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SIMULATION OF FAILURE IN SINGLE-LAP-JOINTS ASSEMBLIES OF CARBON FIBRE TAPES

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Abstract. Failure of single-lap joints of carbon fibre tapes manufactured by thermoforming was characterized, with special regard of the effect of forming pressure and overlap geometry on the ultimate tensile strength. Introducing forming pressure dependent strength parameters, the impact of the structural alterations induced by the forming stage on the assemblies strength is modelled.

1 INTRODUCTION

Automated tape placement process consists of placing thin unidirectional (UD) tapes on a ground structure in order to tailor its mechanical properties to a high degree. This process appears as an attractive alternative when fully exploitation of UD materials and high production rates are desired. In the particular case of forming of thermoplastic composite laminates, the tapes can be welded onto the ground structure directly during the forming operation, reducing significantly the cycle time.

The exact location and orientation of the tapes is defined on the basis of the external loads applied under service conditions. A wide variety of algorithms can be used [1-5] to determine the optimal fibre orientation. However, this design strategy is reliable as long as the cohesion along the reinforcement path is assured. This means that not only tape-to-laminate joints, but also tape-to-tape joints are relevant. Contrarily to the case of the former ones, strength of tape-to-tape joints with special regard of the manufacturing conditions and the overlap geometry has been scarcely addressed. The work of the authors [6] is among the few contributions. In [6] single-lap joints (SLJ) of carbon fibre (CF) tape made by thermoforming were prepared with different overlap geometries (rectangular and rounded) and employing a variety of forming pressures (3 to 100bar). The assemblies were then tested in tension.

The aim of the present work is to provide a further insight on the failure of the SLJ assemblies and its correlation with the observed defects introduced by the forming operation. Special focus on the failure modelling and parameter identification aspects is placed. The optimization procedure employed to calibrate the criterion is delineated and its implementation aspects are discussed. To conclude, model predictions and experiments are compared and functional forms are proposed to describe the strength parameters variation with the manufacturing pressure.

2 FORMING PRESSURE EFFECTS ON ASSEMBLY STRENGTH

The combination of temperature and pressure during the forming stage, avoids the formation of a weaker interface, and the result is instead a sort of continuum material of higher thickness on the overlap area. Consequently, the typical SLJ shear failure is not observed for UD tapes and fibre fracture occurs repeatedly at the end of the overlap as presented in [6].

The dependence of the ultimate tensile strength (UTS) on the forming pressure is reproduced in Figure 1. It can be seen that only for pressures between 3 and 10bar the observed strength is approximately the same independently of the considered geometry and pressure. The strength of rectangular assemblies practically does not vary with respect of the longitudinal strength of UD tapes, for any forming pressure. On the contrary, the strength of rounded assemblies is significantly lower for high pressures.

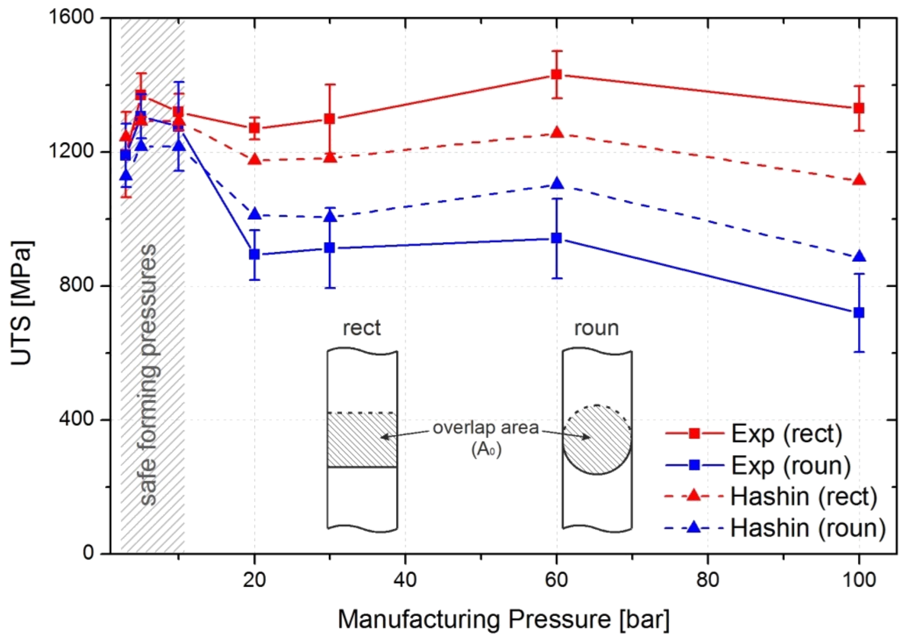

Figure 1: UTS dependence on forming pressure of the SLJs. The UTS is defined as the maximum tensile load divided by the cross-sectional area of one adherend. Hashin predictions are also shown.

