Tensile strength of multi-angle composite laminate scarf joints with FEM

R Roy 1, J-H Kweon 2* and Y Nam 2*

1Research Center for Aircraft Core Technology and ReCAPT, Gyeongsang National University, Jinju, Gyeongsangnam-do, South Korea
2School of Aerospace and Software Engineering, Gyeongsang National University, Jinju, Gyeongsangnam-do, South Korea

* Corresponding authors e-mail: jhkweon@gnu.ac.kr, ywnam@gnu.ac.kr

Abstract. This study focuses on the tensile strength of angle-ply composite laminate scarf joints and corresponding finite element modelling (FEM) methods. Tensile tests are performed at 25°C and 75°C on scarf joint specimens with unidirectional laminate stacking sequences. The joint tensile strength result values at 75°C represent around 86% of those obtained at 25°C. The tensile test is simulated with finite element modelling including cohesive elements to model failure. The joint adhesive film is represented either with only full thickness cohesive elements, or with thin or zero-thickness cohesive elements combined with solid elements having a plastic adhesive material model. Simulations results show that in the case of a unidirectional laminate, the adhesive modelling method had less than 1% effect on the simulated tensile failure strength. For quasi-isotropic laminates with a given ply angle count but of varying ply order, the simulated tensile failure strength varies up to 15%, which confirms tendencies reported in the literature.

1. Introduction
Advanced fiber reinforced polymer composite materials are now being used for large integrated structural parts. In addition to providing high specific strength and stiffness, good environmental and fatigue durability, these materials can reduce parts count and the number of joints. If these large parts get damaged, it can be advantageous economically and schedule-wise to apply a local repair. If the damage is such that reinforcing fibers are broken, the removal of the damaged material and the application of a repair patch is a common repair solution [1]. There is indeed no applicable method to repair broken fibers in-situ, for in the case of carbon fibers each individual fiber has a diameter in the order of 10 μm. The repair patch can be constructed with new material of the same type as the original structure, however there will be an interface between the patch and the remaining sound original structure (hereafter named parent structure). It is common to use an adhesive between the patch and parent structure, and this adhesive can be tailored to achieve desired properties. Structural epoxy adhesives are frequently used, and their toughness can be several times higher than the epoxy matrix of the parent composite. The composite patch can be either pre-cured separately then bonded in place with a film or paste adhesive (secondary bonding), or if prepreg composite and adhesive film is used, the whole patch can be cured in-place in one step (co-bonding) [2]. Great attention is devoted to the configuration of the repair area on the parent structure following the removal of damaged material and
in preparation to patch installation. Two key aspects are the geometry of the repair area and its surface preparation. An angled scarfed joint configuration has proven to be advantageous in smoothly transferring loads better than a lap joint which generally develop stress concentrations in the bond line. The scarf angle is a key parameter, usually defined with the ratio of scarf length to parent laminate thickness (scarf ratio). A scarf ratio of 30:1 has been considered favorable in the literature [3], but a ratio of 50:1 and even up to 100:1 has also been recommended [4]. The repair area surface preparation for bonding is usually done either by sanding, grit blasting, plasma or chemical treatment, and it must ensure that bonding surfaces are free of contaminants [5,6,7]. One goal of surface preparation is also to increase the surface free energy or wettability of the bonding surfaces, which is favorable to strong adhesion, and can be evaluated by measuring the contact angle of liquids. The surface energy is understood to come from the contribution of two main sources: Van der Waals molecular interactions and polar molecular group interactions [8].

