Journal of Green Engineering (JGE)

Volume-10, Issue-12, December 2020

Design Enhancement of Sustainable Glass Fiber Reinforced Polymer (GFRP) Cross Arm

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Abstract

Fibre Reinforced Polymer (FRP) mixtures are widely used in construction fields, such as repair, restoration, reinforcement and new construction, properties like high corrosion resistance, electrical insulation characteristics low thermal conductivity, high strength, and , high strength-weight ratio. Therefore, like their metal equivalents, these composites are not isotropic, that provides more difficult design and development methods for interact about an economical design that could maintain every types of loads. Therefore, this paper aimed to study and enhance a design of a transmission tower cross arm made of Glass Fiber Reinforced Polymer (GFRP) carrying a 275 kV cable by developing a numerical model of a GFRP cross arm. The results showed that stresses developed in the composites were within the safe range. In addition, the cross arm was shown to be governed by the serviceability requirement and it was safe against multiple failure criteria such as fibers and delamination failure. Furthermore, the results showed that the total deformation was reduced by 14.2% by adding 1-meter GFRP sleeves to all members near the cable and by 20.7% if Carbon Fiber Reinforced Polymer (CFRP) sleeves were used.

Keywords: GFRP, Failure Criteria, Numerical Modeling, Total Deformation, Delamination Failure.

Journal of Green Engineering, Vol. 10_12, 13491-13507.

Alpha Publishers

1 Introduction

Transmission towers are usually built using conventional materials such as steel, wood, aluminum or concrete. However, other materials are preferred to construct cross arms such as glass fiber reinforced polymer, i.e. GFRP, especially for those which will be carrying the high voltage cables. Although wood and steel cross arms are used to be the choice for cross arms, GFRP ones on the other hand provide better properties which make them the ideal practical solution in the industry. In addition, GFRP cross arms are inert, unlike wood, and thus require less maintenance and protection in this regard which can be a very crucial and expensive problem in this kind of structures [1],[3],[4].

Although steel is one of the most, if the not the most, construction materials used around the world for its numerous characteristics, the lack of thermal and electrical insulation, high weight and corrosion susceptibility are some of the factors limiting its usage in some applications such as the high voltage transmission towers. The high corrosion resistance, high strength-to-weight ratio, low thermal conductivity, high tensile strength, as well as electrical insulation features of glass fibre reinforced polymers include a fantastic solution, but this involves a lot of providing an orthotropic material which requires more difficult design and production strategies in order to produce an economical design. Based on the assumption that carbon fibre reinforced polymer (CFRP) composites have comparatively stronger strength and rigidity than GFRP, their significantly increased electrical conductivity and cost characteristics are not preferred in such implementations [2][5,6].

Glass fibers usually can be found in many forms such as cloth, roving or mat and they are made of standardized glass filament with diameters that range from 3.5 to 13 micrometers, for the reinforcing phase, combined with a thermosetting polymer which is usually epoxy or vinylester resins, for the matrix phase. Although there are many techniques for manufacturing composites sections, the most suitable one to produce high quality, high fiber volume fraction and continuous sections is known as the pultrusion technique. A variety of assumptions are made to simplify and allow solutions to mathematical models of composites, such as that the matrix and fibres act like structural applications, that the bond between the fibre and the matrix is fine, and that the fiber corresponding to the fibre has the same characteristics as the material in bulk state. On the other hand, there is a linear and nonlinear relationship between the modulus of elasticity of the composite and its constituents for E11 and E22 respectively depending on the volume fraction of those constituents. In addition, the fibers orientation has an exponential effect on the strength and the longitudinal modulus in which they increase as the fibers angle comes close to 0^o [7-8].[9][14-16]

In the case of composites, the failure of a lamina or laminate requires special attention as there are many failure modes at different levels including failure at micro and macro levels. The failure at local level, i.e. fiber and matrix level, is usually referred to as “damage” and therefore the terms “damage growth” and “damage propagation” are used to describe the damage accumulation. However, before a laminate fails and breaks completely, a number of local failures will occur and accumulate gradually which will eventually lead to a macro level complete failure, and therefore, the first local failure in laminates does not mean a complete failure. Micro-level failure occurs at the fiber or matrix level, or both in what is coupled fiber-matrix level but since fibers are responsible for carrying loads, failures at fiber level are considered the most catastrophic mode of failure in laminates [10-13].

