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Numerical and Experimental analysis of interlaminar stresses in bonded composite patch repairs

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Abstract

This study investigates the tensile behaviour of laminated composite plates repaired with bonded composite patches. The material consists of an epoxy matrix reinforced with carbon fibres, offering superior mechanical properties. Experimental and numerical analyses were performed to evaluate the repair efficiency and restore structural performance. A 3D finite element model was developed using two complementary approaches: a UMAT subroutine based on the maximum stress criterion and a progressive damage model implemented in ABAQUS/Implicit. To predict fracture modes, the extended finite element method (XFEM) was combined with cohesive zone modelling (CZM) to simulate adhesive debonding between substrates and plies, using both meshed (UMM) and meshless techniques. The simulation results agreed closely with experimental data, showing less than 5% deviation in ultimate load. The composite patch significantly reduced stress concentration, except for the GFRP plate repaired with a GFRP patch in the (–45/45) stacking sequence, which exhibited a more favourable stress distribution at 5 MPa. The validated model optimises patch design, enhancing performance, durability, and strength of repaired aeronautical composite structures.

Keywords: Composite, Finite laminate model, Bonded repair, Maximum stress criterion, XFEM, CZM

1. Introduction.

Composite materials, thanks to their exceptional mechanical properties, low density, and adaptability [1], are increasingly used in the aerospace industry, particularly in new-generation aircraft such as the Boeing 787, Airbus A380, F-35, and AH-1W [2], as they can withstand significant loads while keeping the overall weight low [3]. Despite their many advantages, composite materials can experience various types of damage in service, such as impacts, cracks, or fibre breakage, thereby compromising their structural integrity and safety [4, 5]. Among these failures, delamination is a major concern, as it manifests as the separation of adjacent layers in the laminated composite. This phenomenon is mainly caused by the lack of reinforcement through the thickness, leading to the separation of neighbouring layers [6, 7].

In other studies, the most critical types of damage in laminated composites are fibre tensile or compressive failures [8]. In addition to their high manufacturing cost and the complexity of recycling, their behaviour under ageing or impact remains difficult to predict. Local repair provides an effective and cost-efficient alternative to the complete replacement of damaged parts, thereby extending their service life. Hence the need for advanced observation tools, for example, Chen et al. [9] described a repair index based on the predicted allowable strain and proposed using the damage size as the minimum repair area. Similarly, Tong et al. [10] proposed an analysis of the repair endurance of composite structures based on collision risk, supported by impact damage tests. Repair methods have been developed since the emergence of modern composite

materials, such as carbon/epoxy systems [11]. Thus, the most commonly used repair method today remains the patch technique, which is mechanically attached by bolting, riveting, or bonding [12], whether it involves metal/metal, composite/metal, or composite/composite assemblies. In aircraft maintenance, the repair of structures using bonded composite patches is a conventional, precise, and cost-effective solution, particularly suitable for components sensitive to corrosion [13]. Composite patch repair is a common method for restoring laminated composites [14]. Composite patches are widely used to repair damaged metallic or composite structures [15-17]; particularly in cases of cracks, fractures, or impacts, as they help restore the mechanical capacity of composite structures.

This technique falls into two main categories: internal patches, which aim to replace a damaged section to achieve a smooth surface a permanent method [18, 19], Despite their advantages, internal patch repairs are more complex, more expensive, and require a larger repair area [20]. External patches, on the other hand, are simpler and more flexible, as they are bonded directly onto the affected area, allowing for quick on-site repair. External bonded repair is a robust and efficient approach for restoring composite structures [21]. For maximum efficiency, these patches are manufactured in various geometric shapes [22, 23], to optimise the coverage of the damaged area, extend service life, reduce stress concentrations, and delay failure and crack propagation. Several criteria guide the selection of the patch material and adhesive properties, particularly for damaged composite laminates repaired using adhesive patches [24]. These criteria include the nature of the patch, its architecture, the effects of the adhesive thickness used, and, most importantly, the size and properties of the patch material itself: ply type, dimensions, and the orientation and selection of fibres [25]. Numerous studies are currently evaluating the mechanical properties of patches and adhesives for the assessment of repaired plates [26-28]. Thus, composite patches are used not only as a means of repair but also as a pre-emptive reinforcement of structures. The effectiveness of the reinforcement naturally depends on the number of plies in the composite patch [29], for example, its shape or size. Experimental and numerical results have shown that fatigue life increases by 30 to 85% compared to non-optimal lay-ups when the crack is in mixed mode [30]. If the crack is purely in mode I, the orientation that allows the greatest reduction in the stress intensity factor is when the fibres are aligned perpendicular to the crack [31]. A comprehensive numerical study was proposed to analyse a cracked plate under mixed-mode conditions, using a large number of stacking sequences combining 90° and +/- 45° orientations [32].

Many failures of repaired composite assemblies are due to stress concentrations in the adhesive, resulting from a progressive load transfer zone between the substrate and the patch. The repair of notched structures using a bonded composite patch is of critical importance to minimise the stress field in areas of high stress concentration. This technique helps relieve highly stressed regions by redirecting the load path. Several studies have focused on the theoretical analysis of stresses within the composite patch and the adhesive, as the latter is often the weakest link in a repair [33, 34]. Indeed, it is often the cause of composite patch failures, as its rupture or debonding leads to the detachment of the composite reinforcement [35]. Composite plates repaired with adhesive patches are sensitive to impact loads, which can cause fibre or matrix failures. Researchers such as Cheng et al. [36] have studied the stress distribution, initiation, and propagation of damage in composites repaired with external bonding using infrared thermography. Kashfuddoja et al. [37] have investigated the displacement and strain fields of the adhesive layer in a unidirectional CFRP specimen repaired with a single-sided patch, using digital image correlation and finite element analysis. To optimise patched perforated plates, it is essential to accurately know the stress state at every point under loading. Most research has focused on analysing stress distribution and calculating the stress intensity factor for damaged plates with different notch shapes, which is of growing interest in fracture mechanics [38-41]. Kumar et al. [42] have reviewed early studies on stress concentration factors and the tensile strength of fibre-reinforced composites with holes, using experimental, analytical, and numerical methods. Fibre-reinforced laminated composites exhibit various damage modes that occur simultaneously under tensile loading [43]. Due to the complexity of these phenomena, experimental methods are time-consuming and costly, while analytical methods are limited to simplified models. Therefore, a robust and efficient numerical analysis is required. Finite Element Analysis (FEA) is commonly employed to study the tensile behaviour of repaired composite structures. Investigations on damaged laminated composites have been conducted using both numerical and experimental approaches, applying various criteria.

The Hashin failure criterion and a material property degradation method were used in the work by Fangyu et al. [44], studied the damage of open-hole laminated composites under tensile loading. McCarthy et al. [45], carried out a numerical analysis of open-hole tension based on the Hashin criterion and a continuous nonlinear material degradation model, which was validated experimentally. Although the Hashin criterion is conventional and widely used, it can be improved for more accurate prediction of damage modes and validation of numerical models. In a study, Feng et al. [46], proposed a three-dimensional tensile damage model for composites, incorporating the Hashin and maximum stress criteria, as well as a cohesive zone model, to predict fibre, matrix, and interfacial damage in carbon fibre-reinforced laminates (CFRP). In studying the strength of composite laminates, Hwang and Sun [47], conducted a failure analysis of laminated composites using a three-dimensional iterative finite element method. Based on the Tsai-Wu failure theory, three different failure modes were proposed: fibre rupture, matrix cracking, and delamination. Alizadeh et al. [48], numerically determined the ultimate residual in-plane compressive strength of delaminated composite laminates. O'Higgins et al. [49], conducted an experimental and numerical study of the notched tensile strength of high-strength carbon/epoxy composites. Recent studies have explored the progressive analysis of composite damage, considering various factors such as interface models, laminated composites, mesh types, mesh partitioning methods, and damage evolution [50, 51]. Other researchers [52], have subsequently improved this damage evolution model. Additionally, the composite is modelled using a Continuum Damage Mechanics (CDM) approach to predict in-plane failure modes [53]. CDM, combined with maximum stress failure criteria, allows for the prediction of damage initiation and assessment by linking internal damage variables to the fracture energy.

High loads degrade the composite structure, particularly through delamination [54]. This phenomenon, exacerbated by the interaction between delamination and microcracks, promotes the opening of transverse cracks at the interfaces and creates leakage paths through the laminate [55]. The stacking sequence and laminate thickness influence the density and permeability of cracks [56]. Several studies developing finite element models capable of predicting fracture modes in composites have employed a unit partition approach for microcracks and a CZM approach for delaminations [57]. 3D XFEM simulations have been performed on multilayered polygonal composites with variable fibre orientations [58, 59]. Other work is based on a combined XFEM and SCZM (surface cohesive zone model) approach for damage modelling in laminated composites, where XFEM is used for the initiation and propagation of microcracks (intra-laminar failure) [60]. Pereira et al. [61], have experimentally and numerically studied adhesive failure using cohesive zone models (CZM) and employed the Tsai-Wu criterion to predict composite fractures. Serna Moreno et al. [62] have numerically and experimentally studied, using the XFEM method under tensile testing, the initiation, path, and propagation rate of cracks in glass fibre-reinforced composites, in agreement with experimental results.

Due to the inability of previous studies to model or validate the predicted damage patterns in three-dimensional laminated composites repaired by bonding, this work proposes a numerical methodology based on experimental data to predict failure modes in bonded laminated composites, thereby contributing to the understanding of composite structure failure. This methodology assesses the impact of patch types, ply orientations, and reinforcement material substitutions (glass or carbon fibres) on the mechanical performance of the repair. Specifically, we determined the maximum normal stress for an unrepaired plate, and for a repaired plate, the shear stresses in the adhesive and peel stresses in the patch—critical values for evaluating the strength of the bonded area and validating our model. These calculations were performed using a damage-based approach. Damage initiation and assessment in the laminated composite plate are predicted by combining the maximum stress criterion and fracture energy, using the XFEM method to predict crack modes. Cohesive zones (CZM) model the inter-laminar adhesion between the plies and the composite patch.

2. Fabrication and Tensile Test of Composite Specimens

The accurate modeling of composite behavior in a finite element code requires determining the stress–strain curve of each ply. To obtain these data, a tensile testing campaign was carried out. The results of these tests made it possible to characterize the mechanical properties of a single-ply specimen. These data were then used to simulate the mechanical behavior of repaired and unrepaired structures. This approach made it possible to estimate the mechanical properties necessary for the proper execution of numerical simulations and to

validate the models thus developed. Researchers [63, 64], The tensile properties of a carbon-fiber-reinforced polymer (CFRP) composite were investigated. The material was manually fabricated using one or multiple layers of carbon/epoxy fabric, a material widely employed in the aerospace and space industries. The main advantage of using fabric as reinforcement lies in achieving balanced laminate properties in the 0° and 90° orientations. The manufacturing process involved a vacuum lay-up (60 kPa) of epoxy resin and carbon fabric (T300SC/EPOCAST 50-A1), followed by curing at 25°C for 8 hours. To enhance adhesive bonding with composite materials during repair operations, two approaches were adopted. Firstly, surface treatment was considered essential to ensure optimal contact between the adhesive and the composite. Surface cleaning using hydrofluoric acid was preferred for its simplicity and improved surface reactivity. Secondly, the structural adhesive ADEKIT-A140 was selected as the bonding agent. In summary, the repair of composite structures should be straightforward, efficient, and unobtrusive, without compromising the functionality of the components. Three composite configurations, each consisting of eight plies (an intact plate, a plate with a central hole, and a plate repaired with a carbon patch), were fabricated. The specimens, composed of an epoxy matrix reinforced with carbon fibers, were cut by water jet according to the ASTM D3039 tensile testing standard, as illustrated in Figure 1. Aluminum tabs were bonded using an epoxy adhesive film to ensure uniform load distribution during testing.

