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Influence of Ply Arrangement on Failure Criteria in Fibre-Reinforced Composite Laminates using ACP Pre-Simulation, Numerical Assessment

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Abstract

Fiber-reinforced composites (FRCs) are among the most widely used materials in modern engineering applications due to their high mechanical properties and light weight. The current study involved a numerical investigation conducted through experimental a validation process using ANSYS Workbench R18.0 to evaluate the mechanical behavior and failure mechanism of (Carbon/Epoxy UD Prepreg). The modelling process was initiated using ACP-PRE to crate four types of laminate structures: balanced cross ply, symmetric, and random. The current model demonstrated an acceptable range of reliability and accuracy to investigate different laminate structures, with a validation error percentage of less than 8% and 13% for both static and explicit analysis. From the study, it has been concluded that the cross-ply layer structure has the highest ultimate stress, reaching 1911.2 MPa, while the random laminate structure has almost 80% in tensile strength reduction. A 700 MPa ultimate tensile stress was obtained for the cross-ply type, although the balanced laminate exhibited a weaker load response, 30 % lower than the cross-ply. Moreover, the laminate configuration of cross-ply stands as the best option in terms of reverse factor, which indicates a value of 6.7, and the highest energy of strain reached 1.5123 with 46% higher safety margin. As a result, this configuration is suggested to be the best combination and capability for the safety structure and energy absorption. These findings highlight the critical role of ply arrangement in enhancing the mechanical integrity of composite structures and support the need for deliberate design strategies in laminate engineering. Moreover, the current paper suggests ACP Pre (Advanced Composite Pre-processor) as an effective tool for simulating composite materials with layered structures.

Keywords: *Carbon/Epoxy Composite, Unidirectional Prepreg, Tensile Test, ANSYS Simulation, Laminate Configuration, Failure Criteria, Fiber* Orientation.

1 Introduction

The growing need for materials with specific properties in engineering design has contributed to the development of new materials. Therefore, lightweight materials are a priority in the development of new materials. This potential exists in composite materials, particularly fiber-reinforced composites, which possess high strength, stiffness, and damping capacity [1]. They also have the potential to reduce construction, operating, and development costs. Because of these unique specifications, they are widely used in high-technology structural applications, such as aeronautics and aerospace. Polymer-based composites have received much attention in recent years due to their diverse properties, which offer many applications, such as conductive polymer composites that substantially drop in weight; they also possess environmentally friendly and biodegradable properties [2, 3].

Traditional aircraft materials include aluminum, steel, and titanium. However, composite materials have become widely used in recent decades due to their advantages, such as weight reduction and simplified assembly. Composites outperform metals by offering higher strength-to-weight and stiffness-to-weight ratios, making aircraft lighter and more efficient [4].

Carbon fiber reinforced polymer composites (CFRPCs) have gained significant attention due to their excellent mechanical properties, such as a high strength-to-weight ratio, corrosion resistance, and superior fatigue performance. These composites are carbon fibers embedded in a polymer matrix, enhancing their unique characteristics. Carbon fiber is highly durable and rigid, 3 to 10 times stronger than fiberglass, and is either grey or black. It is available as a dry fabric pre-saturated with the materials.

One common type is epoxy carbon, which combines carbon fibers with an epoxy resin. This combination provides exceptional strength, durability, and resistance to environmental factors, making it ideal for aerospace, automotive, and sports applications.[5]

Woven laminate composites have attracted tremendous attention due to their exceptional mechanical properties, i.e., stiffness, lightweight, and specific strength and sound reinforcement in all directions. Through a variety of process methods, laminates can be tailored into many forms and used in extensive applications such as aerospace applications, maritime, transportation industries, and civil infrastructures. [6, 7]

A work conducted by Duleba et al. [8] to examine epoxy bisphenol A (BPA) resin composite systems reinforced with a simple carbon fiber and a diagonal carbon fabric with 1% carbon nanotubes. The samples were tested with a 0°–45°–0° layer arrangement using tensile tests and FEM simulations. The diagonal fabric achieved a higher tensile strength (~756 MPa) than the simple fabric (~709 MPa), with good convergence between theoretical and experimental results, confirming the improvement of mechanical properties with nanotubes.

Qi et al. [9] conducted a study to produce a method that could evaluate the interfacial shear stress of CFE using a 45° Fiber Bundle. The 45° tensile test (45FBT) evaluated interfacial shear strength using T700S, T800H, and T800S fiber bundles. The 90° angle was the most susceptible to stress, with maximum stress values of ~107.5 MPa for T700S/epoxy and 114.1 MPa for T800H/epoxy, demonstrating that 45FBT accurately determines interfacial bond strength. In the same failed study in 2019 [10], the focus was on optimizing fiber orientation in carbon fiber-reinforced epoxy composites using ANSYS ACP Pre 16.2. ASTM D3039 specimens with five layers were tested under fifteen models. Model 11 presented the best performance with slight deformation and peak energy distribution. Fiber orientation was concluded as a crucial factor for improving composite properties for high-tensile applications.

An investigation conducted by Zmindak [11] studied the effect of angle orientation lay-up on the uniaxial tensile strength of carbon fiber/epoxy composites manufactured using resin transfer molding and vacuum bagging. Three lay-up configurations ([0/90], [45/-45], hybrid [0/90 45/-45]) were tested using 12 layers of Kyoto 3K 220GSM carbon fiber with Bekelite EPR 174 epoxy resin. The [0/90] orientation produced the highest tensile strength (494 MPa experimentally). ANSYS ACP simulations closely mirrored experimental results, validating the finite element model.

Milan Zmindak et al. [11] (2020) conducted a simulation and demonstration study of the tensile behavior of 3D-printed carbon fiber-reinforced composites. Specimens printed with Onyx and carbon fibers were tested at 0°, 45°, and 90° fiber orientations. The highest strength was at 0° (191.6 MPa) and the lowest at 90° (~28 MPa) with 38% deformation. ANSYS simulations matched the experimental data, confirming the key role of fiber orientation. In Rajak et al. [12], the mechanical properties of a glass fiber reinforced polyester (GFRP) composite were considered using a 0°/90° fiber arrangement. Tensile testing showed that the composite without fillers recorded the highest stress of 104.1 MPa. Bidirectional fiber arrangements improved load distribution, while fillers reduced tensile strength. Glass fibers were confirmed as critical in enhancing tensile performance.