2 Methodology

As Figure 1 shows, the numerical simulation of this paper consists of 4 key phases, beginning with the development of the 3D model in the SOLIDWORKS software. In the finite element investigation programme ANSYS, the remaining steps were then performed, such defining the numerical ideal, running the simulation and optimising the design. While for the material belongings, they were engaged from Wagner's Composite Fibre Technologies (WCFT), Australia.

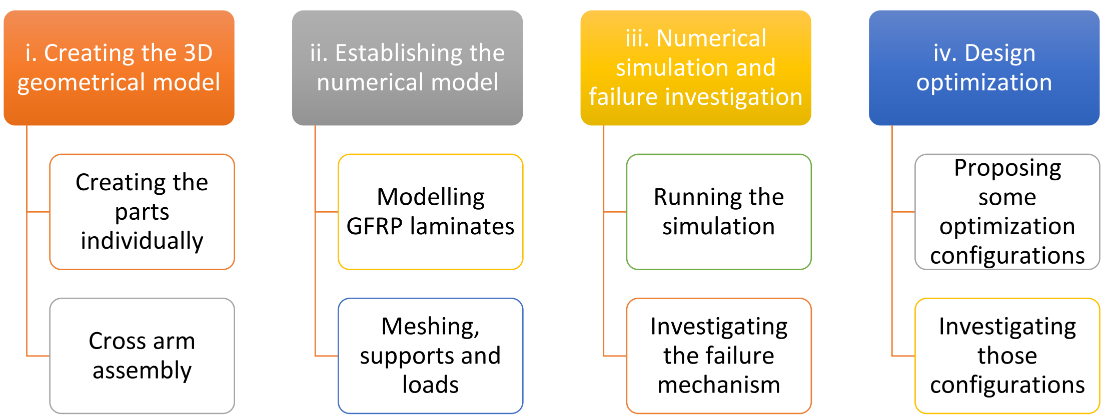

Figure 1: Methodology Overview

2.1 Creating the 3D Geometrical Model

In the SOLIDWORKS programme, including all participants and contacts, the cross arm 3D model was created. In order to permit ply build up advanced in the finite element analysis programme, the chief and tie members were modelled as surface objects, i.e. without thickness. With a square cross section containing a diameter of 127 mm, the principal members had a total length of 4832 mm. They had a length of 4747 mm and a rectangular cross section with proportions of 102 mm and 76 mm with respect to the tie members. They were independently developed as strong components for attachment components and used to bind the members composed and offer a support and loading area. At last, in the same programme, all components were integrated to form a full model as well. The accomplished cross arm 3D model is shown in Figure 2.

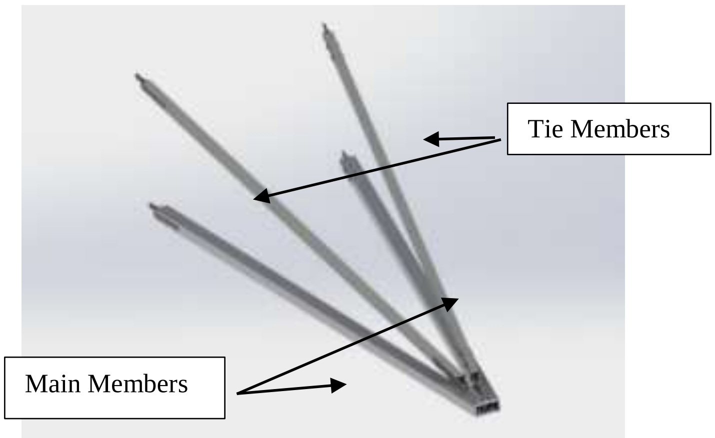

Figure 2: Cross arm 3D model

2.2 The Finite Element Numerical Model

In order to achieve optimum linear analysis, the formed 3D cross arm sections of SOLIDWORKS were moved to the ANSYS software to construct the three-dimensional finite element process. This includes laminate modelling (GFRP) with fibre instructions, the determination of the material properties, supports, meshing, and loads acting on the cross arm. The materials were occupied from, as mentioned earlier, Wagner's Composite Fibre Technologies (WCFT), Australia. A new medium of glass unidirectional fibre was shaped and all orthotropic forms, such as orthotropic strain limits, orthotropic elasticity, and orthotropic stress limits were keyed in. As for the carbon fibre reinforced polymer, the ANSYS database content UD CFRP 230GPa Prepreg was used. Table 1 illustrates all the GFRP, CFRP and Vinylester material belongings that were used in this simulation.