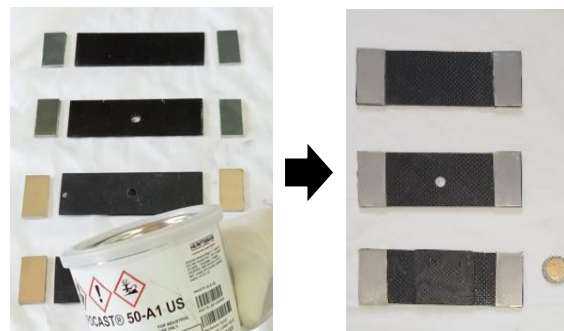


Figure 1. Composite specimen preparation process

Tensile tests were performed on both single-ply and multi-ply specimens in three conditions: intact, damaged, and repaired using patches made from two different types of fibers. All experiments were conducted at room temperature in the LMPM laboratory of the Mechanical Engineering Department at the University of Boumerdes. A 50 kN INSTRON testing machine (Figure 2), equipped with an extensometer, was used for this purpose. The testing system was computer-controlled through the TestExpert software to ensure precise loading and data acquisition. The stress–strain curves obtained for each specimen configuration, including the single-ply plates, the damaged unrepaired plates, and those repaired with bonded composite patches, are presented in the results section.



Figure 2. Tensile testing setup: (a) single-ply carbon composite laminates according to ASTM D3039 standard, (b) eight-ply carbon composite laminates.

Figure 3 shows the model of a damaged composite plate repaired with a patch. The plate, with dimensions of $150 \times 50 \times 1.86$ mm, contains a central hole of 10 mm in diameter simulating impact damage. For the repair, a composite patch measuring $50 \times 50 \times 1.86$ mm was bonded to the plate using an ADEKIT-A140 adhesive layer with a thickness of 0.2 mm. The assembly — consisting of both the plate and the patch — is made up of eight plies with a stacking sequence of $[0/90]_8$ AS (Figure 1).

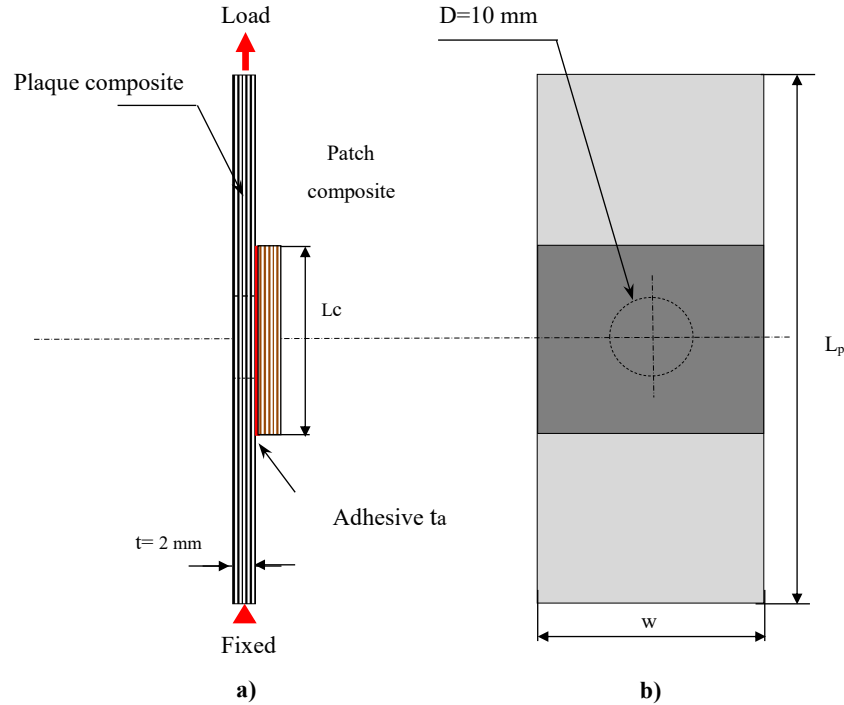


Figure 3. Geometrical model of a composite plate repaired using a composite patch.

To simulate the tensile test, a geometric model of the composite plate was developed with boundary conditions replicating those of the experimental setup. The lower edge of the specimen was fully constrained ($U_1 = U_2 = U_3 = 0$ and $R_1 = R_2 = R_3 = 0$), while a controlled displacement was applied to the upper edge, where transverse displacements and rotation about the loading axis were restricted ($U_1 = U_2 = 0$, $U_3 \neq 0$ and $R_1 = R_2 = R_3 = 0$). This configuration accurately represents the specimen elongation produced by the testing machine grips, thereby allowing the determination of the tensile stress–strain response (see Figure 1.a). The mechanical properties of the adhesives ADEKIT A140 and Epoxy Epocast 50-A1/946 implemented in the numerical models were obtained from the studies of Houari et al. [65] and Djellab et al [66], as summarized in Table 1.

Table.1 : Elastic constants of constituent materials employed in the numerical modeling (Houari et al. [65] and Djellab et al [66]).

Properties	Units	E (GPa)	G (GPa)	ν	σ_r (MPa)	ρ [Kg/m ³]
Adekit A140		2.690	0.99	0.35	32	1300
EPOCAST50-A1/946		3.430	1.4	0.32	50	1100

3. Numerical Study of Patched Composites

The study of the strength of repaired composites is complex due to the difficulty in identifying their damage mechanisms, which makes the selection of an appropriate patch challenging. Modeling these materials requires a specific methodology, as failures may occur simultaneously and crack initiation is unpredictable. This random nature is caused by various factors, such as variations in mechanical properties, geometric tolerances, applied boundary conditions, and the presence of manufacturing defects.

This study presents a three-dimensional finite element analysis of patched composite plates using a damage model. A numerical approach is proposed to monitor the damage evolution of these composite plates under uniaxial loading, thereby meeting the aerospace engineering requirements for numerical assessment of structural degradation. This analysis method simplifies the model by integrating intra-laminar and inter-laminar damage, the patch–cohesive–plate interaction, and by coupling XFEM with an efficient traction model. The XFEM/CZM couplings were used to validate our numerical model against experimental results.

3.1. Damage modeling for composite materials

The damage analysis is carried out in two phases: initiation and propagation. The initiation of failure is determined by the MAXPS criterion (Maximum Principal Stress) under monotonic loading. This simple criterion, commonly used in engineering, identifies the crack initiation in areas of high stress concentration within each layer, reflecting stress interactions and influencing the estimation of failure stress under multiaxial loading modes.

Crack propagation, on the other hand, is analyzed through an energy-based approach using the Extended Finite Element Method (XFEM). This numerical technique enriches the mesh elements, allowing the simulation of crack initiation and propagation paths, as well as the modeling of structural separation under uniaxial loading while accounting for the degradation of material properties.

In the case of plane stress conditions (σ_L longitudinal, σ_T transverse, σ_{LT} in-plane shear), expressed in the principal coordinate system of the ply ($\sigma_L, \sigma_T, \sigma_{LT}$), the maximum stress criterion is defined by the following equation:

$$\begin{cases} X_C < \sigma_L < X_T \\ X_T < \sigma_T < Y_T \\ -S < \sigma_{LT} < S \end{cases} \quad (01)$$

Or X_T and X_C correspond respectively to the strength in the longitudinal direction in tension and in compression, Y_T and Y_C correspond respectively to the transverse tensile and compressive strength, and S to the shear strength. The evolution of damage up to ply failure is modeled using the XFEM technique, which simulates the linear degradation of stiffness as a function of the fracture energies, both in the fiber and in the matrix.

To predict crack propagation, several damage evolution laws, such as the power law, the Reeder law [67], and the Benzeggagh–Kenane (BK) law, can be used. In our study, we opted for the BK law, developed in 1996 [68], which serves as a criterion to simulate the evolution of damage and crack propagation, based on the relationship between the energy release rates.

$$G_{equiv} = G_{IC} + (G_{IIC} - G_{IC}) \left(\frac{G_{II} + G_{III}}{G_I + G_{II} + G_{III}} \right)^\eta \quad (02)$$

Which defines an equivalent critical energy release rate, G_{equiv} , combining energy release rates from all three fracture modes (G_I, G_{II} and G_{III}), where η is a curve fitting parameter. An adapted meshing method allowing the selection of an appropriate finite element characteristic length (L_e), also links the volumetric energy to the fracture energy, which is essential for simulating the opening of a long crack in a composite [69, 70]. Failure is characterized by a gradual decrease in interfacial stress, which vanishes as separation increases. Complete delamination is reached when the damage evolution variable (D) reaches the critical value of 1. In the case of a linear stiffness degradation, the expression of D is simplified.

$$D = \frac{\int_0^{\bar{\epsilon}_f^p} L_e \sigma d\bar{\epsilon}^p}{G_f} \quad (03)$$

All material parameters used for this model were obtained from the results of the previously mentioned tests or from the manufacturer's technical data sheets. The prediction of crack initiation requires the

identification of enrichment zones within the model. In the standard X-FEM formulation, the displacement $u^h(x)$ is approximated by [60, 71-75] :

$$u^h(x) = \sum_{i \in N} N_i(x) u_i + \sum_{i \in N_d} N_i(x) H(x) a_i + \sum_{i \in N_p} N_i(x) \left(\sum_{j=1}^4 F_i(x) b_i^j \right) \quad (04)$$

Where N is the set of mesh nodes, and u_i is the classical degree of freedom at node i . $N_i(x)$ are the standard finite element shape functions associated with node i , while a and b are the corresponding degrees of freedom. $H(x)$ is a Heaviside-type enrichment function, and $F_i(x)$ are enrichment functions that represent the singularity in the vicinity of the crack front. :

$$\{F_i(x)\} = \left\{ \sqrt{r} \sin \frac{\theta}{2}, \sqrt{r} \cos \frac{\theta}{2}, \sqrt{r} \sin \frac{\theta}{2} \sin \frac{\theta}{2}, \sqrt{r} \cos \frac{\theta}{2} \sin \frac{\theta}{2} \right\} \quad (05)$$

Or (r, θ) are the polar coordinates in the local axes at the crack tip. The XFEM method, implemented in ABAQUS and particularly suited for fracture mechanics, simulates the degradation of materials with varying compositions. The 3D maximum stress failure criterion for composite laminates was implemented in a UMAT subroutine for continuous damage degradation. This custom material subroutine allows the definition of the mechanical behavior of a composite. The model iteratively solves a set of equations to obtain a convergent displacement solution, assuming a constant material state at each load increment. The stress/strain calculated at each point is used with the undamaged stiffness matrix to obtain an updated stress/strain state. This is then compared to the failure criterion to determine whether damage has occurred. If no damage is detected, the next load increment is applied. In the event of failure, the damage variable (SDV7) and the post-damage Jacobian matrix are computed, after which the process returns to ABAQUS [65]. The ply coupling method was used to transfer the load between the composite layers using the UMM meshing method.

