Failure analysis of various fiberglass cross-arm designs under multi-axial loading

Daud Mohamad¹, Salmia Beddu¹, Agusril Syamsir², Nazirul Mubin Zahari¹, Muhammad Fauzinizam Razali³*, Sareh Aiman Hilmi Abu Seman³, Aizat Abas³ and Fei Chong Ng³

¹Department of Civil Engineering, Universiti Tenaga Nasional, 43000 Kajang, Malaysia.
²Institute of Energy Infrastructures (IEI), Universiti Tenaga Nasional, 43000 Kajang, Malaysia.
³School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus, 14300, Nibong Tebal, Penang, Malaysia.

*E-mail: mefauzinizam@usm.my

Abstract. This study investigated the type of failure modes of different cross-arm designs under multi-axial static loading. The failure modes were numerically predicted from real-scale finite-element models of cross-arm integrated with a Hashin damage subroutine. Three finite-element models of cross-arm were considered; a model with standard cross-arm design, a standard design engaged with braces, and a standard design engaged with sleeves. The failure analysis of the composite cross-arm was focused on the location and type of failure of the structure upon its application. This investigation revealed that under the applied load, the cross-arm with installed sleeves exhibited the lowest total deflection of 0.21 m. Every cross-arm design exhibited fiber failure due to the tension and compression mode, regardless of the support system installed. Additionally, the installation of sleeves and braces on the cross-arm structure successfully reduced the number of areas associated to failure.

Keywords: Fiberglass Cross-arm, Hashin Failure, Multi-axial Loading.

1. Introduction

After the event of serious weather, recent damage to electrical installations in a number of areas has generated a growing interest in upgrading the design of these substations and energy tower buildings structures situated at those with natural risks [1-3]. The structural reliability is the chance of the structure not reaching its limits in a certain period (e.g. failure state). Therefore, the development of a plan to improve system resilience needs a knowledge of how these loads affect grid failure initiation and advancement. Consequently, the efficacy of distinct models can be recognized to guarantee that the grid is more solid and resilience. Installations of sleeve and braces are the most commonly used methods for resisting horizontal forces in a frame structure, as well as being highly efficient and economic [4, 5]. Even though the effect of sleeve and braces on structural performance has been studied previously [5-8], the knowledge on the type of failures experienced by the composite structure upon the use of sleeve and braces supports is still lacking.

This paper aims to predict the modes of failure of different cross-arm structure design under extreme multi-axial loading condition. Detail finite-element models of the composite cross-arm structure were developed in Abaqus/Explicit FEM code. The Hashin’s failure criterion [9] was implemented using a VUMAT subroutine to predict the location and failure modes of the loaded structure. The methodology examined three distinct cross-arm constructions with and without sleeve
and braces. The magnitude of displacement and the type of failure induced were compared in between designs to assess the effectiveness of sleeves and braces installations on the structural reliability.

2. Development of the cross-arm model

2.1 Geometry and boundary condition

Three numerical models of composite cross-arm were developed in this study by using a finite-element analysis software program Abaqus/CAE. In the overall, each model consisted of two upper arms, two lower arms and two steel connectors. The cross-section of the arms is square (0.14 x 0.14 m), with a thickness of 0.01 m and 4.9 m length. There are 7 stacked plies of glass laminate throughout the thickness, with each ply thickness of 0.0014 m. The stacking sequence of the square arm is [45/ -45/ 0/ 90/ 0/ 90/ 0].

Figure 1 presents the considered designs of the cross-arm model. Figure 1(a) denotes the standard frame design of cross-arm, which consisted of four arms connected at one end and fixed at the other end. The cross-arm model was developed from a total of 73,472 linear hexahedral element with reduced integration (C3D8R). The steel connector was developed from a rigid element (R3D4). As the simulation involves severe bending deformation, multiple elements were set throughout the beam thickness to avoid the issue of hourglassing and severe element distortion [10].