Maneendra et al. [13] investigated the tensile behavior of epoxy refined coconut fiber composites with rice hulls and sawdust. ASTM D638 samples exhibited initial nonlinear behavior followed by rapid failure at maximum stress, unlike dry glass fiber bundles (GFB), which showed a steady reduction in strength. ANSYS ACP simulations confirmed high tensile strength but abrupt failure.

A work conducted by Luo [14], their effort was focused on supplementing a numerical study on hybrid laminates made from sisal and glass fibers, evaluating stacking angle, number of layers, and thickness on deformation and residual stress. Using the Takayama-Buehler model in ANSYS, results showed that increasing layers reduced residual stress, while higher stacking angles improved deformation. Optimizing layer composition improved mechanical act and reduced residual distortion.

Szpoganicz et al. [15] assessed the prepared layer thickness and fiber orientation on the tensile properties of carbon fiber-reinforced composites at low temperatures. Thin layers (0.03 mm) oriented at 0°/90° exhibited greater tensile strength and higher damage resistance. It has been noticed that the ultimate tensile strength of the 0.08 mm-thick sample at ~77 K was ~1228 MPa, with Young's modulus 133.4 GPa. Thicker layers (0.30 mm) had tensile strength 1292 MPa and modulus 148.4 GPa. Lower temperatures enhanced mechanical properties, while ±45° layering reduced strength and increased cracking. A theoretical and experimental study on unidirectional carbon fiber/epoxy composites was conducted by Yasser [16]. The highest tensile strength (2857 MPa) was at 0°, with the highest elongation (7.1%) at 45°. Four failure theories agreed at extreme angles, confirmed a U-relationship between Young's modulus and fiber angle was confirmed.

A study of the tensile behaviour of a glass fiber-carbon composite with epoxy resin using ANSYS 19.2 has been achieved by Kebede [16]. Four stacking arrangements were analyzed: [0/90/45] s, [45/0/90]s, [0c/90/45]s, [45c/0/90]s. The hybrid SS-3 ([0c/90/45] s) had the highest tensile strength (~1935 MPa), confirming that fiber arrangement and carbon layers at the ends enhance tensile strength.

A composite reinforced with glass fiber, carbon fiber, and Kevlar fibers using epoxy resin was investigated by Asthana et al. [17]. ASTM D638 tensile tests showed Kevlar/epoxy had the highest tensile strength (51.42 MPa), modulus 803.8 MPa, and elongation 13.67%, while glass fiber composite had 26.04 MPa. Numerical fatigue damage was studied by Feki et al. [22], who studied a carbon fiber/epoxy composite manufactured by spiral twisting at fiber angles ±15°, ±30°, and multiple compositions. The highest stress was at ±15° (361.4 MPa, 60 GPa, 0.66% elongation). ±30° recorded 206.6 MPa, 36.8 GPa, 1.3% elongation; multiple compositions had 157.1 MPa, 21.1 GPa, 0.94% elongation, confirming fiber orientation improves resistance.

A work was done by Czel [18], which developed a sandwich unidirectional work, using different layers arrangement on epoxy-reinforced glass fibre composites under tensile testing. The $[0°]_8$ layer arrangement had the highest tensile stress (~520 MPa), while ±45° angles had lower strength, demonstrating that longitudinal angles are important in load-bearing. A numerical and vi experiential validation was conducted by Saad et al. [4] using polyphenylene sulphide (PPS) composites reinforced with carbon and glass fibres. Results determined that Tensile strength increased from 173.6 MPa (single glass layer) to 363.52 MPa (four layers), and from 213.76 MPa to 394.24 MPa for carbon layers. ANSYS simulations agreed with experiments within 12.3% deviation.

While some research has been carried out on composite FEA analysis, including Fiber type and orientation with different reinforcement fibers, which have influenced the tensile behavior of polymer composites, clearly, there have been few empirical investigations into combining static and explicit dynamic analyses in ACP Pre/Post. That is still very little scientific understanding and a lack of comprehensive comparison between balanced, cross-ply, symmetric, and random ply arrangements in unidirectional prepreg composites. Indeed, this would provide better prediction and optimization of composite behavior.

This paper provides a numerical procedure for Static Structural and Explicit Dynamic modules in ANSYS to assess the influence of the failure model on various ply arrangements, stress distribution, and load-bearing capacity using the ACP code, which needs further investigation to be understood.

2 Theoretical Background

Composites are among the most critical materials in advanced applications due to their high mechanical properties and low weight. The layered structure of the fibers within the matrix significantly affects the material's response under various loads, especially in tensile conditions. Unidirectional composites reinforced with carbon fibers and impregnated with epoxy resin exhibit complex mechanical behavior. They involve stress transfer across multiple layers in different directions, requiring careful analysis of their failure behavior.

2.1 Failure Criteria And Damage Models

The Hashin Failure Criteria were adopted to understand these composites' failure behaviour. This model is one of the most widely used and accurate for analysing multistage failure in composite materials. The Hashin criterion distinguishes between different failure types, such as fiber failure in tension or compression, and matrix failure in tension or compression. This makes it suitable for modelling materials containing multiple fiber orientations within a layered structure.

The Hashin standard includes four main cases [19]:

1) Fiber tensile failure

When the longitudinal stress is positive (tension)

$$\frac{{\sigma_1}^2}{(\sigma_1^T)^2} + \frac{\tau_{12}^2}{(\tau_{12})_{\text{ult}}^2} = 1 \quad (1)$$

2) Fiber compression failure

When the longitudinal stress is negative (compression):

$$-\frac{\sigma_1}{(\sigma_1^c)_{\text{ult}}} = 1 \quad (2)$$

3) Tensile failure of the matrix

When the transverse stress is positive:

$$\frac{\sigma_2^2}{(\sigma_2^T)_{ult}^2} + \frac{\tau_{12}^2}{(\tau_{12})_{ult}^2} = 1 \quad (3)$$

4) matrix compression failure

When the transverse stress is negative:

$$\frac{\tau_{12}^2}{(\tau_{12})_{ult}^2} - \frac{\sigma_2}{(\sigma_2^c)_{ult}} = 1 \quad (4)$$

Where:

σ_1 Longitudinal stress (in the direction of the fibers)

σ_2 Transverse stress (perpendicular to the fibers)

τ_{12} Shear stress in 1-2 plane.

