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Full Length Research Paper

Static analysis and design of sandwiched composite long-span portable beam

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Long-span portable beams are very important in military operations for the purpose of rapid construction and bridging system. Such structural element can also be utilized in disaster relief operations. In the early days, portable structure, such as military bridges were made from steel, causing the weight of the structure to be huge, and consequently, it will be costly to operate. To overcome these problems, aluminium and metal alloy were introduced to reduce the weight of such structure. The use of composite material such as carbon fibre reinforced polymer (CFRP) emerges as a lighter alternative and is considered to be the primary material for the portable beam. The use of the CFRP as a primary material is due to its high strength to weight ratio, thus it makes it lighter than steel and other alloys. In this research, a long-span portable beam is analysed and designed using finite element method. Several static simulations, with impact factor for dynamic effect, are made to test various possible lay-ups, including the use of core in order to increase stiffness of the member. From the trials, it can be concluded that with proper design and fabrication, CFRP is capable of carrying the design load similar to steel and aluminium. Furthermore, use of core layers for top flange can improve the performance of the structure significantly, while use of core to the webs stiffen the webs against buckling and further improve the overall performance of the structure.

Key words: Composite material, portable beam, sandwiched composite, finite element analysis.

INTRODUCTION

Long-span portable beam is very important in the military for various temporary structures, such as gap bridging; however, it becomes more important nowadays for disaster relief operations. In the early days, military bridges were made from steel, causing the weight of the bridge to be huge; thus, more vehicles are needed to transport the bridge and crane with higher capacity to erect it. Consequently, its operation is more costly. To overcome these problems, aluminium and metal alloy were introduced to reduce the weight of such structure. Then, a new material emerge called composite material, that is, fibre reinforced polymer (FRP) (Allampali et al., 2002; Latif and Hassan, 2005; Norazman et al., 2010).

International non government organizations (NGOs) have an intense interest in cross-country mobility where infrastructure may have been badly damaged by various incidents, conflict or natural disaster (Wight et al., 2002, 2003). The portable beam system can also be used for various other needs, such as to build shelter, bunkers and to cover damaged road surface.

Carbon fibre reinforced polymer (CFRP) has several favorable mechanical properties, such as high strength to weight ratio, corrosion-free characteristics, high degree of free formability and good fatigue resistance that make it as a target material for the construction of portable structure system. CFRP material also has been widely used for strengthening of reinforced concrete (RC) that proves the capabilities of material in construction fields (Ahmed et al., 2011; Hong et al., 2011; Jumaat and Alam, 2010, 2011; Jumaat et al., 2010, 2011; Narmashiri et al.,

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Abbreviations: CFRP, Carbon fibre reinforced polymer; **FRP**, fibre reinforced polymer; **MLC**, military load class; **TDTC**, trilateral design and test code.

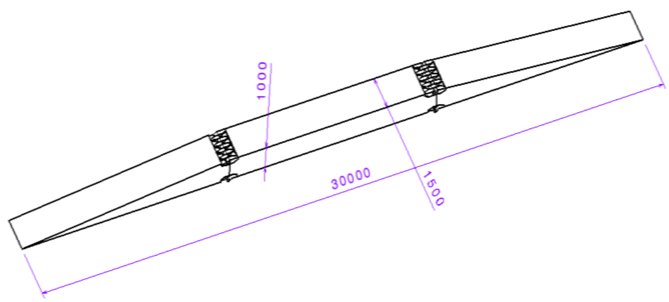

Figure 1. Dimension of beam with 3 sections connected.

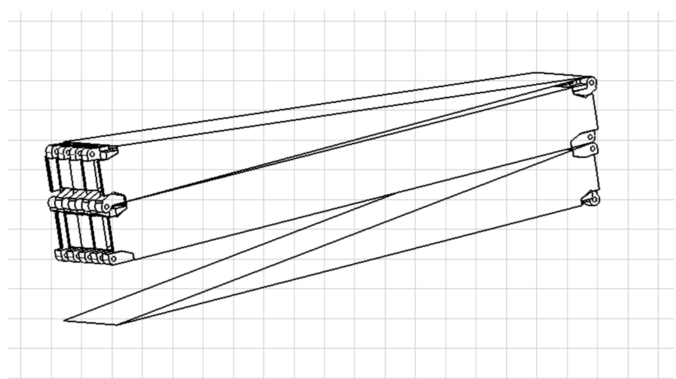

Figure 2. Folding system of the beam.