One end of the cross-arm was fixed in every direction, and the other end was tie constraint towards the steel connector. Three loads of magnitude 6524 N, 84,992 N and 46,416 N were applied in longitudinal (x-axis), vertical (y-axis) and transverse (z-axis) directions, respectively. These load magnitudes were selected after considering the extreme exposure of loading condition with factor of safety of 4, such reported in [11]. These loads were applied at the reference point (RP) coupled at the steel connector.

![Figure 1. Geometry and boundary conditions defined on the cross-arm models: (a) standard design, (b) with braces and (c) with sleeves.](image-url)
Figure 1(b) denotes the standard design of the cross-arm, with additional braces installed and connected at the center of each arm. This design concept was achieved by creating and linking multiple-point constraint (MPC) link between the center of the arms. The main idea is to fix the distance between the linked arms so that flexural deformation can be transferred from the center to the other region of the cross-arm. This is to replicate the case of cross-arm installed with a steel braces, with the purpose of reducing the bending deformation at the center region of the cross-arm (see Figure 1 (b)).

Figure 1(c) denotes the standard cross-arm design installed with a pair of 1-meter long fiberglass sleeve at the center length of the lower beam. The sleeves have the same stacking sequences and thickness with the beams of the cross-arm. A surface-to-surface contact was selected upon assigning the interaction between the sleeve and the lower arm surface, with the normal behaviour was set to “hard” contact and the tangential behaviour set to penalty formulation. These sleeves act as an alternative support system against the brace system proposed in the previous paragraph.

The analysis was considered as quasi-static and carried out with dynamic explicit solver. For the post-processing output, the user-dependent state variables SDV 1 to SDV 4 was requested from the field output manager. The Hashin subroutine characterized these variables onto the four failure modes of composite; fiber breakage in tension (SDV 1), fiber buckling in compression (SDV 2), matrix cracking in tension (SDV 3) and matrix crushing in compression (SDV 4). Additionally, the total deflection magnitude of the whole cross-arm structure was also requested for comparison.

### 2.2 Mesh convergence test
A mesh convergence test was performed to identify the optimal number of elements that satisfactorily balance numerical result and computational cost. The convergence test was performed by increasing the number of elements of the arms, by varying the element size from 0.06 mm (coarse) to 0.01 mm (very fine) by increments of 0.01 mm. In overall, five numerical runs were considered with the total deflection of the cross-arm set as the convergence criteria. Table 1 summarizes the total deflection of the whole model, and it is recognized that the deflection results converged as the mesh density increased. Thus, the mesh of 165,984 elements was selected for the model as it has relatively enough accuracy and lower computational cost than other meshes.

| Run | Element size (mm) | Element number | Total deflection (m) | Computational period (h) |
|-----|------------------|----------------|----------------------|-------------------------|
| 1   | 0.05             | 33,264         | 0.122                | 0.9                     |
| 2   | 0.04             | 41,328         | 0.193                | 2.2                     |
| 3   | 0.03             | 73,472         | 0.257                | 11.4                    |
| 4   | 0.02             | 165,984        | 0.262                | 22.3                    |
| 5   | 0.01             | 662,592        | 0.265                | 40.6                    |

### 2.3 Laminate properties
The composite arms were made from fiber glass. Table 2 summarizes the mechanical properties of the composite arm, which were obtained from the manufacturer. The material data were assigned by means of the *USER MATERIAL instruction in Abaqus framework, to directly link the properties with the VUMAT/Hashin subroutine.
Table 2. Mechanical properties of the glass-fiber laminate.

| No. | Parameters                                      | Value (unit) |
|-----|------------------------------------------------|--------------|
| 1   | Density                                        | 1.8 g/cm³    |
| 2   | Young’s modulus, $E_1$                         | 17000 MPa    |
| 3   | Young’s modulus, $E_2$                         | 5000 MPa     |
| 4   | Young’s modulus, $E_3$                         | 1500 MPa     |
| 5   | Poisson’s ratio ($V_{12}=V_{13}=V_{23}$)       | 0.28         |
| 6   | Shear modulus ($G_{12}=G_{13}=G_{23}$)         | 4000 MPa     |
| 7   | Ultimate tensile stress, $X_{1T}$              | 320 MPa      |
| 8   | Ultimate compressive stress, $X_{1C}$          | 150 MPa      |
| 9   | Ultimate tensile stress, $X_{2T}$              | 80 MPa       |
| 10  | Ultimate compressive stress, $X_{2C}$          | 60 MPa       |
| 11  | Ultimate shear stress, $S_{12}$                | 80 MPa       |
| 12  | Ultimate shear stress, $(S_{13} = S_{23})$     | 50 MPa       |