$(\tau_{12})_{ult}$ In-plane ultimate shear stress

$(\sigma_1^c)_{ult}$ Ultimate longitudinal compressive strength of composite.

$(\sigma_2^c)_{ult}$ Ultimate transverse Compressive strength of composite.

Although the Hashin criterion covers four major failure modes for composite materials, this study focused only on the tensile states of fibers and matrix. This is because the numerical analysis and experimental studies were limited to the tensile test, which naturally excluded compression states from the evaluation. This model was chosen because it provides good agreement with experimental results and allows for applying post-failure stiffness degradation algorithms, making numerical simulations more realistic. Furthermore, the Hashin criterion is directly integrated into numerical analysis programs such as ANSYS within the ACP module, facilitating its use in complex simulations involving composite materials with anisotropic properties.

3 Materials and Methods

In this work, a hand layup method was utilized to fabricate fiber reinforcement composite materials. The materials being used here are epoxy E44 resin as a matrix reinforced with carbon fibers, including a plain uni direction arrangement. A total of ten sheets with approximately 0.2 mm thickness were set into a mould with a square shape, with an edge length of 16 cm. The resin was poured into the mould that already had a unidirection structure settled based on the desired thickness. After that, the produced block was pressed to make a proper compaction, arrange layers, and remove any unwanted resin. Samples were cured for 48 hr. at room temperature. The samples were cut by a water jet machine according to the ASTM D638 to get the tensile and flexural strength data.

3.1 Materials description

The properties of composite materials depend on the components that contribute to their formation and the compatibility between the matrix and its reinforcing agents [20]. In this research, the composite material CF/epoxy was used with the material properties stated in Table 1 and dimensions pointed out by (ASTM D638-02a) in Figure 1.

Table 1. CF/epoxy properties [21]

Property	Value
Longitudinal Tensile Strength (σ_{11})	1500Mpa
Longitudinal Young's Modulus (E_1)	135000Mpa
Transverse Tensile Strength (σ_{22})	50Mpa
Transverse Young's Modulus (E_2)	1000Mpa
In-plane Shear Strength (τ_{12})	100Mpa
In-plane Shear Modulus (G_{12})	5000Mpa

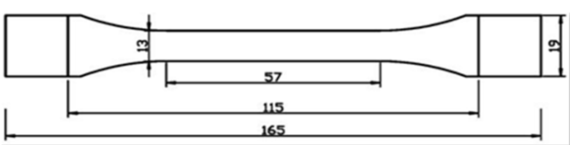

Figure 1. Tensile test Dimension

3.2 Finite Element Modelling Using ANSYS

In this research, a numerical simulation was conducted using ANSYS Workbench R18.0 to evaluate the mechanical behavior and failure mechanism of (Carbon/Epoxy UD Prepreg). The modelling process was initiated using ACP-PRE to determine the arrangement of the layers. The model was built with ten layers, each layer 0.2 mm thick, making the total thickness of the sample 2 mm; as depicted in Figure 2.

Here, in this work, the 3D model was carried out by ANSYS Workbench; Composite Pre/Post (ACP) R18.0. Regarding the setup of the model, cell type, and cell size, it was conducted according to the published literature, see [22, 23]. It is worth mentioning that the solid 187 element type was considered with a minimum element size of 0.2 mm, while the maximum size was 1.03 mm, the average aspect ratio value was 0.5, and the average element quality was determined to be 0.34. The total number of elements in the samples for the four cases was 7900 cells.

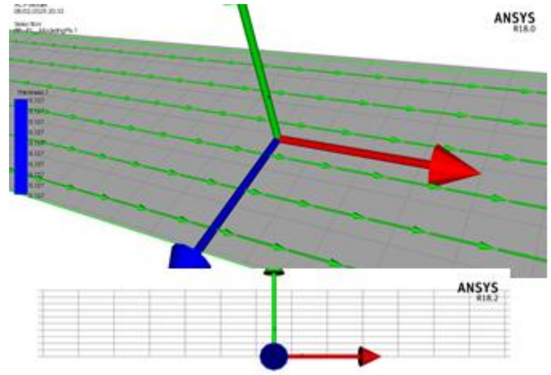

Figure 2. sample section with 10 layers in ACP pre

The test was conducted using four laminate classifications, each depending on different conditions at different angles. The work also relied on a fourth random type that is not subject to any conditions, as shown in Table 2 [24].

Table 2. Classification of Laminate

Laminate Type	Staking sequence
Balanced	$[0/90_2/\pm45]_s$
Cross ply	$[0_3/90_2]_s$
Symmetric	$[0/45/90/45/0]_s$
Random	$[0/-45/90/45/90]_2$

3.3 Methods

In this study, two types of numerical analysis were used within the ANSYS WORKBENCH Workbench to simulate the tensile test of Carbon/Epoxy UD They are: Static Structural Analysis, and Explicit Dynamic Analysis. The aim is not only to understand the material's behaviour under different conditions, but also to make quantitative comparisons with the results of practical experiments.

3.3.1 Static Structural Analysis

The static structure module to analyse the quasi-static load on the sample with the import of layers from ACP (pre) Figure 3, where the sample was fixed on one side and a displacement of 1.5 mm was applied to the other. As shown in the Figure 3.

3.3.2 Explicit Dynamic

The Explicit dynamic module is also used to analyse the quasi-static load on the sample by importing layers from ACP (pre). One end of the specimen was fixed to prevent any unwanted movement, and a gradual displacement was applied to the other end to simulate the effect of continuous tension. ANSYS WORKBENCH uses Explicit Dynamics analysis to analyse a material's behaviour under rapid and time-dependent loads. This type of analysis allows tracking a material's dynamic response when subjected to sudden or time-varying loads, such as a high-speed tensile test.

