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Development and Characterization of Epoxy-Based Laminated Composites: Experimental Characterization and Numerical Simulation

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Abstract: The objective of this project is twofold. First, it focuses on the development of a new hybrid composite material intended for use in various industrial sectors, with particular emphasis on the aeronautical field. This composite is composed of plain weave woven carbon fiber, 8-harness satin (8HS) glass fabric, and metallic reinforcement made of galvanized steel, all embedded in an epoxy resin matrix. The combination of these materials aims to achieve enhanced mechanical performance and durability under different loading conditions. Second, the project involves a comprehensive characterization of the developed composite. This includes experimental mechanical testing, specifically tensile tests and three-point bending tests, in order to determine key properties such as Young's modulus and ultimate tensile strength. In addition to the mechanical tests, micrographic and macrographic analyses are conducted to investigate the internal structure and failure mechanisms of the composite material. These analyses provide insight into how different types of damage initiate and propagate under mechanical loading. To complement the experimental work, a numerical simulation was carried out using ABAQUS finite element software. The Young's modulus of the carbon fiber-based laminated composite was estimated numerically and then compared with the experimental results. The comparison shows a satisfactory agreement, validating the accuracy and reliability of the simulation approach used in this study.

Keywords: Composites, Carbon fibers, Metallic reinforcement, Tensile test, Numerical simulation

Introduction

Polymer matrix composites have gained significant attention due to their outstanding strength-to-weight ratio and versatile mechanical performance (Metahri et al., 2024), making them increasingly valuable in engineering applications (National Transportation and Safety Board. 1989, Zhao et al., 2022). Recent research has focused on understanding their resistance behavior and optimizing their structural performance through material grading

(Ghermaoui et al., 2019). Functionally graded materials (FGMs) represent an advanced class of composites that provide gradual transitions in properties, enhancing their adaptability to varying service conditions (Ghermaoui et al., 2023). Combining the advantages of composite structures and graded materials leads to multifunctional materials capable of meeting complex mechanical and environmental demands (Benzaama et al., 2023).

Several studies have explored innovative composite systems, such as the geopolymer-based composites developed by (Ghermaoui et al., 2023), which were examined under impact and interface damage conditions. Damage analysis in notched composite structures has also been widely investigated using different reinforcement strategies (Kim et al., 1995). Furthermore, numerical approaches like the extended finite element method (XFEM) and cohesive zone modeling (CZM) have proven effective in simulating crack initiation and propagation in composites (Abdelouahed et al., 2023).

Experimental and numerical findings have shown that composite laminates experience multiple damage mechanisms, including matrix cracking and fiber separation. These complex phenomena require advanced modeling tools to predict failure accurately. The XFEM (Mohamed et al., 2024), offers a robust framework for studying interfacial damage without predefining cracks.

In this study, a new meshing strategy is proposed to simulate graded composite behavior by integrating XFEM. This approach enables a detailed analysis of crack initiation, considering the effects of design parameters, volume fraction gradients.

Numerical Approach of Model Geometry and Material Properties

The numerical investigation was performed using the finite element method (FEM) through ABAQUS, where the graded composite structure was discretized with solid continuum elements. The model assumes an ordered fiber arrangement across the thickness, each fiber layer being represented by a row of elements of 0.125 mm thickness, equivalent to the fiber diameter. The notched specimen was modeled as a rectangular plate (200 mm × 30 mm × 1.25 mm) containing a central circular notch of 6 mm radius, serving as a damage initiation site. Only one-quarter of the geometry was simulated due to symmetry Figure 01.

