# Stacking Sequence Effects on Performance of Composite Laminate Structure Subjected To Multi-Axial Quasi-Static Loading

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# Stacking Sequence Effects on Performance of Composite Laminate Structure Subjected To Multi-Axial Quasi-Static Loading

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**Abstract**. In this paper, the effects of the stacking sequence on the mechanical performance and damage formation of composite laminates subjected to multi-axial quasi-static loading is investigated, considering intra-laminar damage onset. The response of the composite laminate configurations characterized by different stacking sequences subjected to multi-axial quasi-static loading have been studied to predict the influence on the static displacement and damage development. A finite element (FE) model has been used to numerically simulate the response of the composite structure. ABAQUS/EXPLICT FE environment has been considered for the analyses and Hashin's failure criteria has been adopted using a VUMAT subroutine to model the intra-laminar damage formation in the analyzed composite structure.

## 1. Introduction

Through years, the advancement of composite materials has been motivated by the growing need of materials with high specific mechanical properties and low specific weight. Many industries have conducted some exploration in search for ideal structural elements able to bear capacity of multi-axial static loading. Composite laminates consisting of multiple layers or plies which oriented in the desired directions are promising. In general, the industrial requirements and practical manufacturing considerations have restricted the stacking sequence combination of laminates to comply with ply orientations of 0, 90, 45 and -45 degrees. Depending on stiffness requirements, different assembling of plies is expectable. Even though a laminate might possess good stiffness properties, a composite laminate with the same fiber orientations is inefficient and may show a poor structural response when applied with in-plane loads. Therefore, the optimization of composite laminate designs towards a better damage resistance and tolerance can be achieved by varying its stacking sequence.

The influence of stacking sequence of laminated composite structure on the quasi-static response has been studied by several authors [1-4]. In this paper the effect of the stacking sequence on the composite mechanical performance and damage formation has been evaluated. A detailed FE model of the composite laminates have been developed in ABAQUS/EXPLICIT FEM code. The Hashin's [5] failure criteria are implemented using a VUMAT subroutine provided by ABAQUS to predict the intra-laminar damage. Three different stacking sequences have been considered, in order to better understand the influence of stacking sequence on the structural deflection and also intra-laminar damages formation.

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## 2. Damage modelling

For the modelling of intra-laminar damages, such as the breaking of the fibers and the progressive damage in the matrix, the progressive failure approach implemented in the algorithms of the Abaqus Explicit solver has been considered. This approach uses the Hashin's criteria [5] for the detection of damage initiation. The intra-laminar failure mode can be represented by a bi-linear constitutive law as shown in figure 1. In figure 1, the point A shows the damage initiation stress–strain values: before this point the material is undamaged. When the limit values defined was exceeded by the element stress, the damage propagation starts up to point B where the element is totally degraded. The damage initiation criteria are based on the Hashin's theory, which is separated by different intra-laminar failure modes. Four different modes of failure have been considered are fiber rupture in tension and compression and matrix cracking under transverse tension and compression. The damage variable for different failure modes are given by the following expression listed in table 1.

**Table 1**: Hashin's failure initiation criteria for each failure mode.

| Failure criteria | Failure modes |
|---|---|
| $(\frac{\sigma_{11}}{X_{1T}})^2 + (\frac{\sigma_{12}}{S_{12}})^2 + (\frac{\sigma_{13}}{S_{13}})^2 = 1$ | Fiber Tensile failure |
| $(\frac{\sigma_{11}}{X_{1C}})^2 = 1$ | Fiber Compressive failure |
| $\frac{(\sigma_{22}+\sigma_{33})^2}{X_{2t}^2} + \frac{\sigma_{23}-\sigma_{22}\sigma_{33}}{S_{23}^2} + \frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2} = 1$ | Matrix Tensile failure |
| $\left[\left(\frac{X_{2c}}{2S_{23}}\right)-1\right]\frac{(\sigma_{22}+\sigma_{33})}{X_{2c}} + \frac{(\sigma_{22}+\sigma_{33})^2}{4S_{23}^2} + \frac{(\sigma_{23}^2-\sigma_{22}\sigma_{33})}{S_{23}^2}] + \frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2} = 1$ | Matrix Compressive failure |

where $X_{1t}$ , $X_{1c}$ , $X_{2t}$ $X_{2c}$ denotes tensile and compressive failure strength in fibre direction 1 and 2 while $S_{12}$ $S_{13}$ and $S_{23}$ denotes failure shear strength in 1-2, 1-3 and 2-3 planes.

