Composite Structures 97 (2013) 165–175

Contents lists available at SciVerse ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Experimental and analytical study of latticed structures made from FRP composite materials

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ARTICLE INFO

Article history:
Available online 6 November 2012

Keywords:
Fibre-reinforced polymers
Composites
Filament winding
Antenna towers
Static behaviour
Dynamic behaviour

ABSTRACT

This paper presents results from a research project carried out at the University of Manitoba, Winnipeg, Canada, in collaboration with the National Technical University of Athens, Greece, which examines the potential of manufacturing fibre-reinforced polymer (FRP) lattice tower segments using the filament winding process. Both theoretical and experimental work has been carried on a tower 8534 mm long segment that consists of four identical parts 2134 mm long each, fabricated and tested under static and dynamic loading conditions. It has been found that the experimental results correlate well with theoretical findings from FEM analyses. The dynamic properties of the tower segment were also verified through a single degree-of-freedom analytical model.

1. Introduction

The use of FRP materials in infrastructure as an alternative to conventional materials has become very popular over the last years [1,2]. Besides having high stiffness and strength-to-weight ratios, excellent fatigue and corrosion resistance, faster installation time, and reduced maintenance costs, composites also offer superior resistance to environmental degradation as compared to traditional materials [3–5]. All these characteristics of FRP lead to several cost-performance benefits [6] when applied for structural applications. Thus, by using FRP materials instead of steel, the maintenance and corrosion resistance of the latticed tower under investigation can be significantly improved.

In contrast to other manufacturing techniques such as lay-up techniques, moulding techniques and pultrusion, the filament winding technique consists of winding resin impregnated fibres or rovings of glass, aramid, or carbon on a rotating mandrel in predetermined patterns [7]. The method provides the greatest control over fibre placement and uniformity of structure. In the wet method, the fibre picks up the low viscosity resin either by passing through a trough or from a metered application system. In the dry method, the reinforcement is in the pre-impregnated form. After the layers are wound, the component is cured and removed from the mandrel. Typical thermoset resins used in filament wound parts include polyesters, vinyl esters, epoxies, and phenolics. Traditionally used to produce pressure vessels, rocket motor cases, tanks, ducting, golf club shafts and fishing rods, filament winding technology has been expanded, and non-cylindrical, non-spherical composite parts are now commonplace [8,9].

A research program is currently in progress at the University of Manitoba, Winnipeg, Canada, in collaboration with the National Technical University of Athens, Greece, to develop FRP latticed meteorological towers via the filament winding process. By continuous closed-loop winding pattern, rovings of E-glass impregnated in epoxy resin were wound over groves in the outer face of a collapsible mandrel producing a structure with no internal discontinuities. The selection of constituent materials, i.e. E-glass and epoxy, has been done in order to comprise low cost and high strength. Tower sections were fabricated without the use of fasteners, thus eliminating the labour-intensive and fatigue-prone bolted connections used in steel towers [10]. Thus, a truss structure can be formed comprising the advantages of low weight, high strength and the ability to sustain loads without excessive deformations in combination with of linear behaviour under high axial stresses. On the other hand, disadvantages such high production cost and UV degradation can be eliminated by mass production and by material chemical improvement with the use of additives.

Both theoretical and experimental work has been carried on a tower segment, 8534 mm (28 ft) in length and consisting of four equal sections 2134 mm (7 ft) in length each, fabricated and tested under static and dynamic loading. This segment was chosen to represent the bottom portion of a 44,804 mm (147 ft) full scale FRP tower spanning between the base and the first set of guys. The tower was designed according the current CSA-S37 Standard [11] and the EIA-222F Specification [12]. The purpose of the testing was to verify a theoretical model obtained from the Finite Element

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http://dx.doi.org/10.1016/j.compstruct.2012.10.032

Program ANSYS Version 8.1 [13]. The test conditions were created to resemble actual restraints and loading conditions acting on the most stressed tower sections. Laboratory testing of standard coupons was also conducted according to ASTM standards to determine all necessary material properties used in the FEA. The experimental results correlate well with theoretical findings from FEM analysis. The dynamic properties of the tower segment were also verified by a single degree of freedom mathematical model. The final product is a lightweight tower, which allowed for noticeable savings in transportation and assembly costs of guyed latticed towers.

This novel technique of filament winding allows the design of towers that can handle more severe loading conditions, especially icing, that have been the cause of several tower failures across USA and Canada [14,15]. Since meteorological wind towers do not presently measure icing conditions, the proposed facility will be unique as capacity-based icing sensors can be installed to quantity the severity of icing and to evaluate the performance of both meteorological instruments and the tower structure under extreme weather conditions. Nevertheless, the behaviour of the FRP tower at high temperature conditions has been also examined numerically.