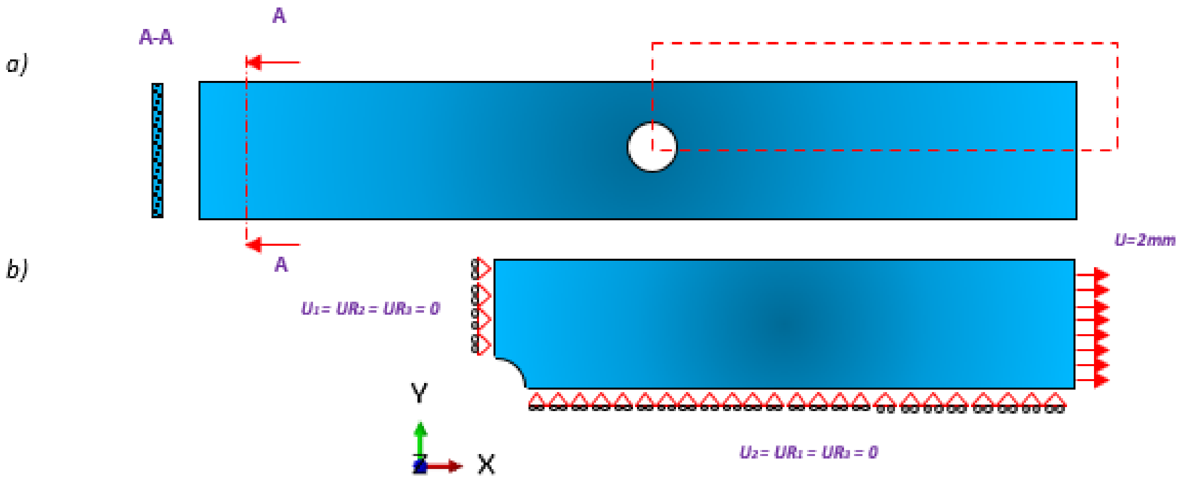


Figure 1. Overview of the studied geometry. a) Complete structure, b) quarter of the structure

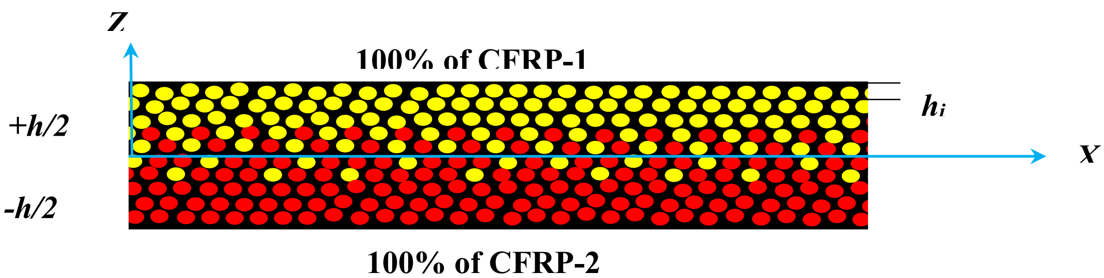


Figure 2. Graduation according to the thickness of CFRP-2 toward CFRP-1 (Ghermaoui & Mokhtari, 2023).

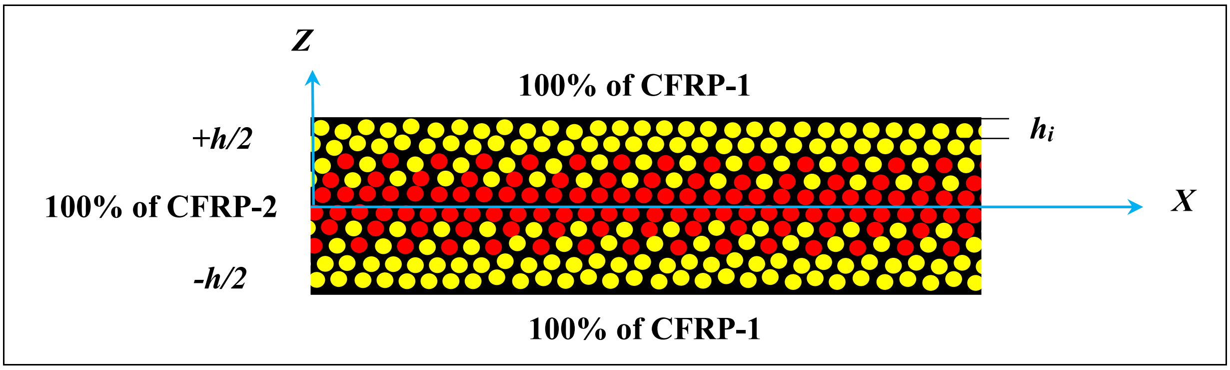


Figure 3. Graduation according to the thickness from CFRP-2 in the middle toward the composite CFRP-1 at the end (Ghermaoui & Mokhtari, 2023).