Considerations for the geometry of the repair area and its surface preparation can be applicable, with varying parameters, to polymer composite laminates or a more isotropic material like aluminum. A notable difference with angle-ply composite laminates, which can be composed of several unidirectional laminas with different orientations, is the discontinuous nature of their stress state at the ply level. For example, under a given tensile loading, an angle-ply laminate essentially has a constant strain level for every ply at a given point, but the stress level in each ply varies greatly. Locally stiff plies which fibers are aligned with the loading direction are the site of higher stress level than plies with fibers at an angle with the loading direction. In the context of a patch repair or a joint, this stress discontinuity will be transferred at the bond line interface. It has been shown that stress concentrations occur in the bond line of scarf joints in front of plies with fiber orientation aligned with the loading direction (i.e., zero degree plies) [9]. The objective of this study is to evaluate the effect of multi-angle composite laminate adherends on the tensile strength of scarf joints. Laboratory tensile tests were performed on composite laminate scarf joint specimens and material properties were deducted. Finite element modeling (FEM) simulation of laminate scarf joints was carried out with solid 3D and cohesive elements. Cohesive elements were used to model the adhesive layer failure in order to capture the effect of ply angles on the joint tensile strength.

2. Experiments

2.1. Specimen fabrication

One set of laminate scarf joint specimens were prepared for tensile testing. The base composite laminate used is a carbon/epoxy unidirectional lamina prepreg (USN-125B, SK Chemicals, South Korea), with 33% resin weight fraction (approximately 57.5% resin volume fraction) and a nominal ply thickness of 0.12 mm. Laminates with a scarf angle ratio of 30:1 were produced by first laying-up plies at a staggered distance and then sanding this stepped surface flat after curing with #100 grit sandpaper backed by a flat metal bar. The stacking sequence used was [0°]_{24} in order to produce a quasi-uniform shear stress distribution in the bond line and thus better characterize the adhesive strength. A structural epoxy adhesive film with nominal areal weight of 147 g/m² (FM-300-2M, Solvay, United States), giving a thickness of 0.12 mm, was used to secondary bond two identical scarfed laminates and form a single scarf joint. A section of this film was cut to a length exceeding the scarf surface by about 2 mm at each ends to ensure a complete coverage. Prior to its installation, the adhesive film section was placed in an environmental chamber at 40°C and below 10% relative humidity for 30 minutes to favor elimination of humidity content in the adhesive. The carbon/epoxy prepreg stack was first cured in a vacuum bag and autoclave oven with a two-step cycle at 80°C/120°C and a pressure of 5 atmospheres. Subsequently, the two cured laminates were secondary bonding also in a vacuum bag and autoclave with a single step cure cycle at 120°C and 5 atmosphere pressure. Glass fiber composite tab panels of 55 mm length with one end chamfered at 45° were then installed on each ends and sides of the secondary bonded scarf joint panel (four tab panels in total). These tab panels were adhered with a room temperature cure epoxy paste and with the assembly enclosed in a
vacuum bag. Specimens were cut to dimensions following ASTM standard D3039 [10], with a width of 25 mm and a total length of 310 mm. The distance between tab ends was 200 mm, with the scarf joint being centered at mid distance. The average laminate thickness was 2.89 mm, giving a nominal scarf length of 86.4 mm for a scarf ratio of 30:1 (or a scarf angle ($\theta$) of 1.91°). The average thickness at the scarf center location was 3.01 mm, which reflects the added thickness of the adhesive film and reveals a slight eccentricity in the joint tensile axis.

2.2. Tensile testing
Scarf joint tensile testing was performed with an Instron 5582 universal testing machine equipped with an environmental chamber (Illinois Tool Works Inc., Norwood, USA). The tensile load was applied at a displacement controlled rate of 2 mm/min. The load and machine extension were recorded at a rate of 10 Hz. Twelve specimens were tested until failure: six at room temperature (25°C), and six at 75°C (figure 1). All specimen failed abruptly through the scarf joint bond line.