2.4 Hashin failure criteria

A VUMAT/Hashin subroutine was integrated into the developed finite-element model to predict the failure modes of the cross-arm. In general, the Hashin failure criterion is based on the work of Hashin [9]. The advantage of Hashin criterion over other stress-based criteria is it identifies four distinct modes of failure for composite material, in specific, fiber breakage in tension, fiber buckling in compression, matrix cracking in tension and matrix crushing in compression. These failure modes of fiber and matrix occur whenever the following equations are satisfied (equivalent or greater than 1).

If $\sigma_{11} \geq 0$, the tensile fiber failure criterion is:

$$\left(\frac{\sigma_{11}}{X_{1T}}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{F_{13}}\right)^2 \geq 1 \quad (1)$$

If $\sigma_{11} \leq 0$, the compressive fiber failure criterion is:

$$\left(\frac{\sigma_{11}}{X_{1C}}\right)^2 \geq 1 \quad (2)$$

If $\sigma_{22} \geq 0$, the tensile matrix failure criterion is:

$$\frac{(\sigma_{22}+\sigma_{33})^2}{X_{2T}^2} + \frac{\sigma_{23}^2}{S_{23}^2} + \frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2} \geq 1 \quad (3)$$

If $\sigma_{22} \leq 0$, the compressive matrix failure criterion is:

$$\left[\frac{X_{2C}}{2S_{23}} - 1\right] \frac{(\sigma_{22}+\sigma_{33})^2}{X_{2C}} + \frac{(\sigma_{22}+\sigma_{33})^2}{4S_{23}^2} + \frac{(\sigma_{23}^2-\sigma_{22}\sigma_{33})}{S_{23}^2} + \frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2} \geq 1 \quad (4)$$

Where $\sigma$, $X$ and $S$ is the components of applied stress, the ultimate stress and the shear stress, respectively.
3. Results and discussion
This paper deals with the failure prediction of different cross-arm designs under severe flexural loading. Three cross-arm designs were considered, which are the standard cross-arm design and a standard design with installed sleeves and braces for the supports. The installation of the supports at the middle region of the lower arm was motivated by our previous work [12], which reported the critical bending deformation about the middle region of the cross-arm. The numerical approach considered in this study served as a cost and time saving method to access the effectiveness of the supports towards the reliability and integrity of the cross-arm structure.

Table 3 summarizes the total deflection, and the failure modes exhibited by the different design of composite cross-arm upon loading. It is seen that the largest total deflection of 0.262 m was recorded both for the cross-arm with standard design and with installed braces. The installation of the 1-meter sleeves on the lower arm successfully increased the stiffness of the structure, thus considerably reduced the total deflection to about 0.21 m.

For the failure analysis, every design ends up with a failure of the fiber in tension (SDV 1) and compression (SDV 2). This finding shows that the installation of the support system such as sleeve and braces at the lower part of the cross-arm is not effective in preventing the occurrence of the failures. Interestingly, the installation of braces on the cross-arm has led to the existence of matrix cracking in tension (SDV 3); a failure which was not appeared in standard design case. This type of failure was induced due to the stiffening of the structure, as the middle regions of the cross-arm were constrained from deformation by the braces.

