance" would be ineffective and complicated by the fact that it would now not only depend on the geometry, material and stacking sequence but also on the value of the applied clamp, washer geometry, and hole clearance.

Progressive damage models for intralaminar and interlaminar damage need the definition of both physically-based failure criteria and appropriate softening laws to model the damage onset and the damage evolution, respectively. While the effect of stress triaxiality on the damage onset can be taken into account using one of the numerous three-dimensional failure criteria available, the effect of the triaxiality on the definition of the softening law (i.e on the fracture toughness) is not yet completely understood. It is reasonable to suppose that transverse compressive stresses influence the intra- and the interlaminar values of the fracture toughness, but how? Here a partial answer to this question is provided for the mode II interlaminar fracture toughness.

There are experimental evidences that the mode II interlaminar fracture toughness, increases with the applied compressive stress. It should be pointed out that the mode II interlaminar fracture toughness is the key parameter when modelling, in a Finite Element model, the onset and propagation of the interlaminar cracks in bolted joints or filled hole specimens (with tightening). The presence of the bolt, in fact, constrains the reciprocal movement of the plies; if a delamination originates from the border of the hole it can only propagate at pure mode II, because the opening mode (mode I) is restrained by the presence of the bolt. Neglecting the effect of the compressive stress yields a conservative prediction of the strength of the subcomponent and, consequently, its over-dimensioning that will be reflected in an increase of both its weight and cost.

Despite its importance, the dependence of the mode II interlaminar fracture toughness on the through-the-thickness compressive stresses was experimentally investigated, in the best knowledge of

the authors, only in few works [1,2] using essentially the ENF specimen in a pressurized environment. It should be noted that the previous experimental attempts present some severe drawbacks: (i) the hydrostatic pressure does not represent a realistic stress state; (ii) the ENF is not a suitable specimen for applying through the thickness compression (while the TCT is). Since not much data is available, and, moreover, there is no established experimental procedure to measure the influence of the through-the-thickness compressive stress on the mode II interlaminar fracture toughness, the main objective of this paper is to propose, and to validate, a simple and effective test method to quantify this influence.

2 EXPERIMENTS

In a previous investigation [3] it was demonstrated that the Transverse Crack Tensile test (TCT test) response depends on the specimen geometry, local defects and asymmetries, leading to four non simultaneous cracks propagations that invalidate the analytical model and, thus, the test itself. In addition to this, crack propagation cannot be assumed to be of pure mode II. To overcome the intrinsic drawbacks of this TCT test, the author proposed a simple but effective solution: the modified TCT sample has the same geometry as a TCT, but it contains four precracks, created using release films during the manufacturing of the laminate, that allow to move the crack tips far from the region around the central transverse notch.

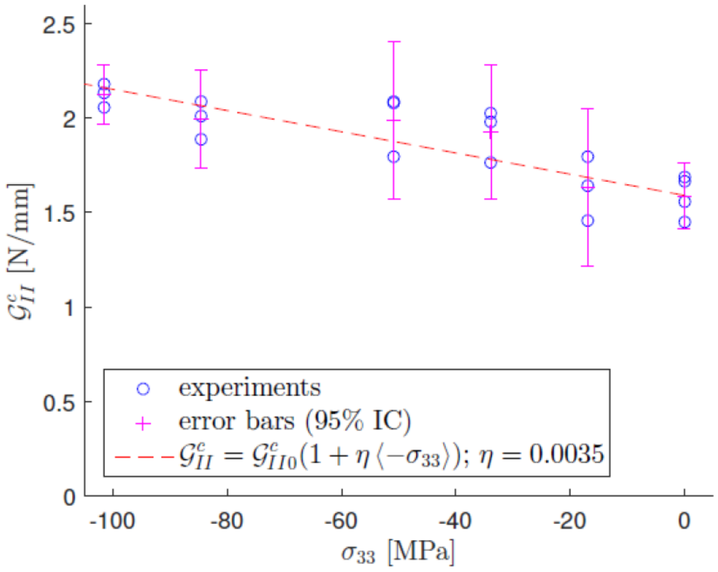


Figure 1: Mode II interlaminar fracture toughness vs. through-the-thickness stress.