Following the determination of the properties of all components, the 3D geometrical method of the composite members was obtained. It was then meshed with a mesh scale of 20 mm, which was evaluated and established to create a compromise among the computational time accuracy and efficiency. Quadrilateral elements were recycled and the aspect ratio checked as much as possible, and almost all elements were found to have a ratio of 1 or quite close to that ratio. The plies were then produced and stacked on the basis of the configuration and fibre direction required through the desired fabric thickness. As Muttashar et al.[5] stated, the typical configuration was set in which they used the same hollow sections that were modelled in this paper from Wagner's Composite Fibre Technologies (WCFT), Australia. The stack up contained of 9 plies of GFRP with a thickness of 0.7 mm per ply with a total thickness of 6.3 mm, and fiber directions (0^o /+45^o /0^o /-45^o /0^o /-45^o /0^o /+45^o /0^o) in which 0o direction signifies the member's longitudinal direction.

The avoidance structural steel was picked from ANSYS' existing engineering data library for the connection pieces. A finer mesh of 10 mm was developed for the mesh, meanwhile these components are critical for the loads and the boundary conditions being borne. Then, all the boundary conditions and loads were applied in order to perform the necessary analysis. If no sliding or separating is permitted between the faces or sides, the touch surfaces of both pieces have been taken as 'Bonded' and a linear solution is possible. In order to provide a new natural pinned support, a cylindrical support was used for every end connections in which the tangential component was left free to facilitate rotation, while the radial and axial components were set to stop any motion around all axes.

As shown in Table 2, there are two load cases which have been added to the cross arm. As a bearing load, the vertical portion was simulated, while the longitudinal and transverse loads were imitation as normal forces, as seen in Fig. 3. In addition, the normal Earth gravity acceleration of 9.81 m/s2 was introduced to provide the cross arm's self-weight. All other settings were left to be managed by default or software.

After acquiring the analysis results, some proposed modifications or designs were modelled and simulated to test their reliability and adequacy. In an attempt to meet the serviceability requirements, the concept of sleeves was introduced and investigated by trying different locations to minimize the deflection as shown in Figure 4 for main members and Figure 5 for tie members The plies stackup used for sleeves was the typical one used in the members, and thus, the number of plies was 18 and the total thickness 12.6 mm at the sleeve area. Table 3 shows the different optimization configurations investigated and their respective lengths and materials.

Table 1: GFRP orthotropic material properties [6,14,15]

Property		GFRP	CFRP	Vinylester (isotropic)	Unit
		Value			
Density		2050	1490	1070	Kg/m^3
Longitudinal Direction	Young's Modulus X direction	36.3	121	4	GPa
	Poisson's Ratio XY & XZ	0.28	0.27	0.33	
	Shear Modulus XY & XZ	4	4.7	1.504	GPa
	Tensile Stress Limit X direction	596	2231	90	MPa
	Compression Stress Limit X direction	550	1082		MPa
	Shear Stress Limit XY & XZ	86	60		MPa
	Tensile Strain Limit X direction	0.01603	0.0167		
	Compression Strain Limit X direction	0.01145	0.0108		
	Shear Strain Limit XY & XZ	0.0196	0.012		
Transverse Direction	Young's Modulus Y & Z directions	10.8	8.6		GPa
	Poisson's Ratio YZ	0.09	0.4		
	Shear Modulus YZ	3	3.1		GPa
	Tensile Stress Limit Y & Z directions	55	29		MPa
	Compression Stress Limit Y & Z directions	120	100		MPa
	Shear Stress Limit YZ	44	32		MPa
	Tensile Strain Limit Y & Z directions	0.0051	0.0032		
	Compression Strain Limit Y & Z directions	0.0103	0.0192		
	Shear Strain Limit YZ	0.015	0.011		

Table 2: Load Cases

Load Case		Transverse (N)	Longitudinal (N)	Vertical (N)
Ultimate Limit State	1. Normal	23436	42496	0
	2. Broken wire	10834	20545	32224
Serviceability Limit State	1. Normal	11718	21248	0