3.2. Cohesive Modeling of Repaired Composite Interfaces

Several numerical models have been proposed to predict the fracture behavior of bonded interfaces, such as the VCCT, XFEM, ZCM, and Adhesive as a Third Material (Tie) methods, with or without VCCT [65, 76]. Contact-based models represent the adhesive as a simple interaction between surfaces—a faster method, but one that does not allow for a detailed study of crack propagation. Another approach is to model the adhesive using 3D solid elements, which provides an accurate representation of its behavior but can make the computation heavy and time-consuming. Finally, the Cohesive Zone Model (CZM) is the most common for delamination, as it simulates the progressive failure of an adhesive layer. Although highly effective for crack propagation analysis, it requires knowledge of a traction–separation law, which is difficult to determine experimentally [22, 65, 77, 78]. The latter are particularly useful for studying delamination, which is a major failure mode in composite materials. They provide a more realistic approach than traditional fracture models by simulating the damage process progressively. This allows for accurate prediction of defect initiation and evolution, which is crucial for the design and reliability of composite structures. To model the interaction between the layers of the composite plate and the adhesive, we used a cohesive zone model through two complementary methods to simulate the adhesive layer of the repairs, as highlighted in red in Figure 4. This modeling is based on the properties of an equivalent layer between the warp and weft of a composite fabric ply.

The first method simulates cohesive behavior without meshing, using a simple “surface-to-surface” interaction defined by a contact property. This approach enables the bond to be modeled without introducing new elements into the geometry. The second method employs a dedicated mesh, where the bonding interface is represented by cohesive elements (COH3D8). These elements were modeled with an initial zero thickness to avoid increasing the total thickness of the laminate, which is crucial for maintaining an accurate representation of the structure. We inserted seven cohesive interfaces within the composite plate.

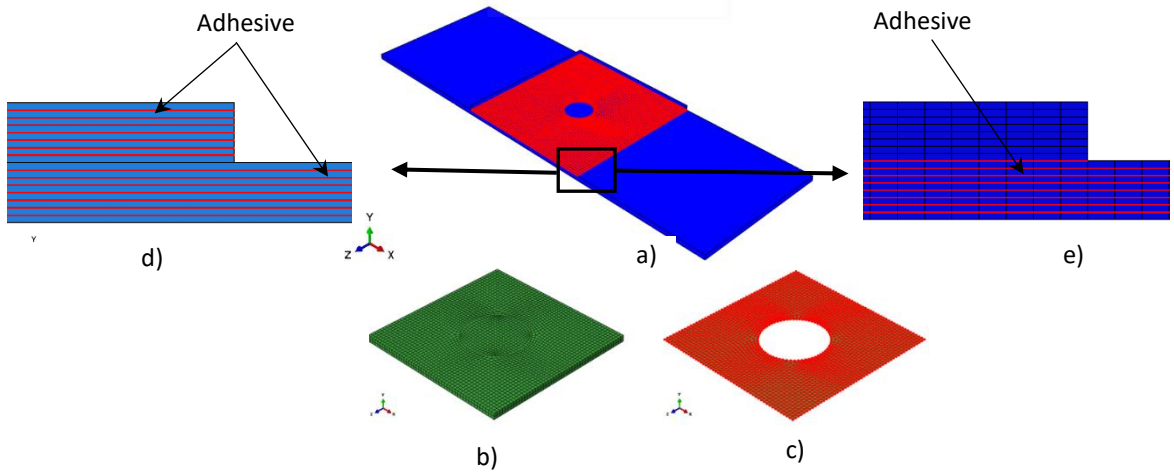


Figure 4: Meshing method in a composite patch-repaired plate: (a) the repaired plate, (b) the patch, (c) the adhesive, (d) cohesive model without meshing, and (e) cohesive model with meshing.

Mixed triangular CZM models are based on a traction–separation law that relates the interfacial stress (t) to the layer separation (δ). The maximum stress ($t_{\max}$) represents the energy required for crack propagation [60, 79], It is equivalent to the area under the traction–separation curve. The nominal strains can be defined as:

$$\varepsilon_n = \frac{\delta_n}{T_0}, \varepsilon_s = \frac{\delta_s}{T_0}, \varepsilon_t = \frac{\delta_t}{T_0} \quad (06)$$

T_0 : Denoting by the original thickness of the cohesive element, the nominal traction stress vector consists of three components (t_n, t_s, t_t) which represent the normal and the two shear tractions, respectively. The elastic behaviour can then be expressed as follows :

$$t = \begin{Bmatrix} t_n \\ t_s \\ t_t \end{Bmatrix} = \begin{bmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{ns} & K_{ss} & K_{st} \\ K_{nt} & K_{st} & K_{tt} \end{bmatrix} \begin{Bmatrix} \varepsilon_n \\ \varepsilon_s \\ \varepsilon_t \end{Bmatrix} = K\varepsilon \quad (07)$$

A cohesive traction finite element exhibits stiffness in three directions — one normal and two shear directions. The stiffness is determined based on the material parameters E, G_1, G_2 and the original thickness of the element. The numerical thickness of the cohesive layer does not need to be the same as the visual geometric thickness in ABAQUS. The simplest way to obtain the desired stiffness is to select the default parameter for the thickness, which assigns it a zero value. This means that E, G_1, G_2 can be treated as K_{nn}, K_{ss}, K_{tt} respectively.

The QUADS criterion is used to define the damage initiation in the cohesive model, serving to simulate the debonding between the patch and the plate. This criterion is a quadratic function that compares the nominal stress to the maximum stress in order to predict the onset of failure between the laminated layers [65, 79], This criterion is represented by :

$$\left(\frac{t_n}{t_n^0}\right)^2 + \left(\frac{t_s}{t_s^0}\right)^2 + \left(\frac{t_t}{t_t^0}\right)^2 = 1 \quad (08)$$

t_n^0, t_s^0, t_t^0 : are the maximum interlaminar traction stresses in pure modes I, II and III respectively, while t_n, t_s and t_t represent their critical values. The normal t_n^0 and shear t_s^0, t_t^0 traction stresses reach their corresponding critical values t_n, t_s and t_t at the onset of damage, which is defined as unity. The propagation of the adhesive debonding is governed by energy-based fracture criteria determined experimentally. The dependence of the fracture energy on the mixed-mode ratio can be described by the power law failure criterion.

This criterion assumes that mixed-mode failure is governed by a power-law interaction of the energy release rates associated with each mode. In this study, an identical energy release rate is assumed for all directions [65].

$$\left(\frac{G_n}{G_{IC}}\right)^n + \left(\frac{G_t}{G_{IIC}}\right)^n + \left(\frac{G_s}{G_{IIIC}}\right)^n = 1 \quad (9)$$

Where G_I , G_{II} and G_{III} represent the energy release rates for the opening (mode I), sliding (mode II), and tearing (mode III) failure modes, respectively, and n is a coefficient determined experimentally. The critical energy release rates. G_{IC} , G_{IIC} and G_{IIIC} are also defined experimentally. In the case of delamination in a composite material, cohesive interface elements are introduced between the plies. The damage of these interfaces is modelled using fracture mechanics, based on a linear coupling criterion between the three failure modes.

$$\frac{G_I}{G_{IC}} + \frac{G_{II}}{G_{IIC}} + \frac{G_{III}}{G_{IIIC}} = 1 \quad (10)$$

In this case G_{IC} , G_{IIC} and G_{IIIC} are assumed to be identical. To employ the traction, separation behaviour of the cohesive law, the criterion is expressed in terms of an equivalent displacement for the three modes:

$$d_{eq} = \sqrt{(d_I)^2 + \left(\frac{d_I^0}{d_{II}^0} d_{II}\right)^2 + \left(\frac{d_I^0}{d_{III}^0} d_{III}\right)^2} \quad (11)$$

With d_I^0 , d_{II}^0 , d_{III}^0 The critical equivalent displacements correspond to the initiation of damage. When the equivalent displacement at failure is reached, the damage propagation occurs through either a linear or an exponential law governing the stress relaxation.

3.3. Proposed configuration

The sizing of structures made of composite materials repaired with patches is a complex problem that can be addressed using analytical approaches or numerical methods. Analytical approaches offer the advantage of general applicability, enabling a better understanding of the influence of various design parameters through different criteria. However, the inherent complexity of the customized shaping of composite materials requires advanced analysis tools and the use of computational methods from the earliest stages of the design process.

Effective sizing relies on a multi-step approach. The mechanical properties of the layers are first determined through experimental testing. These data serve as the foundation for analytical models that describe the behavior of laminates, upon which numerical design methods are then built. The final optimization of the structure therefore combines computer-aided design with performance analysis using the finite element method (FEM). The stacking sequence of composite patches, or the fiber orientations within the fabric, significantly improves strength and fatigue life. Determining the optimal stacking sequence of a composite patch for structural repair is costly and time-consuming due to the numerous performance tests required. To address this issue, we defined approximate stacking limits based on the analysis of simulation results. The distribution, concentration, and orientation of fibers have a tremendous influence on the load-bearing capacity of fiber-reinforced composite materials [80]. To achieve optimal mechanical stress parameters such as strength and stiffness, the composite requires a maximum fiber volume fraction of about 70%. A higher fiber content may lead to incomplete encapsulation of the fibers within the matrix. By controlling the fiber orientation, the load-carrying capacity of the composite material can be adjusted in different stress directions. For example, short randomly oriented discontinuous fibers exhibit a relatively isotropic behavior similar to that of homogeneous materials. Anisotropic behavior is achieved by stacking layers of continuous fibers in the same direction, resulting in excellent load-bearing properties along the fiber direction but poor strength perpendicular to it. If the composite material needs to efficiently withstand loads in multiple directions, the fiber plies are stacked with angular offsets. The finite element code ABAQUS 6.14 was used to perform the FEM modeling of a damaged composite plate repaired with a composite patch. In ABAQUS, finite element analysis of composites differs from that of metals, particularly

in the definition of each ply's properties, which depend on its orientation. For each ply, the mechanical parameters (E_1 , E_2 , etc.) and the desired stacking sequence are input. ABAQUS then applies Classical Laminate Theory (CLT) to calculate the mechanical properties of each element. Once the composite analysis is completed, stress, strain, and other derived quantities are determined for each ply. Since a woven carbon fiber composite layer is produced with a [Weft yarn/Warp yarn] pattern, as illustrated in Figure 5, the material's behavior in the laminate plane is isotropic, which agrees with tensile test data. In another study, the fracture behavior of woven carbon fiber/polyetherimide composites with edge cracks under Mode I, Mode II, and mixed Mode I/II loading was investigated both experimentally and numerically [81].

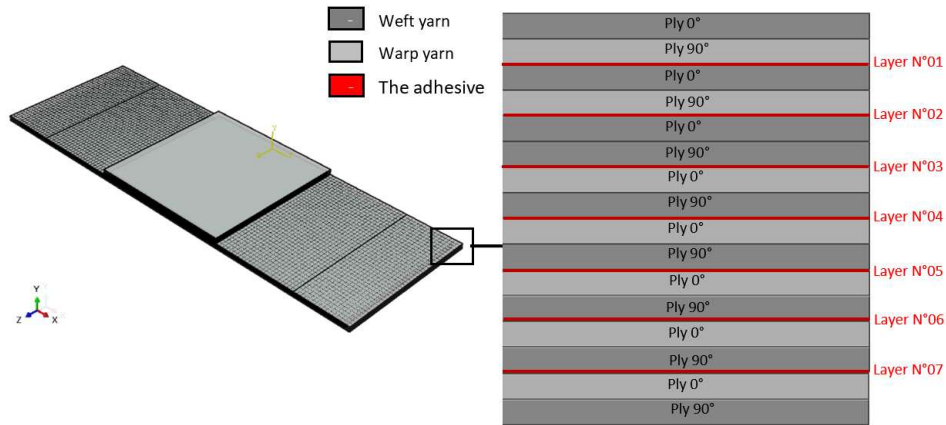


Figure 5: Schematic of the stacking sequences used

Four types of configurations were studied with identical dimensions, using different materials for the repaired plates and the patches, in order to optimize the best combinations based on the results from each test. In summary, the different configurations tested are shown in Table 2.