2. Experimental program

The experimental program was carried out in the W.R. McQuade Laboratory of the University of Manitoba, Canada. An FRP tower segment, 8534 mm (28 ft) long and consisting of four equal sections 2134 mm (7 ft) long each, was fabricated for testing under lateral loading. The prototype FRP tower is a 44,804 mm (147 ft) long and is shown in half-section in Fig. 1a. The segment is chosen to represent the bottom portion of the FRP tower spanning between the base and the first set of guys, as shown in Fig. 1b. The purpose of the testing was to verify the theoretical model obtained using the Finite Element Program ANSYS Ver. 8.1 [13].

2.1. Initial section selection of trial tower segment

In the initial stage of the research program, a significant amount of time was spent in establishing appropriate section properties, which would meet both the required loading conditions and the manufacturing constraints. The final size and arrangement of the vertical and diagonal members, as well as the lattice pattern shown in Figs. 2 and 3, were selected for the ease of fabrication and for the significant bending and torsional stiffness this system provides. Two vertical chord members comprised each corner of the tower as shown in Fig. 3. The tower sections were interconnected at the corners using a lap splice arrangement shown in Fig. 4. The material and structural properties of the sections are given in Table 1.

2.2. Testing of tower segment

The FRP tower test specimen consisted of four 2134 mm (7 ft) long sections assembled as shown in Figs. 5 and 6. A "whiffle tree" loading arrangement was designed to provide the uniformly distributed lateral load to the tower. The loading was applied by an overhead crane and was measured by a load cell. The eight distributed forces applied to the tower, shown in Fig. 6, were measured using calibrated strain gauges. The deflection of the tower was monitored at four locations using Linear Motion Transducers (LMTs) and Linear Variable Differential Transducers (LVDTs) attached at the spliced locations and at the end, as shown in Fig. 6. The tower segment was tested horizontally attached to a concrete strong wall trough a knife-edge, which allowed for free rotation of the tower in the plane of loading. The free end of the tower was supported by two 5 mm (3/16 in.) diameter steel cables of length 2099 mm (82.625 in.), as shown in Fig. 6, which were pretensioned by a force of 5.0 kN.

3. Static analysis of tower segment

3.1. Finite element analysis of tower segment

The static structural performance of the tower segment subjected to a uniformly distributed loading was analysed using ANSYS software. The loading arrangement used is shown in Fig. 7. The chord members along the three corners, as well as all bracing members, were modelled as BEAM4 – elements from the ANSYS elements library. The guy cables were modelled using COMBIN14 elements to simulate the elastic behaviour of guy cables used on the full height tower. The properties of the cables were obtained from the supplier's catalogue [16]. All tower members were modelled with material properties obtained through unidirectional coupon tests [17]. The tower segment was analysed under a lateral load of 328 N (73.74 lbs) at each loading location shown in Fig. 7. This corresponds to a design wind speed of 95 km/h (59 mph).

The maximum end deflection of the tower segment under this loading, according to the FEA, was 26.21 mm or (1.039 in.), as shown in Fig. 8.

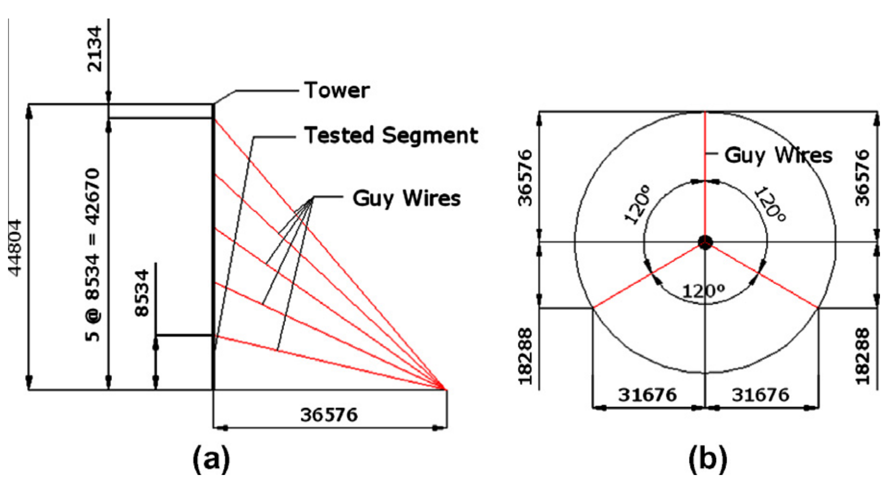

Fig. 1. FRP prototype tower under investigation: (a) elevation and (b) plan (units in mm).