Two fibers of different mechanical properties (CFRP-1 and CFRP-2) were embedded in the same epoxy matrix, with a total fiber volume fraction fixed at 60%. The study explored different grading designs: (i) a simple gradient from CFRP-1 to CFRP-2 figure 2 and (ii) symmetric configurations, where the fiber types vary from the mid-plane toward the surfaces figure 3. A uniaxial tensile load of 450 MPa was applied quasi-statically to ensure progressive crack propagation. Material anisotropy was accounted for by assigning local coordinate systems to each layer. Mechanical properties and damage parameters (Tables 1–2) were interpolated between the two materials using a rule of mixtures:

Table 1. Mechanical properties of IM7/8552 CFRP; CFRP-1(Shojaei, A. & Li, G 2014) and CFRP-2(Murakami, S 2014) . Used

Variables	*Young'smodulus, E*	*Poisson's ratio, ν*	*Shearmodulus, G*
CFRP-1	E1 = 162000MPa	*ν 12 = 0.316*	*G12 = 4690MPa*
	E2 = 8960MPa	*ν 13 = 0.316*	*G13 = 4690MPa*
	E3 = 8960MPa	*ν 23 = 0.316*	*G23 = 3973MPa*
	E1 = 171400MPa	*ν 12 = 0.32*	*G12 = 5290MPa*
CFRP-2	*E2 = 8960MPa*	*ν 13 = 0.32*	*G13 = 5290MPa*
	E3 = 8960MPa	*ν 23 = 0.5*	*G23 = 2800MPa*

Table 2. Input parameter is for the damage of each CFRP-1(Shojaei, A. & Li, G 2014) and CFRP-2(Murakami, S 2014) used

Variables	CFRP-1	CFRP-2
Longitudinal tensile strength, *XT* (MPa)	*2560*	*2326*
Transverse tensile strength, *YT* (MPa)	*64*	*62.3*
Longitudinal tensile fracture energy (kJ/m^2)	*81.5*	*0.277*
Transversal tensile fracture energy (kJ/m^2)	*0.277*	*0.788*

$X_{T-C} = X_{T-C1}.V_{C1} + X_{T-C2}.V_{C2}$ and $Y_{T-C} = Y_{T-C1}.V_{C1} + Y_{T-C2}.V_{C2}$ (1)

$G_{Ic}^{C} = G_{Ic-C1}.V_{C1} + G_{Ic-C2}.V_{C2}$ and $G_{IIc}^{C} = G_{IIIc}^{C} = G_{IIc-C1}.V_{C1} + G_{IIc-C2}.V_{C2}$ (2)

X_{T-C},Y_{T-C}: is the ultimate stress in tensile of composite, X_{T-C1},X_{T-C2},Y_{T-C1}, Y_{T-C2} are the ultimate stressin tensile of the CFRP-1 and CFRP-2. $G_{IC}^{C}, G_{IIc}^{C}, G_{IIIc}^{C}$ Is the critical energy release rates of composite, $G_{Ic-CFRP1}$,$G_{Ic-CFRP2}$ are the critical energy release rates of the CFRP-1 and CFRP-2.

The XFEM technique was implemented to simulate crack initiation and propagation without predefined paths. The QUADS criterion was chosen for crack initiation, and energy-based evolution laws governed damage propagation. Cohesive zone models (CZM) were inserted between layers to capture interfacial debonding, with stiffness terms (Knn,Kss,KttK_{nn}, K_{ss}, K_{tt}Knn,Kss,Ktt) derived from the layer modulus divided by an equivalent thickness (0.2 mm). Debonding was simulated using a quadratic stress criterion:

$$\left(\frac{\sigma_{I}}{\sigma_{u,I}}\right)^2+\left(\frac{\sigma_{II}}{\sigma_{u,II}}\right)^2+\left(\frac{\sigma_{III}}{\sigma_{u,III}}\right)^2=\begin{cases}1 \text{ if} & \sigma 1 \geq 0 \\ 0 \text{ if} & \sigma 1 \leq 0\end{cases} \tag{3}$$

and propagation followed an energetic law:

$$\left(\frac{G_{I}}{C_{IC}}\right)+\left(\frac{G_{II}}{G_{IIC}}\right)+\left(\frac{G_{III}}{G_{IIIC}}\right)=1 \tag{4}$$

Each cohesive layer represented a zero-thickness interface with averaged material properties between adjacent layers. A mesh sensitivity study was carried out using C3D8 solid elements, ensuring convergence with approximately 12,000 elements. Overall, this numerical approach accurately captures the graded behavior of CFRP composites by combining FGM-based gradation, XFEM for matrix cracking, allowing precise prediction of failure initiation and crack evolution through the graded structure.