Table 2: Configuration of the specimens for tensile tests.

Nature of the plate	Nature of the Patch	Symbol	Type of stacking configuration
CFRP	CFRP	CFRP_C 01	Non-symmetry [0/90/0/90/0/90/0/90/0/90/0/90/0/90] s
		CFRP_C 02	Cross-ply [0/90] ₈ s
		CFRP_C 03	Sequence [0/90/45/-45/0/90/45/-45/90/0/45/-45/90/0/45/-45] s
		CFRP_C 04	Antisymmetry [45/-45] ₈ s
	GFRP	CFRP_G 01	Non-symmetry [0/90/0/90/0/90/0/90/0/90/0/90/0/90] s
		CFRP_G 02	Cross-ply [0/90] ₈ s
		CFRP_G 03	Sequence [0/90/45/-45/0/90/45/-45/90/0/45/-45/90/0/45/-45] s
		CFRP_G 04	Antisymmetry [45/-45] ₈ s
GFRP	CFRP	GFRP_C 01	Non-symmetry [0/90/0/90/0/90/0/90/0/90/0/90/0/90] s
		GFRP_C 02	Cross-ply [0/90] ₈ s
		GFRP_C 03	Sequence [0/90/45/-45/0/90/45/-45/90/0/45/-45/90/0/45/-45] s
		GFRP_C 04	Antisymmetry [45/-45] ₈ s
	GFRP	GFRP_G 01	Non-symmetry [0/90/0/90/0/90/0/90/0/90/0/90/0/90] s
		GFRP_G 02	Cross-ply [0/90] ₈ s
		GFRP_G 03	Sequence [0/90/45/-45/0/90/45/-45/90/0/45/-45/90/0/45/-45] s
		GFRP_G 04	Antisymmetry [45/-45] ₈ s

4. Results and Analysis

4.1. Tensile Test

Figure 6 presents the results of the tensile test on the composite specimens. Figure 6(a) compares the tensile behavior of the different single-layer fiber types used. It can be observed that all the curves exhibit a similar trend regardless of the configuration. These curves show an elastic region, indicating the stiffness of the plate at room temperature. Figure 6(b) compares different curves, showing that the presence of a hole causes a significant drop in the mechanical properties of the intact composite plate. The repaired plate recovers about 20% of the property value compared to the damaged plate, which has a positive impact on the durability of the assemblies.

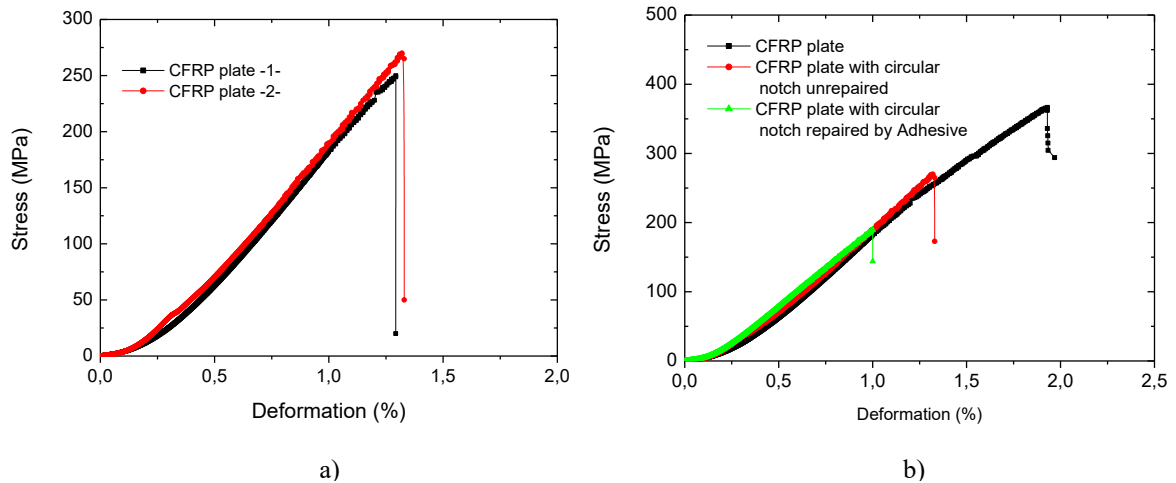


Figure 6: Comparative tensile curves between the different specimens of the EPOCAST 50-A1/carbon fiber fabric laminate

The values obtained for the elastic modulus, maximum stress, and strain at failure of each specimen are summarized and presented in Table 3. This table provides a clear comparison of the different mechanical behaviors observed during the tensile tests, highlighting the variations in stiffness, strength, and ductility depending on the fiber type and laminate configuration.

Table 3. Mechanical parameters of laminated composite specimens.

Specimen	Young Module's E GPa)	Deformation (%)	Maximal stress (MPa)
CFRP plate with one layer	42.23 ± 0.1	1.25	270 ± 5.23
CFRP plate with 8 layers	47.23 ± 0.1	1.95	360 ± 2.31
CFRP plate with notch	48.14 ± 0.1	1.01	198 ± 4.23
CFRP plate with notch repaired by adhesive	49.02 ± 0.1	1.37	274 ± 2.14

The tests show that an epoxy matrix reinforced with carbon fabric has a tensile strength of approximately 360 MPa at 0° and 367 MPa at 90°. The repaired composites exhibit a tensile strength of around 274 MPa at 90°, followed by the reference from the tensile testing machine. After the tensile tests, microscopic examinations were carried out. Figure 7 shows microscopic images of the fracture of intact specimens to analyze the failure modes of the samples, specimens with a 10 mm diameter hole (Figure 7(a)), and specimens repaired with patches (Figure 7(b)). A complete linear fracture of the laminates due to perforation was observed in both the holed and repaired specimens. This fracture occurred despite the different orientations of the warp and weft of the carbon fabrics. Carbon-fabric-reinforced composites exhibit more linear and brittle fractures compared to repaired plates of the same fabric, which show brittle fractures along multiple planes. This behavior is linked to

the rearrangement of the warp and weft of the fabric. The carbon fabric facilitates crack propagation, leading to faster composite failure.

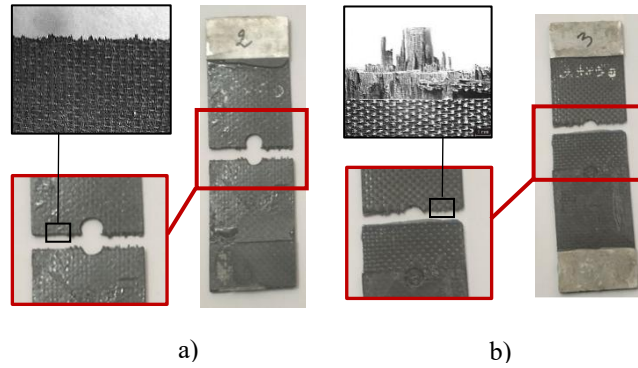


Figure 7. Microscopic images of the fracture of the tested specimens, a) CFRP plate with 8 layers, b) CFRP plate with notch Repaired by Adhesive

4.2. Mesh Sensitivity and Validation.

A mesh convergence study is essential to determine the optimal mesh division that ensures accurate and mesh-independent results. A refined mesh is necessary to guarantee the reliability of the results, particularly for stress analysis in composites. This section investigates the sensitivity of the number of elements in the proposed model to the stress distribution for the two cohesive techniques used. This sensitivity was validated through multiple mesh sensitivity calculations with increased mesh density. The results were then compared to tensile test data.

The mesh element type C3D8 was kept constant, while the element density was varied throughout the study. The mesh density was increased around the hole, based on the plate dimensions, to achieve greater accuracy in this region of interest. Outside this area, the mesh was coarsened. Each composite layer was represented by a single layer of elements to simplify calculations and determine individual layer properties. The patch employed the same mesh and element type as the damaged plate (Figure 8).

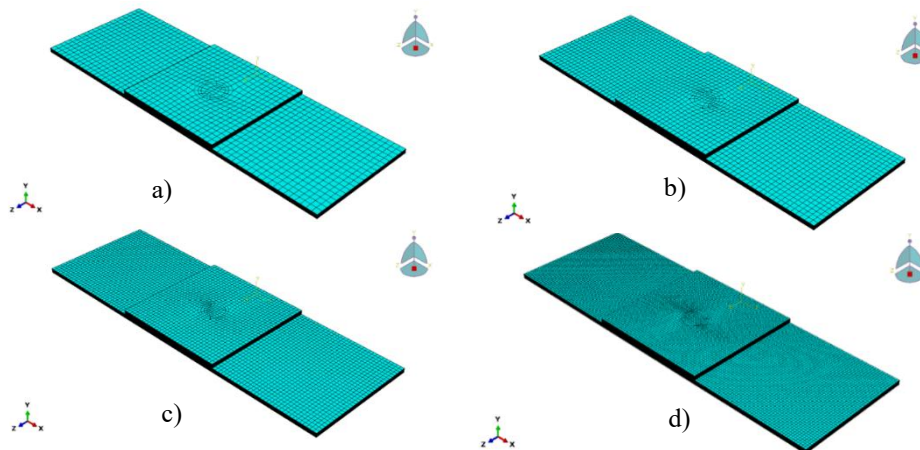


Figure 8: Representation of C3D8 finite element density in a damaged composite plate repaired with a patch. a) C3D8 – 25,000 elements, b) C3D8 – 50,000 elements, c) C3D8 – 75,000 elements, d) C3D8 – 160,000 elements

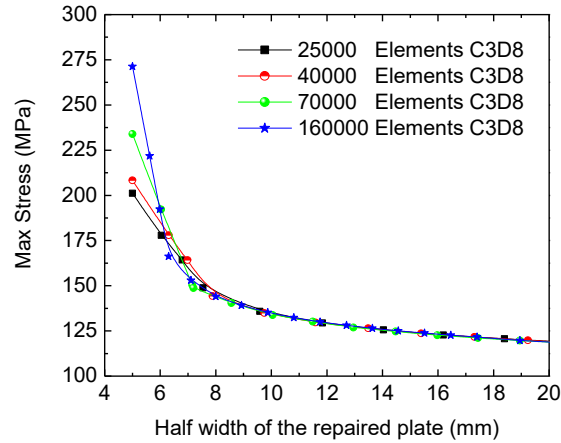


Figure 9. Variation of maximum stress along the mid-width of the damaged composite plate repaired with a patch for different mesh densities.

Figure 9 illustrates the distribution of maximum stress along the half-width of a holed plate repaired with a patch, using a linear C3D8 mesh. The analysis of the curves showed that the best result was obtained with a mesh density of 160,000 elements, yielding a maximum stress of 274 MPa. This value is consistent with the experimental results. It is noteworthy that this maximum stress is concentrated at the edge of the hole—the crack initiation point observed during experimental testing. These results highlight the crucial influence of mesh density on the accurate prediction of maximum stress in a damaged plate repaired with a bonded composite patch. The mesh sensitivity study of the composite model was limited to the elastic phase, extending up to the maximum stress. This simplification facilitated the determination of the element density and volume in the global model, since the complex behavior and composition of composites make fracture predictions particularly difficult. Following a convergence analysis, the C3D8 element size was set to 0.5 mm. This mesh size (90,000 elements for the laminate and 50,000 for the patch) optimizes both accuracy and computational efficiency for validating our model through a tensile test.

