Performance Evaluation of Composite Cross-Arm Structure Under Different Magnitude of Loading

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Abstract. In this paper, the effects of load with increasing factor of safety on the mechanical performance and intra-laminar damage formation of cross-arm structure made up of two different schemes are studied. The composite structure has been numerically modelled by a finite element (FE) model. Research was carried out using a VUMAT subroutine to model intra-laminar damage formation in the analysed composite structure, and Hashin's failure criteria have been used. This investigation revealed that with a good combination of stacking sequence and ply properties as shown by scheme A which has combination of 90 and 45-degree plies at the both ends and much higher value of ply properties, a safety reserve can be obtained that provides a margin between actual load conditions and those leading to cross-arms structure failure.

1. Introduction

Different kinds of loads during service life such as a windstorm, rain and other serious climate can endanger composite structures commonly used in electricity grid structure building. The extreme and very rare weather and climate induces significantly higher load than the actual grid load. Once the grid fails, the transmission line overload will lead to a cascade failure that will weaken the power system successively and could lead to electric instability and large-scale blackouts [1, 2]. A lot of studies into the susceptibility of power grids in severe conditions has been driven by massive financial and social impacts of these occurrences [3-5]. Therefore, it is important to understand how such loads affect distinct types of grids failure if the grid is designed to become solid and more resilient to failure.

As protective systems, laminate composite structures are usually utilized for resisting severe loads. During the past two decades, a number of studies have focused on the failure response of laminate structures under different load types [3, 6, 7]. Tuo, Lu [8] found that the compressed effects damage to the matrix and fibers of composite laminate depends on impact energy levels as damage is severe when it comes to higher impact energy.. The effect of different loading magnitudes based on three different safety factors on the structural deflection and the development of matrix and fibers damage of the cross-arm structure with distinct designed laminate scheme was evaluated in this analysis. In the ABAQUS / EXPLICIT environment, a detailed FE model for the laminate composite was created. A VUMAT
subroutine provided by ABAQUS for the prediction of intra-lamina damage is used to execute the Hashin failure criteria [9]. Two different schemes have been considered to develop the cross-arm structures, in order to better understand which scheme is more solid and resilient to structural deflection and intra-laminar damages formation under much higher load that a structure is required to withstand.

2. Damage modelling
In order to model intra-laminar damages including breakage of fibers and progressive matrix damages, the progressive failure strategy implemented in ABAQUS/EXPLICIT solver algorithm was considered. This analysis employs the Hashin criteria [9] to detect the initiation of damage. A bilinear constitutive law as shown in Figure 1 can be used to represent the intra-laminar failure mode. In Figure 1, point A indicates the activating value of damage and the material before this point is undamaged. Then, damage propagates until point B, where the elements stress has exceeded the limit values and degraded completely. The criteria for damage initiation is based on the theory of Hashin which takes into account different intra-laminar modes of failure. Tension and compression fiber fracturing and matrix cracking in transverse tension and compression are four different types of failure considered. For each failure mode, the damage variable is specified as set out in Table 1.

![Figure 1. Damage initiation and propagation points.](image-url)

Table 1. Initiation criteria for Hashin failure in each mode of failure

| Failure criteria | Failure modes |
|------------------|---------------|
| \( \frac{(\sigma_{11}x_{1})^2 + (\sigma_{12}x_{2})^2 + (\sigma_{13}x_{3})^2}{x_{12}} = 1 \) | Fiber tensile failure |
| \( \frac{(\sigma_{11}x_{1c})^2}{x_{1c}} = 1 \) | Fiber compressive failure |
| \( \frac{(\sigma_{22}+\sigma_{33})x_{2}^2}{x_{2c}} + \frac{(\sigma_{23}-\sigma_{22}\sigma_{33})}{S_{23}^2} + \frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2} = 1 \) | Matrix tensile failure |
| \( \left( \frac{X_{2c}}{2S_{23}} \right) - 1 \left( \frac{(\sigma_{22}+\sigma_{33})x_{2c}}{S_{2c}} + \frac{(\sigma_{23}-\sigma_{22}\sigma_{33})}{S_{23}^2} + \frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2} \right) = 1 \) | Matrix compressive failure |

