The Effect of Ply Constraining on Transverse Ply Crack Formation in Laminated Composites

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ABSTRACT

A critical component for damage-based progressive failure analysis of laminated composites is the ability to properly capture the influence of ply constraining on crack formation. In this study a computational micro-mechanical model was developed to predict the in-situ constraining effect on 90°-ply crack initiation of [0/90/0] cross-ply laminates subjected to transverse tensile loading. The laminate representative volume element (RVE) comprised a full-thickness 90°-ply with a non-uniform spatial fiber distribution constrained between two homogenized 0°-plies. In all cases, periodic boundary conditions were assigned to the RVE. First, the 90°-ply stress states for three different fiber arrangements, *i.e.* square, hexagonal, and non-uniform, under the same mechanical loading condition were compared. The results revealed that RVEs with realistic fiber distributions produced notably higher local stresses in the 90°-ply when compared to RVEs with structured fiber arrangements, suggesting their necessity for predicting the initiation of local failure. Residual stresses in the matrix were also obtained by simulating the cooling down process after resin curing to properly address local stress states in the 90°-ply. Analysing the local peak stresses in the [0/90/0] laminate revealed the notable influence of adjacent 0°-plies on the constrained 90°-ply matrix phase stresses under simultaneous application of thermal and mechanical loads. Specifically, the local von Mises and hydrostatic stresses in the matrix were investigated to better understand the potential for initiation of matrix cracking in the transverse layer. The results suggest that the in-situ effect is a decisive factor for determining local matrix yielding and cavitation.

KEYWORDS: *Matrix Cracking, In-Situ Effect, Computational Micro-mechanics*

1 INTRODUCTION

Motivated by lightweighting efforts fiber-reinforced plastics (FRPs) have been extensively used in many industrial sectors including aerospace, automotive, energy, and marine. FRPs have outstanding strength- and stiffness-to-weight ratios, tailorable properties, and they are inherently damage tolerant. Nevertheless, the complexity of progressive failure processes in laminated composites, involving damage evolution at different length scales, still presents a challenge for researchers in spite of many years of studies (Kaddour et al., 2013). Damage evolution of mechanically loaded FRP laminates typically begins with the formation and, subsequently, multiplication of intralaminar transverse matrix cracks which is known as the sub-critical cracking stage. This stage is typically followed by a stage of critical crack growth that may include delamination and fiber breakage, ultimately leading to catastrophic failure.

Nevertheless, a notable degradation of the laminate properties occurs during the sub-critical cracking stage, which indicates the necessity of modelling progressive failure for applications where structural components are subjected to cyclic loads.

To address the effect of damage on the overall degradation of composite materials, micro- and macro-damage mechanics approaches were utilized in previous studies. Micro-damage mechanics (MIDM) primarily focuses on analysing damage at the crack formation level while macro-damage mechanics (MADM) investigates the effect of crack formation on the overall response of the composite material. Employing the MIDM approach, physical-based models such as shear lag (Garrett and Bailey, 1977), variational (Hashin, 1985), that of McCartney (McCartney, 1992), and crack opening displacement (COD)-based methods (Gudmundson and Östlund, 1992; Varna et al., 1999) were developed. Furthermore, Talreja (1985), among others, introduced MADM by utilizing the continuum damage mechanics concept for for fiber-reinforced composite materials to investigate the overall response of the material. This modelling approach was later extended to account for damage evolution in multidirectional laminates using a multiscale approach (Singh and Talreja, 2008), and more recently to account for general laminates lay-ups and multiaxial loading conditions (Montesano and Singh, 2015).

