# Fibre composite wind mill structure – investigations and design considerations

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ABSTRACT: During the celebration of the 40th anniversary of the University of Southern Queensland, an artistic concept was put to merge the Australian tradition of using windmills with the advanced usage of composite materials. With the main structural system based on fibre composite sandwich construction, its behavioural issues and failure modes are presented. The FE modelling considerations for this type of structure is presented. Limited experimental program was conducted to investigate the behaviour of sandwich panel under compression and verify the test results with the FE analysis approach. To assess the suitability of the connection between the fibre composite tower and the footing, prototype brackets that comprised from all-composite infill and steel plate infill were tested under tension to assess their load carrying capacity. This experiment showed that using all-composite brackets achieved higher capacity when compared to composite skins filled with steel plate. The paper concludes with general discussion of using composites for the main structural elements.

## 1 INTRODUCTION

During the celebration of the 40$^{th}$ anniversary of the University of Southern Queensland, an artistic concept was put to merge the Australian tradition of using windmills with the advanced usage of fibre composite materials. This sculpture represents bridging the old and the new in a project where staff members of the Faculty of Arts, the Centre of Excellence in Engineered Fibre Composites (CEEFC) of the Faculty of Engineering and Surveying along with experienced fibre composite manufacturing company gathered to achieve completing this project by using tried and true technology alongside with the cutting edge.

The structure can be divided into three parts. The first part is the windmill gearbox with its supporting shaft, which is commonly fixed on a steel lattice tower. The second part is the footing and the third is the fibre composite tower. The tower design should accommodate reasonable connection to the footing and the gearbox.

A few alternatives are proposed for the FC tower. The first alternative was based on using pultrusions for the tower corners with connecting diaphragm panels (Fig. 1a). This alternative allows easier connection to the foundations and the gearbox shaft. In addition, pultrusions are among the most efficient sections in composites with most of its strength aligning with its axes.

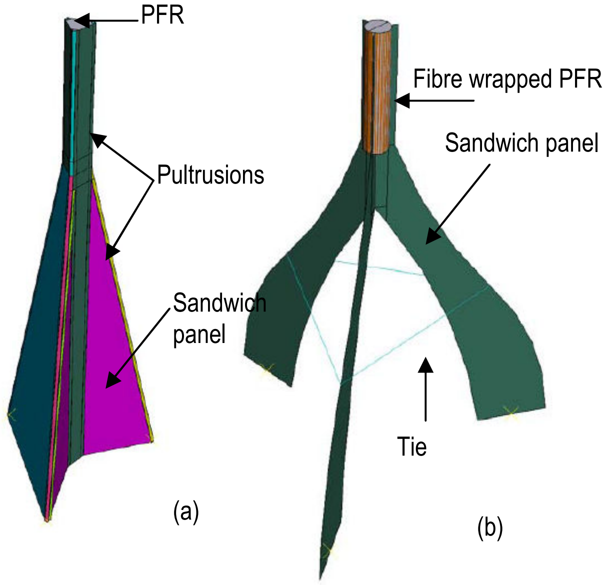


Figure 1. Windmill alternatives (a) Pultrusion/sandwich, (b) Spread sandwich legs

The top three meters of the eight meter - tower is formed from three pultrusions joined by sandwich panels and filled with particulate filled resin (PFR) for connection with the gearbox shaft. The second alternative used a separate leg configuration that are formed from sandwich panels and meet at the top into circular section that is formed by wrapping PFR with glass reinforced composites. To control the buckling of the sandwich panels, the legs are tied together by steel ties (Fig. 1b).

In fibre composites, the cost of setting the manufacturing procedures is significant and accordingly needed to be considered early in the design. Unlike other industries, civil engineering applications of fibre composites is of one-off nature. This necessitates selecting structural system that can be manufactured following close procedures to that used by the manufacturing company. Accordingly, all-sandwich structural system was selected. This decision was made at the early stage of the design process with close coordination with the manufacturer (Fig. 2).