3. Finite element model
The ABAQUS/Explicit FE code has been employed to build the finite element model. Due to the high calculation time needed for full model evaluation, this alternative method was chosen for quasi-static modeling. A successful balance of loading rates and mass scaling methods was therefore implemented to reduce the time for the explicit time integration process [10]. The composite laminate was modelled in this study as a cross-arm structure. Two cross arm structures have been modelled based on scheme A and B as shown in Figure 2 which each arm was modelled with 9 and 7 equal thickness plies respectively. Nevertheless, the collective laminate thickness of both schemes is equal. Composite laminate was
developed using Abaqus database's solid element formulation. Every element has eight nodes and at each node with three degrees of freedom and an integration point. Each ply is modeled along the thickness with two solid elements to better predict the onset of intra-laminar damage. The deletion of the element during the analysis has assured localized stiffness reduction. A perfect bonding between the plies was assumed for the interface conditions. Figure 2 displays the two different stacking sequence schemes used in this analysis. The arm framework has been fixed at four ends and increased multiaxial loads have been applied to the front end with the safety factor of 1, 2 and 4 (load 1, load 2 and load 3) as shown in Figure 3. The magnitude of load 1 (safety factor of 1) which consisting of longitudinal force (Fl), a vertical downward force (Fv) and a transverse force (Ft) are 6524 N, 84992 N and 46416 N respectively. Friction between all contact surfaces was implemented with an average friction coefficient of 0.25 as it gave good result convergence and shorter computer run time. The material properties given in Table 2 and 3 have been defined to each ply in scheme A and B.

![Figure 2. Laminate structure of scheme A and B.](image)

![Figure 3. FE model of cross-arm structure.](image)

### Table 2. Material properties of each ply in scheme A.

| Intra-laminar properties of scheme A |  |
|-------------------------------------|---|
| Density                            | 1900 kg/m³ |
| Orthotropic properties             |  |
| $E_1 = 18.3$GPa $E_2 = 1.089$GPa $E_3 = 0.327$GPa |
| $G_{12} = G_{13} = G_{23} = 4$Gpa |
| $v_{12} = v_{13} = v_{23} = 0.28$ |
| Ultimate stress                    |  |
| $X^T = 429$Mpa $Y^T = 100$Mpa |
| $X^C = 320$Mpa $Y^C = 76$Mpa |
| $Z^T = Z^C = 80$Mpa |
| $S_{12} = 89$Mpa $S_{13} = S_{23} = 50$Mpa |
Table 3. Material properties of each ply in scheme B.

| Intra-laminar properties of scheme B |  |
| --- | --- |
| Density | 1900 kg/m³ |
| Orthotropic properties |  |
| $E_1 = 17$Gpa $E_2 = E_3 = 5.1$Gpa |
| $G_{12} = G_{13} = G_{23} = 4$Gpa |
| $\nu_{12} = \nu_{13} = \nu_{23} = 0.26$ |
| Ultimate stress |  |
| $X_T^f = 321$Mpa $Y_T^f = 80$Mpa |
| $X^c = 151$Mpa $Y^c = 65$Mpa |
| $S_{12} = 89$Mpa $S_{13} = S_{23} = 50$Mpa |

4. Results and discussions

Simulations of the two separate scheme structures studied under the multiaxial loading are described and discussed. The numerical models' mechanical and damage behavior is expressed by the static displacement contour and the position of intra-laminar damage formation. In Figure 4(a), 5(a) and Table 4, total structure displacement for different composite laminate schemes are shown. As shown in Figure 4(a) and 5(a), at the front end close to the applied load area, the peak deflection of the two structures was predicted and it was more obvious as much higher load being applied. Based on Table 4, the maximum deflection of both schemes increases with different value as load increases. The value of maximum deformation is bigger in scheme B compared to scheme A. The less deformation suggests stronger characteristics of quasi-static loads. Scheme A is the ideal lay-up scheme with a minimum deformation as load increases.