Although the failure does not happen on the overlap area, the strength does depend on the overlap geometry. This fact is explained by the structural alteration introduced by the forming stage. During this stage, in-plane compression stresses are normally generated due to tape-tool friction [7]. As a result, fibre waviness (in-plane and out-of-plane) is observed in pressed assemblies. However, due to the different overlap geometry, fibre rotation was identified as additional defect in the case of rounded geometries (Figure 2). The observations here made are in concordance with the results presented by Hallander et al. [7], who identified global fibre angle variations, local fibre angle variations and spreading/tightening of fibre tow as the main effects introduced while forming of laminates due to the action of in-plane compression.

Fibre waviness has been associated with reduction of the strength of composites laminates [8]. However, fibre straightening takes place under tensile loading [9] and eliminates fibre waviness, not affecting the assembly strength in the case of rectangular overlaps. On the other hand, off-axis strength differential effects are well known [10]. Fibre rotation introduced in rounded geometries becomes significant at high manufacturing pressures and fibres are not completely re-aligned under tensile. Consequently, the strength of the SLJ is reduced by local off-axis load.

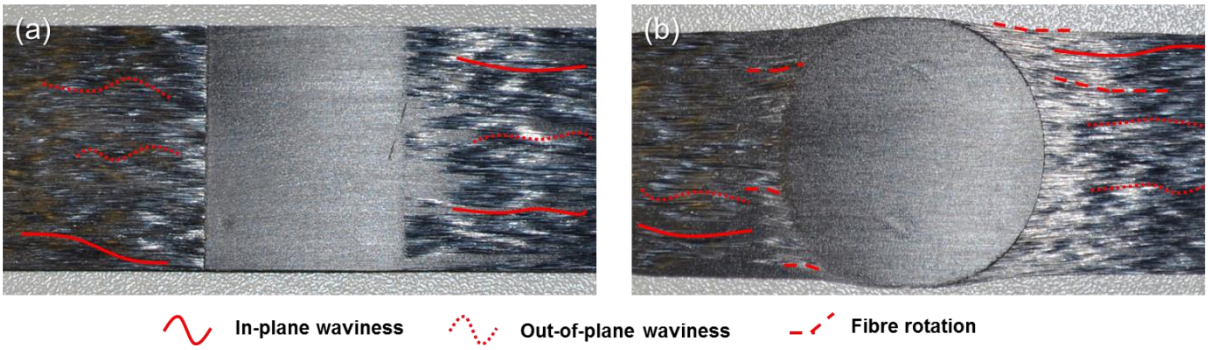

Figure 2: Observed defects after the joining process.

3 FAILURE MODELLING

3.1 Failure criterion dependence on forming pressure

Since brittle failure was observed on the adherends, Hashin's failure criterion [11] was used. This criterion, besides its simplicity, has the additional advantage of distinguishing between failures modes. In this work only the tension modes will be analysed, since they are the most relevant for the tape placement applications and the study of compression modes is not possible without a ground material.

The following assumptions were made in the formulation of the forming-pressure dependent failure criterion:

- The strength behaviour depends only on the manufacturing pressure. Temperature-time effects are here disregarded as all SLJ were manufactured varying only the pressure.
- The strength in the fibre direction (X^T) is not affected by the pressing stage, indistinctly of the employed pressure.
- Although local fibre rotations were identified after the forming, local orientations are disregarded and the SLJ assembly is considered as if the fibres were initially perfectly aligned with the loading direction.

Considering the above mentioned assumptions and adopting general power-law forms for the shear and matrix strengths (S^L and Y^T, respectively) the extended Hashin's criterion has the following form:

Fibre tension $$\left[\frac{\sigma_{11}}{X^T(p)}\right]^2 + \left[\frac{\tau_{12}}{S^L(p)}\right]^2 = 1 \quad (1)$$

Matrix tension $$\left[\frac{\sigma_{22}}{Y^T(p)}\right]^2 + \left[\frac{\tau_{12}}{S^L(p)}\right]^2 = 1 \quad (2)$$

with

$$X^T(p) = S_{11} \quad (3)$$

$$Y^T(p) = A\,p^n \quad (4)$$

$$S^L(p) = B\,p^m \quad (5)$$

where S_{11} is the strength of the tape material in the fibre direction, p is the manufacturing pressure and A, B, n and m are fitting parameters.