Mesh Sensitivity and Comparison of Numerical Results

Prior to analyzing the graded CFRP, a reference numerical model was developed and validated against the experimental findings of (Kim et al., 1955), who tested a glass–polyester composite plate with dimensions of 200 × 30 × 2.3 mm and a fiber volume fraction of 60% Figure 04. The specimen was subjected to uniaxial tension, as illustrated in Figure 10. Several preliminary mesh sensitivity studies were conducted, varying both element density and element type, as shown in Figure 5.

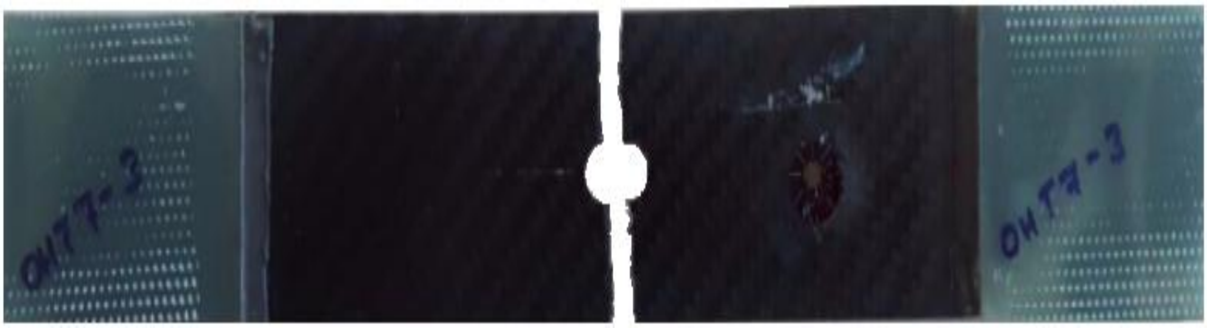


Figure 4. Overview of the damaged structure by (Kim & kim 1955).

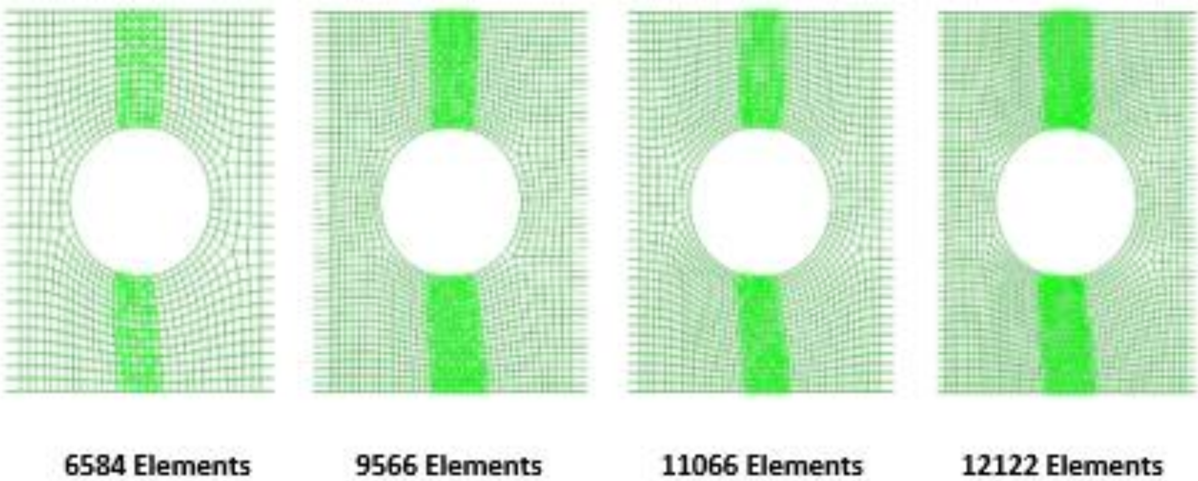


Figure 5. Mesh sensitivity by element density (Ghermaoui & Mokhtari, 2023).