Table 3. Deflection and failure modes of different cross-arm designs.

| No | Parameters                          | Cross-arm designs |
|----|-------------------------------------|-------------------|
|    |                                     | Standard | Braces | Sleeves |
| 1  | Total deflection (m)                | 0.26     | 0.26   | 0.21    |
| 2  | Fiber breakage in tension (SDV 1)   | 1        | 1      | 1       |
| 3  | Fiber buckling in compression (SDV 2)| 1        | 1      | 1       |
| 4  | Matrix cracking in tension (SDV 3)  | 0        | 1      | 0       |
| 5  | Matrix crushing in compression (SDV 4)| 0        | 0      | 0       |

Figure 2 shows the locations of fiber breakage in tension (SDV 1) for different cross-arm designs upon loading. The 0.0 and 1.0 magnitude denote the non-failure and failure region with respect to the deformation of the composite structure. For every design, the fiber breakage occurred about the end where the arms were pinned to the steel connector. This type of failure appeared mostly on the upper part of the cross-arm, signifying that this section suffered in tension the most during the loading. Between the designs, it was observed that the design with installed sleeves and braces suffered more in terms of fiber failure, such indicated by the greater area of red contours at the upper part of the cross-arm. This observation highlighted that the stiffening of the lower arm (due to the installed support) had caused the upper arm to bear most with the applied loads and experienced greater deformation. Essentially, it is now clear that the installation of the supports on the composite trusses structure in transverse direction is not that effective in preventing structural failures as in the building structure case [4, 5].
Figure 2. Failure locations of cross-arm structure due to fiber breakage in tension (SDV 1): (a) standard design, (b) with braces and (c) with sleeves.

Figure 3 shows the locations of fiber buckling in compression (SDV 2) for different cross-arm designs upon loading. It is seen that the large bending deformation appeared somewhere near the pinned area, and the location of failure is approximately identical to the one observed on the onsite failed cross-arm (unpublished work). It is interesting to note that the total deflection reported in previous section was referring to this region of lower part of the cross-arm. Since there was no support installed for the standard design, the large deflection of the structure caused the failure to occur at two locations; one about the middle region of the lower arm and the other one occurs about the fixed ends. On the other hand, the installation of supports such as braces and sleeves successfully reduced the number of failure location into one, which localized at the region near the pinned location.

Figure 3. Failure locations of cross-arm structure due to fiber buckling in compression (SDV 2): (a) standard design, (b) with braces and (c) with sleeves.
4. Conclusions

Every cross-arm design considered in this study exhibited failures in terms of fiber breakage and buckling due to tension and compression load, respectively. The cross-arm installed with braces presented extra failure of matrix cracking in tension load. In overall, the installation of additional supports for the existing cross-arm material is not effective in preventing the failure of the structure for the current loading condition. It is suggested for the manufacturer to improve the integrity of the current cross-arm structure by strengthening the properties and increasing the number of layers of the composite laminates.

References

[1] A. L. López, L. E. P. Rocha, D. L. Escobedo, and J. S. Sesma 2009 Proceedings of the 11th Americas Conference on Wind Engineering (San Juan: Puerto Rico) p 22.

[2] K. D. Piltakis et al. 2007 Proceedings and Monographs in Engineering, Water and Earth Sciences p 583.

[3] A. Nadhirah et al. 2017 Int. J. Appl. Eng. Res. 12 15228.

[4] J. H. Ling, A. B. A. Rahman, I. S. Ibrahim, and Z. A. Hamid 2017 Int. J. Concr. Struct. Mater. 11 525.

[5] M. A. Haque, M. A. Masum, M. M. Ratul, and Z. Tafheem 2018 Proceedings of the 4th International Conference on Civil Engineering for Sustainable Development p 4905.

[6] M. Xu, Z. Xu, L. Zhang, and S. Liu 2018 Aust. J. Mech. Eng. 16 68.

[7] D. Mohamad et al. 2019 IOP Conf. Ser. Mater. Sci. Eng. 530 12028.

[8] D. Mohamad et al. 2019 IOP Conf. Ser. Mater. Sci. Eng. 530 12027.

[9] Z. Hashin 1980 J. Appl. Mech. 47 329.

[10] “Abaqus Analysis User’s Manual,” 2015.

[11] M. Selvaraj, S. Kulkarni, & R. R. Babu 2013 Composite Structures 96 1.

[12] D. Mohamad et al. 2019 IOP Conf. Ser. Mater. Sci. Eng. 530 12029.

Acknowledgements

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.