3.2 Parameter identification

The strength parameters were obtained for each forming pressure considering both geometries simultaneously. An overall cost function G was defined, which was additively decomposed in G_{rect} in regard to rectangular joint and G_{roun} concerning the rounded joint. The cost function was defined only in terms of ultimate load (P) and is only dependent on the failure variable x, an array containing the strength parameters (X^T, Y^T and S^L). The above mentioned definitions are expressed in the Equations (6) and (7).

$$G_{rect} = \left(\overline{P_{rect}^{exp}} - P_{rect}^{FE}(x)\right)^2 \quad (6)$$

$$G_{roun} = \left(\overline{P_{roun}^{exp}} - P_{roun}^{FE}(x)\right)^2 \quad (7)$$

The calibration of the failure parameters can be then given by the following optimization problem:

$$min\big(G_{rect}(x), G_{roun}(x)\big) = min\big(G_{rect}(x) + G_{roun}(x)\big) \quad (8)$$

For solving the above explained problem an iterative procedure was programmed using Matlab, where both joint cases are iteratively simulated in Abaqus and compared with the experimental data. The parameters are updated using a trust-region algorithm [12] until one of the convergence conditions is met. The procedure is schematised in Figure 3.

The tensile tests were simulated using quadratic shell elements (S8R) to model the adherends. Cohesive contact formulation was used on the overlap area to model the elastic interface behaviour. Due to the iterative nature of the calibration process and since each iteration requires the simulation up to fracture of both geometries, short computation wall times are almost mandatory. In this way, coarser meshes and high damage stabilization are preferred. A sensitivity analysis was previously carried out to determine the optimal combination that allows fast computations and 10% repeatability.

Once the strength parameters where obtained for each manufacturing pressure, data sets were adjusted with the functional forms of Equations (3-5) using least square difference method.

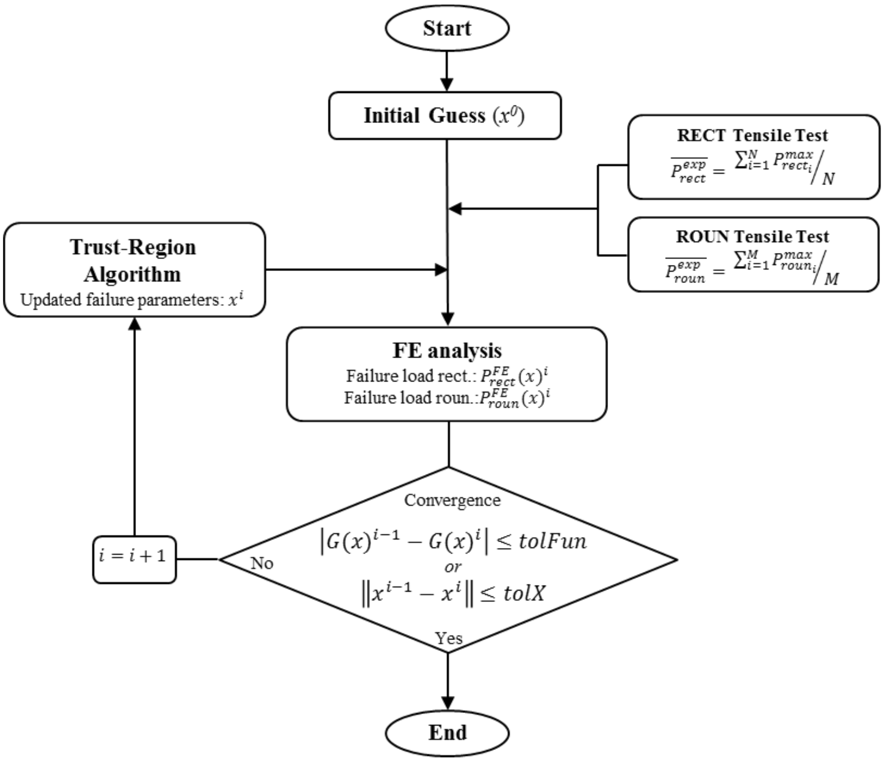

Figure 3: Scheme of the calibration process.