![Figure 1. Tensile test scarf joint specimens and test set-up.](image)

3. Test results
The ultimate tensile strength ($F_t$) of each specimen was calculated by dividing the failure load by the specimen’s laminate cross section area (outside of the scarf area). The adhesive bond line average shear ($\tau_{av}$) and peel ($\sigma_{av}$) stresses at failure were also calculated with equations (1-2), where $\theta$ is the scarf angle. One specimen in each test group was rejected from results compilation due to their apparent premature failure. The section tensile stress versus displacement curves are presented in figure 2. The average test results and corresponding coefficient of variation (CV) are listed in table 1. The failure mode of all specimens was predominantly cohesive failure with some less important areas having the appearance of adhesive failure (see [11] for terminology). The areal percentage of each failure mode was determined by visual inspection and is reported in table 2 for the room temperature tests. The areas of adhesive failure were associated with zones where a bare composite surface is visible; these zones were more predominant at the scarf ends (figure 3). Among the room temperature specimens, there was no clear influence of the failure modes on tensile strength (e.g., specimens 2,3,4 versus specimens 1,5). The elevated temperature specimen 6 had a larger adhesive failure area (29%) which coincided with its relatively lower strength result. The presence of adhesive failure areas can indicate that the tested joints could still benefit from improved surface treatment prior to bonding.

$$\tau_{av} = 0.5\cdot F_t \cdot \sin(2\theta)$$  \hspace{1cm} (1)

$$\sigma_{av} = F_t \cdot \sin^2(\theta)$$  \hspace{1cm} (2)
Figure 2. Scarf joint specimen section tensile stress versus displacement curves.

Table 1. Scarf joint specimen tensile test results.

| Test condition                     | Section tensile strength [MPa] | Average bond line shear stress at failure [MPa] | Average bond line peel stress at failure [MPa] |
|------------------------------------|---------------------------------|-----------------------------------------------|-----------------------------------------------|
| Room temperature (25°C)            | 1092.7 (CV=7.53%)              | 36.38 (CV=7.98%)                               | 1.21 (CV=8.47%)                               |
| Elevated temperature (75°C)        | 939.2 (CV=4.32%)               | 31.57 (CV=4.08%)                               | 1.06 (CV=3.90%)                               |

Table 2. Scarf joint specimen failure mode areal percentages.

| Failure mode | Sp#1 | Sp#2 | Sp#3 | Sp#4 | Sp#5 | Sp#6 | Sp#7 | Sp#8 | Sp#9 | Sp#10 |
|--------------|------|------|------|------|------|------|------|------|------|-------|
| Cohesive     | 80%  | 85%  | 80%  | 82%  | 81%  | 71%  | 78%  | 77%  | 81%  | 77%   |
| Adhesive     | 20%  | 15%  | 20%  | 18%  | 19%  | 29%  | 22%  | 23%  | 19%  | 23%   |

Figure 3. Failure surface of room temperature specimens #3 and #5.

4. Simulation

4.1. FEM model

A 3D solid half-width symmetric finite element model of the tensile test was built with the software Abaqus/CAE 6.14-2 (Dassault Systèmes SE, Vélizy-Villacoublay, France). Cohesive elements were used for the adhesive material in order to simulate failure. The inputted material mechanical properties
were obtained from manufacturer published data sheets and the literature [12,13,14,15,16] (table 3). The adhesive plastic shear properties [16] were entered in the software as converted tensile properties by Von Mises yield criterion theory. The general mesh size was 1 mm, except for one element thick per ply and cohesive elements of 0.12 mm thickness and length [17].

