SPATIAL PROPERTY CHARACTERISATION OF GFRP PANELS

Srinivas Sriramula and Marios K. Chryssanthopoulos

Faculty of Engineering and Physical Sciences (FEPS)
University of Surrey, Guildford, UK, GU2 7XH
s.sriramula@surrey.ac.uk

ABSTRACT

In this paper, probabilistic characterisation of glass fibre reinforced composite is carried out through experimental studies undertaken on the composite panels obtained from Mondial House, London, a building constructed in 1974 with cladding comprised of large GFRP panels. The test results were used to develop stochastic models for the material properties and to provide information on weathering effects on GFRP panels with a fire retardant white isophthalic polyester gel coat. Coupons to carry out tensile and compressive tests are cut from these panels in a pattern suitable for stochastic modelling. Coupon dimensions and testing methodology are adopted from the relevant ASTM and BS EN ISO standards. The random variables considered are maximum tensile strength (X_T), Young's modulus (E), maximum compressive strength (X_C) and thickness (t).

1. INTRODUCTION

The complicated processes involved in the manufacture and assembly of composite structures induce uncertainties in their mechanical properties. Significance of this inherent uncertainty has long been recognised by researchers and a wide range of models are available for the appropriate stochastic analysis [1-3]. A popular approach suitable for a majority of these studies is by prescribing appropriate probability models and dependencies of the significant random variables. Calibrating and refining these stochastic models based on experimental studies forms an important part of such studies.

In the present study, probabilistic modelling of composite material properties is studied based on experimental studies undertaken on the GFRP panels made of chopped strand mat (CSM) composite. These panels were used as cladding for Mondial House, London and were obtained after being exposed to the severe environmental conditions for 32 years. Exploring the residual strength properties of these panels assists to assess their behavior and to enhance the stochastic models of CSM composite. A total of 157 coupons from three panels, each of dimensions 1.7 m × 1.5 m, are tested for the tensile and compressive properties. The guidelines provided by the Military handbook MIL-HDBK-17-1F [4] are followed to study the inter-panel and intra-panel variations of the random variables and to validate the isotropic nature of these CSM composites.

2. DESCRIPTION OF COMPOSITE PANELS

The GFRP used in the present study is obtained from Mondial House, a 45m building constructed at London in 1974 as an international telephone exchange [5]. The building was designed for an in-service life of 60 years and utilised extensive GFRP cladding panels. The panels were fixed to the building at two points at each level by means of clamps and were connected to the main bracket by single stud. The panel ribs and bracket were also designed to allow for movement and adjustment during assembly with the panel joints accommodating thermal fluctuations.

Starr [6] assessed the performance of these panels after 25 years of construction and observed that they were in excellent condition with very limited laminate surface degradation and no structural damage. Also, similar panels used in the American Express building at the coastal town of Brighton in UK exhibited no adverse effects from the English Channel hurricane in late 1986. This was attributed to the high quality materials used in the panels and appropriate safeguards exercised during the design and installation and highlighted the suitability of GFRP as an important material for engineering structures. Mondial House was demolished as an in-service building in 2006 and a number of panels were obtained for the experimental study. Pictures of Mondial House while standing and during demolition process are shown in Figure 1. It is aimed to study the performance of these panels which have been exposed to fluctuating temperatures, ultraviolet radiations, pollution, frost, wind and rain for 32 years. Typical views of the in-service panels are shown in Figure 2.