In general, these theories were developed based on simplifying assumptions without accounting for the local behaviour at the microscopic scale. Hence, many of these models did not accurately capture the so-called in-situ ply constraining effect, which is defined as the influence of the neighbouring constraining plies on the local stress states in a particular ply. This effect can significantly influence the stress state of the constrained layer as it was observed both experimentally (Saito et al., 2012) and numerically (Arteiro et al., 2014; Montesano and Singh, 2015). In this mechanism, the embedded transverse ply interestingly exploits the strength of the adjacent plies to postpone its failure in comparison with a single unidirectional ply. Since this constraining effect is often neglected or not properly accounted for by many damage mechanics models, the laminate strength is conservatively predicted. Utilizing linear elastic fracture mechanics (LEFM) some research groups (Camanho et al., 2006; Pinho et al., 2005) were able to develop physical-based models to encounter the influence of in-situ effect on matrix cracking. However, merely LEFM cannot predict the local nonlinear behaviour of the composite which can influence the constraining effect (Arteiro et al., 2014). Moreover, these studies reported the in-situ effect on ply failure in laminates (i.e., formation of a full transverse ply crack), while this influence may be seen during earlier stages of cracking by considering the local stress fields. This may otherwise provide a great deal of insight on the formation of transverse ply cracks.

During the past decades, the initiation of matrix cracking, *i.e.* yielding, cavitation, debonding, at the microscale, was extensively investigated by means of stress-based (Arteiro et al., 2014; Melro et al., 2013) and energy-based (Asp et al., 1996 a, b, c; Asp et al., 1995) approaches. Developing a stress-based model, Melro et al. (2013) proposed a pressure-dependent plasticity model to address local yielding in the polymer matrix of FRPs. Distinctly, Asp et al. (1995; 1996 a, b, c) proposed two different scenarios of failure for a fiber-reinforced matrix material: cavitation-induced brittle failure and yielding which respectively occur due to the critical state of dilatation and distortion energy density. Asp et al. (1995; 1996 a, b, c) suggested that these energy densities are functions of von Mises and hydrostatic stresses, respectively.

In this study, the influence of in-situ ply constraining effect on initiation of matrix cracking in cross-ply laminates was investigated by focusing on the local von Mises and hydrostatic stress states in the matrix. Developing a finite element (FE) model, the behaviour of a single 90°-ply was compared with that of the similar ply constrained between two homogenized 0°-plies. In the FE model, the non-uniform spatial fiber distribution in the transverse ply was generated using the algorithm proposed by Li et al. (2018). The significance of modelling the non-uniform fiber distribution was outlined by comparing the local stress states for different fiber arrangements, *i.e.* square and hexagonal. Also, the influence of thermal residual stress on the formation of ply cracks was investigated. The local stress states in the transverse ply were analysed in order to study the presence of the in-situ effect in the constrained layer.

2 COMPUTATIONAL MODEL

In the current work, a representative volume element (RVE) was generated to explicitly represent the fibers and matrix in the 90°-ply and the adjacent homogenized constraining layers. The proposed method by Li et al. (2018) based on a well-developed event-driven molecular dynamics (EDMD) simulator (Bannerman et al., 2011) was employed to randomly generate the non-uniform fiber distribution in the transverse ply. Previously, the capability of this method in generating statistically accurate RVEs was examined by Li et al. (2018). An important capability of this method is the creation of periodic geometry which becomes crucial in analysing local stress fields within the RVE. **Error! Reference source not found.** illustrates the schematic representation of the simulated 2D RVE. As it is indicated, the laminate plies have a constant 0.5 mm thickness which is captured in the RVE. Also, the RVE width of 0.5 mm is appropriately large to represent the realistic behaviour of the materials at higher scales. The corresponding geometrical and material properties of the reported glass fiber-reinforced plastic (GFRP) by Tong et al. (1997) were utilized, and the phase properties are reported in Table 1.

Within the commercial finite element (FE) code Abaqus®, CPE4R 4-node bilinear plain strain quadrilateral elements with reduced integration, were used to mesh the homogenized 0°-plies and the 90°-ply of the RVE. Nonetheless, some elements were set as CPE3 3-node linear plane strain triangles due to the non-uniform geometry of the transverse layer. Perfect bonding was assumed between two layers and at the fiber/matrix interfaces. The fiber volume fraction of the 0° and 90°-ply was set to $V_f = 62\%$ and the glass fiber diameter was $D_f = 20\mu m$. The glass fibers and matrix in the 90° lamina were modelled as a linear-elastic isotropic material. It worth noting that the property of the homogenized layer was obtained from the elastic properties of each constituent in Table 1 using strength of materials approaches. In this study, the generated RVEs were subjected to a $\varepsilon_x = 0.4\%$ transverse tension, which is large enough for the origination of the first full ply crack. To investigate the effect of the cooling down process exhibited during laminate fabrication on the matrix phase, a temperature drop of $\Delta T = -125^oC$ was applied to some of the FE models. One-dimensional periodic boundary conditions in the $x-$direction were applied to the vertical edges of the RVE by employing the Abaqus plug-in developed by Lejeunes (2011).