To ensure reliable numerical predictions, all simulation parameters-such as mesh density, element type, and loading conditions—were kept consistent with those used in Kim's experimental setup. The interpolation of finite elements in the proposed meshing technique was achieved through each element's own nodal connections, providing high accuracy and numerical stability. Among the tested element types, the C3D8 solid element demonstrated the best performance, particularly when combined with the XFEM damage modeling technique.

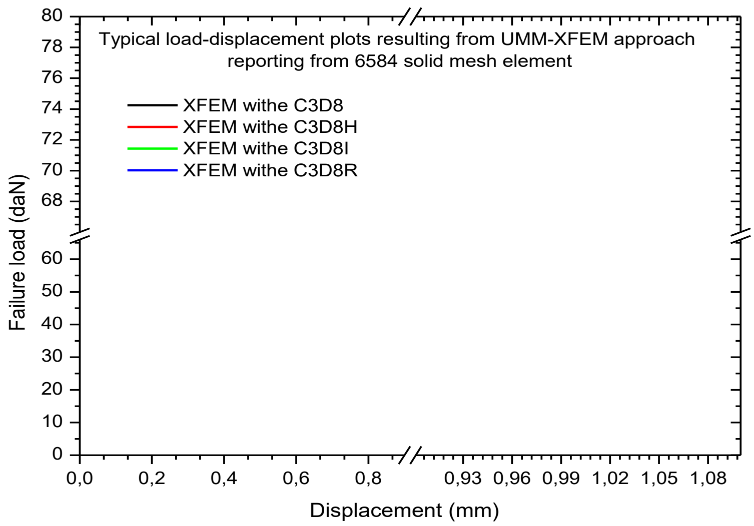


Figure 6. Typical load-displacement plots resulting from XFEM approach reporting from 6584 solid mesh element (Ghermaoui & Mokhtari, 2023).

Within the C3D8 family, several formulations were examined, including C3D8R, C3D8H, C3D8I, and C3D8S. The C3D8S element is mainly suitable for surface visualization purposes. The C3D8I (incompatible mode) element, enhanced with improved shape functions, proved effective for bending-dominated structures such as graded composites. The C3D8H (hybrid mode) element performed well for nearly incompressible materials, minimizing distortion near the notch. Conversely, the C3D8R (reduced integration) element required a finer mesh to maintain accuracy.

After several trials, an optimal mesh density of approximately 12,122 elements was adopted for the model. Validation against Kim's experimental results showed that this configuration achieved accurate damage prediction, with an element size fine enough to capture crack initiation yet coarse enough to prevent numerical instability. Figure 6 indicates that the element-type effect remains within the order of 10^{-2}. The C3D8 element with a mesh density of 6,584 elements yielded the closest correlation with the experimental load–displacement behavior, confirming the validity of the proposed numerical approach.

Results and Discussion

By the use of several techniques including the finite element method, the CFRP structure graded in its response to damage is evaluated by several concepts and graduation parameters. Compatibility in strength capacities between graded fibers is important. The separation between these two qualities of graded fibers is the very probable phenomenon that can occur as a mode of damage, something that was not taken into account in the numerical prediction. The graded fibers are presented by finite elements in the material property is homogenized and oriented by a local coordinate system, something that can make this prediction incomplete in certain damage modes.

Damage of CFRP Structure Under Simple Graded

The graded CFRP was modeled as an orthotropic functionally graded material, exhibiting mechanical behavior that varies with loading conditions. This section focuses on the simple grading concept, introduced to analyze how the material responds and fails under specific parameters, particularly the volume fraction index (n). In this configuration, a bending moment develops due to the variation in stiffness along the plate's thickness. Under uniaxial tension applied to the specimen's cross-section, the stress distribution becomes nonuniform until the stiffer outer layers begin to fail, after which the bending moment is released.

Figure 7 illustrates the linear mechanical response of the graded CFRP under loading and its corresponding damage evolution for a simple gradation from CFRP-1 to CFRP-2 through the thickness. The figure also highlights the influence of the volume fraction index (n) on the force–displacement response and the crack propagation length. This dual interpretation relating load capacity to crack progression clarifies how grading parameters affect the material's resistance and fracture behavior.

Results reveal that the volume fraction index (n) significantly affects both stiffness and strength. However, because the mechanical properties of CFRP-1 and CFRP-2 are relatively close and the plate thickness is small (1.25 mm), this influence remains modest, around 1.8 daN. The stiffer configurations exhibit higher failure loads but lower deformation at rupture. The gradation also alters crack initiation and propagation, leading to brittle fracture characterized by short critical crack lengths (LC). These critical lengths vary across the graded layers, depending on their local material properties and stiffness distribution.