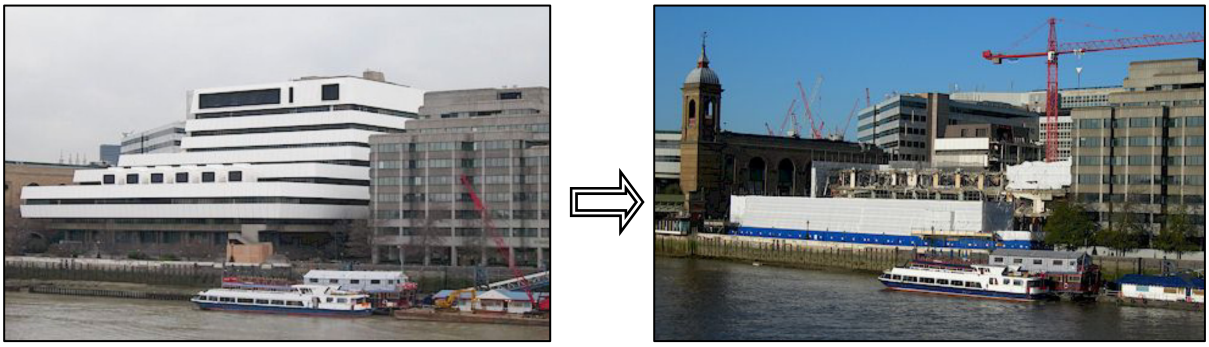

Figure 1: Demolition process of Mondial House

Figure 2: Typical views of cladding on Mondial House

The obtained panels have an average dimension of 1.5m × 1.7m and are surface coated using a fire retardant white isophthalic polyester gel coat. The gel coat was provided as a low profile vertically reeded surface texture for self-cleaning of the panels. The panels have contact-moulded chopped strand mat (CSM) sandwich construction with polyurethane placed on a foam core, and reinforced with reverse face ‘top hat’ ribbed stiffeners. It is observed that the surface of panels has weathered to a semi-gloss finish though cleaning with a non-abrasive cloth quickly restores the high gloss finish present at the start of their design life. Front and rear views of a typical panel after demolition are shown in Figure 3 and closer views of reinforcing stiffeners are shown in Figure 4.

a) Front view b) Rear view

Figure 3: Obtained panels

Figure 4: Reinforcing ribbed sections

3. CHOPPED STRAND MAT COMPOSITES

CSM composites are short fibre composites having chopped glass fibre strands in two-dimensional random orientation held by chemical or mechanical bonding [7, 8]. In general, fibre length is greater than panel thickness and fibre volume fraction varies between 10 and 25%. The characteristics of CSM composites are significantly affected by the matrix properties. The values of material characteristics of these composites are much lower than those of continuous fibre composites due to shorter fibre length, lower fibre volume fraction and random fibre arrangement. Notwithstanding, CSM composites are widely used in the automobile industry, the manufacturing of electrical components, process pressure vessels, large boat hulls, chemical and agricultural containment structures and in various civil engineering applications [9]. This is due to the following advantages:

i. less labour intensive mass production with low cost machinery
ii. good strength per unit cost properties
iii. mechanical properties are direction independent

Moulding of CSM panels involves cutting and stacking the CSMs and pre-forming in a press to the required shape. A catalysed thermosetting resin is then poured into the mould over the preform and cured with a relatively low pressure; a final gel coat can be applied accordingly. If not, integrity of the perform can be maintained with mechanical bonding using entanglement, stitching or knitting. The CSM properties are significantly influenced by the lamination quality. It is observed that due to variation of glass fibre content and void content, within the same panel, the composite characteristics usually have higher variation than what might be expected in pultruded or other types of composite in which the degree of manufacturing control and automation is significantly higher.

4. EXPERIMENTAL MODELLING

Experimental studies are planned to provide information on mechanical properties and to formulate appropriate stochastic models. The intra-panel and inter-panel variability associated with these properties is also highlighted. Coupon dimensions and testing methodology are adopted from the relevant ASTM standards [10] for tensile tests and as per ASTM and BS EN ISO 14126:1999 [11] for compressive tests. The panels are labeled as A, B, C in the sequence of being tested. As described earlier and shown in Figure 3(b), each panel has a stiffening top hat section on either side of a central area. In the present study the central portion is referred as main cut (MC) and the cantilevering portions from stiffeners are referred as offset cuts (OC). Panel cutting is carried out using appropriate mechanical cutting devices. As the panels contain vertically reeded surface texture of gel coat, it is decided to study the effect of this on overall composite characteristics. This would help explain any correlation between gel coat and loading direction and to validate, or otherwise, the isotropy assumption of CSM composites. The k-sample Anderson Darling (kAD) test suggested by the Military handbook and an analysis of variance (ANOVA) methodology are adopted in the present study to understand these factors.