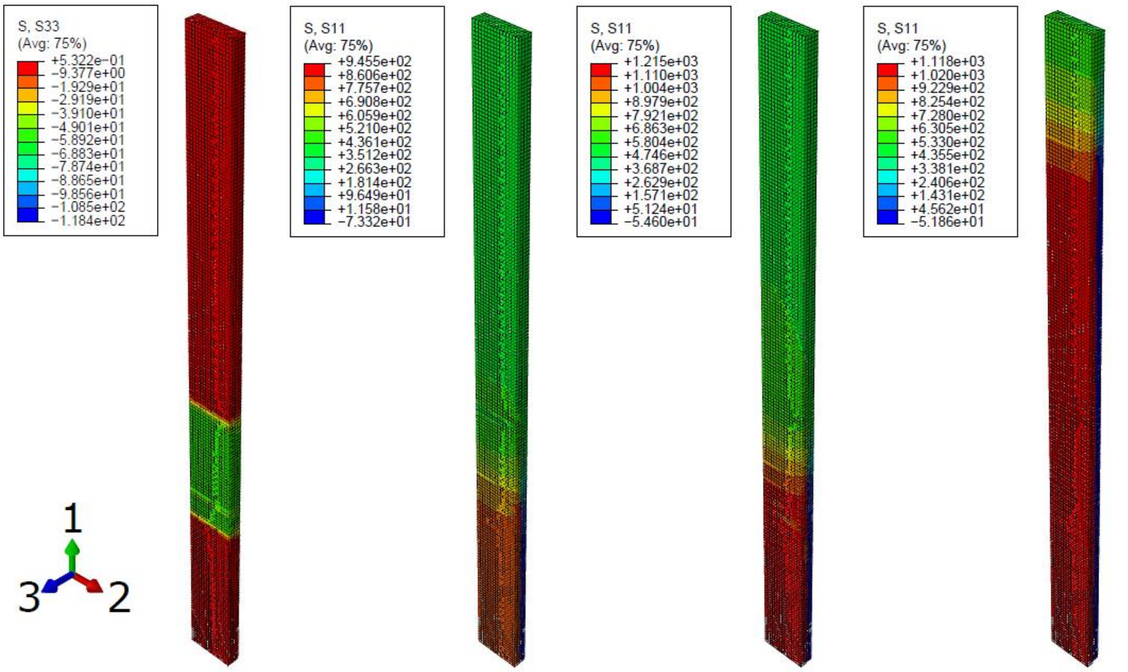
Taking into account those results, the modified specimen is used here to measure the interlaminar fracture toughness as a function of the applied compressive stress. The geometry of the modified TCT is perfectly suitable for the present study, where a compressive stress is superimposed to the stress field due to the load, P, applied to the specimen. Compressive stresses are applied using an appropriate device designed to apply a constant and uniform compressive stress, during the test. Experiments are conducted on IM7/8552 specimens for different compressive stresses, ranging from 0 to 100 MPa, covering all the practical applications commonly encountered in the aeronautical industry (e.g., tightened filled holes or bolted joints). A good fit is obtained assuming that the mode II interlaminar fracture toughness increases linearly with the applied compressive through-the-thickness stress as reported in Figure 1.

3 NUMERICAL MODELLING

With the aim of reproducing the experiments, a Finite Element (FE) model of the specimen was implemented in Abaqus.

To reduce the computational effort, only one eighth of the specimen was modelled. The plies were meshed using C3D8R brick elements with a dimension of 0.5X0.5X0.5 mm^3, while COH3D8 finite-thickness cohesive elements were used for the interface. A thickness of 0.01 mm was used for the interface elements as recommended in the Abaqus Documentation.

The simulation was performed in two steps. In the first, a transverse pressure was applied to the specimen, trying to reproduce the effect of the lateral grips at the beginning of the test. In the second step this pressure is maintained and a longitudinal displacement is applied to the specimen; this will cause (i) the reaching of damage onset in the cohesive elements (see Figure 2b); (ii) the reaching of the peak load (see Figure 2c); (iii) suddenly followed by an unstable crack propagation (see Figure 2d).



(a) before loading (b) At damage onset (c) At peak load (d) At unstable crack propagation

Figure 2: Numerical results.

The dependence of the mode II fracture properties on the transverse stress is introduced via a VUMAT (user defined material) subroutine.

Alfano and Sacco [9] proposed an approach to combine interface damage with friction, using the damage evolution law proposed by Mi et al. [8] and a simple Coulomb friction law. Since any cohesive zone model and friction law can be used, the Coulomb friction law combined with the cohesive zone model proposed by Turon et al. [6,7] is used here, similar to the implementation by Van de Meer and Sluys [10].

The methodology proposed by Alfano and Sacco, briefly reported below, assumes that a Representative Elementary Area (REA) of the interface can be divided into an undamaged and a damaged part. The relative displacement Δ experienced in both parts is equal. The interface traction can be divided into an undamaged component, τ_u, and a damaged component, τ_d.

The homogenized interface traction over the REA, τ, is given by:

$$\tau=(1\text{-d})\ \tau_u+d\ \tau_d \tag{1}$$

where the term =(1-d) τ_u comes from the cohesive law and the term τ_d represents friction and contact on the damaged surface.

The undamaged component follows a linear elastic law:

$$\tau_u=K\ \Delta \tag{1}$$

where K is the diagonal stiffness matrix. Following Turon it reads:

$$\text{K=diag}\{\text{K}_{sh},\text{K}_{sh},\text{K}_n\} \tag{1}$$

The damaged component of the interface traction is computed after division of the relative displacement into an elastic part, Δ_{de} and an inelastic part Δ_{di}. The traction in the damaged part τ_d, is related to $\Delta_{de} = \Delta - \Delta_{di}$ as:

$$\text{T}_d=K\ \Delta_{di}\text{-<-}\ \Delta_{dn} > \tag{1}$$

In Figure 3 the stress vs. displacement curves are shown for different values of the applied transverse stress (in the range [0 -110] MPa with pressure increments of 10 MPa).