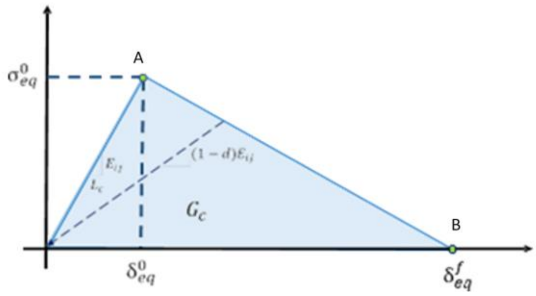


**Figure 1**. Damage initiation and propagation points.

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## 3. FE Model

The finite element model has been built in the ABAQUS/EXPLICIT FE code. This alternative approach has been selected for quasi-static modelling due to high computational time needed for whole model analysis. Therefore, a proper combination of loading rates and mass scaling methods have been applied to reduce the computational time of the explicit time integration method [6]. In this study, the composite laminate has been modelled as the electric power grid substation structure. Each arm which made-up of composite laminate was modelled with 7 equal thickness plies. The composite laminate has been modelled by using the solid element formulation available in the Abaqus database. Each element has eight nodes with three degrees of freedom at each node and one integration point. Two solid elements have been modelled across the thickness in each ply in order to improve the prediction of intra-laminar damage. Throughout the analysis, localized stiffness reduction is definite due to the existence of failed elements and subsequent element deletion. For the interface conditions, a perfect bonding was assumed between the plies. The arm structure was pinned on both four end and multi-axial loads were applied on the front end as shown in figure 2. Friction has been introduced between all the contacting surfaces with an average friction coefficient of 0.25. Figure 3 shows the three different stacking sequence schemes used in this paper. For all the numerical models the material properties reported in table 2 have been considered.

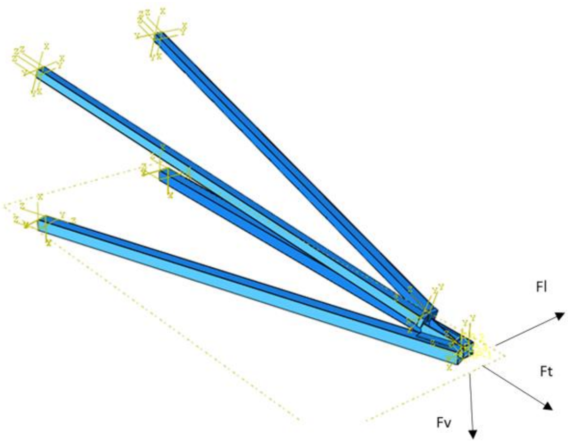


**Figure 2.** FE model of electric power grid substation structure.

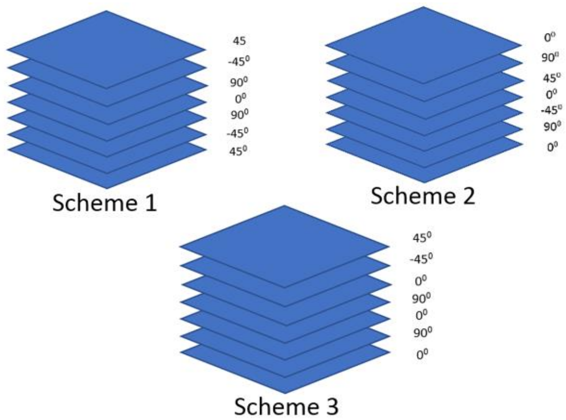


**Figure 3.** Different stacking sequences.

**Table 2.** Material properties of each ply.

| Intra-laminar model properties | |
|---|---|
| Density | 1900 kg/m$^3$ |
| Orthotropic properties | $E_1$ = 17Gpa $E_2 = E_3$ = 5.1Gpa |
| | $G_{12} = G_{13} = G_{23}$ = 4Gpa |
| | $\nu_{12} = \nu_{13} = \nu_{23}$ = 0.26 |
| Ultimate stress | $X^T$ = 321Mpa $Y^T$ = 80Mpa |
| | $X^C$ = 151Mpa $Y^C$ = 65Mpa |
| | $S_{12}$ = 89Mpa $S_{13} = S_{23}$ = 50Mpa |