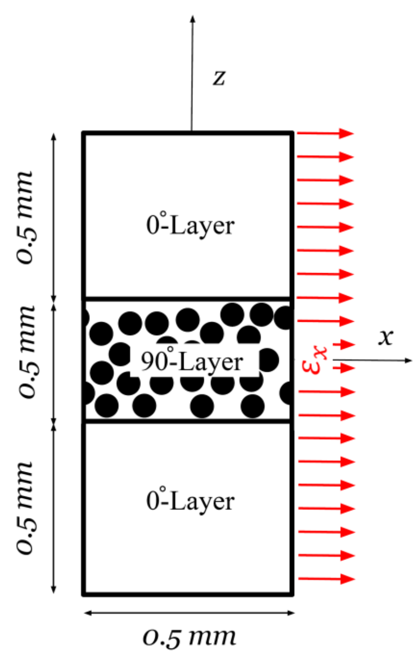

Figure 1: Schematic representation of the 2D periodic RVE under transverse tensile loading

Table 1 Properties of the GFRP composite constituent

	$E(GPa)$	ν_{12}	$V_f\,(\%)$	$\alpha\left(ppm/{}^{o}C\right)$	Fiber Diameter (μm)
Glass Fiber	72	0.21	62	5	20
Epikote 828/NMA/BDMA	3.35	0.35	38	46.5	-

3 RESULTS AND DISCUSSION

To obtain the proper size of the element for investigating the local stresses, a mesh sensitivity analysis was performed on a generated RVE of the 90°-ply without constraining layers subjected to a transverse strain only. **Error! Reference source not found.** shows the variation of volume averaged stresses in the matrix phase of the 90°-ply along the transverse direction with the element size. The volume averaged stress is generally defined as:

$$\sigma_{ij}^{avg} = \frac{\sum_{k=1}^{n} \sigma_{ij}^{k} A^{k}}{\sum_{k=1}^{n} A^{k}} \tag{1}$$

where n, σ_{ij}^{k}, and A^{k} respectively represent the total number of elements, stress components, and the area of the k^{th} element. The obtained results indicate that an average element size of $30\mu m$, *i.e.* 80000 elements, can lead to a satisfactory result.

Due to the difficulties in fabricating unidirectional FRP composites, fibers are non-uniformly distributed in the matrix phase which leads to variations in the local stress state and failure for distinct fiber dispersions. Therefore, an investigation was performed to analyse the peak local stress concentration factor (SCF) for different fiber arrangements, including hexagonal, square, and non-uniform distributions. Here, the SCF is defined as the ratio of the peak stress to the volume averaged stress along the transverse direction. In order to examine the consistency of the randomly generated non-uniform fiber distribution, 4