The study began by building the material layers in the ACP (Pre) module, then linking the model to the Explicit Dynamics module to apply loads and define boundary conditions.
The following Figure 4; illustrates the complete workflow involved in this type of analysis, from model preparation to extracting final results such as stress and strain. It is worth to mention that Figure 4; is used for both analysis considered in this work.

The following diagram of Figure 5 illustrates the sequence of steps in the static structural analysis, starting with geometry and material definition, and ending with results extraction and failure analysis.

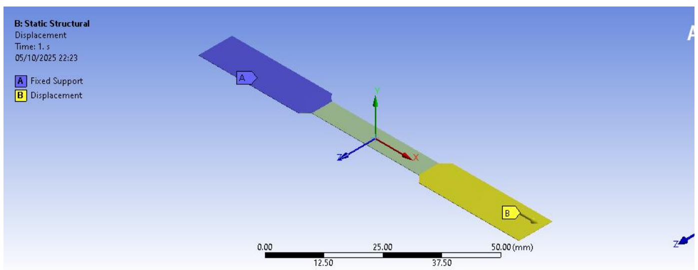

Figure 3: (a) Fixed support, (b) Displacement

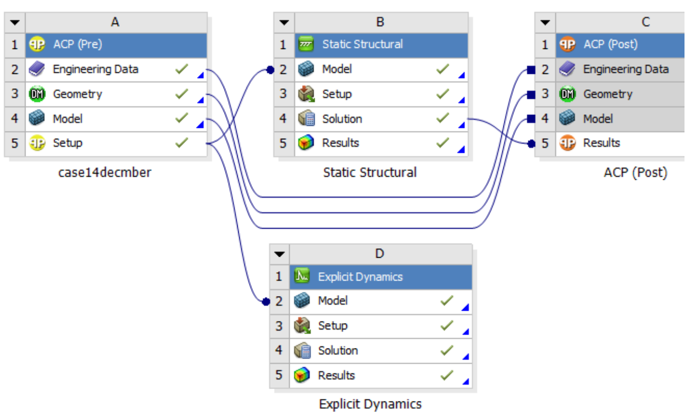

Figure 4. Linking composite Layup for both analyses in ANSYS WORKBENCH

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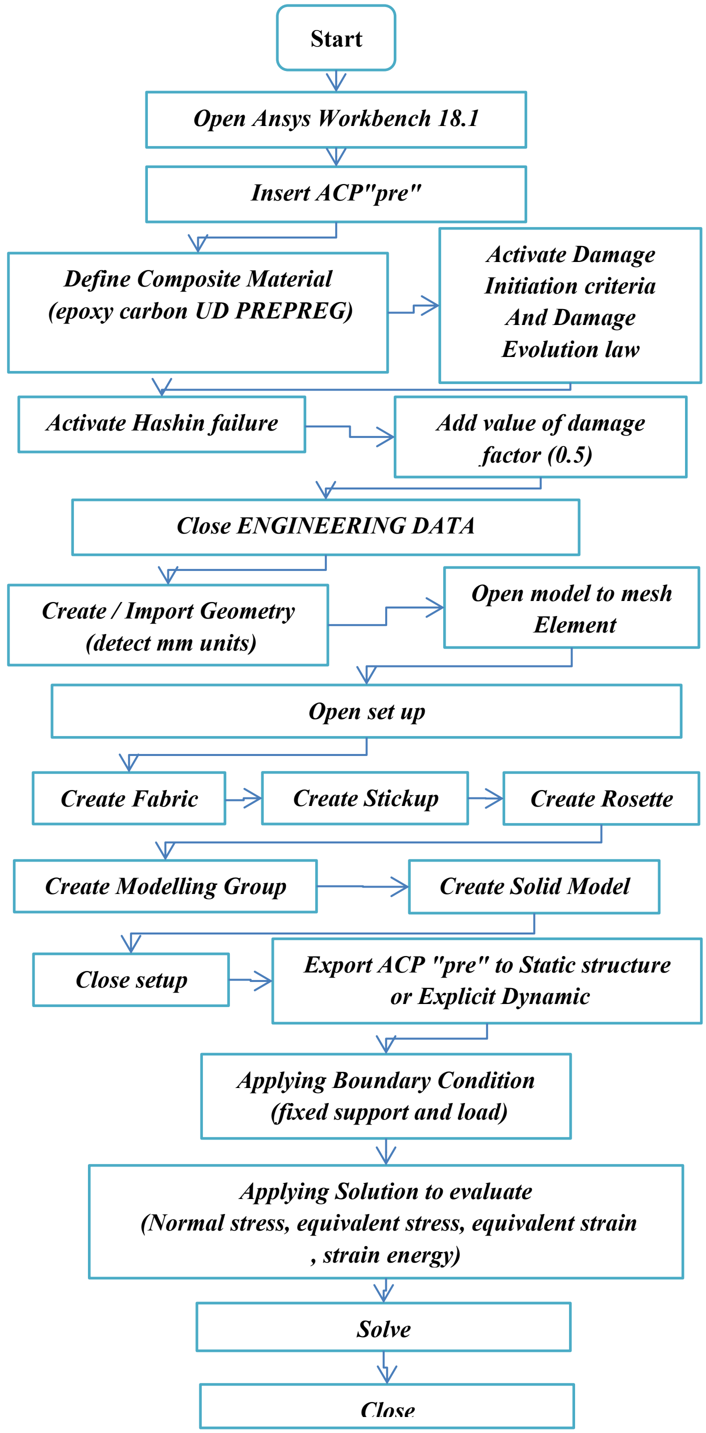

Figure 5. Numerical Analysis steps using the static structure and explicit dynamic module in ANSYS WORKBENCH

4 Result

This research analysed the behaviour of four different types of composite laminates (Balanced, Cross-Ply, Symmetric, and Random) under applied loads. The results showed significant variation in the stress-strain relationship of each kind, reflecting the influence of fiber structural arrangement on mechanical performance. It was observed that some arrangements provide higher stiffness, while others offer greater deformation capacity before failure. These results enable selecting the optimal design according to engineering application requirements.