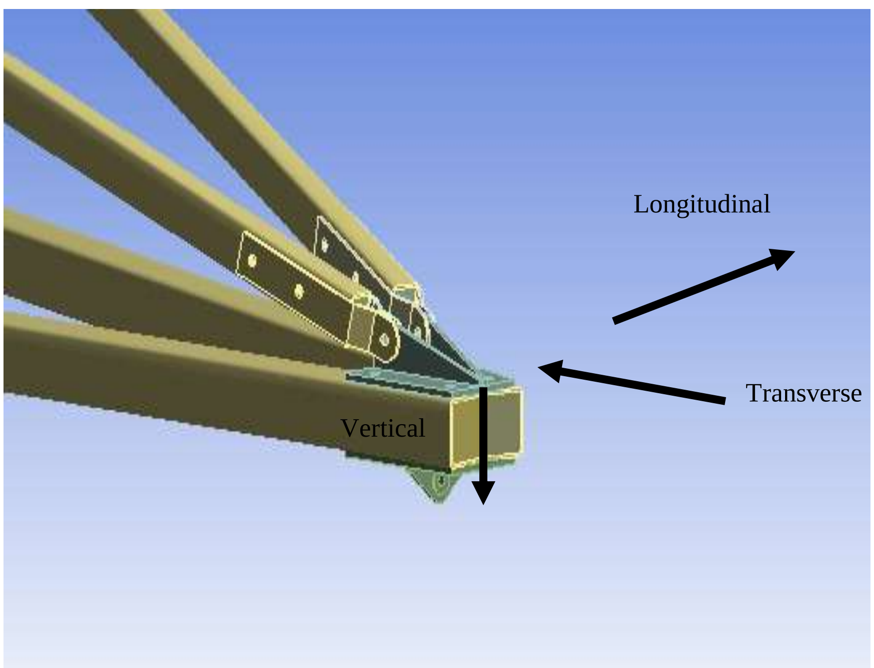

Figure 3: Load components orientations

Table 3: Load Cases

Sleeves Location	Sleeve Length (mm)	Sleeved Members	Case Notation	Members Material	Sleeve Material
No Sleeves	-	-	No-S	GFRP	-
Tower Side	1000	Main Members	T-S	GFRP	GFRP
Middle Span	1000	Main Members	M-S	GFRP	GFRP
Cable Side	1000	Main Members	C-S	GFRP	GFRP
Cable Side	1500	Main Members	C-S2	GFRP	GFRP
Cable Side	1000	All Members	CA-S	GFRP	GFRP
Cable Side	1000	Main Members	C-S-CFRP	GFRP	CFRP
Cable Side	1000	All Members	CA-S-CFRP	GFRP	CFRP

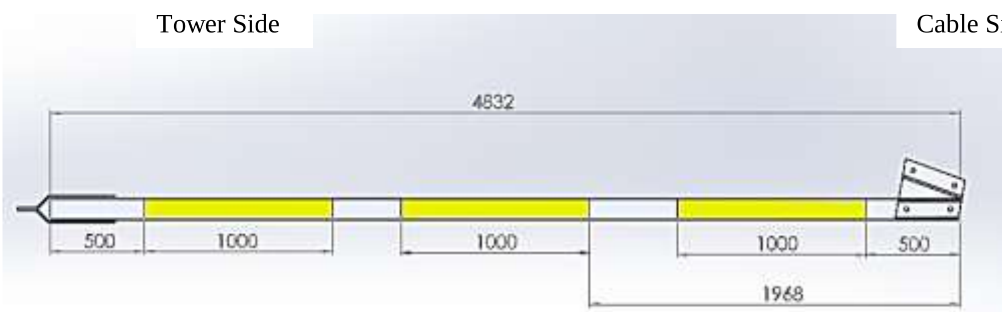

Figure 4: Sleeve locations in the main members (mm)