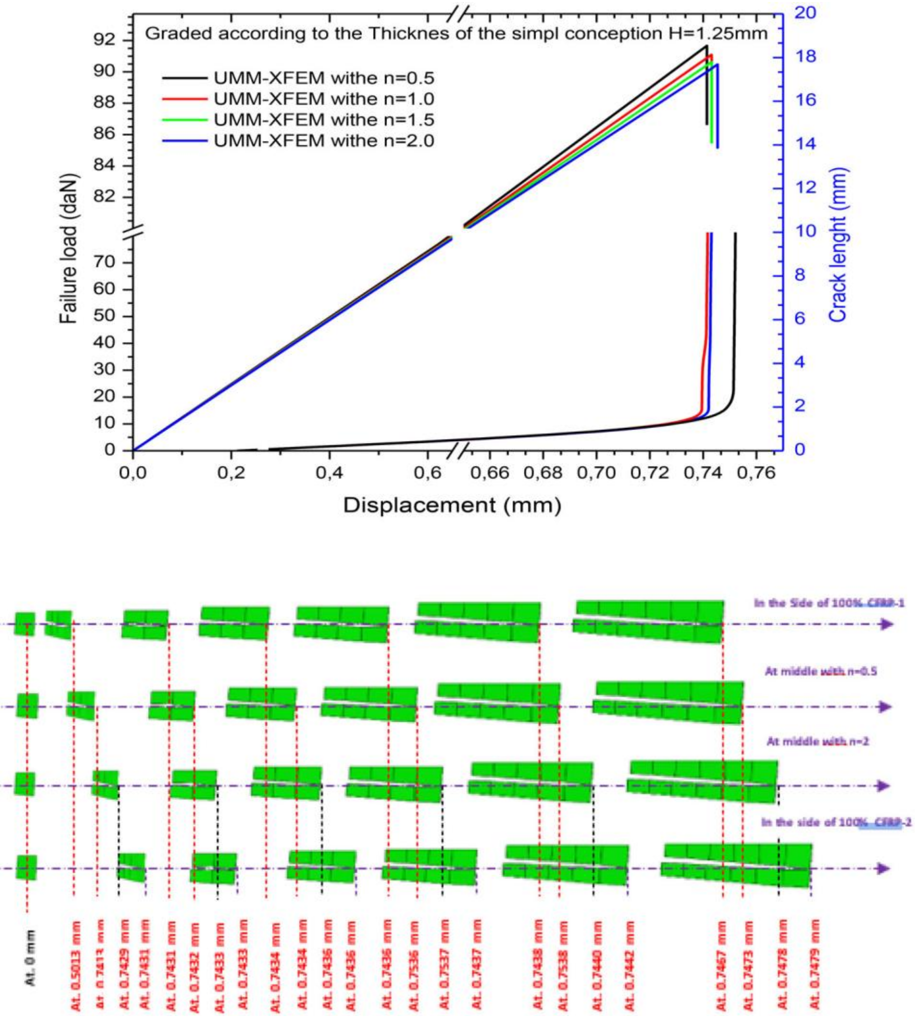


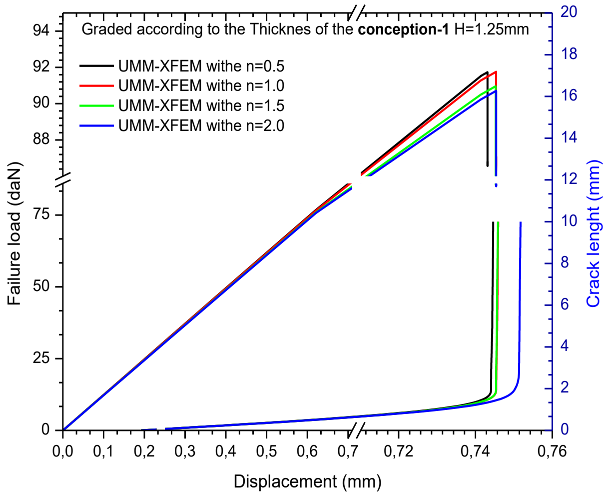
Figure 7. a) Load – displacement curves and propagation length crack in W=30mm, vf= 60% results by UMM-XFEM techniques (number of 6584-C3D8 solid mesh element) as a function of the values of the exponent n in the case of simple gradation of CFRP according to the thickness. b) Crack length propagation in each layer as a function of n=0.5; 1; 2 (Ghermaoui & Mokhtari, 2023).