4.1 Model validation

A preliminary analysis was performed on a carbon/epoxy composite using ANSYS WORKBENCH to validate the numerical model. The results were compared with experimental tests for the sample that was prepared and explained in the previous section. The results of the validation are shown in Figure 6.
It is obvious that the numerical plots are very close to experimental, with the difference not exceeding 8% in static analysis, while not exceeding 13 % in the case of explicit dynamic. From the plot, it appears that the high stress values have a difference ranging from 5-8% in static mechanical analysis. On the other hand, lower stress was reported, particularly beyond strain 0.03, in the case of explicit dynamic analysis. This provides slightly high gradual stress; in both analyses, the validation showed slightly less stiffening variation. These results reinforce the researcher's confidence in the reliability of the numerical model for studying more complex multi-layer models.

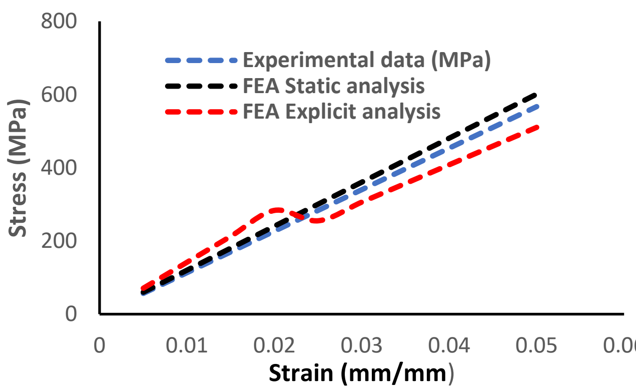

Figure 6. Model validation for both cases: static and explicit FEA

4.1.1 Static stress &strain distribution

Figure 7 illustrates the stress distribution along a specific path created in ANSYS to measure the stress distribution across the specimen when applying a tensile load. First of all, all the laminate types exhibited initial linear behavior, representing the elastic region. Then a nonlinear region was seen for all plots of different kinds of composites, with gradual development as the strain value increased. A higher stress value was determined in the cross ply arrangement, reaching nearly 700 MPa, indicating higher bearing load capability. Nevertheless, a lower load-bearing capacity was reported for the case of composite arranging, with a value of 500 MPa, which determined a less efficient tensile load transfer. Finally, the other types of laminates were proposed to have stable deformation with sensible stress load transfer.
Figure 8 shows the numerical results of the stress distribution in ten-layer epoxy-carbon composite samples, using ANSYS WORKBENCH software for static structural analysis under tensile testing.
Figure (a) represents the stress distribution in a sample with a balanced laminate, where the layers are arranged at opposite angles, such as +45° and -45 °, resulting in a high stress concentration in the centre (shown in red). This reflects a good mechanical response in multiple directions but accumulates stress in the centre. Figure (b) shows the stress distribution in a cross-ply laminate with an alternating 0°/90° arrangement. Here, the distribution is more uniform, with no significant critical concentrations, and the predominant green-yellow colour indicates moderate stress levels. Figure (c) represents a symmetric laminate, which achieves a good balance around the axis of symmetry. Here, stress appears less concentrated in the centre and better distributed across the sample, reducing the possibility of undesired deformations.
Finally, Figure (d) represents a random laminate arrangement, showing a dispersed stress distribution within a composite material and how the layer arrangement affects stress concentration and distribution, helping to evaluate the mechanical performance of each type of arrangement with almost no high-stress areas, reflecting moderate tensile strength but less uniform than other arrangements.
From these results, it is clear that the laminate arrangement directly affects the way stress is distributed and the sample's tensile strength, with a balanced and symmetrical arrangement contributing to improved mechanical performance compared to a random or cross-laminated arrangement.

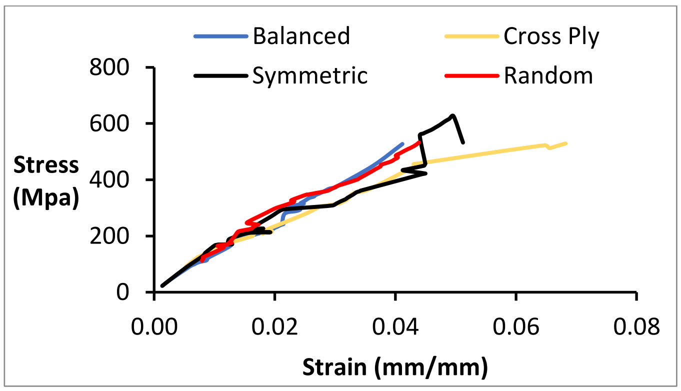

Figure 7. Diagram of stress &strain in static

The results of various stacking sequences under tension for a balanced composite laminate are shown in Figure 9. It can be seen that the top and bottom layers exhibited peak stress values ranging from 120 to 140 MPa, respectively, as indicated by the red colour. Whereas, the inner layers of plys exhibited relatively less stress values with a green and blue region, reaching about (45 –8. MPa), this stress zone could refer to a lower failure zone with much better stress distribution. It is important to mention that the red colour zones represent the gripping area as they directly affect the applied load, and play a crucial role in resisting and transferring the tension stress to the other plies.

