Fibre composite windmill structure – challenges in the design and development

T. Aravinthan & T. Omar
University of Southern Queensland, Toowoomba, Queensland, Australia

ABSTRACT: Fibre composite materials have the advantage of flexibility in design by making use of the materials to suit the required application. Their usage in civil infrastructure is limited to a few applications with some attempts to use them as the main load carrying elements. As part of the 40th anniversary celebration of the University of Southern Queensland, an artistic concept based on the Australian traditional wind mill was materialised in monumental structure using advanced composite materials. The main purpose of this paper is to present concepts of designing fibre composite structures highlighting some of the challenges faced in the design and development. The background of the project and the design considerations are discussed showing the importance of the early coordination between the design and manufacturing. With the main structural system based on sandwich construction, its behavioural issues and failure modes are presented. As there is no design codes or guidelines can be located in the literature, engineering judgement, understanding of the basic modes of failure of the structure and the manufacturing limitations and tolerances are essential in developing the appropriate design. The paper concludes with general discussion of using fibre composites as main structural elements in complex shaped structures.

1 INTRODUCTION

Australians are linked to windmill structures during their modern history. Windmills are used to convert the wind energy into other useful forms, such as generating electricity, operating water pumps and traditionally as grain grinders. Vertical axle windmills were first developed in Persia by the 9th century AD (Hassan & Hill, 1986). The currently used horizontal axle windmills were invented in North-western Europe in the 1180s (Wikipedia). The Wickham Terrace windmill tower is the oldest remaining convict building in Queensland and the oldest windmill tower extant in Australia that was built in the 1820s. The old windmill has been an important landmark since its construction. It first played a vital role in the existence of the Moreton Bay penal settlement by providing flour for survival and later as a steamer signal station, fire-spotting observation tower and site for pioneering communications' experiments (EPA). The windmill tapering circular tower is made of rendered stone and brick with a lookout platform which has an iron railing and hexagonal cabin (Figure 1).

The Windmill is a unique icon scattered all over the Australian Continent that served the farming sector for decades. In spite of the widespread of electricity supplies, using solar power pumps and the need for high volume water, windmills are still the cheapest and most reliable pumping machines used in Australia. The lattice tower windmills have been constructed all around Australia since the 1800s. The lattice structural system of the tower allows legs to act as tension and compression members to transfer the loads applied at the top of the tower to the ground. The wind drag on of the tower members is small and does not require trussing. The secondary members are used to limit the buckling length of legs in compression.
During the 40th anniversary celebration 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 technology 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 a well experienced fibre composite manufacturing company got-together to successfully complete this project (Figure 2).

In fibre composites, the manufacturing costs can be significant especially in a one-off structure such as this monumental windmill. Hence this was one of the major consideration in the decision making process among possible alternative solutions. The first solution is based on using pultrusions in lattice form with cladding system to meet the artistic concept. The second one is based on using a combination of pultrusions and sandwich panel to form the tower. However, due to the manufacturing technology available within the selected fabricator, who specialises in boat and submarine structures, all-sandwich windmill structure was used to avoid high manufacturing costs. This decision was made at early stage of the design process with close coordination with the manufacturer.
2 STRUCTURAL SYSTEM AND MATERIALS USED

The components of the windmill are explained in this section. The tower is 7900mm high with a 2300mm base that has two wings extending 300mm at the ground level. The two wings stoped mid-height of the tower that tapered to 400mm at the top, Figure 3. The tower structure was manufactured from double skins of glass/vinyl ester with 15mm closed-cell PVC foam R60 & H100 grades. The material properties used to model each laminate ply is shown in Table 1, where tensile properties (t) were determined according to ISO 527-4/2/2(1993) in both the fibre direction (1) and the normal-to-fibre direction (2). Similarly, compression properties (c) were determined according to ISO 14126(1999). The shear properties (12) were determined according to the ISO 14129(1997). Double bias glass fibres 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 were connected by using angles that were laminated then laid on the faces. The fibre architecture of the different components is shown in Figure 3 where the zero definition of the fibre architecture is along the centre of each face of the tower. To avoid the wrinkling failure and increase capacity of the sandwich panels, higher grade (H100) foam was used at corners.

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 was supported to the tower through top steel bracket with the mill shaft welded. At connection to steel brackets, solid laminates replaced the core foam.