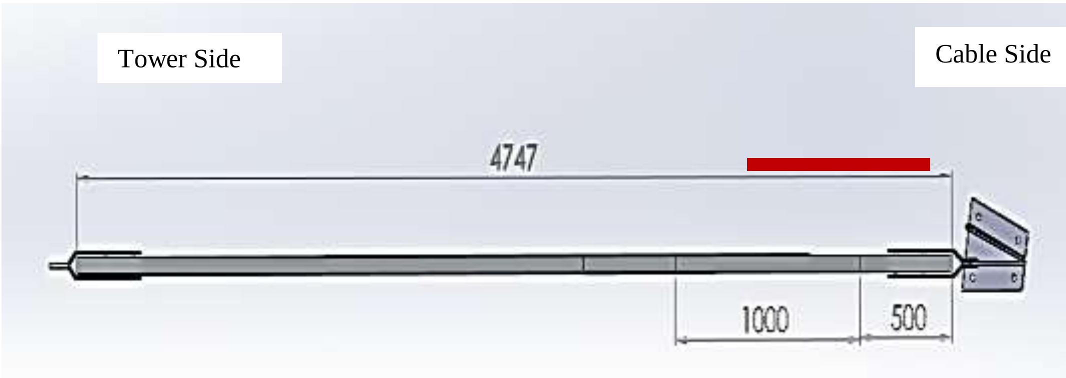

Figure 5: Sleeve location in the tie members (mm)

3 Results and Discussion

3.1 Numerical Verification

The confirmation approach was performed on the outcomes of the Muttashar et al.[5] paper, meanwhile their experiments were based on GFRP cells from the same source, Wagner's Composite Fibre Technologies (WCFT), Australia. The same material features and orientations of fibres were also valid and modelled. For verification, a single empty cell case with the descriptions as seen in Table 4 and Figure 6 was selected.

Table 4. Description of the GFRP verified beam [4]

Specimen	L_t (mm)	a (mm)	L (mm)
1C-H-0	2000	525	1350

In ANSYS, a single hollow member was modelled and simulated, related to the members used in this project. The experimental deformation from Muttashar et al. research was found to be 18.8 mm, while the replicated one caused in 18.75 mm with a 0.26 percent difference as seen in Figure 7.

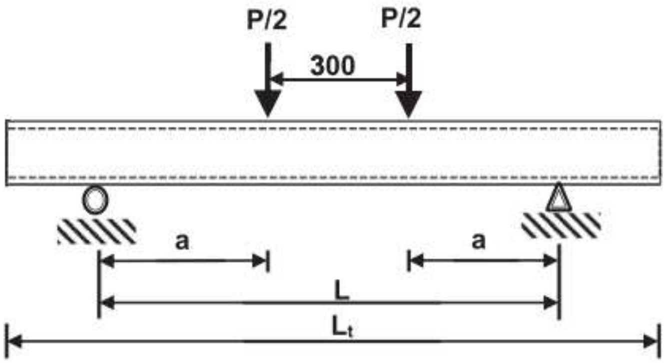

Figure 6: Flexural test setup based on Muttashar et al. [4]

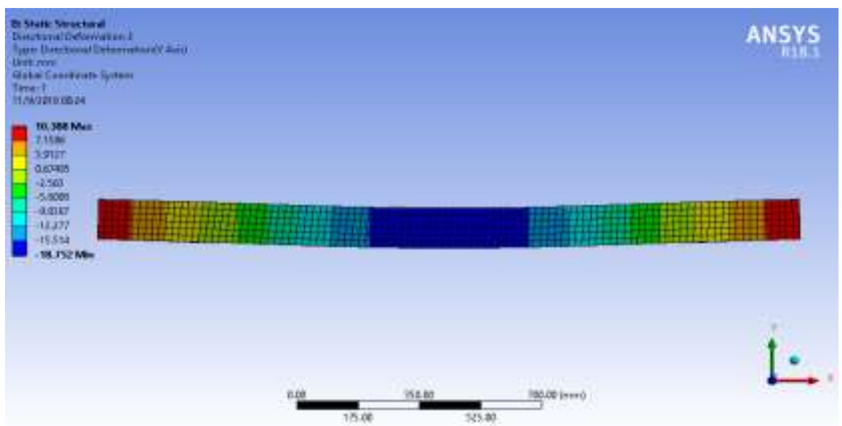

Figure 7: Deformation result of the verified member

3.2 Optimization Results

The concept of using sleeves at certain locations was applied in order to increase the stiffness of the members to compensate for the low elasticity modulus in GFRP. Figure 8 shows the maximum deflection achieved for every sleeve location in SLS load case. As illustrated in Table 5, adding sleeves near the tower, i.e. T-S case, did not seem to have the desirable effect on the deformation for the SLS load case as the reduction was around 2.1% with a similar outcome for the M-S case at almost 4.5% as illustrated in Figure 9. However, transferring the sleeves near the cable showed a noticeable reduction percentage at around 10% for the C-S case and 14.23% for the CA-S case and these reductions went higher when CFRP sleeves were used to become 13.88% and 20.67% for C-S-CFRP and CA-S-CFRP respectively. As seen in Figure 10, the maximum stresses created in the composite members for different sleeve locations ranged in between 90-105 MPa for ULS normal load case and 105-115 MPa for ULS broken wire load case. Figure 11 demonstrates the deflection reduction achieved in all sleeve locations under the different load cases while Figure 12 shows the stress distribution for the case CA-S-CFRP.