4 RESULTS

The results of the model predictions are shown in dotted lines in Figure 1. The modified criterion describes well the observed behaviour up to 30bar, capturing the transition from the safe forming pressures to the geometry-dependent pressure range. Nevertheless, as the reduction of the strength by off-axis load is modelled here by a reduction of S^L, predictions for higher forming pressures (60 and 100bar), where the orientation is severely modified after forming, are not adequate. The strength parameters obtained by the optimization routine are shown Figure 4. The fit using the proposed functions is also included. The power-law forms provide a good enough description of Y^T and S^{TL} in the whole pressure range.

Hashin failure envelopes can be constructed based on the results of Figure 4. Figure 5 presents the dependence of the failure envelope on the forming pressure under tension-shear states. It must be noted that the envelopes narrow in the shear-axis as the manufacture pressure increases. A summary of the extended failure criterion and the obtained parameters are presented in Table 1.

Table 1: Summary of failure criterion.

$X^T(p) = S_{11}$	S_{11} [MPa]	1375
$Y^T(p) = A\,p^n$	A [MPa/bar^n]	16,54
	n [-]	0,141
$S^L(p) = B\,p^m$	B [MPa/bar^m]	110,8
	m [-]	0,416

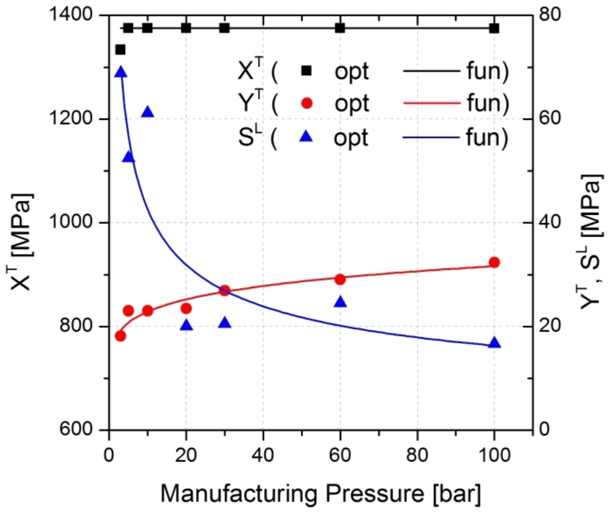

Figure 4: Strength parameters for different forming pressures. Output of the optimization routine (opt) and correlation of proposed functions (fun) are shown.

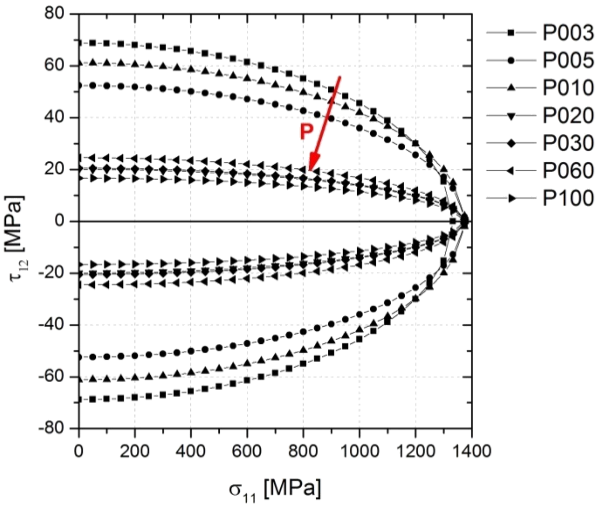

Figure 5: Failure envelope variation with forming pressure. Tension-shear plane.

5 CONCLUSIONS

- Fibre waviness is introduced during forming in rectangular overlaps while not only waviness but also global fibre rotation are introduced in the rounded case.
- This rotation seems not to be reversed under tensile loading beyond a limit manufacturing pressure, reducing notoriously the UTS of the SLJ assembly. Therefore, rounded assemblies should be avoided for forming pressures exceeding 10 bars.
- Using the presented approach, the failure of SLJ assemblies could be successfully modelled up to forming pressures of 30 bars. The current approach has the advantage of disregarding the local fibre rotation, which makes it more versatile to support technology development as only ultimate loads are required as input data.
- For higher forming pressures, failure modelling should consider the fibre rotation produced during forming to obtain more accurate results. However, higher forming pressures should be avoided since the integrity of tapes is then severely compromised due to excessive fibre spreading.

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