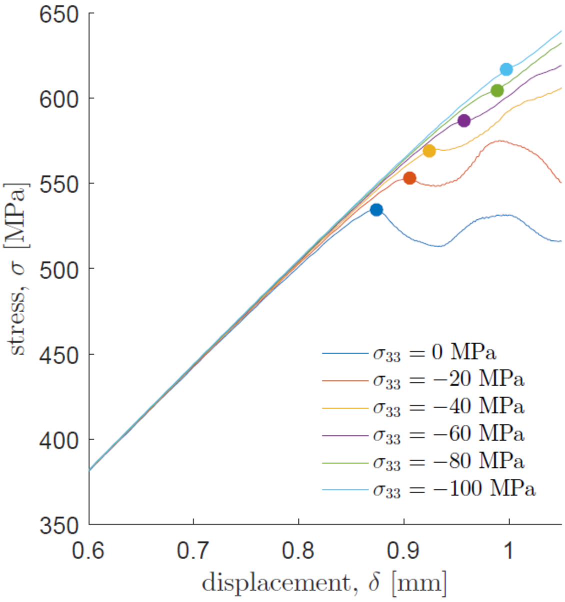


Figure 3: Peak stress as a function of the transverse stress.

The typical linear displacement up to the point corresponding to damage onset, followed by a non linear relation up to the point at which the fracture process zone is completely developed, is observed for all the cases simulated. The VUMAT represents the rise of the load, due to the friction between the fracture surfaces, that occurs after crack propagation has happened. This effect is substantial when high transversal stresses are applied and is highly representative of the physics of the problem observed during the experiments.

Finally, Figure 4 shows the comparison between the predicted values of the peak stresses and the experimental results (experimental values and Confidence Interval at 95%). A good agreement between the predictions and the experimental results is observed.

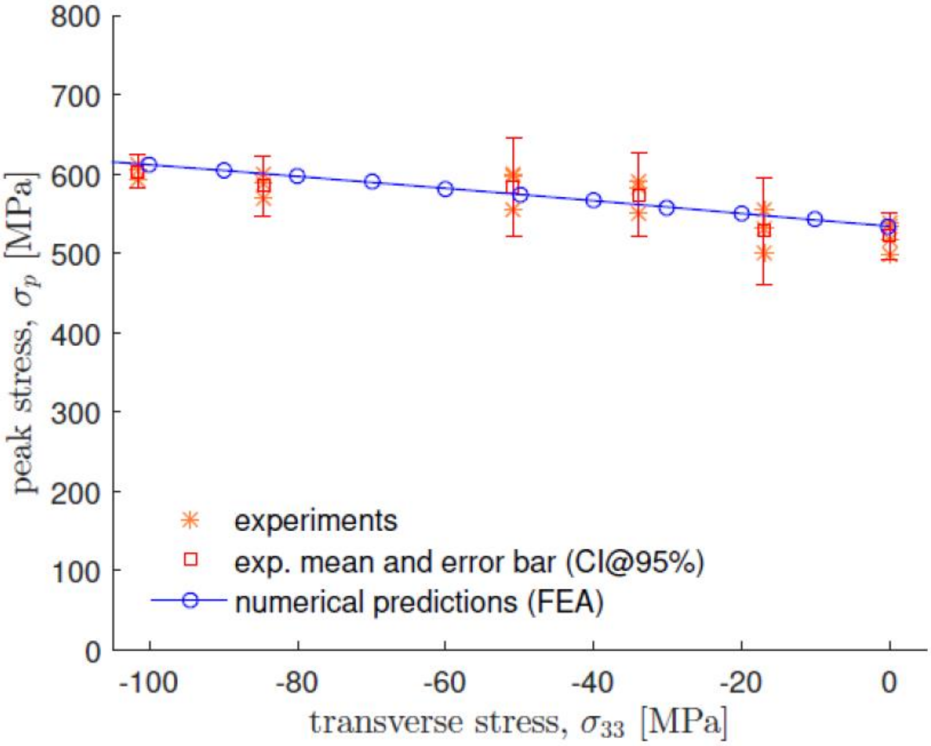


Figure 4: Peak stress as a function of the transverse stress.

4 CONCLUSIONS

A modified TCT specimen recently proposed by the authors was used to measure the dependence of the mode II interlaminar fracture toughness on the through-the-thickness compressive stress. A simple and effective experimental device has been designed to apply the through-the-thickness stress and to avoid loss of pressure due to Poisson's effects. The main conclusions may be summarised as follows:

i) The tests conducted between 0 and 100 MPa showed that the mode II interlaminar fracture toughness increases linearly with the applied through-the-thickness pressure.

ii) For the IM7/8552 material system the empirical parameter that describes this linear dependence, η, is found to be equal to $\eta = 0.0035 \text{MPa}^{-1}$$.

iii) The proposed numerical approach is able to take into account the increasing of the peak load necessary to propagate the crack in the modified TCT.

The experimental results of this work will be used to validate and/or feed progressive damage models for the interlaminar crack propagation (i.e. cohesive elements formulation). It is envisaged that their use will be relevant when modelling the behaviour of bolted joints or filled holes with tightening.

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