Table 5 Total deformation for SLS load case for different sleeves locations

Case Notation	Sleeves Location	Total Deformation (mm)	Reduction %
No-S	No sleeves	34.04	0.00
T-S	Near Tower	33.33	2.10
M-S	Middle Span	32.51	4.49
C-S	Near Cable	30.62	10.04
C-S2	Near Cable	29.16	14.33
CA-S	Near Cable (All members)	29.20	14.23
C-S-CFRP	Near Cable	29.32	13.88
CA-S-CFRP	Near Cable (All members)	27.00	20.67

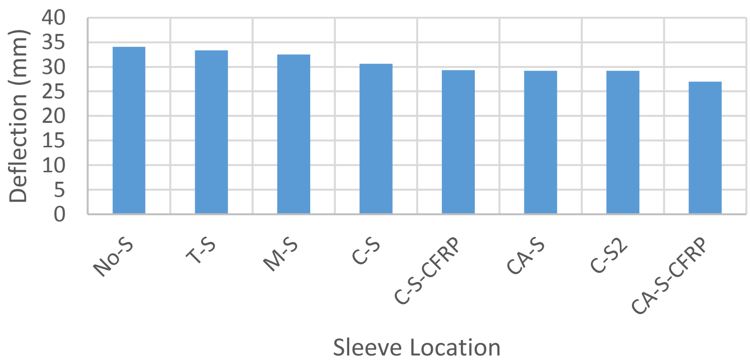

Figure 8: Maximum deflection in composite members for different sleeve locations (SLS load case).

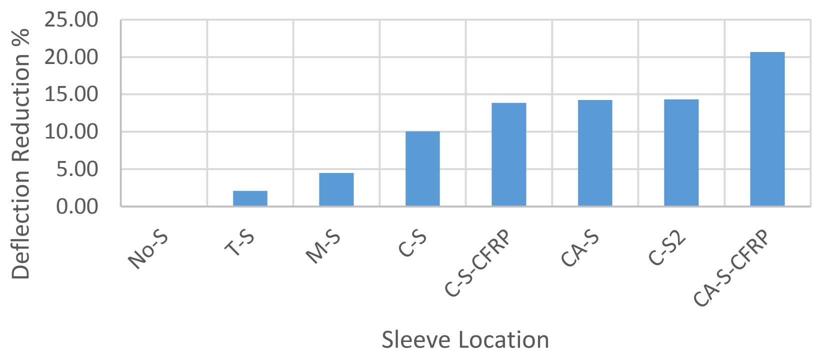

Figure 9: Deflection reduction percentage for different sleeve locations (SLS load case).

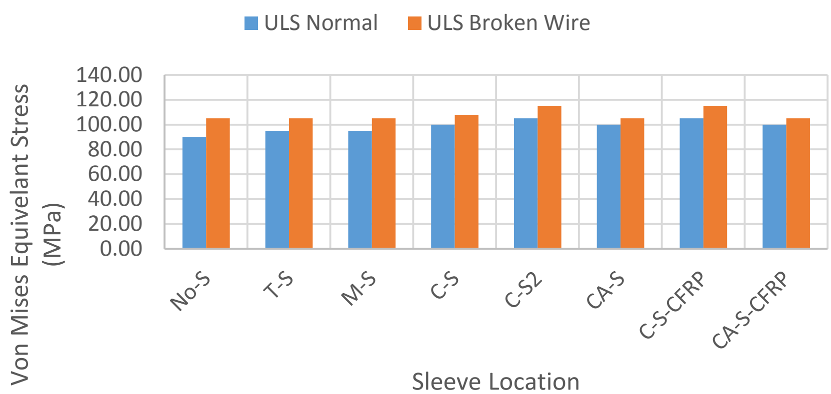

Figure 10: Maximum stress in composite members for different sleeve positions.

On the other hand, using 3 m of total sleeves lengths in C-S2 case resulted in 14.33% reduction in total deformation which is almost equal to CA-S case where 4 m of total sleeves lengths were used. This can be an appealing solution from an economic stand point as it shows 25% less length with the same deflection effect.