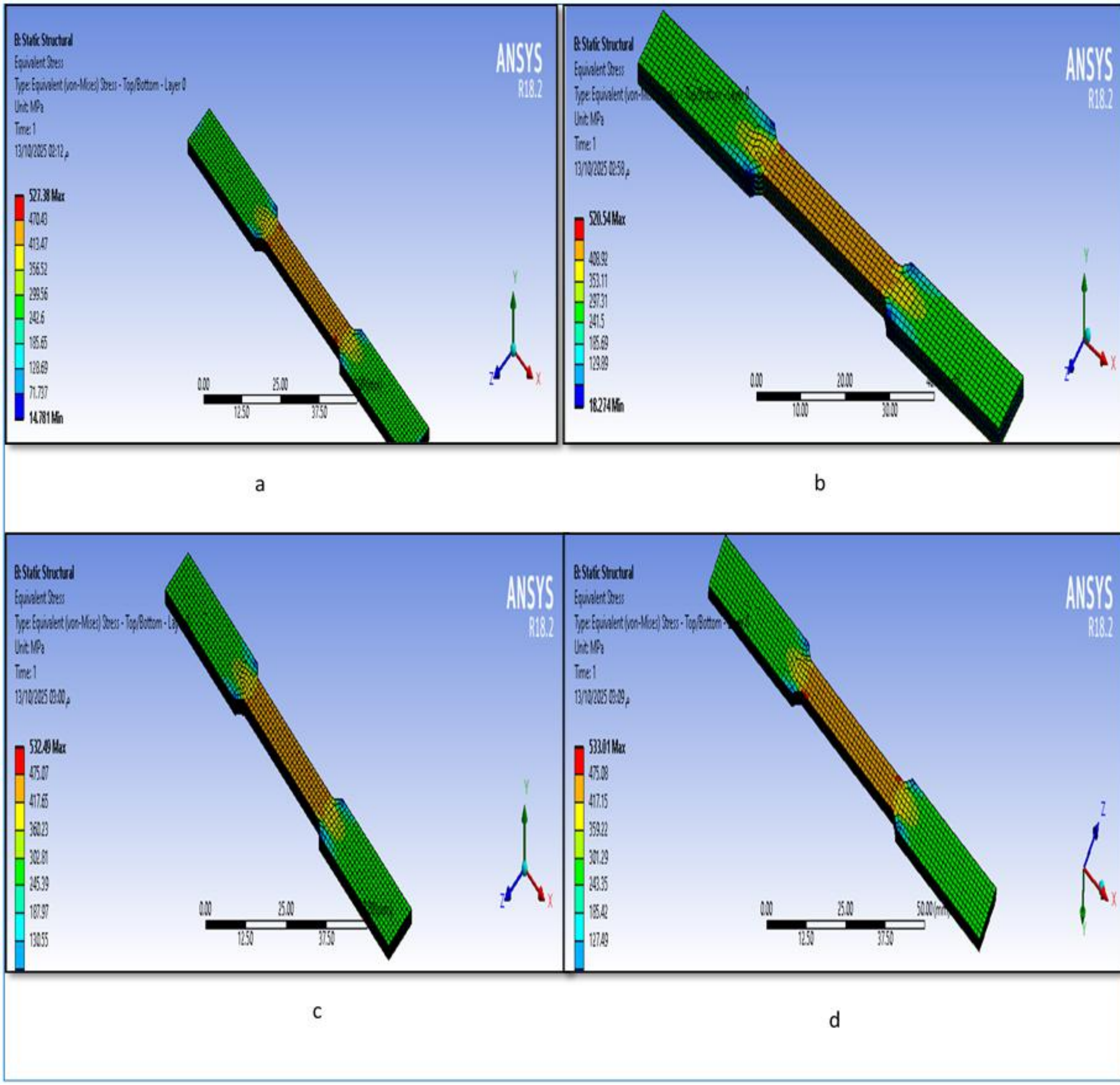

Figure 8.(a) Balanced, (b) Cross ply, (c) Symmetric laminate, (d) Random

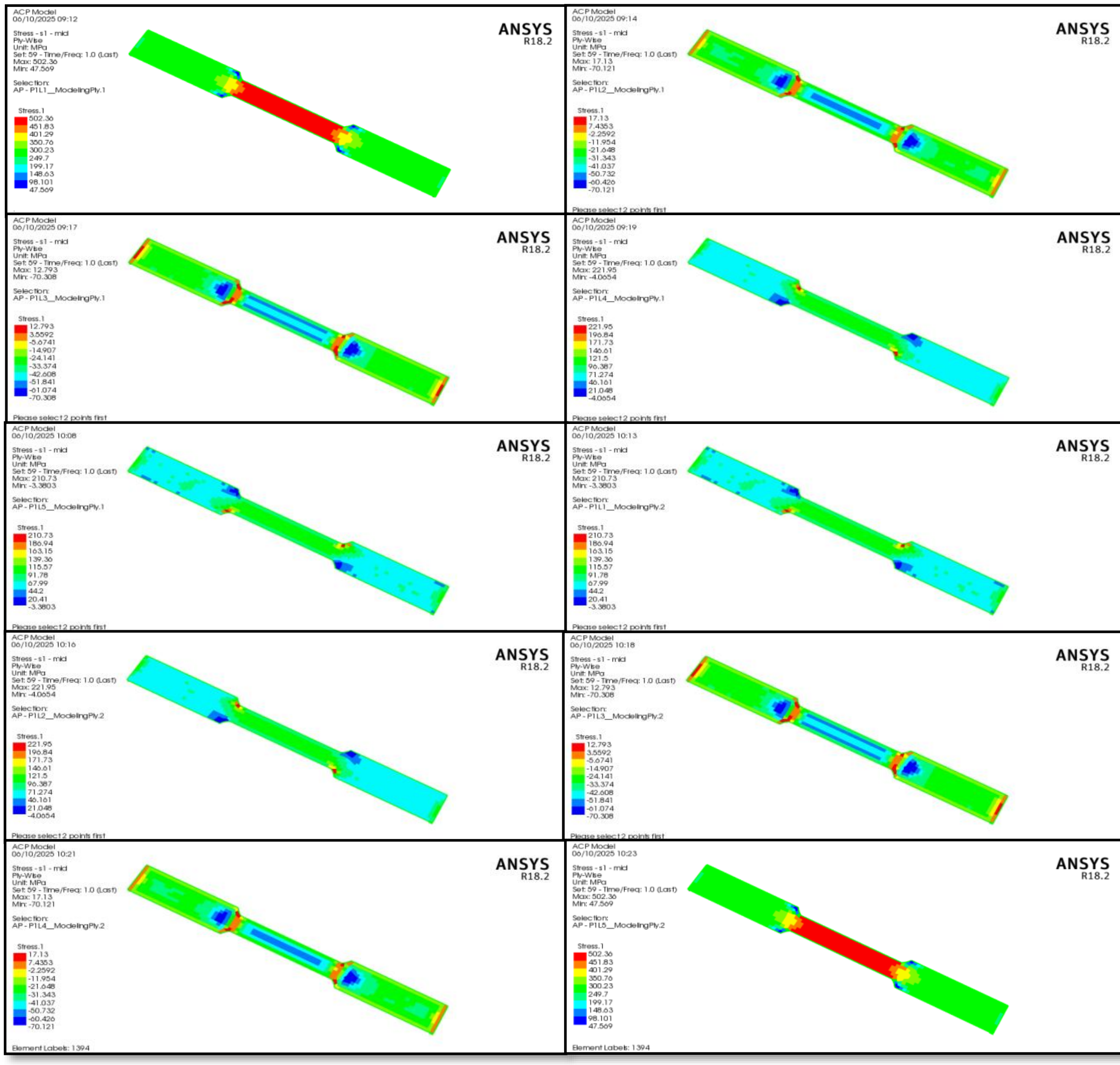

Figure 9. stress in each layer of balanced laminate

Figure 10 illustrates the stress distribution along a specific path created in ANSYS WORKBENCH to measure the stress distribution across the specimen when applying A tensile load.