| USN-125B Elastic solid | $E_1$ [MPa] | $E_2$ [MPa] | $E_3$ [MPa] | $G_{12}$ [MPa] | $G_{13}$ [MPa] | $G_{23}$ [MPa] | $v_{12}$ | $v_{13}$ | $v_{23}$ |
|------------------------|-------------|-------------|-------------|----------------|----------------|----------------|---------|---------|---------|
| 131000                 | 7600        | 7600        | 5340        | 5340           | 3060           | 0.31            | 0.31    | 0.47    |
| FM-300-2M Cohesive (thk = 0.12 mm) | $K_I$ [N/mm$^3$] | $K_{II}$ [N/mm$^3$] | $K_{III}$ [N/mm$^3$] | $T_I$ [MPa] | $T_{II}$ [MPa] | $T_{III}$ [MPa] | $G_{IC}$ [N/mm$^3$] | $G_{IIIC}$ [N/mm$^3$] | $G_{IIIIC}$ [N/mm$^3$] |
| 22083                  | 996         | 996         | 50          | 38.5           | 38.5           | 1.0             | 2.45    | 2.45    |
| FM-300-2M Elastic solid | $E$ [MPa] | $G$ [MPa] | $\nu$ | 2650          | 907.5          | 0.4             |
| FM-300-2M Plastic solid | $\sigma_1$ [MPa] | $\epsilon_{p1}$ | $\sigma_2$ [MPa] | $\epsilon_{p2}$ | $\sigma_3$ [MPa] | $\epsilon_{p3}$ | $\sigma_4$ [MPa] | $\epsilon_{p4}$ |
| 19.01                  | 0.0000      | 56.37       | 0.0460      | 66.68          | 0.3138         | 67.72           | 0.3405  |

4.2. Simulation results
We estimated that in this experiment the specimen tensile strength is predominantly governed by the shear strength of the adhesive material. Therefore, in order to calibrate the FEM model, we adjusted by trial and error the adhesive shear damage initiation criteria ($T_{II}, T_{III}$). We obtained FEM match to room temperature test results ($F_t = 1093$ MPa) with $T_{II}$ and $T_{III}$ values of 38.5 MPa and a numerical viscous regularization parameter ($\eta$) of $1.7 \times 10^{-4}$ applied to the cohesive elements. The damage initiation value of 38.5 MPa is coherent with the average bond line shear stress at failure test result of 36.38 MPa: in this case of homogeneous material scarf joint, the bond line shear stress distribution is expected to be smooth and parabolic, with its peak value slightly higher than its average. In addition to modeling the adhesive layer entirely with cohesive elements, two alternative configurations were evaluated: thinner cohesive elements ($t = 0.02$ mm) sandwiched between plastic material solid elements (total of three elements thick), or zero-thickness cohesive elements sandwiched between pairs of plastic material solid elements (total of five elements thick) (figure 4). The simulated scarf joint tensile strength varied little between these three configurations (table 4). Further simulations were performed with the calibrated half-width model, but by implementing various quasi-isotropic laminate stacking sequence angles. The simulated tensile strength varied for the different stacking sequences used (figure 5). The 676 MPa tensile strength result of the [0/-45/90/45]$_3S$ stacking sequence model confirm that zero-degree plies placed on the laminate surfaces cause stress peaks in the adhesive at the joint edges which reduce tensile strength [9].

Figure 4. Adhesive layer FEM configurations.
Table 4. FEM simulation tensile strength results.

| Adhesive layer model type                                                                 | $F_t$ [MPa] |
|------------------------------------------------------------------------------------------|-------------|
| Cohesive elements only, half-width model (12.5 mm)                                        | 1093        |
| One cohesive element ($t = 0.02$ mm) between plastic material solid elements, 1 mm width model | 1100        |
| One zero-thickness element between pairs of plastic material solid elements, 1 mm width model | 1104        |

Figure 5. FEM simulation results for the tensile strength of angle-ply scarf joints.

5. Conclusion
In this study, the tensile strength of angle-ply composite laminate scarf joints was evaluated by experiment and FEM simulation. The test results showed predominant failure in the adhesive material. A FEM model with cohesive elements was calibrated to replicate the joint tensile strength test result. This model was then used to evaluate the effect of laminate stacking sequence. It was shown that through the stacking sequence effect on the bond line shear stress distribution, it was possible to capture the stacking sequence effect on scarf joint tensile strength. The different stacking sequences simulated captured tendencies observed in published literature.

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