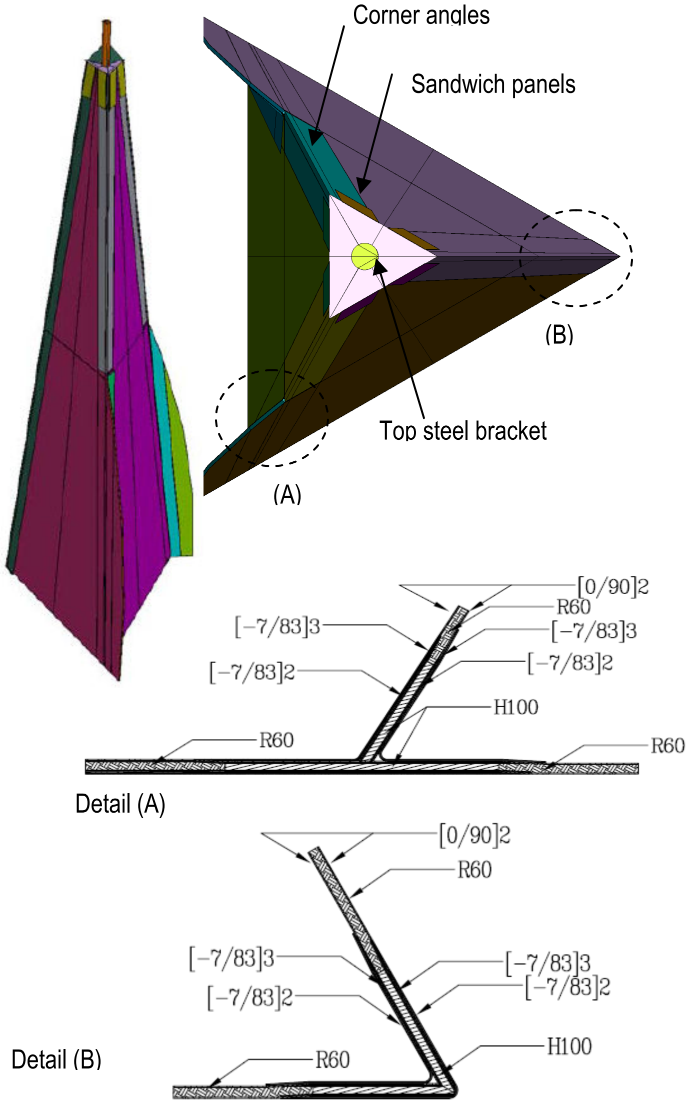


Figure 2. Layout of the windmill and its connection detail

## 2 WINDMILL STRUCTURAL SYSTEM AND MATERIALS USED

The USQ windmill structure has few components. The tower is 7900 mm high with 2300 mm base that has two wings extending 300 mm at the ground level. The two wings stoped mid-height of the tower that tapered to 400 mm at the top (Fig. 2). The tower structure was manufactured from double skins of glass/vinyl ester with 15 mm closed-cell PVC foam R60 and H100 grades. Based on material characterisation, the material properties used in the FE model to model each laminate ply is shown in Table 1. The tensile properties were determined according to ISO 527-4/2/2 (1993) in both the fibre direction (1-1) and the normal-to-fibre direction (2-2). Similarly, compression properties were determined according to ISO 14126 (1999). The shear properties (1-2) were determined according to the ISO 14129 (1997). Double bias glass fibres [+45/-45] were used with 800gsm weight. As most of the loads are transferred as axial forces at the tower corners, skins are reinforced at these areas. Flat panels are connected by using angles that were laminated then laid on the faces. The fibre architecture of the different components is shown in Figure 2 with the zero direction definition along the centre of each tower face. At corners, to improve the wrinkling capacity of the sandwich panels, higher grade (H100) foam is used. The tower composite structure is connected to the foundations through steel brackets that are connected to the raft footing on three piers by using M20 Reo 502 ChemSet studs. The windmill gearbox is supported to the tower through top steel bracket with the mill shaft welded. At the connection to the steel brackets, solid laminates replaced the core foam. Steel plates are used due to the limited budget and time allowed to develop fibre composite connections. However, this development is considered for future investigations.

Sandwich sheets were manufactured by vacuum bagging with the bottom laminate and the core material in place. After curing for 24 hours at ambient temperature, the other laminate was applied by hand lay-up. The assembled tower (Fig. 3) was formed by cutting the sandwich faces then joining them by forming the corner angles by hand lay-up.