2010, 2011).

Hundreds of pedestrian and several vehicular FRP bridges have been built, proving the feasibility of this material for lightweight structures (Johansen et al., 1992; Johansen, 1996; Keller, 2002; Sedlacek et al., 2004; Weaver, 1997; Wight et al., 2006). CFRP is being considered to be used as primary material for the portable beam. The reason to use the CFRP as the primary material is due to its high strength to weight ratio, thus making it lighter than steel and other alloy.

The present study is performed to investigate the advantages of using sandwiched composite structure for a long-span portable beam which is imposing one and two tanks loads. The effect of lamina, core thickness and fibre orientation on the beam deflection also will be observed to get the best performance of structure itself.

PRELIMINARY DESIGN

In preliminary design, dimensions of the beam should be defined, where the simple analysis can be performed to observe the response of the beam subjected to the loads. After defining the dimension of the beam, the detail analysis can then be performed using finite element software.

The dimensions of the bridge main beam have total length of up to 30 m, width of 1.5 m and height of 1 m as shown in Figure 1. In certain situation, the beam can be assembled in two sections only, so that the total length is reduced to 20 m.

PORTABLE SYSTEM DESIGN

The bridge with total length of 30 m will have difficulty in transporting. In order to solve this problem, a foldable system is designed so the beam can be folded in three sections, thus reducing the length to 10 m as shown in Figure 2. The system is using connections in the form of hinges.

Finite element analysis of the beam

The quadrilateral elements with four nodes were used in meshing of the beam. The laminate modeller facility in MSC PATRAN; MSC PATRAN (2007) was used to apply lamina composite material properties. In this research, loads were applied at the top-flange of beam as static loads with impact factor to cater for dynamic effect as required by the design code (TDTC, 2006). The load was applied as multiple line load and distributed load for imposed and dead loads, respectively.

The bridge will be supported at the ends by embankment or compacted soil, with the length of 1000 mm from each end of the beam resting on the support. These conditions were represented on the finite element model as a pin and roller constraint at the support or embankment. The pin-constraint at the left side of beam was represented by constraining x, y and z translation in one line of nodes and the roller-constraint at the right side of beam was represented by constraining y and z translation only in one line of the nodes.

Effect of lamina and core thickness on the deflection of the beam

The thickness of laminate and core on the parts of the beam such as top, bottom flange and the web at the mid and ramp-sections was observed. The purpose of this study is to investigate the effect of adding core on the structure and to determine the location of core in order to optimise the design.

The optimization in the design will be achieved if we can determine the minimum thickness of the laminate and the core, as well as the placement of the core that results in minimum stresses and strains, and acceptable deflection.

In general we know that adding laminate and core thickness at any part will improve the performance of the bridge at the cost of the bridge becoming heavier. Thus, in the simulation processes, we need to optimise the design so that we can achieve the required performance with lightest structure.

Effect of fibre orientation on reducing the beam deflection

In general we know that fibre strength is greatest in tension; however, due to the various loading behaviour and response from the structure we need to do simulation to analyse the structural performance due to various fibre orientation.

From the simulation, it is discovered that changing of fibre orientation from combination of 0 and 90° to 0° only, result in reduction of the deflection significantly. Contrarily, the use of 45° fibre orientation gave the largest deflection. In reality, the fabrication of laminate needs 90° fibre orientation to prevent possible longitudinal crack.

The effect of using 90° fibre on the laminate can increase the deflection if it is to replace 0° fibre, but the layer must exist to avoid

Table 1. Loading for static analysis (Agusril, 2010).