Figure (a) represents the specimen with balanced laminates, where the stress path appears oblique across The specimen with high stress values in the centre, as indicated by The stress path appears oblique across the specimen with high stress values in the centre, as indicated by the red representing the highest value on the scale. Figure (b), the specimen with a cross-ply laminate, shows a uniformly graded stress distribution from the centre to the edges, with lower peak values than in the balanced case.
Figure (c), which represents the symmetric laminate, shows the random laminate's regular resistance to dynamic loading and its random propagation to failure. The stress path appears oblique across the specimen with high stress values in the centre, as indicated by the red representing the highest value on the scale.

Finally, Figure (d), which represents the specimen with random laminates, shows an irregular stress path, with high stress regions concentrated at random locations within the specimen, reflecting the heterogeneous nature of this arrangement and its impact on load distribution. Overall, path analysis in ANSYS WORKBENCH provides essential insight into how load is transmitted.

4.1.2 Explicit stress &strain distribution

The results of the explicit analysis predict stress–strain analysis as shown in the Figure 10. It can be noticed that there were different load responses for laminates of composite configuration. As seen in static analysis, the cross ply composite offered the ultimate stress value among the four laminate configurations, reaching a value of 1911.2 MPa. Additionally, a laminate configuration with balanced exhibited the second top-ranked with a value of 1890 MPa, whereas a symmetric configuration provided a load bearing capacity of 1881 MPa, a significant reduction in the stress was reported for the random configuration

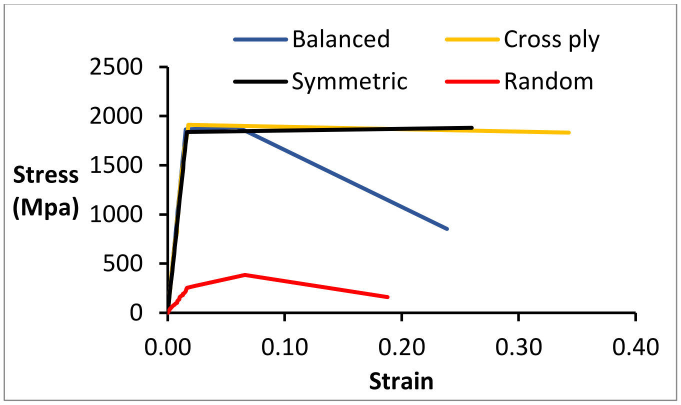

Figure 10. stress-strain in explicit

Figure 11illustrates the results of an explicit dynamic analysis in ANSYS WORKBENCH to study the behaviour of ten-layer epoxy-carbon specimens under dynamic tensile loading, with varying layer arrangement. Figure (a) shows the specimen with a balanced laminate, where we notice a pronounced deformation in the centre region with a gradual stress distribution from red (highest stress) to blue (lowest stress), reflecting the ability of this arrangement to absorb load gradually. Figure (b) represents the cross-ply laminate arrangement, where we notice random deformation and multiple failure zones spread across the specimen, indicating a less uniform response to dynamic loading.

Figure (c), which represents the symmetric laminate, shows a more organised stress distribution with stress concentrated in the centre of the specimen, reflecting the effectiveness of this arrangement in resisting dynamic loading. Finally, Figure (d) of the random laminate shows severe, random failure and deformation zones, with large stress concentrations at multiple points; it demonstrates that people with low incomes are at risk. Overall, the explicit dynamic analysis shows the effect of the laminate arrangement on the composite material's resistance to dynamic loading. Balanced and symmetrical arrangements lead to better and more consistent performance, while crisscrossed and random arrangements exhibit an unstable response and are more prone to failure.