Table 1. Laminate properties

| Property | Direction | | |
|---|---|---|---|
| | 1-1 | 2-2 | 1-2 |
| Modulus (MPa) | 22800 | 5707 | |
| Tensile Strength(MPa) | 440 | 24 | |
| Compression Strength(MPa) | 360 | 97 | |
| Shear Modulus (MPa) | | | 2300 |
| Poisson's ratio | 0.30 | | |

Figure 3. Fibre composite windmill tower after joining faces using corner angles

## 3 WINDMILL STRUCTURAL ANALYSIS AND DESIGN CHECKING

The design of the windmill has been through few stages. The first stage was assessing the design loads. Wind load calculations were based on the AS/NZS1170.2 (Standards Australia, 2002) assuming solid frontal area of the blades and the tower structure. This 'conservative' approach was followed as there was no design specification for this type of structure found either in the design codes or the manufacturer specifications. In addition, equivalent gyroscopic moment was calculated and applied to the tower assuming that blades are rotating at 5Hz.

The second stage was to investigate the behaviour of sandwich members under compression (most critical) and ensure that the FE representation correctly simulate the behaviour of the structure. Four failure modes for sandwich structures (two global and two local) are presented in the US Military Handbook MIL-HDBK-23 (Anon, 1955) and found in many references such as Vinson (1999), Fleck and Sridhar (2002), and Omar et al (2007). In addition to the overall buckling, shear crimping failure is another form of general overall buckling in which the wavelength of the buckles is very small, because of the low core-shear modulus. The crimping of the sandwich occurs suddenly and usually causes the core to fail in shear at the crimp; it may also cause shear failure in the bond between the facing and the core. It is important to note that the critical skin stress, where core shear instability can occur, is independent of the panel dimensions. However, it is related to the core and skin properties and the boundary conditions (Vinson, 1999). If the core is of cellular structure, honeycomb, it is possible for the facings to buckle or dimple into the spaces between core walls or corrugations. Wrinkling is the fourth form of failure. It can occur if the skin buckles inward or outward, depending on the flat-wise compressive strength of the core relative to the flat-wise tensile strength of the bond between the facing and the core. If the bond between the facing and the core is strong, facings can wrinkle and cause tension failure in the core. This simulates plate-on-elastic foundation. The wrinkling load depends upon the elasticity and strength of the foundation system, namely, the core and the bond between the facing and the core. Since the facing is never perfectly flat, the wrinkling load will also depend upon the initial eccentricity of the facing or original waviness (Allen, 1969).

A few FE modelling techniques are established to simulate sandwich structures (Vannucci et al (1998), Akfert (1994), Muc and Zuchara (2000), & Bazant and Beghini (2004)). It is concluded that using 3D solid elements for the core and thick shell elements for the skins well presented the behaviour of sandwich structures (Omar et al (2007)).

## 4 EXPERIMENTAL PROGRAM AND THE FE VERIFICATION

A testing program was set to investigate the behaviour of sandwich column and correlate the test results with the developed FE model. The column dimensions are 550mmH (clear height 460mm) x 120mmW x 20mmthk. End blocks of 250mm length formed from SHS50x50x5 pultrusions filled with PFR were used. Column tests were conducted on Shimadzu CSP-300 machine. Clamped-end restraints were implemented using a special fixture attached to the machine ram (Fig. 4). Applied loads were recorded by 222kN loading cell, vertical displacement was recorded using a string pot while horizontal displacement was recorded using a LVDT. Strain gauges were attached at the mid-height of the column at both faces. All data were collected by System-5000 data-acquisition system and recorded on a standard PC at time increments of 0.10s. Two FE models are used to simulate the test. The first model used solid-shell elements (CSO) with material properties as presented in Table 1 for the laminates and elastic material for the core material (PVC closed cell foam R45) with shear modulus of 15 MPa and Poisson's ratio of 0.30. The second model used reduced integration thick shell elements with properties assigned as composite shell. Commercial FE software ABAQUS (Hibbitt et al, 2004) was used to conduct the analysis. ABAQUS computes the shell transverse-shear stiffness by matching the shear response for the case of the shell bending about one axis, using a parabolic variation of transverse-shear stress in each layer. Generally, this approach provides a reasonable estimate of the shear flexibility of the shell. It also provides estimates of inter-laminar shear stresses in composite shells (Hibbitt et al, 2004). In calculating the transverse-shear stiffness, ABAQUS assumes that the shell section directions are the principal bending directions (bending about one principal direction does not require a restraining moment about the other direction). These assumptions are satisfied in the tested columns. The analysis results of both the FE models were verified with the test records to ensure their capability in predicting the sandwich column behaviour. In addition Eigen-Value buckling analysis (EV) was conducted. The analysis results along with test results (T02-01) are presented in Figures 5 and 6.