Type of loading	Unit	Value	Description
Vehicle's vertical load	N	62272	For 1 contact area
Vehicle's braking load (x-direction)	N	33731	For 1 contact area (1 tank*)
Vehicle skewing load (y-direction)	N	5189	For 1 contact area
Ramp-section distributed load	N/m^2	12155	(D, M, F, W)**
Mid-section distributed load	N/m^2	12155	(D, M, F, W)

*Tank referred to MLC70 main battle tank load. **D, M, F, and W are dead, mud, foot-walk and wind load, respectively.

Table 2. Static responses analysis.

Response	Value	
	2 tanks	1 tank
Maximum stress of lamina in x-axis (σ_x), MPa	-149	-104
Maximum stress of lamina in y-axis (σ_y), MPa	-6.03	-4.02
Maximum shear stress of lamina in x-y plane (τ_{xy}), MPa	11.3	-7.44
Maximum strain of lamina in x-axis (ε_x)	-0.00128	-0.00089
Maximum strain of lamina in y-axis (ε_y)	-0.00118	-0.000885
Maximum shear strain of lamina in x-y plane (γ_{xy})	-0.00328	-0.00242
Deflection (mm) - Limit	150	149
Weight of the bridge (ton)	20.44	16.4

longitudinal crack on structure. Thus, we can conclude that the deflection of laminated composite beam can be reduced by adding 0° fibre orientation proportionally. The 45° fibre orientation cannot be used to reduce the beam deflection. This result can be proof using the following equations (Heslehurst, 2008).

$$F_1 = \left[0.9 + \frac{\upsilon_0^{\,2}}{10}\right]P0 + \left[\frac{1-\upsilon_{12}}{4}\right]P45 + \left[\frac{1-\upsilon_{12}\upsilon_0}{10}\right]100 \quad (1)$$

$$F_2 = \left[0.9 + \frac{\upsilon_0^{\,2}}{10}\right]P90 + \left[\frac{1-\upsilon_{21}}{4}\right]P45 + \left[\frac{1-\upsilon_{21}\upsilon_0}{10}\right]100 \quad (2)$$

where F1 and F2 are the lamina strength in the longitudinal and transverse direction, respectively and P0, P45 and P90 are fibre in 0°, 45° and 90° direction, respectively.

According to Equation 1, it can be observed that the effect of fibre in 0° is significant in increasing the lamina strength in longitudinal direction, while Equation 2 shows the significant effect of 90° effect to increase lamina strength in transverse direction. Fibre direction of 45° gives little contribution to the lamina strength in the longitudinal and transverse direction.

The deflection of the beam was significantly influenced by the lamina strength in longitudinal direction or 0° fibre direction, thus by increasing the percentage of using of 0° fibre direction will reduce the beam deflection significantly. This condition is similar to simulation result as mentioned earlier.

Static analysis of bridge

Static analysis is performed to observe the responses of bridge when imposing loads without any inertia forces occurring. The inertia forces, from Newton's law, are equal to the mass times the acceleration. All of loads include vehicle load with its impact factor considered as static loads. The impact factor is applied to an induced static load to give the equivalent induced dynamic load caused by load's movement. The responses, such as maximum stress, strain and deflection will be presented in this study.

Loading calculation

The subjected loads of bridge are calculated using TDTC code (Agusril, 2010; TDTC, 1996). In static analysis, all factors as described in such code are considered in loading calculation. Loading value is as shown in Table 1. The value of vehicle's vertical load is included the impact factor of 1.2 to cover dynamic effect caused by vehicle movements.

RESULTS

The responses of the bridge

After defining the finite elements model, the structure was then analyzed using MSC NASTRAN finite element software. The responses of bridge structure which is needed for performance assessment of the bridge can be obtained by taking critical value of responses as maybe observed in Table 2.

Table 2 shows maximum stress, strain, deflection and the total weight comparison of the bridge when subjected to one and two tanks loads. In this simulation, deflection is being used as controlling variable and set not to exceed 150 mm.

From static analyses performed, we summarized the

Table 3. Optimum lamina sequence and orientation in the laminate.