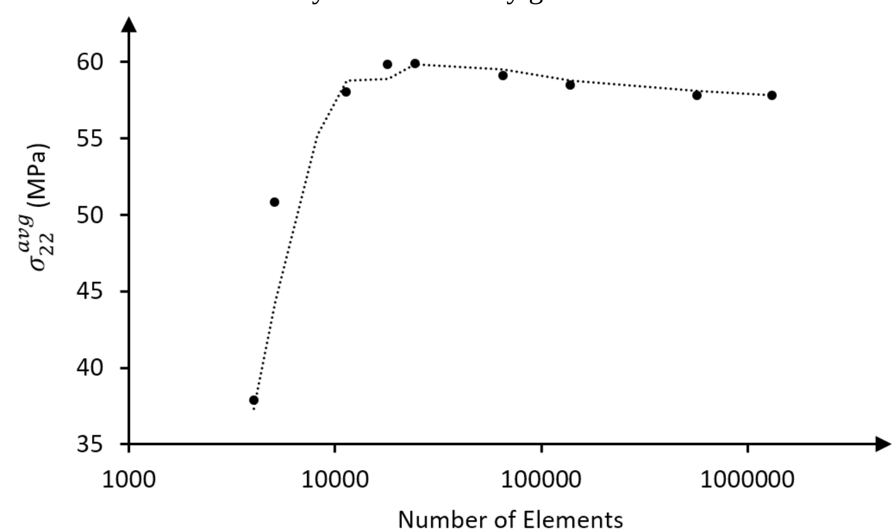

Figure 2: Variation of the volume averaged transverse stress of the matrix phase for an unconstrained 90°-ply RVE subjected to transverse loading

different RVE models were simulated. It worth noting that in all of the FE simulations a mesh sensitivity analysis was performed. Table 2 presents the volume averaged and local peak transverse matrix stresses for different fiber arrangements, where the $x-$direction is parallel to the fibers in the $0^{\circ}-$ply (see Figure 1). The peak von Mises stresses in the matrix phase are also included in Table 2. The results clearly indicate the distribution of fibers can play a significant role in the local peak stresses and thus the initiation of local failure. For example, the peak transverse matrix stress in RVE non-uniform distribution #2 was 2.7 times greater than the RVE with a square fiber array. It should be noted that the peak stresses reported in Table 2 are notable greater than the strength of the matrix, and are in part due to the linear elastic assumption used for matrix deformation. Moreover, the corresponding stress contours of this analysis showed the non-uniform distribution of fibers could change the potential path of crack as depicted by the locations of peak stresses in Figure 3. Thereby, using a non-uniform fiber distribution is necessary in order to properly predict damage evolution in unidirectional FRP composites.

Table 2 Volume averaged and local peak stress of the matrix phase in 90° ply RVEs without constraining layers subjected to $\varepsilon_x = 0.4\%$ transverse tension, for different fiber arrangements

	$\sigma_x^{avg}\,(MPa)$	$\sigma_{Mises}^{\max}\,(MPa)$	$\sigma_x^{\max}\,(MPa)$	SCF
Square Array	59.62	66.4	122.4	2.05
Hexagonal Array	50.96	64.98	95.2	1.87
Non-uniform Distribution #1	57.8	182.9	242.2	4.24
Non-uniform Distribution #2	56.57	242.2	330.9	5.85
Non-uniform Distribution #3	57.82	192.2	270.1	4.67
Non-uniform Distribution #4	51.56	239.8	262.4	5.09

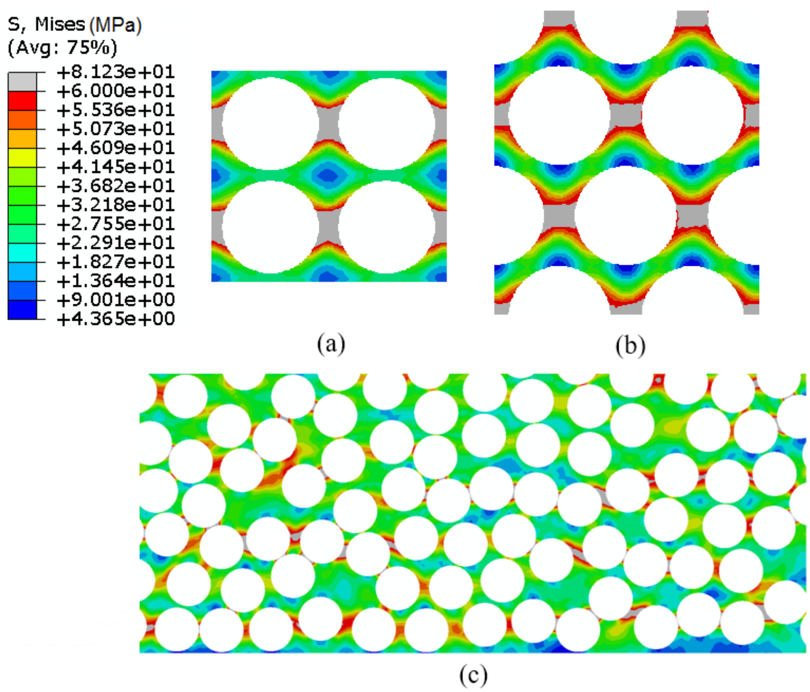

Figure 3: von Mises stress contours of the matrix in an unconstrained 90° ply with (a) square, (b) hexagonal, and (c) non-uniform fiber arrangement under transverse tensile loading.