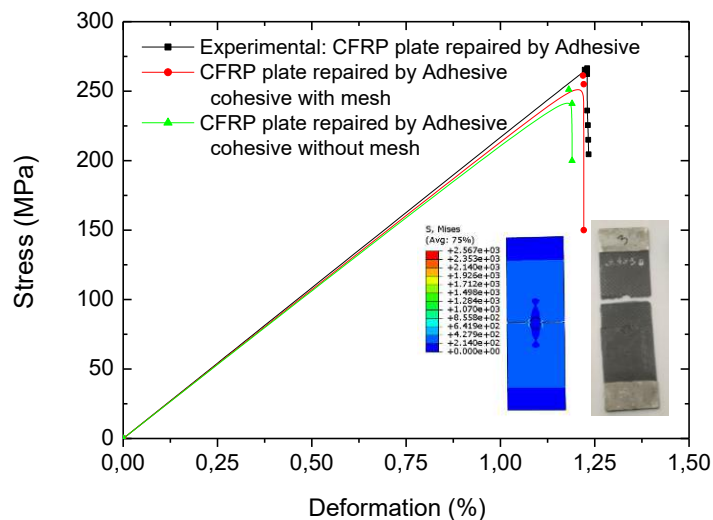


Figure 10.: Comparative tensile curves between the different specimens.

Figure 10 validates our numerical results by comparing the stress–strain curves obtained from the three cohesive simulation methods with data from an experimental tensile test conducted on repaired composite

specimens. An excellent agreement is observed between the numerical and experimental results, with only a slight difference in the ultimate stress value. The three techniques used the same mesh density and geometry for reliable comparison. The meshed method (UMM), which employs cohesive elements (C3D8 type) to model the interface between plies, explicitly simulates delamination and provides better agreement with experimental data, especially when combined with the XFEM technique (Figure 10). In contrast, the mesh less method (surface-to-surface contact), which simulates cohesive behavior through a nodal interpolation approach without meshing the interface, produces results that are less consistent with experimental observations.

The maximum stress criterion modeling using UMAT yielded satisfactory results, but the prediction and tracking of crack propagation remain challenging, making this approach less efficient than the other two methods (Figure 10). In summary, although both approaches rely on similar finite elements, their functioning differs fundamentally: the meshed UMM approach allows direct simulation of delamination, thus providing more accurate results for the fracture behavior of composite materials.

To validate the relevance of our models, we analyzed the behavior of the three proposed models. The comparison was based on the maximum stress value at the onset of initial cracking, as illustrated in Figure 11. This approach confirmed the convergence of the model with the relevant experimental results. The analysis also allowed us to identify the most damage-sensitive areas and to gain a better understanding of the interaction between the interlaminar layers within the repaired structure under applied tensile loading.

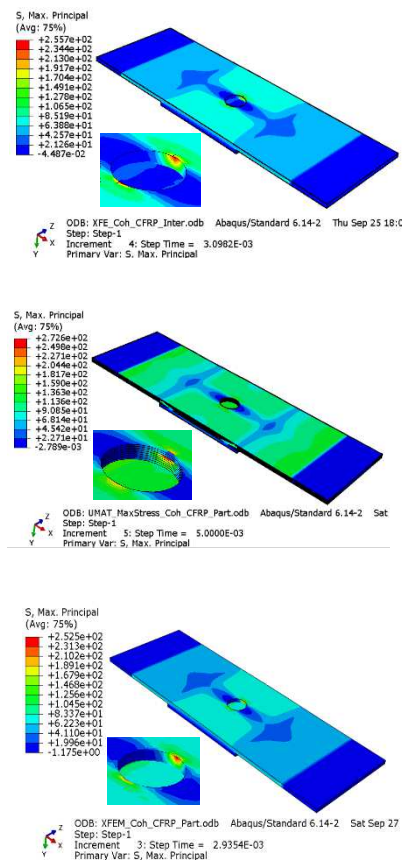


Figure 11. Behavior of the three proposed models.

Figures 12 and 13 show the stress distribution in the adhesive layer and in the seven adhesive layers inserted into the repaired plate, which was initially composed of eight composite plies. The analysis of Figure 12 reveals a significant concentration of Von Mises stresses at the edges and around the hole within the cohesive layer. The UMAT technique exhibits the most critical stress values among the three techniques studied, highlighting the importance of an efficient meshing technique—particularly when combined with XFEM—to activate and maintain the structural cohesion.

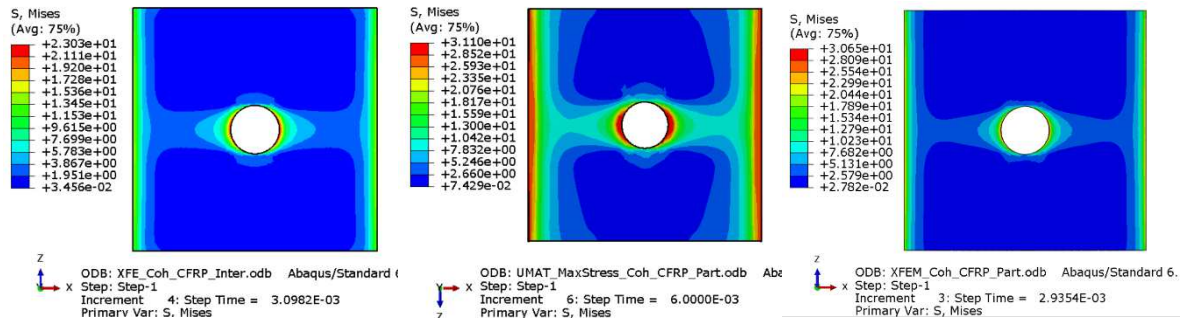


Figure 12. Distribution of Von Mises stresses in the cohesive layer for the three approaches.

This numerical study also aims to demonstrate the effect of interlayer interaction in a composite plate repaired with a bonded patch under tensile loading, using the cohesive layer technique. It highlights the influence of interlaminar interactions in a patched composite plate subjected to tension, employing the meshed cohesive modeling approach.

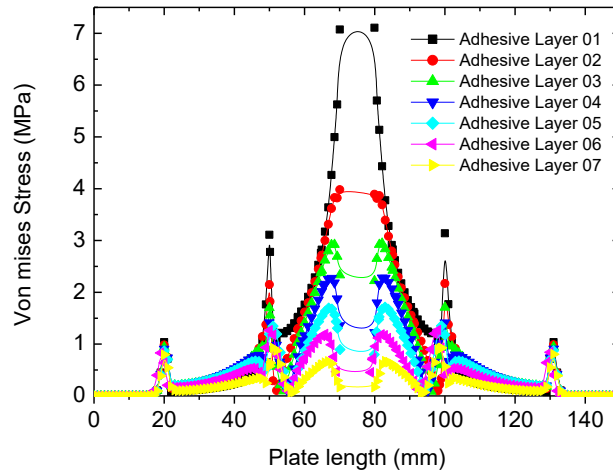


Figure 13. Von Mises stress distribution in the interlaminar region of the repaired plate using the UMM meshed technique.

Figure 13 shows the distribution of maximum stress along the plate, with a value of approximately 10 MPa for the first layer—twice that of the second. This stress concentration in the joint area highlights the importance of the first layer in stabilizing the bond between the repair substrates, in contrast to the opposite layer, which exhibits a stress deficit. Consequently, a careful selection of the adhesive between the panel layers is essential to achieve a balanced stress distribution in composite materials. This finding warrants further investigation in future studies on laminate fabrication, where the definition of the outer and inner faces plays a key role.

According to the stress distribution within the interlaminar layers, illustrated in Figure 14, a gradual increase in stress is observed from the inner layer toward the outer one, particularly at the ends of the overlap zone and around the hole. The presence of high stress near the hole is consistent with the location of the initial crack in the structure. Significant stress concentration zones are also detected between the two plies closest to the contact interface between the patch and the composite plate when the structure is subjected to tensile loading.

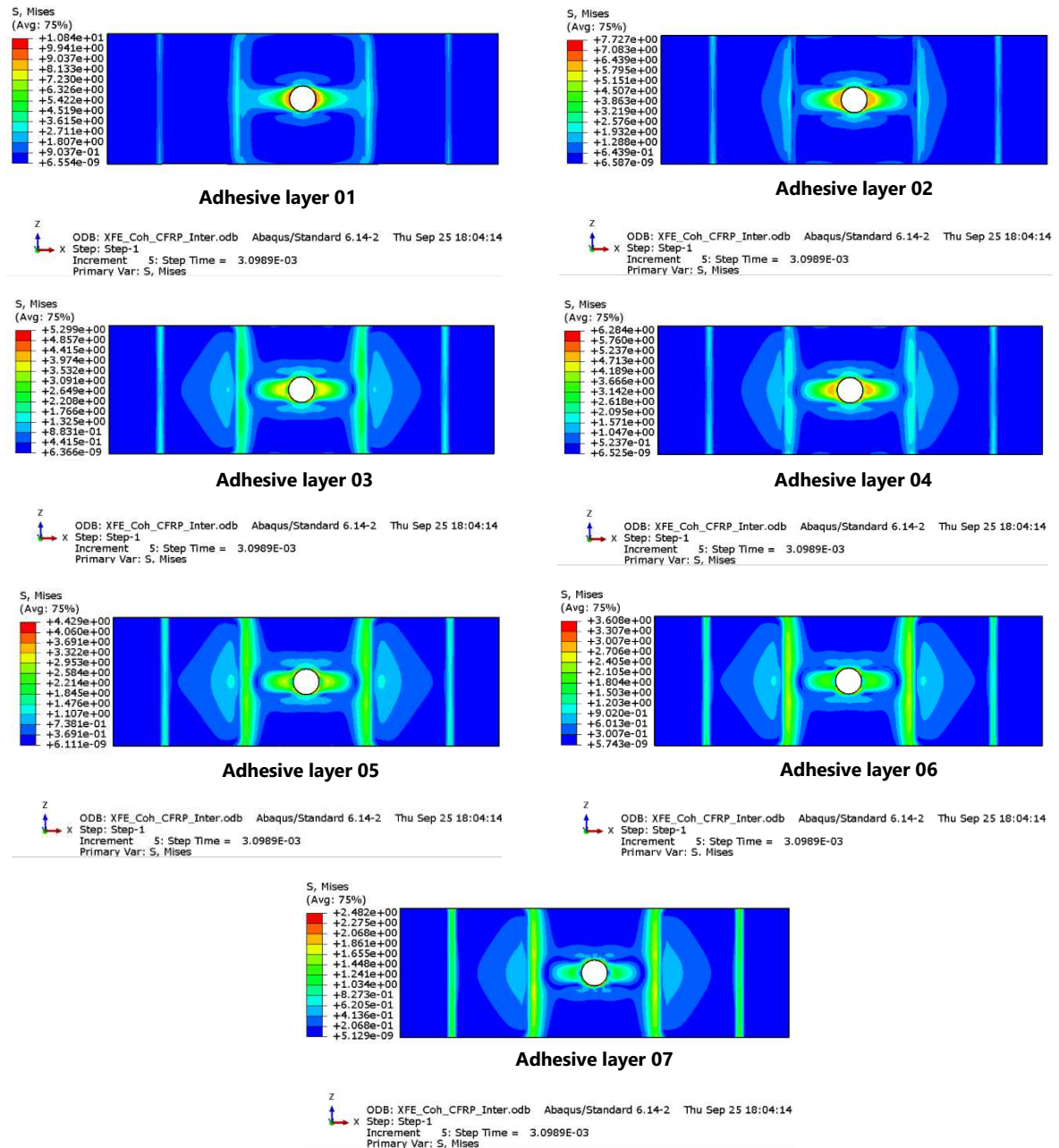


Figure.14. The level of von Mises stresses in the inter-laminar layer of the plate repaired using the UMM mesh technique.