The analysis results showed an excellent correlation with the test data. This indicates that both the solid-shell (CSO) and the shell-only (CSH) models can be used effectively to predict the behaviour of sandwich panels. In addition, the Eigen Factor slightly overestimated the buckling capacity (8%). Accordingly, it can be concluded that the FE modelling procedures can be used to design the windmill structure.

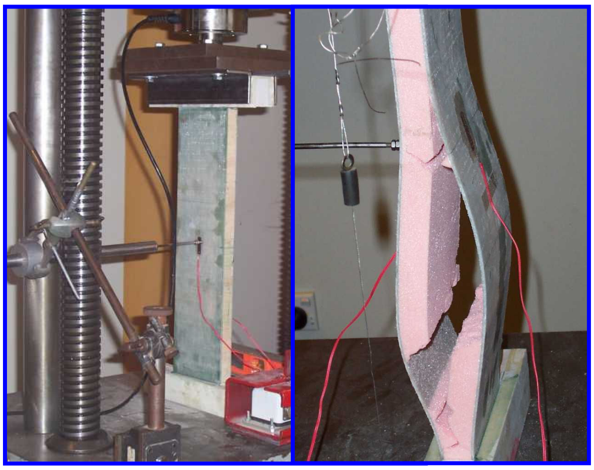

Figure 4. Sandwich column test set up and failure mode

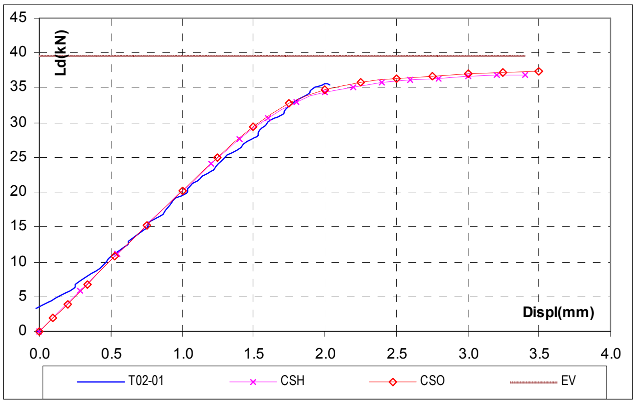


Figure 5. Load-deflection curves

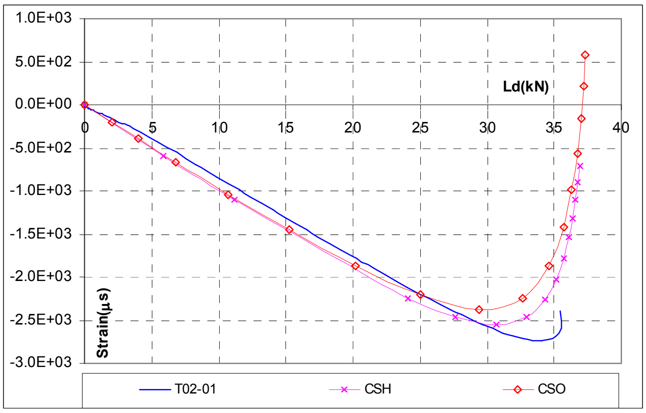


Figure 6. Strain-load curves

In checking the windmill tower, solid-shell model was used to investigate the stress levels at the skins, adhesive layers and core materials. This was essential in this project due the limited testing conducted. Thick shell elements were used for the skins and the corner angle, with the laminate properties specified in Table 1, while 3D solid elements were used to model the core material and the adhesive layers, assuming isotropic material properties, modulus of elasticity 42MPa, 90MPa & 2430MPa and Poisson's ratio 0.10, 0.30 & 0.30 for the R60, H100 foams and adhesive layers respectively. This can be considered a reasonable assumption as both the adhesive layers and the core material will not be stressed to a level higher than their elastic limit.