## 4. Result and Discussions

In this section, the simulations performed on the analyzed three different stacking sequences for the considered multi-axial static loading are presented and discussed. The mechanical and damage behavior of the numerical models are represented by the graph of the static displacement contour and damage formation location. In figure 4a and Table 3, the maximum displacement of structure for the different composite schemes are presented. As shown in Figure 4a, the maximum deflection of all three structure with different stacking sequence were predicted at the front end near the applied load area. Based on table 3, the total deflection value of structure was different for each composite laminate schemes. Obviously, the value of maximum deformation is getting bigger from Lay-up Schemes 1 to 3. As proportion of 45-degree plies decreased within the composite laminate structure, amount of deflection has been increased. Besides, results comparison of scheme 2 and 3 show that stacking sequence has only a slight effect on maximum deflection.

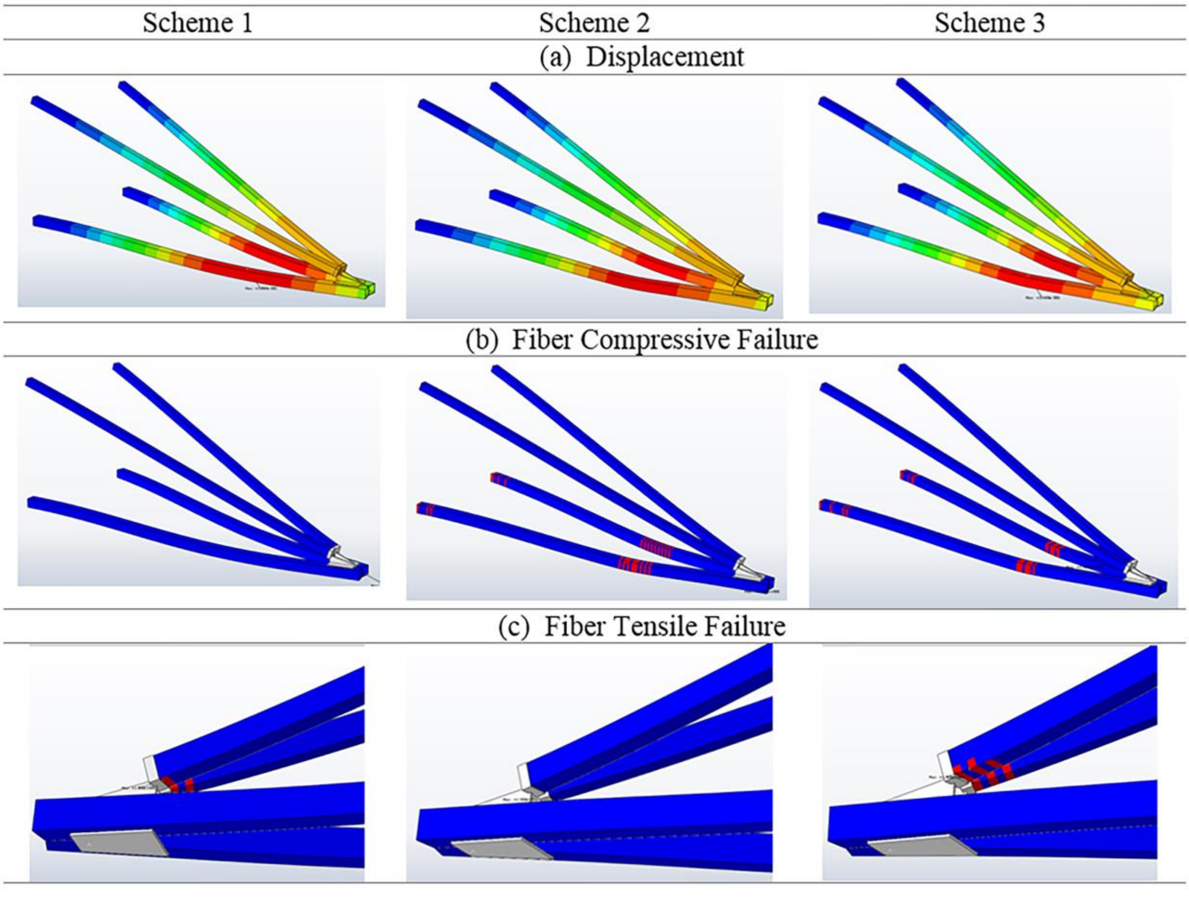


**Figure 4.** Numerical results (a) Displacement contour (b) Fiber compressive failure location (c) Fiber tensile failure location.

**Table 3.** Maximum deflection of structure with different stacking sequence

| Scheme | Composite laminate lay-up | Maximum deflection of structure (mm) |
|---|---|---|
| 1 | [45/-45/90/0/90/-45/45] | 189 |
| 2 | [0/90/45/0/-45/90/0] | 234 |
| 3 | [45/-45/0/90/0/90/0] | 245 |

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The smaller permanent deformation indicates better quasi-static loads characteristics. Scheme 1 with minimal permanent deformation (189 mm) is the optimal lay-up scheme. The results show that stacking sequence has little effect on static displacement, and proportion of layers with different fiber directions has obvious effect on static displacement. The higher the proportion of layers with 45-degree fiber directions is, the lesser the static displacement will be. A good improvement on the impact performance has also been reported by Hu et al. [7] when a higher proportion of layers with ±45° fiber directions was included in the composite laminate.

As can be seen in figure 4b, the localized damage was predicted near the area where the displacement is maximum and concentrated around the area where the arms were pinned. The damage in the structure which is fiber compressive failure was predicted in both lower arms of scheme 2 and 3. However, the predicted results show a wider area of damage on the lower arm of scheme 2. Comparison of results between scheme 2 and 3 show that movement of 45-degree plies from the extreme end has amplified the element normal stresses, $\sigma_{11}$ which has disrupted the ability of composite laminate to resist fiber compressive failure formation. On the other hand, for scheme 1, due to higher proportion of 45-degree layers located on both ends, element normal stresses, $\sigma_{11}$ have been reduced which consequently avoided the formation of fiber compressive failure.