During the process of producing FRP composite materials, parts are typically subjected to thermal loading during the cooling down stage which can induce residual stresses in the matrix due to the different thermal expansion coefficients of constituents. This issue is more pronounced when fabricating laminated composites due to the mismatch in ply-level thermal expansion coefficients along different orthotropic directions. To investigate the effect of this loading on the matrix phase, a $\Delta T = -125^{o}C$ was applied to the FE model. In this study, the $90^{\circ}-\text{ply}$ and $[0/90/0]$ laminate were compared in two scenarios (a) applying a mechanical load (b) applying a thermal load followed by a mechanical load ($\varepsilon_x = 0.4\%$). **Error! Reference source not found.** illustrates the von Mises stress contours in the matrix phase for the same region of the RVE for both lay-ups under combined thermal and mechanical loading. These results endorsed the existence of the constraining effect of the adjacent layers on the 90° ply, also known as the in-situ effect, which is evident by comparing the stress contours in Figures 4a and 4b. For instance, the von Mises stress for the constrained ply was 60.43 MPa at the indicated point in **Error! Reference source not found.**, while for the unconstrained ply the stress was 47.27 MPa. It is worth noting that dissimilar variations in the stress were observed in different locations of the matrix due to the non-uniform fiber dispersion as is clear in Figure 4.

To further assess the variation of stress state due to thermal loading, the peak and volume averaged stresses in the matrix phase were compared for RVEs subjected to only mechanical loading and combined thermal/mechanical loading. As presented in Table 3, the residual stresses in the matrix induced by thermal loading were found to considerably influence the total stress states after applying the mechanical load for both the constrained and unconstrained 90° plies. Furthermore, thermal loading was found to affect the location and magnitude of the local peak stresses, *i.e.* von Mises (σ_{Mises}) and hydrostatic (σ_m) (not shown). Additionally, it can be observed that the in-situ effect emerges in the transverse layer only after by considering application of the thermal load (see Table 3); this in-situ effect was not observed when only applying the mechanical load for the FRPs studied. These variations can substantially change the local failure mechanism, *i.e.* yielding or cavitation, the potential path of ply crack, and the required stress for failure initiation. Thus, it is essential to consider the residual stress caused by cooling down in