The coupons have gel coat on one face (top) and foam at the other (bottom). The latter is scraped to just leave the composite for testing and is cleaned properly so that the end tabs give better performance. Some representative views of coupons for tensile testing after cutting and removing the form are shown in Figure 5. Strain measurements in testing composites of the type considered in the present study are complicated as the top and bottom surfaces are uneven. It was attempted to use the conventional strain gauges by polishing the central locations of the coupon. Even though this approach was successful, it was not continued as this process required substantial effort and could also result in surface damage of the composite. In the present study, an Instron 2650 series averaging extensometer with gauge length up to 50mm is used for measuring strain. This is suitable for composite coupons, though it is recommended to remove the extensometer from coupons before failure to avoid any damage. A validation experiment of a coupon with both extensometer and strain gauges supported the use of extensometer as shown in Figure 6 with strain 1 and 2 representing top and bottom strains respectively.

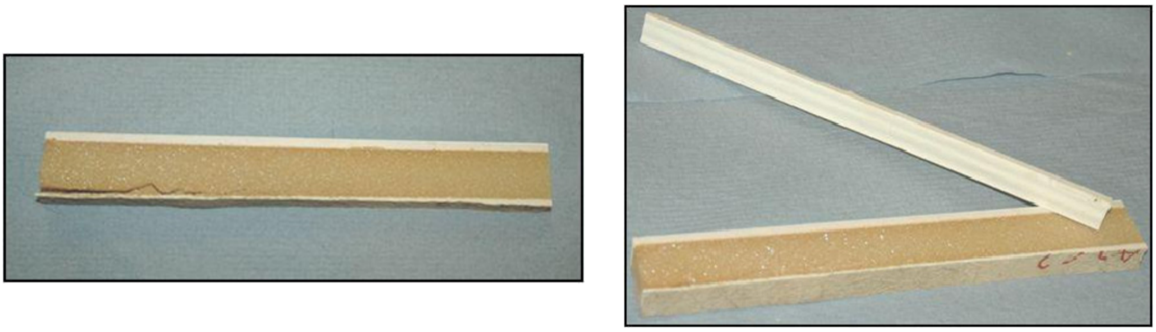

Figure 5: Representative views of processed coupons

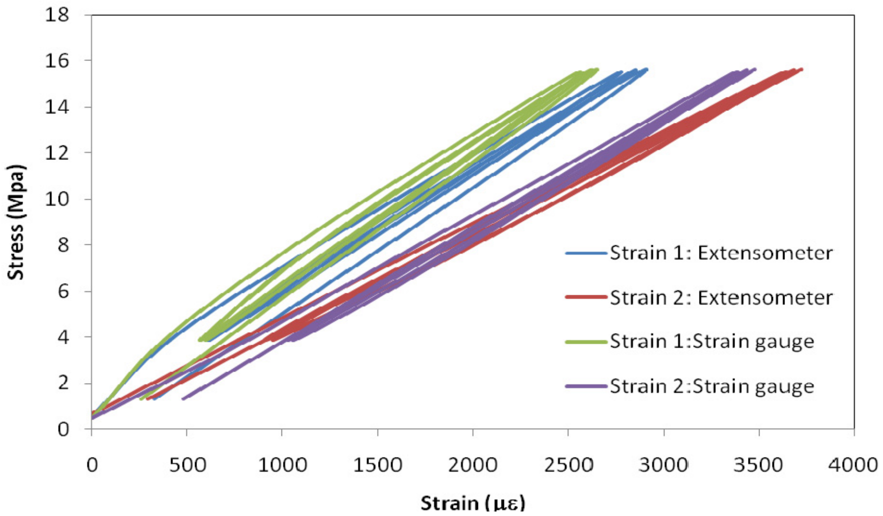

Figure 6: Stress-strain plot of the validating test

4.1 Tensile and compressive tests on coupons

The initial tests on composite tensile characteristics are aimed at establishing the testing pattern and to study the significance of gel coat direction and isotropy assumption. The coupons are obtained from MC as well as OC portions of the panel A. The coupon directions are considered to represent 0^0, 45^0 and 90^0 alignments to loading direction in the testing machine. As can be seen from Figure 7, a total of 29 coupons comprising 12 for 0^0, 10 for 45^0 and 7 for 90^0 alignments are obtained. The specified statistical tests and ANOVA performed at a significance level of 0.05 do not reject the hypothesis that different alignment groups can be treated as a single group, thus supporting the assumed isotropy of CSM composites and nullifying any gel coat direction dependency on mechanical properties. As the effect of gel coat alignment on tensile properties is not statistically significant, all further experiments are planned with coupons at 0^0 and 90^0 alignment. The panels are marked in the MC portion creating a grid pattern and locating compressive coupons adjacent to tensile coupons. This gives an opportunity to explore tensile and compressive strength variations as closely as possible and also to study any corresponding statistical dependence between these properties. Furthermore, this cutting plan assists in modelling spatial variability of mechanical properties with a low number of cuts. A typical panel marked for cutting is shown in Figure 8; coupon sizes of 18 mm × 250mm for tensile tests and 25 mm × 121 mm for compressive tests are used considering the specification and testing requirements. Typical tensile and compressive test setups are shown in Figure 9 and 10. The typical spatial variation of tensile strength over a panel based on the coupon locations is shown in Figure 11 as surface and contour plots and dispersion in the maximum value locations is prominently observed.