Damage of CFRP Graded According to Concept-1

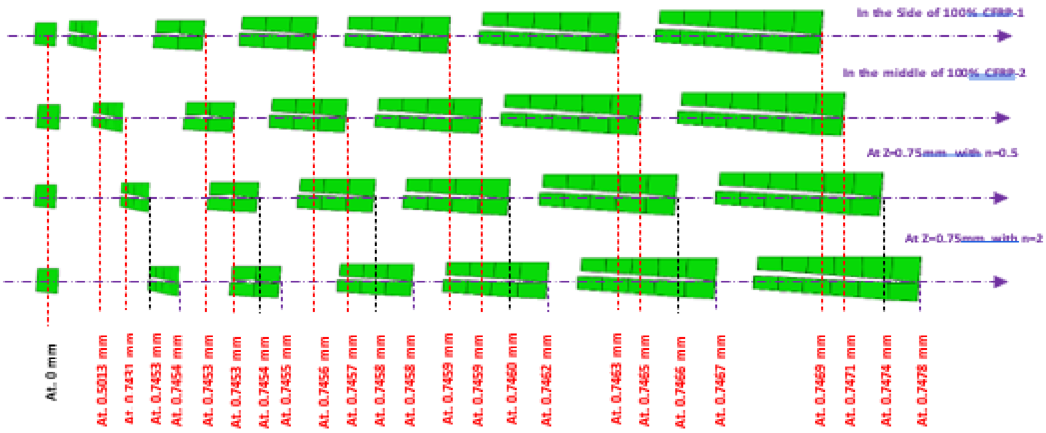
Building upon the findings obtained from the simple grading configuration, this section focuses on the analysis of symmetrical grading concepts. The objective of this approach is to achieve a balanced mechanical response across the thickness of the composite under uniaxial tension until failure. Symmetrical designs were proposed Concept-1 each representing a transition from stiffer to more compliant layers. The study examines two main parameters: the grading concept itself and the volume fraction index (n). The results are illustrated through force–displacement and crack-length–displacement curves for each design. Introducing symmetry within the laminate effectively eliminates the bending moment observed in the simple grading case, as the stiffness distribution becomes balanced through the thickness.

In Figure 8-a, the mechanical response and failure progression of the Concept-1 configuration are presented. This concept involves outer layers made of the stiffer CFRP-1 material and inner layers of the more compliant

CFRP-2. Crack propagation occurs gradually from the exterior to the interior layers, as shown in Figure 8-b. The influence of the volume fraction index (n) remains modest around 1.8 daN similar to the simple grading model. As the structure becomes less rigid (higher n values), it exhibits lower strength but greater deformation capacity, reaching an elongation of approximately 0.01 mm before failure. Only minor variations are observed between layers in terms of crack initiation and critical crack length. These differences are primarily attributed to the position of each layer within the graded thickness. The average critical crack length across all layers is slightly reduced and varies according to the value of n.



a)



b)

Figure 8. a) Load – displacement curves and propagation length crack In W=30mm, vf= 60% results by XFEM-mesh techniques (number of 6584-C3D8 solid mesh element) as a function of the values of the exponent n in the case of simple gradation of CFRP according to the thickness. B) Crack length propagation in each layer as a function of n=0.5; 1; 2 (Ghermaoui & Mokhtari, 2023).

Conclusion

The findings of this study demonstrate that the proposed meshing technique combined with the XFEM approach provides a highly reliable framework for predicting the mechanical behavior and damage evolution in graded CFRP composites. The numerical model, validated against experimental results from a simple composite structure, proved effective when extended to graded configurations. Using the global properties of each composite layer simplifies the modeling process by avoiding complex constitutive formulations for property gradation, while grading finite elements at the fiber scale offers a more realistic representation of the actual material architecture. Based on the numerical analyses conducted, the following conclusions can be drawn:

- The proposed meshing technique allows each finite element to act independently through self-interpolation of its nodes, enabling the introduction of element-based enrichment functions. This significantly mitigates convergence issues typically encountered in complex meshes.