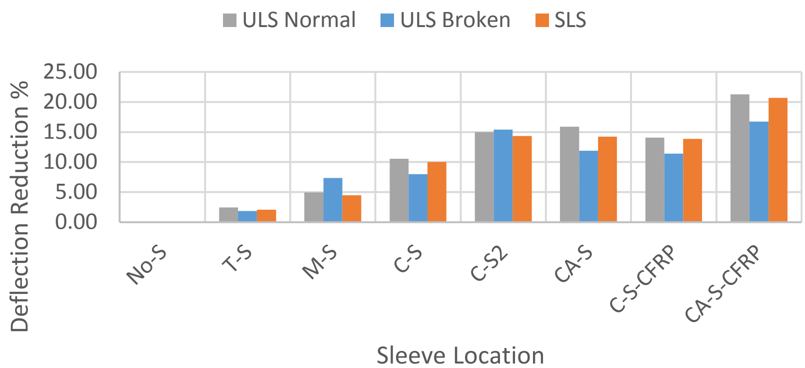

Figure 11: Deflection reduction percentage for different sleeve locations.

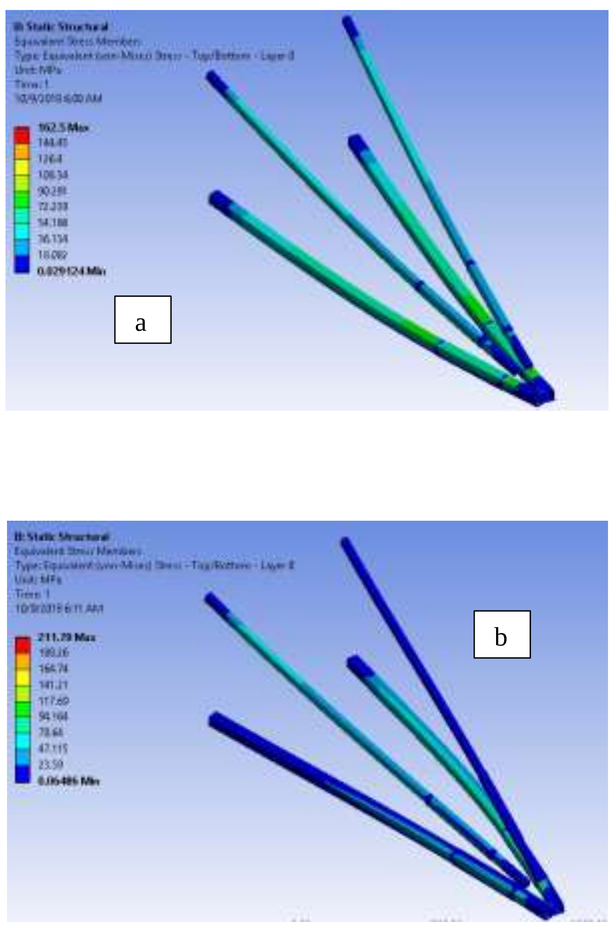

Figure 12: Stress distribution for CA-S-CFRP a) ULS normal case. b) ULS broken wire case.

4 Conclusion

This paper investigated a glass fiber reinforced composite cross arm and to tried to propose some enhanced designs. To achieve that, a 3D model of the cross arm was created in SOLIDWORKS software and then transferred to ANSYS finite element analysis program to develop the numerical model and perform the required analysis. Finally, six enhancement configurations were introduced and analyzed. The conclusions taken from the results of this research were as follow:

i. In all load situations, the cross arm was considered to be protected towards the faults of fibre, matrix, out-of-plane shear, in-plane shear, as well as delamination, that meets the specifications of the performance point, but managed to retain a deflection of 34 mm on the structural system.

ii. A serviceability requirement of maximum deflection less than L/400 was found to be very difficult to achieve and was barely met by using a full CFRP cross arm members. Despite that, the results showed that the total deformation was reduced by 14.2% by adding 1-meter GFRP sleeves to all members near the cable and by 20.7% if CFRP sleeves were used.

iii. The verification result matched the experimental one with a 0.26% difference which found to be very accurate.

Acknowledgments

The authors express their gratitude to Universiti Tenaga Nasional (UNITEN), Malaysia for supporting this research under UNIIG 2018, through Project No: J510050801and BOLD 2025. Special thanks to those who are contributed to this project directly or indirectly.

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