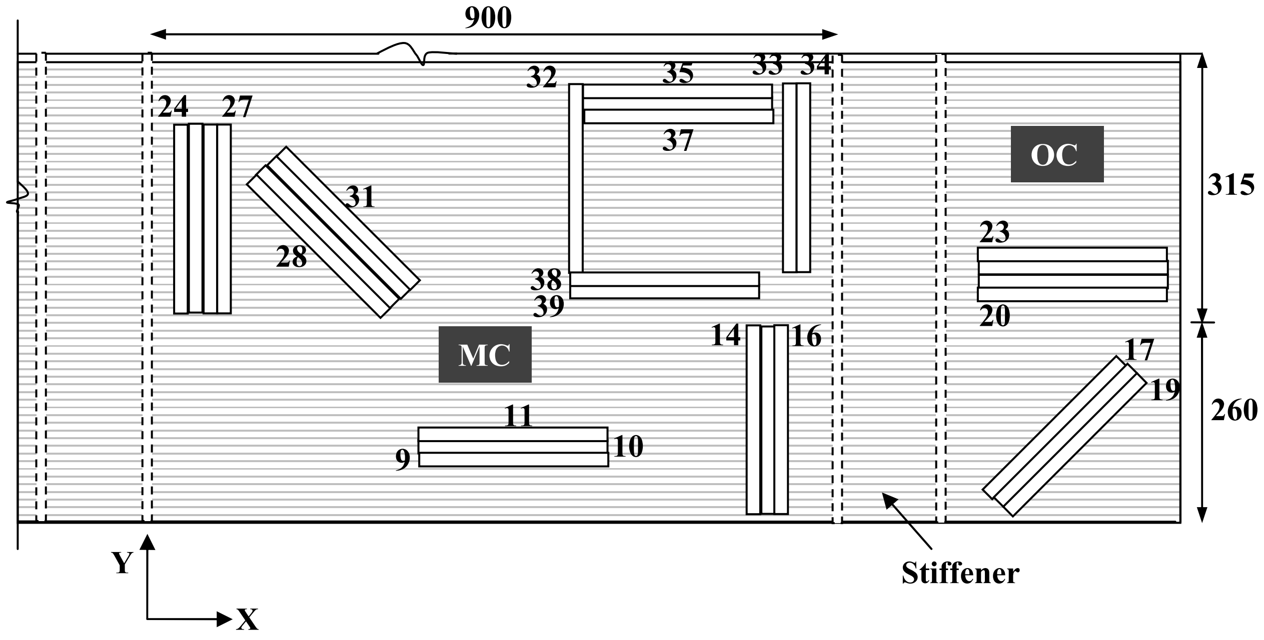

Figure 7: Direction and location of preliminary coupons

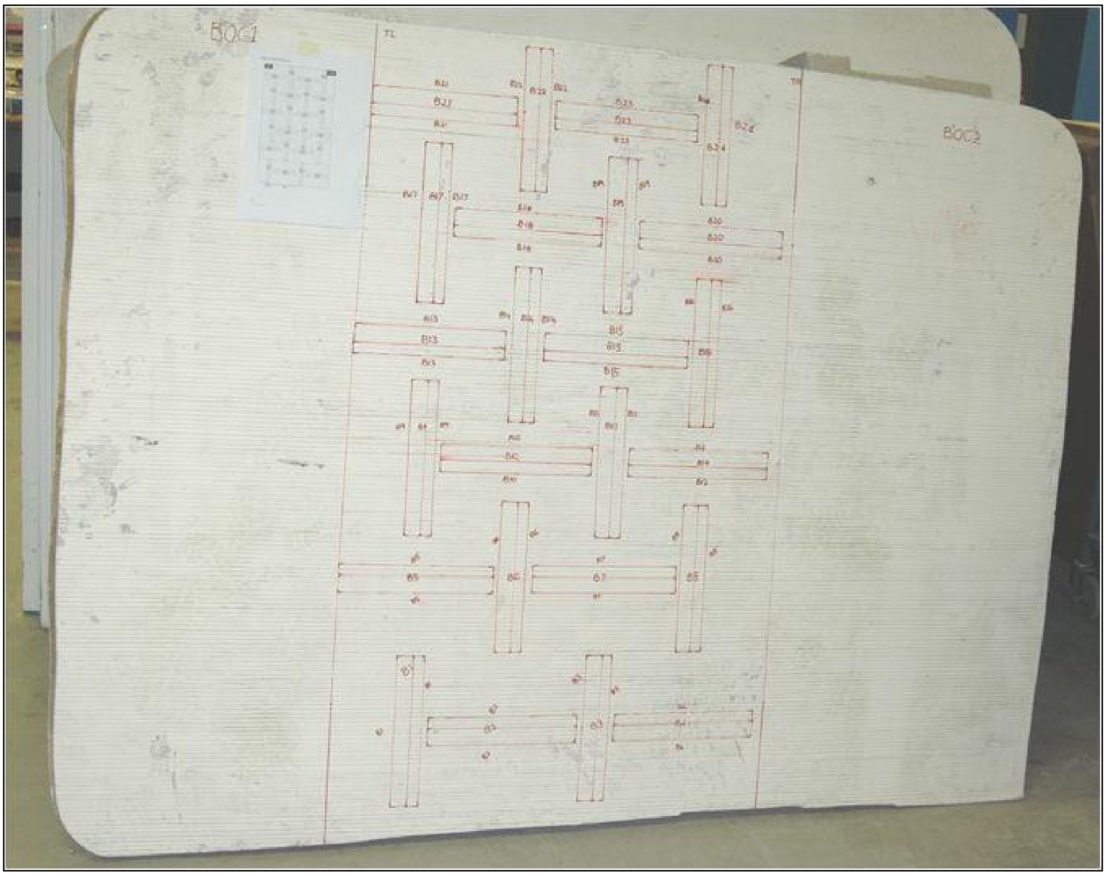

Figure 8: Panel B marked for cutting

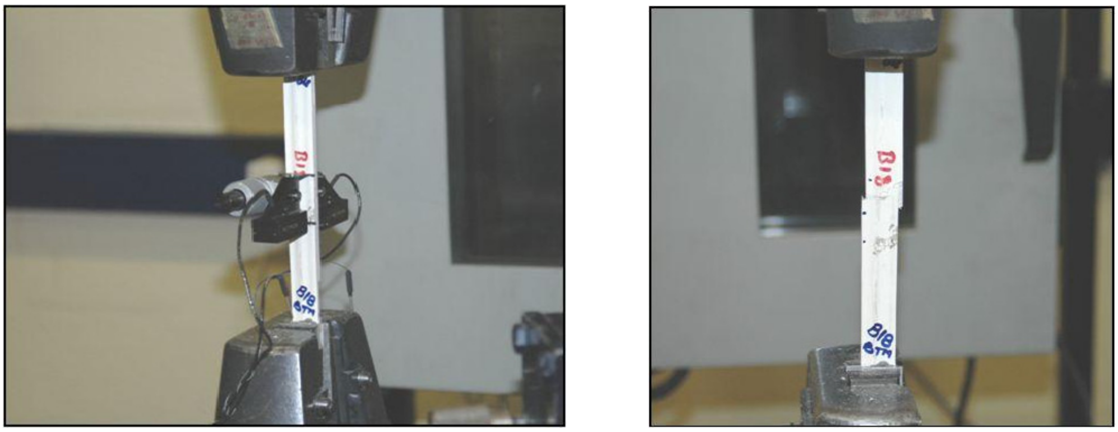

Figure 9: Representative tensile coupon test at failure

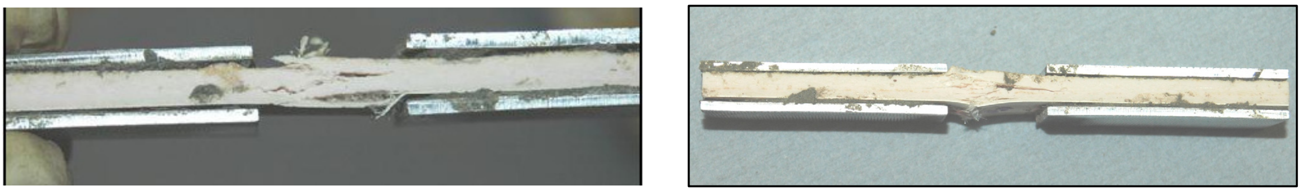

Figure 10: Representative compression failures

4. PROBABLISTIC MODELLING

As the statistical analysis at intra panel level suggest that the data are from similar groups, the data of random variables from all the panels is pooled together to develop the probability models at inter panel level. The dependency among the variables is computed in terms of Pearson's linear correlation coefficient (ρ) and nonparametric correlation coefficients such as Kendall's coefficient (τ) and Spearman's coefficient (ρ_S) and tested for significance. All the three panels exhibit a significant negative dependence between X_T and t in terms of the parametric and nonparametric correlation measures supporting the general perception, with the dependence being very high in case of panel B for all the measures. The tensile strength and tensile modulus are found to be positively correlated. It is observed that none of the correlation measures pass the significance test for the dependence to be considerate between X_C and X_T. The statistical independence of these parameters can be attributed to the failure modes being different for the CSM composites under tensile and compressive loading. The tensile failure strength is expected to be closely influenced by fibre characteristics while the compressive strength is influenced by a combination of fibre and matrix properties. The statistics of the random variables are shown in terms of a box plot in Figure 12 and the obtained ρ values are given in Table 1.