Case	Part	Part of structure (Optimum design)			Deflection (mm)
		Top	Bottom	Web	
1 tank	R-S*	$[90_1/0_{23}/\text{core}]_s$	$[90_1/0_{14}]_s$	$[90_1/0_{17}/\text{core}]_s$	149
	M-S**	$[90_1/0_{23}/\text{core}]_s$	$[90_1/0_{17}]_s$	$[90_1/0_{20}/\ \text{core}]_s$	
2 tanks	R-S	$[90_1/0_{23}/\text{core}]_s$	$[90_1/0_{23}]_s$	$[90_1/0_{23}/\text{core}]_s$	150
	M-S	$[90_1/0_{23}/\text{core}]_s$	$[90_1/0_{23}]_s$	$[90_1/0_{23}/\text{core}]_s$	

*R-S is ramp section; ** M-S is mid section.

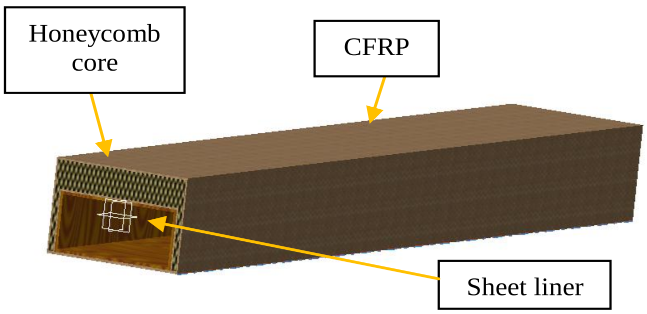

Figure 3. The location of honeycomb (core structure) on the mid-section.

optimum sequences of laminas with fibre-orientation as shown in Table 3. The table shows that no core was required for the bottom flange. Generally, the core has function to stiffen panel member against bending and local buckling, while the bottom panels are in tension and this tensile stress can be resisted by the fibre.

Generally, the core increases the stiffness by holding the laminas apart and improving the moment of inertia of the laminate. The core-to-skin adhesive rigidly joins the sandwich components, and allows them to act as one unit with a high bending rigidity. Thus, giving more stiffness and reducing the flexural stress and the deflection.

In the laminate design, the strength in the fibre direction is greater than the perpendicular of fibre direction. In this case, the loads generally act in *x* and *z* direction, which requires more strength in x-direction for reducing the strain and deflection. The placement of fibre in 0° direction will increase the lamina's stiffness in *x*-direction, and together with the core will improve the performance of the bridge in withstanding the deflection. The location of core at the top flange and web can be seen in Figure 3. The sheet liner acts as the mould for the sections, which is made from metal sheet. The structural layers are the honeycomb core sandwiched by CFRP layers.

Performance analysis

Performance of structure needs to be observed to ensure that the structure can be loaded as designed without any damage on the structure. The performance of bridge structure, such as resistance to failure is presented here.

The failure of structure was observed using failure criterion, such as maximum stress theory, maximum strain theory, Tsai-Wu theory and Tsai-Hill theory. The failure theories can be formulated using Excel Spreadsheet, and we can create graphics based on such formulation (Greg, 2008). Once the graphs have been generated, the maximum stresses of the structure can be attached into such graphic.

Table 4 shows the strength of carbon reinforced epoxy in *x* and *y* direction for tensile, compressive and the shear strength. These values were used in failure formulation to create the failure graphic.

Table 5 shows that the maximum stresses on the bridge were chosen from certain layer of laminate which has maximum stress in x, y direction and xy plane. The conversion unit from MPa (Mega Pascal) to KSI (kilo pound per square-inch) need to be done due to the fact that the available failure formulation is in KSI, while the analysis was performed using MPa.

Figure 4 shows the position of structure stresses and strain whether within the allowable limit or outside.

In this analysis, the stresses and strain of the structure are still within the allowable range, as shown in Figure 4. Thus, the structure will not fail in the operation.