The analysis of Figure 15 reveals that the numerical models using the UMM meshed technique for the repaired plate experienced a Mode I failure under uniaxial loading, which is consistent with the experimental results. The maximum stresses induced in the plate layers led to cracking and delamination, followed by crack propagation.

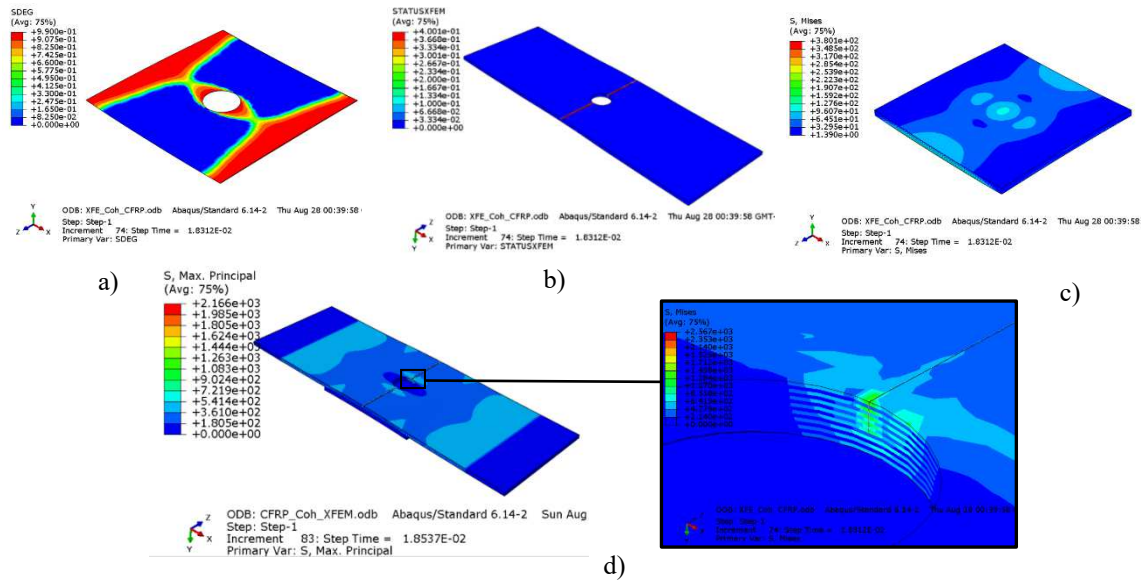


Figure 15. Damage in the CFRP plate repaired with a CFRP patch, a) Adhesive, b) CFRP plate, c) CFRP patch, d) XFEM

4.3. Effect of layer sequence on stress distribution

A detailed analysis of the stress distribution within the patch layer is of great importance, as this region plays a decisive role in the overall mechanical behavior of the repaired composite structure. Among the different stress components, the maximum tensile stress (σ_{22}) is particularly significant, as it governs the initiation and evolution of damage under tensile loading. Figure 16 illustrates the variation of σ_{22} as a function of the patch width for several configurations that differ in the orientation of the plies within both the patch and the repaired plate, considering two types of reinforcing fibers.

The results reveal that the highest stress values are consistently located near the center of the patch, which corresponds to the region most affected by the stress concentration around the hole edges in the composite plate. This pattern is observed for all tested configurations, highlighting the strong influence of geometrical discontinuities on the local stress field. The numerical simulations show that the first three configurations exhibit relatively high maximum stresses, reaching approximately 30 MPa, while Configuration 4 demonstrates a significantly more uniform and favorable stress distribution, with a lower peak value of about 5 MPa.

Furthermore, it can be noted that CFRP plates, irrespective of the patch material used, tend to retain elevated stress levels at the patch center. In contrast, GFRP plates display a noticeable reduction in stress magnitude for both types of patches, particularly when repaired using a carbon composite patch in the fourth configuration. This behavior underscores the key influence of fiber orientation and material type on the redistribution of stresses within repaired composites. Consequently, optimizing the stacking sequence of plies and selecting compatible materials between the patch and the base plate are crucial for achieving enhanced load transfer efficiency and improved durability of bonded composite repairs.

A detailed examination of Figures 17 through 20 reveals several important trends regarding the distribution of the maximum stress component σ_{22} within the composite patches applied to repaired plates. In general, for most configurations, the stress distribution within the patch exhibits a symmetric pattern, indicating that the tensile load is distributed relatively evenly across the patch width. This symmetry suggests that the interaction between the patch and the underlying composite plate is balanced, allowing for efficient stress transfer without creating significant localized concentrations.

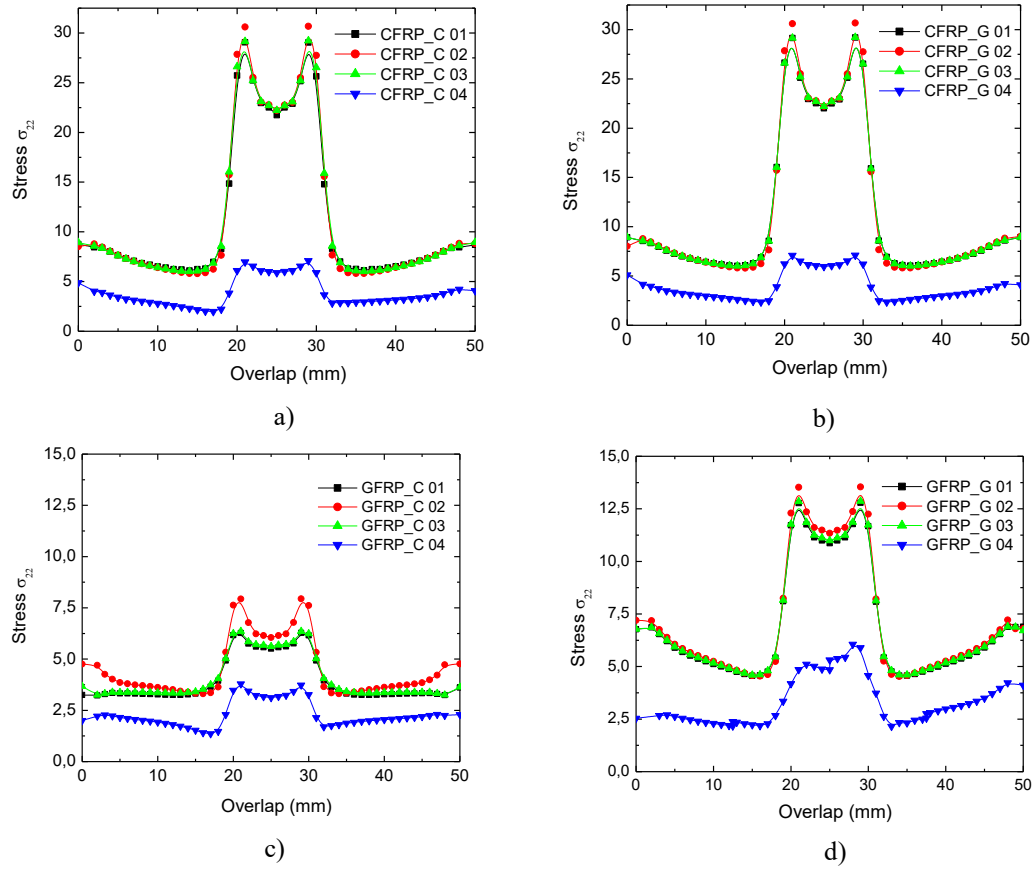


Figure 16. Variation of the maximum stress σ_{22} with patch width for different ply orientation configurations of the patch, a) CFRP_C, b) CFRP_G, c) GFRP_C, d) GFRP_G

In the CFRP_C configuration (Figure 17), the highest stresses are concentrated near the center of the patch, reflecting the influence of stress accumulation around the hole in the plate. The symmetry and peak stress levels in this configuration highlight the effectiveness of the ply orientation in managing stress concentrations and maintaining the structural integrity of the repaired area. The results indicate that a carefully designed ply sequence allows the patch to share tensile loads effectively, reducing the likelihood of localized failures or premature delamination. In the CFRP_G configuration (Figure 18), the stress distribution remains mostly symmetric, with the peak stress again located at the patch center. However, the stress magnitudes are slightly lower than those observed in the CFRP_C configuration, which can be attributed to the use of a different patch fiber type. This demonstrates that material selection, in addition to ply orientation, significantly influences the patch's stiffness, the local stress field, and the overall efficiency of load transfer from the plate to the patch. The ability of the patch to distribute stresses uniformly across its width reduces high-stress concentrations, which is critical for improving the durability and reliability of repaired composite plates.

The GFRP_C configuration (Figure 19) exhibits a similar, largely symmetric stress pattern, with maximum stresses concentrated near the patch center. Small variations along the width suggest that differences in the interfacial properties and stiffness between the glass fiber patch and the CFRP plate can influence the local stress distribution. The results emphasize that the interaction between the patch and the plate depends not only on the patch material but also on the sequence of plies, which affects how stresses are transmitted through the repaired structure. In contrast, the GFRP_G configuration (Figure 20), characterized by an antisymmetric stacking sequence, shows a noticeably less symmetric stress distribution. The overall stress levels within the patch are lower than in the previous configurations, and the central peak stress is significantly reduced. The antisymmetric ply arrangement redistributes stresses more evenly across the patch, mitigating the formation of localized peaks

and reducing the risk of early failure. This observation highlights the critical role of stacking sequence in controlling stress concentrations, particularly for composite patches with different fiber types. Overall, these results demonstrate that both ply orientation and patch material profoundly affect the distribution and magnitude of stresses within repaired composite plates, underscoring the importance of careful patch design to enhance structural performance, load-bearing capacity, and durability.

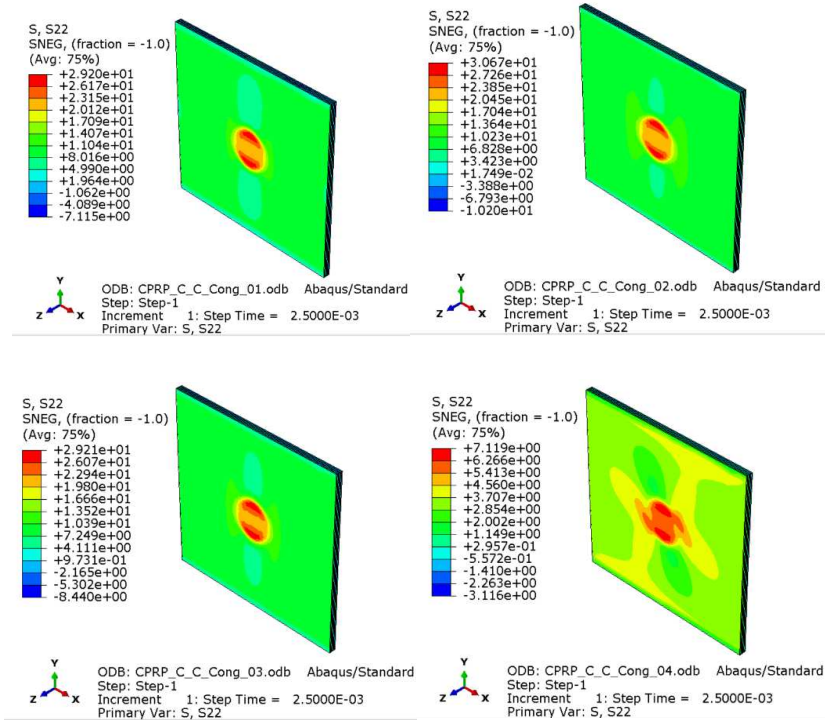


Figure 17. Distribution of the maximum stress σ_{22} in the composite patch for the CFRP_C configuration.