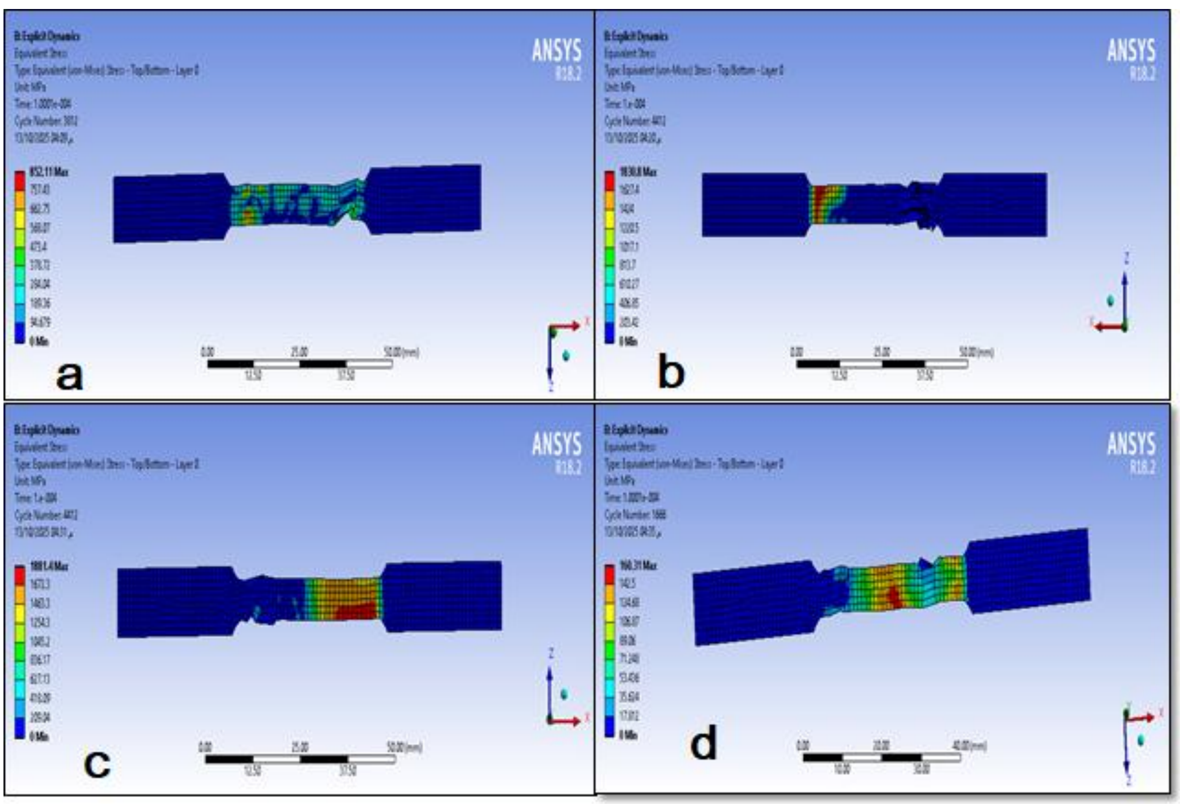

Figure 11. (a) Balanced (b) Cross ply (c) Symmetric laminate (d) Random

Compared to previous studies, such as those by Ahmed Fadhil (2013) and Milan Žmindák (2020), we observe a significant convergence in composite materials' failure mode and behaviour. In Ahmed's study, the maximum stress for the carbon specimen reached 394 MPa. In contrast, in Milan's study, values ranged from 191 MPa in the 90° direction to over 500 MPa in the 0° direction, confirming the influence of fiber arrangement. Thus, the results of this research reinforce the literature and demonstrate the accuracy of the numerical model used to represent failure and analyse stored energy and strain. Finally, static and explicit dynamic analysis provided a more comprehensive understanding of material behaviour and demonstrated that the layered design and type of numerical analysis significantly impact predicting actual failure.

4.2 Failure Criteria

In this current investigation, two crucial correlated metrics have been utilized to determine the failure analysis for composite materials being used in this investigation. These metrics are the Failure Index (FI) and Reserve Factor (RF), respectively. Essentially, it is important to explain each term. The first one refers to a direct ratio where a value above 1 points to failure. On the other hand, the RF denotes the factor of safety, meaning how many times the load might be increased before failure occurs. The RF value is inversely related to FI. Table 3 reports the maximum failure criteria based on the Hashing model for the four types of composite laminates under specific loading conditions; indeed, this would provide an indication for the most critical design between the set. On the other hand, the symmetric and random laminate structure provided moderate failure criteria values. It could be suggested that from the moderate values for balanced and symmetric configurations, there is reasonable stability and strength, because of their resistance to defamation with stiffness enhancement. What can emerge from the table is that the cross-ply laminate implies a great configuration that would provide much better load-bearing capacity for long-term applications, which offer strong structural integrity. It could justify this superior result for the cross-ply laminate due to the fact that most of the load will be distributed and carried by the matrix, while the fibre load would apply perpendicularly. The 90 ° are fully engaged in stress distribution and charring, while the 0° fibres are underutilized considerably because the applied loads were aligned with fibre orientations [24, 25]. Further analysis data was obtined from the FEA model is the strain energy, as seen in Table 3; for all cases of laminte configurations the value ranging from 0.899 to 1.514 MJ. The results exhibited a superior stiffness and can stain within lear elastic beaviour under this loading condition.

Table 3: Failure Criteria Result

Laminate Type	Reserve Factor	Failure Index Conversion	Strain energy
Balanced	4.6	0.217	0.89916
Cross ply	6.7	0.149	1.5123
Symmetric	6.6	0.152	1.4892
Random	5.3	0.189	1.5136

5. Conclusions

This research investigates the tensile behaviour of Unidirectional Prepreg carbon/epoxy composites through experimental tests and numerical analysis using ANSYS WORKBENCH. From the study, several points can be concluded as listed below:

1. The study's validation exhibited an error percentage of less than 8% and 13% for both static and explicit analysis correspondingly. Therefore, the current model demonstrated an acceptable range of reliability and accuracy to investigate different laminate structures.
2. The static analysis revealed that a 700 MPa ultimate tensile stress was obtained for the cross-ply type, while the balanced laminate exhibited a weaker load response, 30 % lower than the cross-ply. From the results, it can be concluded that the laminate arrangement and fiber orientation significantly influence the strength of the composite material considered in this work
3. Regarding explicit dynamic results, it has been concluded that the cross-ply layer structure has a peak value of ultimate stress reached 1911.2MP, which beats the other configurations by nearly 1.6% . In contrast, a noticeable reduction was reported for the random laminate structure by almost 80% in tensile value. Confirming the dependency stacking sequence and fiber orientation strength of these composites.
4. These findings highlight the critical role of ply arrangement in enhancing the mechanical integrity of composite structures and support the need for deliberate design strategies in laminate engineering.
5. From the study, the laminate configuration of cross-ply stands as the best option in terms of reverse factor, which indicates a value of 6.7, and the highest energy of strain reached 1.5123 with 46% higher safety margin. As a result, this configuration is suggested to be the best combination and capability for the safety structure and energy absorption.
6. The current paper recommends ACP Pre (Advanced Composite Pre-processor) as an effective tool for simulating composite materials with layered structures.
7. Adopting strategic ply arrangements, particularly Cross-ply or Balanced, to maximise strength is essential to decrease premature failure and optimise load-bearing capacity.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

AI Declaration Statement

The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

Author Contribution Statement

Ahmed F Hasan: proposed the research problem.

Zainab Jasim Mahmood .: developed the theory and performed the computations.

Zainab Jasim Mahmood .: verified the analytical methods and investigated the resserch gap, Ahmed F Hasan :supervised the findings of this work.

Both authors discussed the results and contributed to the final manuscript.

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