Conclusion

From the literature, we realised that portable bridge is very useful in time of emergency and in conflict areas. General characteristic of portable bridges are: light, easy in transporting, handling, launching and retracting. The use of composite materials, that is, carbon fibre reinforced polymer (CFRP) for the bridge structure can fulfil such requirements successfully.

Static analyses have been performed to investigate the effect of vehicle's movement on the bridge. The requirements in TDTC including the impact factor (IF) of 1.2 are to cover the dynamic effect.

The performance of the bridge to resist the local buckling effect was achieved by using the core layer in the web. However, the deflection is found to be the

Table 4. Strength of carbon fibre reinforced epoxy (Greg, 2008).

Property	Value	
	MPa	KSI
Tensile strength in fibre-direction (X_t)	1219	176.84
Tensile strength in perpendicular to fibre-direction (Y_t)	18	2.65
Compressive strength in fibre-direction (X_c)	1219	176.84
Compressive strength in fibre-direction (Y_c)	18	2.65
Shear strength (S)	70	10.20

Table 5. Stresses on the bridge structure.

Property	Value	
	MPa	KSI
Stress in fibre-direction (σ_1)	-104	-15.09
Stress in perpendicular to fibre-direction (σ_2)	-4.02	-0. 58
Shear stress (τ_{12})	-7.44	-1.08

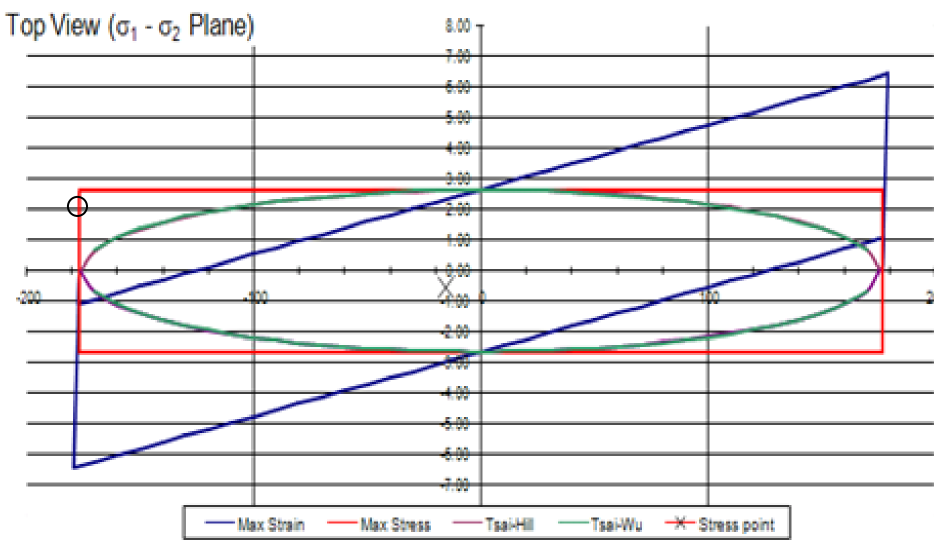

Figure 4. Failure criterion graphics in KSI unit.

most critical criteria for design of bridge beam from CFRP. But this problem can be overcome by arranging the fibre orientation dominant in 0° or parallel to the length of the beam and using the core structure as mentioned earlier.

RECOMMENDATION

The material data used in the portable bridge design was retrieved from journals and acceptable resources. Actual data can be obtained from testing of materials, such as carbon fibre, epoxy, honeycomb and steel material. In order to verify the analysis, a prototype should be produced and tested using scaled loads. Once the results are obtained, the comparison can be made between analytical or simulation result with experimental results.

FUTURE RESEARCH

The use of CFRP material for long-span portable beam shows good performance to resist the designed load. However fabrication and maintenance cost of CFRP beam need to be investigated to evaluate the cost effectiveness of using such material. Comparative study also needs to be performed with other advanced material, such as aluminium alloy. Aluminium alloy has been widely used for various military portable structures, thus, we need to ensure effectiveness of CFRP against aluminium alloy.

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