ABAQUS commercial package was used for the analysis. The FE model was built in parts that were assembled to create the overall model. The individual parts were interconnected using tie (kinematic) constraints. Kinematic constraints were imposed by eliminating the degrees of freedom (DOF) at the dependent (slave) nodes and constraining them to the governing (master) nodes. A surface-based tie constraint was used in the FE model. This concept is useful for mesh refinement purposes. It allows rapid transitions in mesh density within the model (Hibbitt et al, 2004). In checking the structure, the following were considered:

- For the laminates, partial safety factors (EuroComp, Clarke, 1996) were assumed as $\gamma_{m,1}$ = 1.50, $\gamma_{m,2}$ = 1.20 & $\gamma_{m,3}$ = 1.10 that totalled $\gamma_m$ = 2.00.
- For the laminates, the Tsai-Wu failure index was used.
- For the adhesive stresses, maximum stresses obtained from analysis are compared with the shear and tensile test values.
- Stresses in the sandwich skins were limited by the different sandwich panel failure modes.

After conducting the necessary stress checks, it was necessary to assess the buckling capacity of the tower. Eigen-Value analysis was conducted for the tower by using shell-only model. To achieve a minimum factor of safety against buckling of 2, it was necessary to provide stiffeners at 1m from the base of the tower. This arrangement increased the Eigen Factor from 1.44 to 2.45 with a change in the buckling mode as shown in Figure 7.

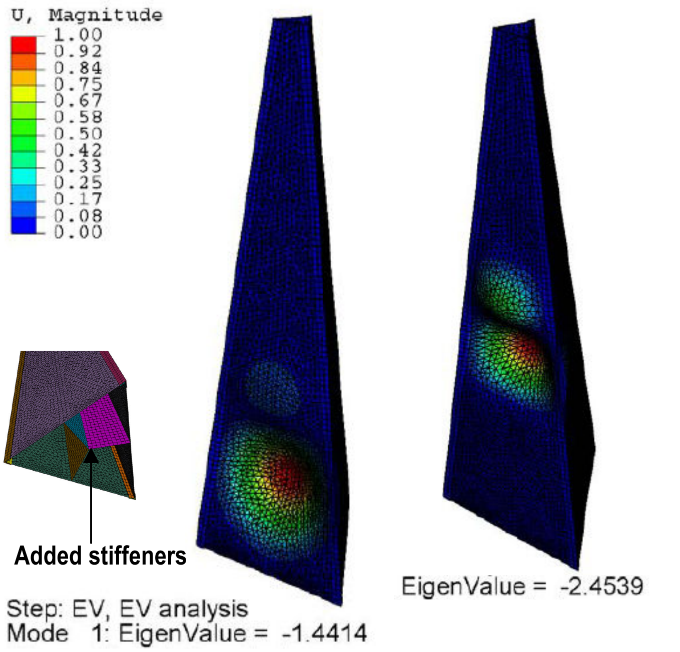


Figure 7. Change of bucking mode with the addition of stiffeners

## 5 TESTING OF CONNECTIONS

Based on the structural analysis of the tower, the peak forces transferred through one bracket are 47kN in tension and 7.7kN in shear. Two designs were proposed for the connection between the fibre composite tower and the concrete pad. In using bolted connection, the first design was based on replacing the core material at the connection with solid steel plate of similar thickness. The second design was based on using laminate of multiple tri-axial layers [+45/-45/0] to replace the foam at the connection locations. To investigate the capacity of the joint under tension, the two designs were tested as shown in Figure 8. In preparing the steel specimens, steel plates were cut to dimension then their surface were roughed by machining to increase the bond with the laminate system, by mobilising the mechanical locking between the steel and the resin system.

The load-deflection curves for the steel-infill brackets (ST) are shown in Figure 9 while that for the composite-infill brackets (FC) are shown in Figure 10. The failure of both connections is shown in Figure 11. The main observations obtained during testing are summarised as follows.