Referring to Figure 4(b), 4(c), 5(b), 5(c) and Table 5, both schemes structure able to withstand the load 1 and load 2 without any fiber tensile and compressive damages. However, as much higher load being applied (load 3), the compressive fiber damage has been formed as indicated by red elements on both lower arms of Scheme B close to the area in which the highest displacement is occurring and clustered around the area of pinned arms. Meanwhile, on both upper arms of scheme B, the fiber tensile damage was formed as indicated by red elements near the area where the arms were attached to a connector. The fiber damage results have been tabulated in Table 5. The value 1 indicates that the criterion of damage initiation has been met. Based on the results shown in Figure 4 and 5, stacking sequence and properties of plies have obvious effect on maximum deflection value and damage formation of both schemes as the load increased. Comparison of results between cross-arm structure of scheme A and B show that the combination of 90 and 45-degree plies at the both end has encourage the ability of composite laminate structure to reduce deflection and resist both the fiber tensile and compressive failure formation under much higher loading (load 3) compared to scheme B which either 90 or 45-degree ply is presented at the extreme end. A huge leap in performance of the composite laminate structure has also been reported by Mohamad, Syamsir [11] when a ±45-degree ply is presented at both ends and Riccio, Di Felice [12] also confirmed that plate composed of 45 and -45 oriented plies would withstand significantly higher impact intensity than the 0/90 oriented ply configuration.
Figure 4. Numerical results of scheme A under different loading a) Displacement contour b) Fiber compressive failure location c) Fiber tensile failure location

Figure 5. Numerical results of scheme B under different loading a) Displacement contour b) Fiber compressive failure location c) Fiber tensile failure location

Table 4. Maximum deflection of scheme A and B structures.

| Load | Scheme A | Scheme B |
|------|----------|----------|
| 1    | 33       | 46       |
| 2    | 68       | 97       |
| 3    | 159      | 259      |
Table 5: Failure modes and indicators of Scheme A and B structures.

| Failure modes          | Load 1 | Load 2 | Load 3 |
|------------------------|--------|--------|--------|
| Fiber tensile failure  | Scheme A | Scheme B | Scheme A | Scheme B | Scheme A | Scheme B |
|                        | 0      | 0      | 0      | 0      | 0      | 0      |
| Fiber compressive      | Scheme A | Scheme B | Scheme A | Scheme B | Scheme A | Scheme B |
| failure                | 0      | 0      | 0      | 0      | 0      | 1      |

Properties of ply also plays a major part in deciding the performance of composite laminate structures. Scheme A which defined with higher value of Young’s Modulus and ultimate stresses compared to scheme B showed smaller deflection and none of fiber tensile and compressive were formed when it was being subjected beyond the intended load. The effect of ply properties on composite laminate structure performance has been studied by [Mohamad, Syamsir [13]]. They found that composite laminate structures which defined with much higher properties gave a good overall performance improvement when subjected to multi-axial loading. Ozsoy, Mimaroglu [14] have also found that composite laminate with higher value of properties able to withstand much higher tensile and bending loads. Based on the above discussions, through a good combination of stacking sequence and ply properties, a much stronger composite laminate structure performance can be achieved which it can bear extra load beyond what is intended a structure will actually take which is shown by scheme A.

5. Conclusions
FE analyses have been carried out to identify the capability of the cross-arm structure which made up of two different schemes when subjected to multi-axial static loading with increasing factor of safety based on the displacement value and formation of damage. Based on the above results, both structures with different scheme were able to bear the load 1 and load 2 successfully. However, when load 3 being applied, stacking sequence and ply properties have huge effect on the overall structural deflection as well as damage formation. Combination of 90 and 45-degree plies at the both ends, and selection of much higher ply properties have improve the overall performance of composite laminate structure to reduce deflection and resist the damage formation even it is being applied with much higher load than it needs to be for an intended load. In this study, scheme A has proved to be the ideal solution to the safe design of cross-arm structure which show smaller and no permanent deformation under three different load magnitude.

6. Acknowledgement
The authors acknowledge Tenaga Nasional Berhad (TNB), UNITEN R&D, and Institute of Energy Infrastructure (IEI) for the lab facilities and financial support (TNB Seeding Fund: U-TS-RD-19-03). Special thanks to those who contributed to this project directly or indirectly.

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