- The XFEM method enables smooth and continuous initiation and propagation of damage throughout the graded CFRP structure.
- Comparison with experimental data is essential for selecting the most suitable element type and optimal mesh density, ensuring accurate numerical predictions.
- The overall structural strength of graded CFRP composites depends primarily on the appropriate selection of the two fiber types used in the gradation.
- Graded composites exhibit an average critical crack length across all layers, which varies according to the volume fraction index (n).
- Due to the intrinsic nature of composites, crack propagation rates in graded structures are relatively fast once initiated.
- The notch geometry continues to influence damage initiation despite the evaluated parameters; after crack initiation, propagation paths are determined by the gradation design and the exponent n.

However, the proposed numerical approach remains limited in capturing stacking effects since it does not explicitly model fibers at their true scale within the matrix. Despite this limitation, the suggested meshing technique offers a simple and efficient solution for analyzing material gradation and damage behavior in composite structures.

To further enhance the accuracy of these predictions, experimental testing campaigns should be carried out to validate and refine the numerical model. Such tests would help identify additional damage mechanisms and contribute to establishing a more realistic understanding of the failure modes in graded CFRP composites.

Scientific Ethics Declaration

* The authors declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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References

Benzaama, A., Mokhtari, M., Ahmed-Bouziane, N.-E.-I., Elamine, A., Benzaama, H., Ghermaoui, I. M. A., & Aliane, I. (2023). Using a UMM-XFEM technique to predict the damage in CFRP bi-graded with glass-epoxy materials of notched plate under quasi-static loading. *Mechanics of Advanced Materials and Structures*. *31*(25), 7367-7385.

Elamine, A., Mokhtari, M., Benzaama, H., Ghermaoui, I. M. A., Ezzine, M. C. E., Ghomari, A., & Merasli, Y. (2023). Using a non-linear mixed model behavior of CZM to predict the damage in single lap bonded joint with bi-composite graded materials. *Mechanics of Advanced Materials and Structures*, 31(25), 7180-7194.

Ghermaoui, I. M. A., Mokhtari, M., Benzaama, H., & Elamine, A. (2023). Using FGM concept and combined XFEM-CZM techniques to predict the damage in carbon/carbon-epoxy graded composites. *Mechanics of Advanced Materials and Structures*. *31*(25), 7526-7544.

Ghermaoui, I. M. A., Oudriss, A., Metsue, A., & Feaugas, X. (2019). Multiscale analysis of hydrogen-induced softening in f.c.c. nickel single crystals oriented for multiple slips: Elastic screening effect. *Scientific Reports, 9*, 13042.

Kim, J. K., Kim, D. S., & Takeda, N. (1995). Notched strength and fracture criterion in fabric composite plates containing a circular hole. *Journal of Composite Materials, 29*(7), 982-998.

Metehri, A., Madani, K., Mechab, B., Mokhtari, M., & Ghermaoui, I. M. A. (2024). Tensile examination of progressive damage and failure in porous ceramic composite materials using the XFEM. *Vojnotehnički glasnik, 72*(3), 1188-1213.

Mohamed, C., Kaci Djafar, A., Abdelmajid, M., Abderahmane, S., & Ghermaoui, I. M. A. (2024). Numerical study of tensile-shear fracture behaviour of resistance spot welded sheet steel with DP 450 and DP 980. *Acta Mechanica Slovaca, 28*(4), 14-24.

Murakami, S. (2012). *Continuum damage mechanics: A continuum mechanics approach to the analysis of damage and fracture*. Springer.

National Transportation Safety Board. (1989). *Aircraft accident report: Aloha Airlines Flight 243, Boeing 737-200, N73711, near Maui, Hawaii, April 28, 1988* (Report No. NTSB/AAR-89/03).

Shojaei, A., Li, G., Fish, J., & Tan, P. J. (2014). Multi-scale constitutive modeling of ceramic matrix composites by continuum damage mechanics. *International Journal of Solids and Structures, 51*(23–24), 4068-4081.

Zhao, Y., Wang, Z., Jiang, P., Wang, A., Chang, Z., & Kang, Y. (2022). Numerical simulation on mechanical properties and damage behavior of CFRP with self-healing microvascular channels. *Mechanics of Advanced Materials and Structures, 26*(1), 1-17.

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