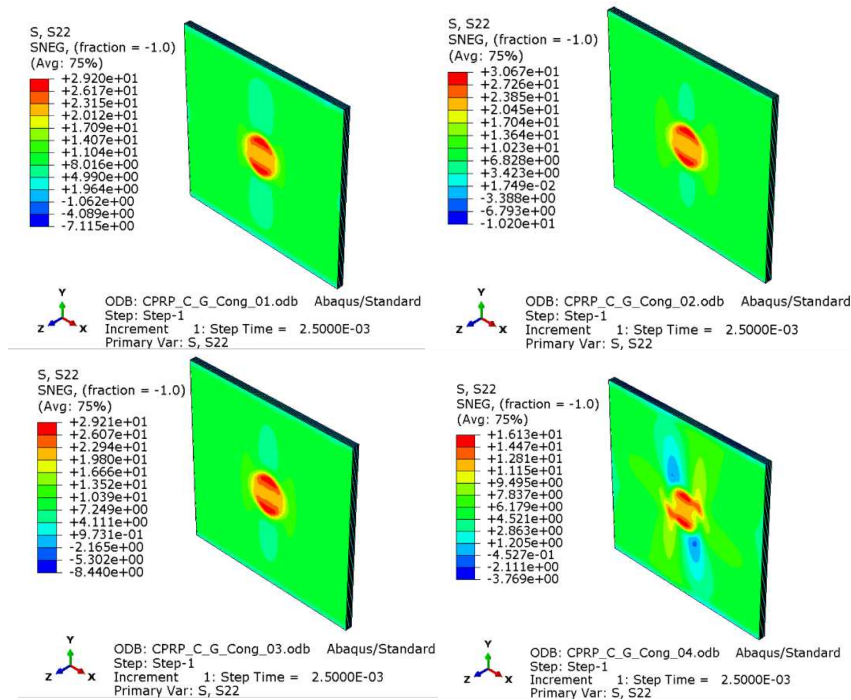


Figure 18. Distribution of the maximum stress σ_{22} in the composite patch for the CFRP_G configuration.

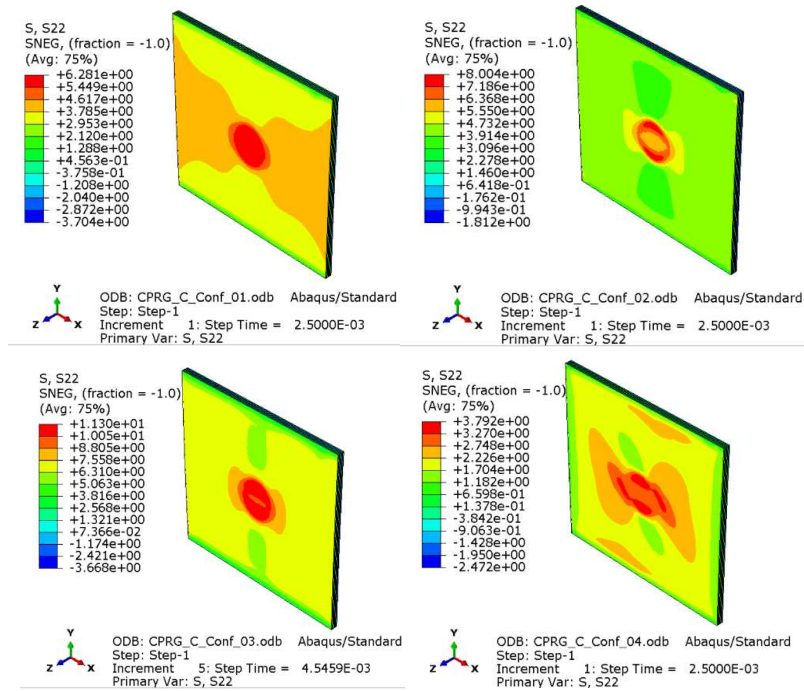


Figure 19. Distribution of the maximum stress σ_{22} in the composite patch for the GFRP_C configuration.

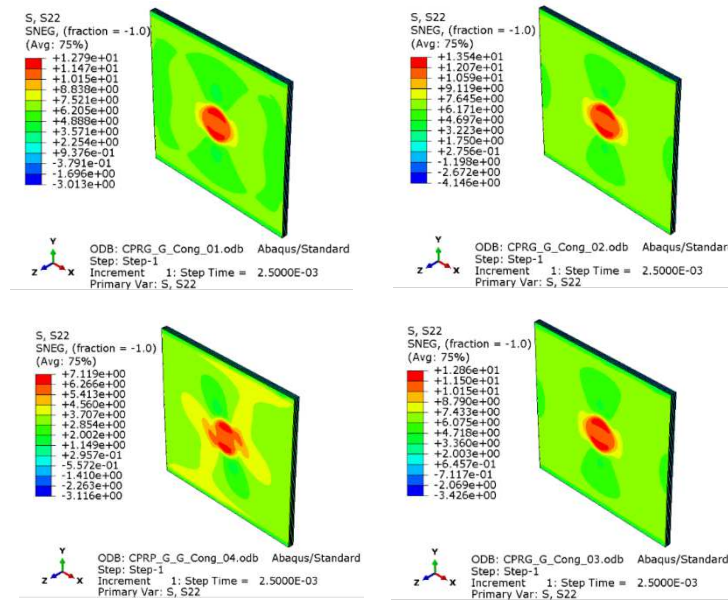


Figure 20. Distribution of the maximum stress σ_{22} in the composite patch for the GFRP_G configuration.

4.4. Effect of Ply Sequence on Von Mises Stress Distribution in the Cohesive Layer

Figure 21 illustrates the variation of Von Mises stress along the width of the adhesive joint for different stacking configurations. For CFRP plates repaired with composite patches, the highest Von Mises stresses in the adhesive layer are observed in configurations 1 to 3, particularly near the hole, while the fourth configuration exhibits a lower overall stress distribution, although the stress at the hole remains higher than in other regions. In contrast, for GFRP plates, the Von Mises stress levels are generally lower compared to the CFRP plates across all four configurations. In these GFRP configurations, the highest stress values are concentrated at the edges of

the adhesive layer, which is the opposite of the stress distribution pattern observed in the CFRP plates. This highlights the significant influence of both plate material and ply stacking sequence on stress distribution within the adhesive joint. The results indicate that material type and stacking orientation critically affect how stresses are transferred through the cohesive layer, which has important implications for the design and durability of repaired composite structures.

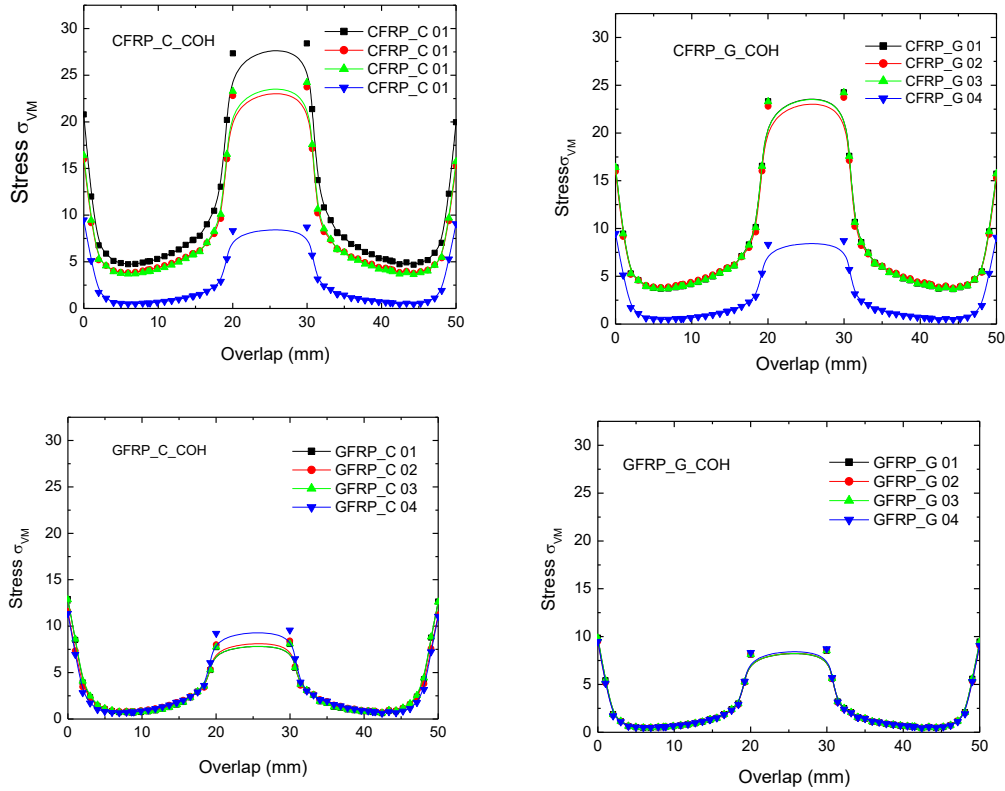


Figure 21. Variation of the Von Mises stress σ_{VM} along the cohesive layer width for different patch ply orientations, a) CFRP_C, b) CFRP_G, c) GFRP_C, d) GFRP_G

The distribution of Von Mises stresses within the adhesive joint is illustrated in Figures 22 through 25, highlighting the influence of plate and patch material as well as ply configuration on stress concentrations. Across all configurations, it is evident that the stresses are primarily concentrated at the two edges of the adhesive layer, while the central region of the adhesive remains largely inactive. This pattern indicates that the edges act as the most critical zones for potential adhesive delamination, with the stress magnitude and the size of the high-stress zones varying according to the material combination and stacking sequence.

In the CFRP_C configuration (Figure 22), the highest stresses are observed, and the high-stress zones extend over a larger area along the adhesive edges. Similarly, in the CFRP_G configuration (Figure 23), the stress concentration remains at the edges, although the magnitude is slightly reduced compared to CFRP_C. These observations suggest that the carbon patch, when combined with a CFRP plate, results in a more pronounced stress transfer to the adhesive, emphasizing the importance of careful ply design to mitigate potential failure.

For GFRP plates repaired with carbon or glass patches (Figures 24 and 25), the overall stress levels in the adhesive are significantly lower, and the zones of high stress at the edges are more localized. The central adhesive region remains almost inactive, similar to the CFRP cases, but the reduced stress magnitudes indicate a more favorable distribution that lowers the risk of delamination. Notably, the GFRP_G configuration exhibits the lowest stress levels among all studied cases, demonstrating the combined effect of material selection and ply sequence on stress redistribution.

Overall, these results indicate that the initiation of adhesive delamination occurs predominantly at the hole and the edges of the adhesive joint, and the location and intensity of stress concentrations are strongly dependent on both the type of plate and patch material and the stacking configuration. Proper selection of materials and ply orientation is therefore essential to enhance the durability and structural integrity of repaired composite assemblies.