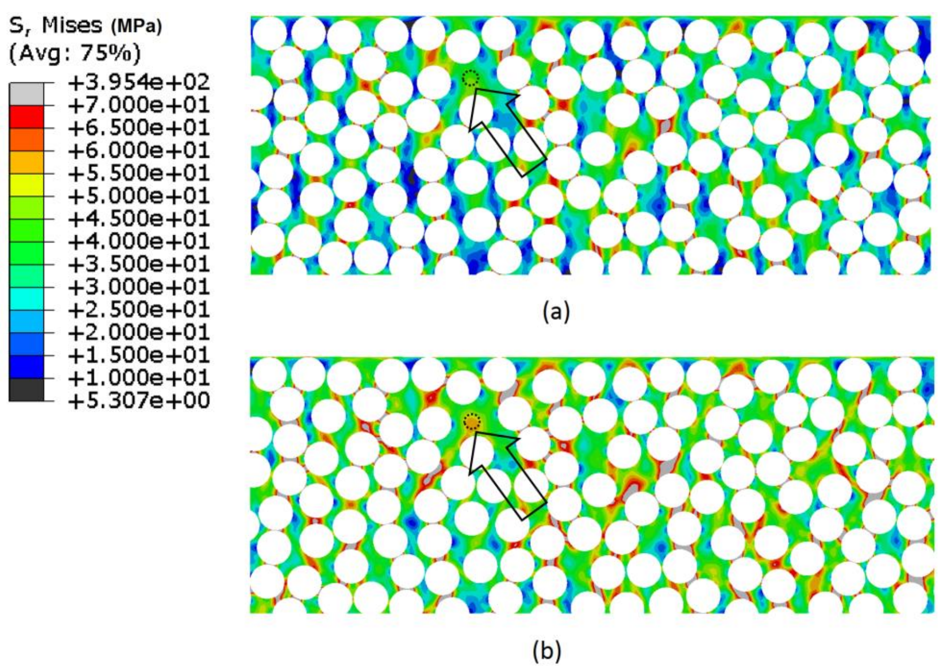

Figure 4: von Mises stress contours of the matrix for (a) $90^{\circ}-\text{ply}$ and (b) $[0/90/0]$ laminate with the non-uniform fiber distribution under sequential mechanical and thermal loading

Table 3 Variation of volume average and local peak stress in the matrix for the indicated laminate subjected to mechanical and thermal loading

	Mechanical Load (MPa)				Mechanical and Thermal Load (MPa)			
Lay-up	σ_x^{avg}	σ_z^{avg}	$\sigma_{Mises}^{\max}$	$\sigma_m^{\max}$	σ_x^{avg}	σ_z^{avg}	$\sigma_{Mises}^{\max}$	$\sigma_m^{\max}$
90° – ply	37.91	6.54	252	208	57.40	25.64	283	108
[0/90/0]	37.93	6.62	253	211	77.94	29.62	395	192

the simulation both at the local intraply level (i.e., due to fiber/matrix thermal property mismatch) and that the interply level (i.e., due to orthotropic thermal properties of unidirectional plies). One important point to note is that the matrix phase in the constrained 90°-ply exhibited higher peak local stresses when compared to the unconstrained ply (Table 3), which mainly stems from the interply constraining effect caused by the 0°-plies during thermal cool down. This in fact may contradict the understanding that constrained layers should exhibit lower stresses and delayed ply crack formation when compared to unconstrained plies; however, this will be investigated further in a future study.

4 CONCLUSION

Employing a previously developed method to randomly generate non-uniform fiber distributed representative volume elements (RVEs), a finite element (FE) model was developed to study the influence of in-situ constraining effect on the local stress state of unidirectional fiber-reinforced plastic (FRP) laminates, including [90] and [0/90/0] lay-ups. First, the significance of considering realistic fiber distribution in the transverse ply was examined for the laminates when subjected to transverse mechanical tensile loading. Comparing different fiber arrangements, a considerable change was observed in local stress states of the matrix while the average response of the laminate was not affected. Moreover, consistency in mechanical responses was observed when comparing the stresses in various randomly generated RVEs with non-uniform fiber dispersion. To more accurately simulate the local response of the laminate, the cooling down stage exhibited during laminate fabrication processes was also modelled which notably influenced the local stresses in the 90°-ply for both laminates as expected. An interesting result is that the in-situ effect was not observed for the laminates studied when subjected to only a mechanical load, while the influence of the constraining effect emerged by applying combined thermal and mechanical loads. Despite previous numerical studies representing the presence of this effect for laminates under pure mechanical loading, the constraining effect due to a mechanical load was not seen in this study for a pristine material. This suggests that the observation of the constraining effect may only be prevalent once a transverse ply crack cavitates or if an existing defect is present in the material to trigger the stress transfer to the neighbour layers. Furthermore, a considerable increase in the peak von Mises and hydrostatic stresses was observed in the matrix phase of the constrained 90° plies when combined mechanical and thermal loads were applied to the RVEs. The constrained plies were expected to exhibit lower stresses, thus further studies are required to properly address this point.

In general, it can be concluded that local variations in the stress state of the matrix phase will directly influence local crack cavitation and yielding mechanisms and ulitmately the formation of sub-critical transverse ply cracks. Hence, it is necessary to account for manufacturing defects, *i.e.* thermal residual stress, non-uniform distribution of fibers, and the presence of local voids, to realistically simulate local cracking of FRP laminates.

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