Table 1: Correlation of random variables

	X_T (MPa)	E (GPa)	X_C (MPa)	t (mm)
Linear Correlations	1.000	0.231*	-0.037	-0.619†
	0.231*	1.000	0.000	-0.133
	-0.037	0.000	1.000	0.262*
	-0.619†	-0.133	0.262*	1.000

* Correlation is significant at the 0.05 level (2-tailed)

† Correlation is significant at the 0.01 level (2-tailed)

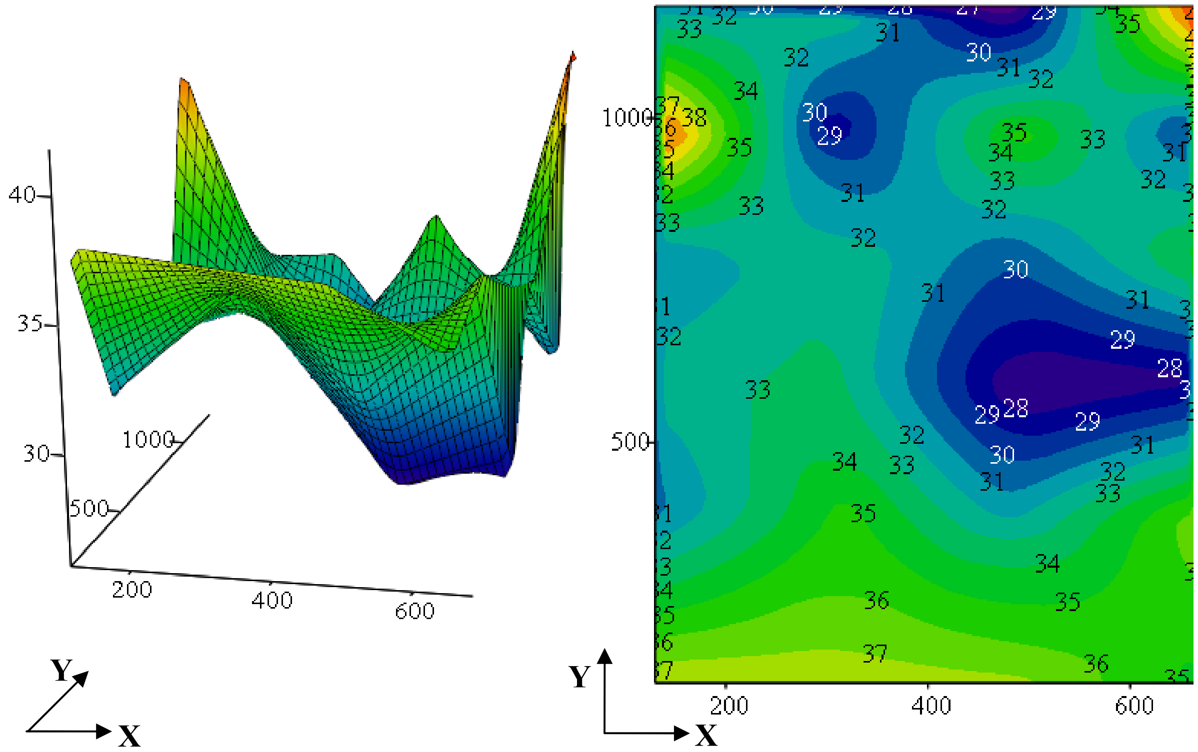

Figure 11: Spatial variation of X_T for a typical panel

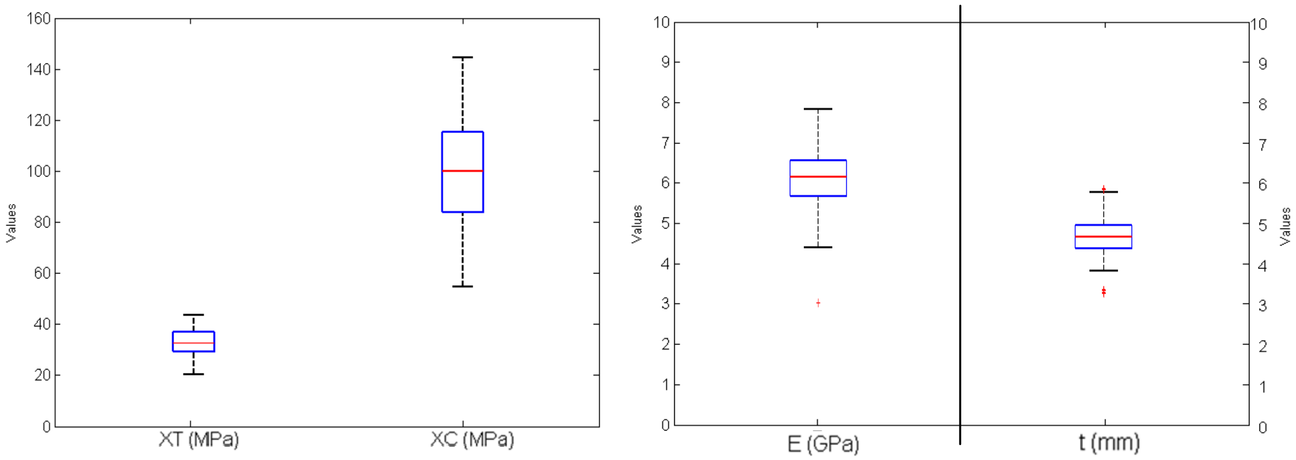

Figure 12: Box plot of random variables

The sequence of testing the suitability of probability distribution models is based on the guidelines provided by the Military handbook [4], which suggests that the data should be tested first for a two parameter Weibull distribution based on the goodness of fit provided by Anderson-Darling hypothesis