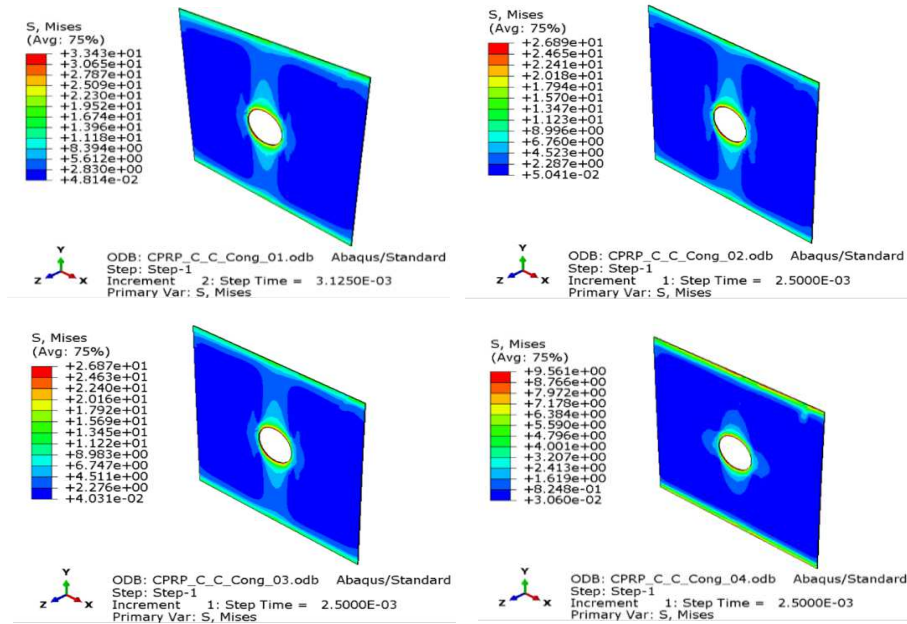


Figure 22. Distribution of Von Mises stresses in the cohesive layer for the CFRP_C configuration.

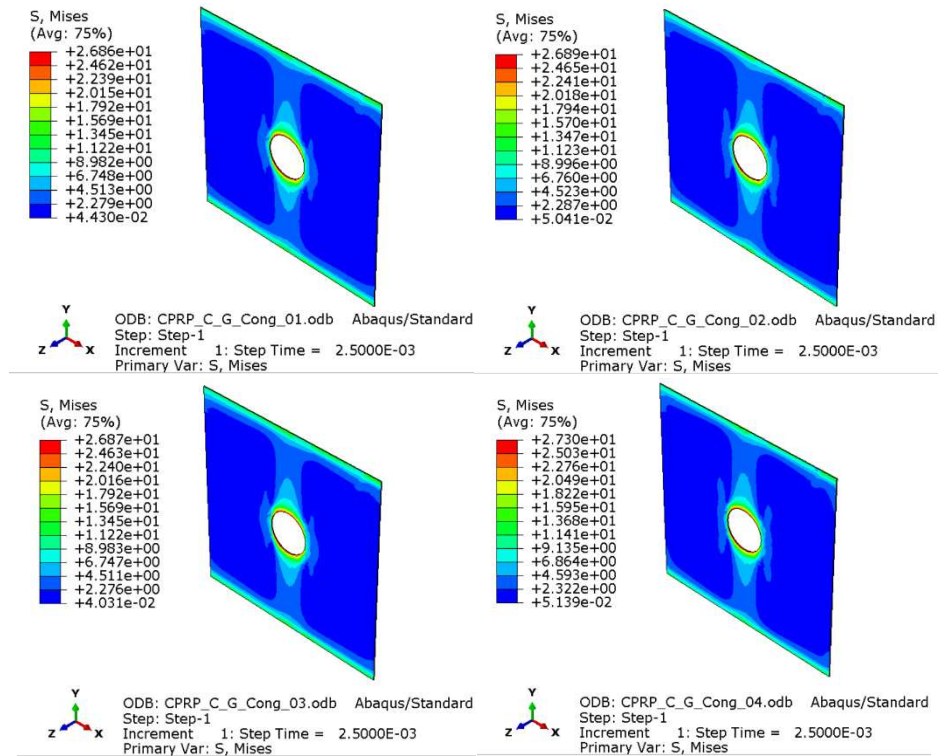


Figure 23. Distribution of Von Mises stresses in the cohesive layer for the CFRP_G configuration.

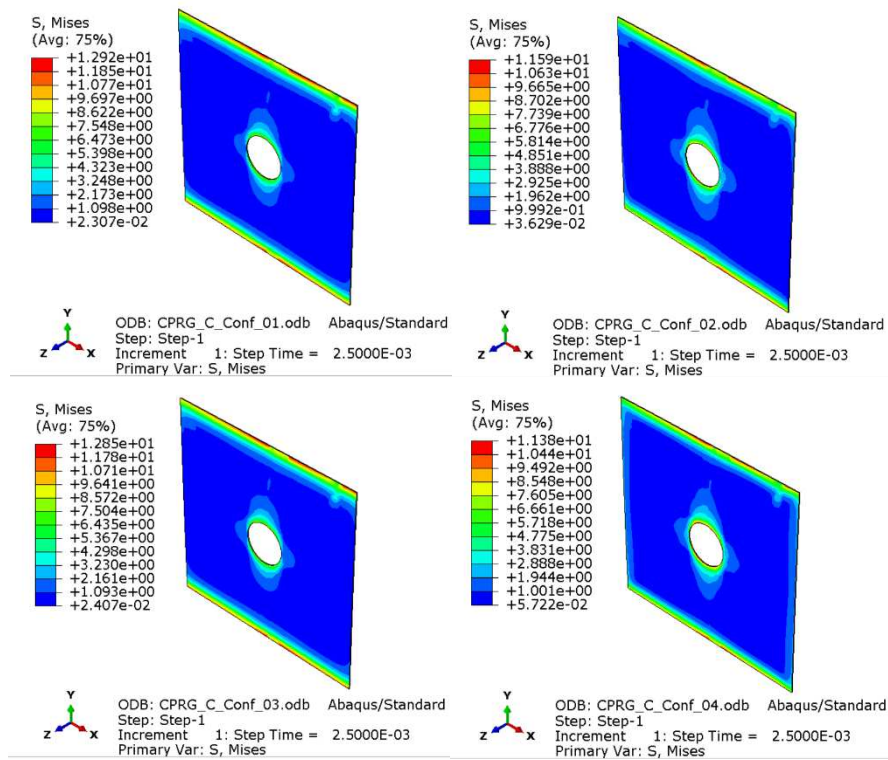


Figure 24. Distribution of Von Mises stresses in the cohesive layer for the GFRP_G configuration.

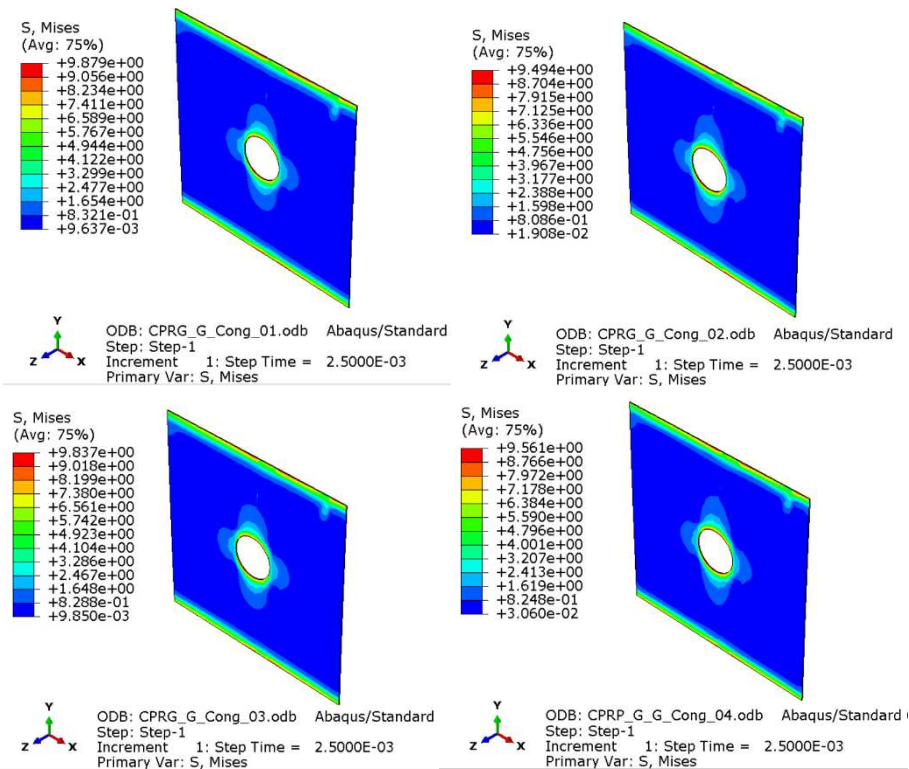


Figure 25. Distribution of Von Mises stresses in the cohesive layer for the GFRP_G configuration.

5. Conclusion

This work aims to evaluate the influence of geometric parameters (such as the nature and dimensions of the patch) and meshing parameters on the behavior of adhesively bonded repaired composite plates. The study highlights the importance of a comprehensive approach that considers not only the external design of the repair but also the internal structure of the substrate and the adhesive layer to ensure optimal performance.

- To achieve this, we employed a coupled approach combining the XFEM and CZM methods. Two modeling techniques of the cohesive layer were used to predict delamination between the plies, while the XFEM technique was applied to simulate the initiation and propagation of microcracks within the composite plies. This coupling enabled us to model the complex failure modes of the repaired structure and to predict potential sudden failure. The results obtained provide concrete insights for improving the design of composite repairs and pave the way for future experimental studies integrating thermomechanical, durability, or fatigue aspects.
- The analysis results concerning the effects of patch geometry and mesh type show that:
- The 3D numerical model successfully reproduced the experimentally observed failure modes. This outcome emphasizes the crucial importance of accurately characterizing the mechanical properties and failure mechanisms of each material layer.
- The evaluation of geometric parameter influence in the numerical model of repaired structures yielded satisfactory results. The effect of fiber nature and patch stacking sequence led to a reduction in stresses within the plate–patch assembly. Only the [-45/45] stacking configuration for a GFRP plate repaired with a GFRP patch showed a particularly favorable stress distribution, with a stress value of 5 MPa. This result highlights the importance of stacking sequence: an optimized sequence aligning fibers with the load direction allows better stress redistribution and improved local stiffness of the patch.
- In the field of bonded repair, research often focuses on the long-term durability of the adhesive layer under mechanical and thermal loads. A key objective in this context is to achieve a more uniform stress distribution within the adhesive layer by reducing the high stress concentrations typically observed at the free edges of the joint. Our work contributes to this objective by demonstrating, through finite element analysis, that the type of composite substrate stacking can significantly reduce stress concentrations at the bonded edges.
- This numerical study demonstrates the effect of interlayer interaction in a composite plate repaired with a bonded patch under tensile loading, using the cohesive technique with meshing.

Author contributions statement

All authors contributed to the conception and design of the study. Amin HOUARI, Salah AMROUNE, and Nashmi Alrasheedi prepared materials, collected data, and performed analyses. The first draft of the manuscript was written by Boutkhil Mohamed GUÉMOUR and Ahmed CHELLIL. Bassima TABLIT, Chouaib ARIBI, and Mohamed Slamani supervised the project and provided guidance throughout the research process. All authors read and approved the final manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

Data sharing is not applicable to this article as no data sets were generated or analyzed during the current study.

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