In figure 4c, the localized damage was predicted near the area where the arms were attached to a connector. Fiber tensile failure formation was predicted in both upper arms of scheme 1 and 3. However, the predicted results show a broader area of damage on the upper arm of scheme 3. Comparison of results between scheme 2 and 3 show that movement of 45-degree plies from the extreme end has encourage the ability of composite laminate to resist the fiber tensile failure formation. This is because the +45° and -45° plies have resisted the element shear stresses, $S_{12}$ and $S_{13}$ that were localized on the center region of composite laminate.

Referring to figure 4b and 4c, both stacking sequence and proportion of layers with different fiber directions have obvious effect on damage formation. In scheme 2 and 3, the movement of 45-degree plies from the extreme end has increased the formation of fiber compressive failure but able to resist the formation of fiber tensile failure. Additionally, the higher proportion of layers with 45-degree fiber directions was able to reduce the formation of fiber tensile and compressive failure.

Based on the above discussion to determine best stacking sequence for composite laminate, the best stacking sequence is for scheme 1, when two layers of 45 and -45 oriented plies are at both ends and remaining three layers of 0 and 90 are in between them. The position and sequence of arrangement of plies in which the properties come second is for scheme 2 followed by scheme 3.

## 5. Conclusion

FE analysis have been carried out on the electric power grid substation structure subjected to multi-axial static loading to investigate the effect of stacking sequence on the mechanical performance and damage location of the laminated composites. Based on the above results, stacking sequence has little effect on static displacement but proportion of layers with different fiber directions has obvious effect on static displacement. The higher the proportion of layers with 45-degree fiber directions is, the lesser the static displacement will be. However, both stacking sequence and proportion of layers with different fiber directions have obvious effect on the damage formation. The best stacking sequence (position and orientation) is for scheme 1 which show smaller deformation and lesser area of damage formation.

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