- All brackets failed in a sudden brittle mode by rupturing of the skin fibres at the first row of bolts.
- Fibre composite infill brackets had higher characteristic ultimate capacity of 340kN (average 378kN, standard deviation 23kN) compared to 249kN for steel infill brackets (average 326kN, standard deviation 47kN).
- During loading, the steel infill brackets experienced frequent local failures (at the interface between the steel plates and the skins), shown as kinks in the load-deflection curves. These failures occurred at load level of 100kN (Fig. 9).
- The local failure observed in the fibre composite infill was of much less frequency and at much higher load of 274kN (Fig. 10).
- Fibre composite infill brackets showed much lower variance of 524 compared to 2203 for steel infill brackets (higher uniformity of results).

Based on the test results, the choice of fibre composite for the connecting brackets was obvious. This configuration provides partial safety factor of 5.83 (against the minimum initial local failure) and 7.23 (against the characteristic capacity of the bracket). This conservative approach in designing the bracket was essential as no further investigations were conducted to assess the dynamic capacity of the bracket. The steel infill bracket was inferior with higher scatter of its results. In addition, its manufacturing process was more complicated due to the additional procedure required to machine the steel plates and embed them in the laminates during the manufacturing of the panels.


Figure 8. Bracket during testing

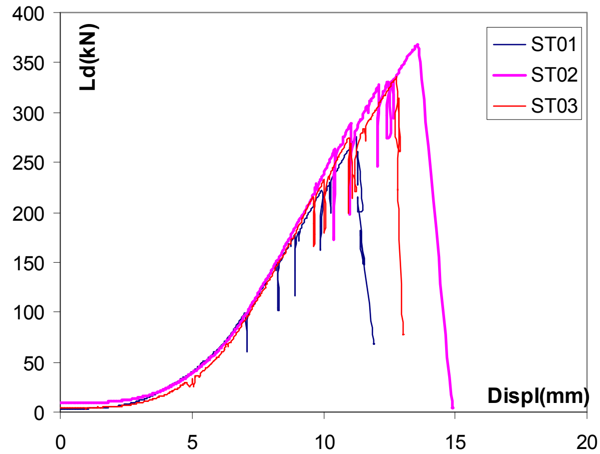

Figure 9. Connection with steel plate fill load-deflection curves

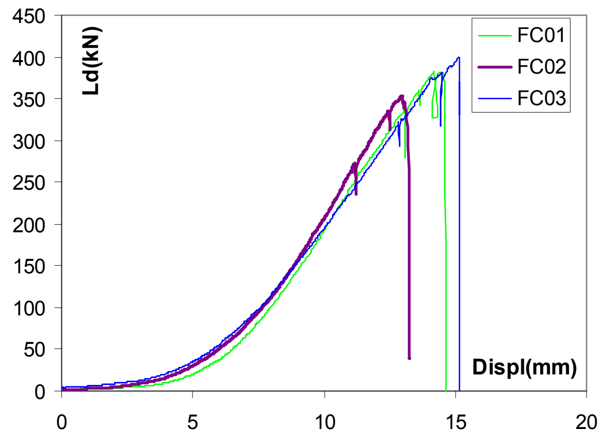

Figure 10. Connection with all-composite fill load-deflection curves


Figure 11. Failure modes for the tested brackets

## 6 CONCLUDING REMARKS

Fibre composites in civil engineering applications have huge potential. However, there is a great challenge for the structural designer when there are no specific design standards and familiarity with the behaviour of such materials. This is further affected by the limitations of the manufacturing technology possessed by the contractor.

This paper highlights how such issues have been overcome by discussing the case study of a windmill monument structure. By forming an alliance of the designer, client and the manufacturer, working towards the best outcome for the project within the constraints had led to the successful completion of the structure. It is believed that such model could be very effective in gaining the acceptance of innovative materials in civil infrastructure.

Different forms of fibre composites can be used in the structural system for the windmill tower. However, the final system selected considered the ability to manufacture in the designated premises. Also, a good understanding of the behaviour of the used system is essential. The FE analysis is an important tool to predict the behaviour of fibre composite structures. However, it is essential to understand the inherent assumptions. In most cases, it is essential to conduct experimental testing on part of the structure to ensure its expected performance. In composites, like in many other forms of construction, compatibility of the system components is essential to ensure its performance.

## 7 AKNOWLEDGEMENT

The authors acknowledge the help by Mr Norm Watt, Managing Director of Buchannan Advanced Composites for providing information and photographs about the manufacturing of the windmill tower.

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