Table 1 Laminate properties

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3 STRUCTURAL ANALYSIS AND DESIGN CHECKING

Wind load calculations were based on the AS1170.2 assuming solid frontal area of the blades and the tower structure. This conservative approach was followed as there was no design specification for these types of structures found either in the design codes or the manufacturer specifications. In addition, equivalent gyroscopic moment was calculated and applied to tower assuming that blades are rotating at 5Hz.

Simplified FE model (using thick shell elements) can be used to predict the stress distributions in the tower. However, a more detailed model was used to investigate the stress levels at the skins, adhesive layers and core materials. This was essential in this project due to limitations in the testing. Accordingly, Solid-Shell elements were used to model the tower. 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.

ABAQUS FE commercial package was used for the analysis. The FE model was built in parts that were then assembled to create the overall model, Figure 4. 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).

After conducting the necessary stress checks, it was necessary to assess the buckling capacity of the tower. Compared with the detailed nonlinear analysis, it was found that eigenvalue analysis provides good representation of the buckling capacity of sandwich panels (Omar, 2008). Eigen value analysis was conducted for the tower by using simplified model (thick shell elements to represent the sandwich panels). To achieve a minimum factor of safety against buckling of 2, it was necessary to provide stiffeners for 1m from the base of the tower. This arrangement increased the eigenvalue from 1.44 to 2.45 with a change in the buckling mode, Figure 4.

Figure 4. Buckling mode shapes and stiffener layout
4 GENERAL DISCUSSIONS OF USING FIBRE COMPOSITES AS A MAIN STRUCTURAL SYSTEM

Fibre composites are relatively new materials that have been developed since last century. They provide the designer greater flexibility in the choice of materials to be used, how to combine these materials and in which form. This flexibility is associated with challenges of delivering a safe structure with limitations on the availability of test data and understanding of the essential behavioural issues of the material and the structural system it is used for. As a consequence, the popularity of these materials in structures and acceptance among structural engineers is being affected. There are a few important considerations that need to be understood by designers working with these materials which can be highlighted as follows:

- In spite of being under development for many years, there is a lack of understanding of the mechanisms that lead to failure in composite materials. This is especially true for matrix or fibres under compression (Davila et al, 2005). This explains the generally poor predictions by most of the participants in the World-Wide Failure Exercise (WWFE). The current design practices place little or no reliance on the ability to predict the ultimate strength of the composite structure with any great accuracy. Failure theories are often used in the initial calculations to size the structure. Then experimental tests on coupons or structural elements are used to determine the global design allowables, which are usually less than 30% of the ultimate load (Soden et al, 1998). The issue addressed was the definition of failure. A designer would define failure as the point at which the structure ceases to fulfil its function. This definition is accordingly application-specific. It was concluded that the connection between events at the lamina level and the definitions of structural failure required by designers need to be established (Hinton and Soden, 1998).

- Tsai’s theory is one of the best available theories in predicting the failure of the laminate. It employs the interactive Tsai-Wu failure criterion which is one of the best-known and mathematically satisfying theories (Hinton et al, 2002). However, like many of the other theories, this theory is linear-elastic and it cannot predict the large non-linear strains observed in tests with high lamina shear.

- The orthotropic nature of the composites makes them different from other commonly used construction materials. Accordingly, this effect needs to be considered while designing with these materials.

- Transverse shear properties of the composite are another important consideration that needs to be incorporated in the FE analysis.

- For sandwich structures, the core properties, especially shear modulus, significantly affect the failure mode and capacities.

- Due to its sudden brittle nature, overall buckling of sandwich panels need to be carefully considered in any of its analysis.

- There are still differences in opinion in predicting the capacity of some of the failure modes of sandwich columns. Accordingly, this need to be considered related to the problem in hand.

- It is important to allow smooth transition of stresses at the joints. This may necessitate allow larger curvatures and laminate transition zones. In addition, manufacturing tolerances should be considered. These issues should be recognised by the designer at early stage of his/her design.

5 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 new 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 with the designer, client and the manu-
facturer, 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 acceptance of innovative materials in civil infrastructure.

Other challenges faced by the structural designer in such cases are the understanding of the behaviour of the materials, its failure mode and adopting available design guidelines to the local needs. This also emphasise the need to train structural engineers in fibre composites and the development of relevant design standards/guidelines in Australia. When these are achieved, the fibre composites will become competitive with the traditional construction materials and it would be possible to harness its potential in civil infrastructure.

6 REFERENCES