test (ADH) at a significance level of 0.05. If the Weibull distribution does not pass the AD test, the data is tested for normal and lognormal distributions in succession. The choice of a two parameter Weibull model over a three parameter Weibull for FRP material properties is also suggested by Alqam et al. [12] after studying the experimental results of pultruded composite characteristics. A typical probability plot for Weibull distribution of X_C is shown in Figure 13 and the best fitted probability models on the histogram of tensile modulus is shown in Figure 14. The Weibull model is found to be supported by ADH for material properties whereas thickness is found to be best described by a normal distribution model.

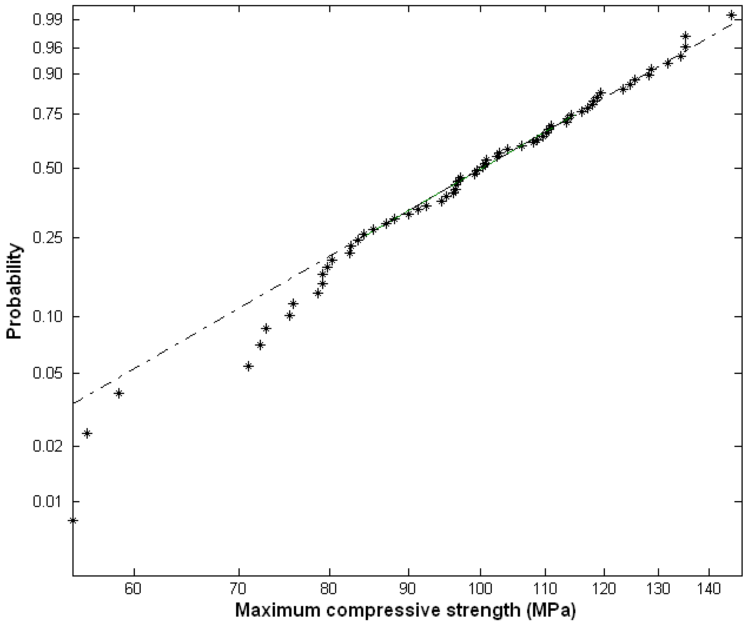

Figure 13: Weibull probability plot of X_C

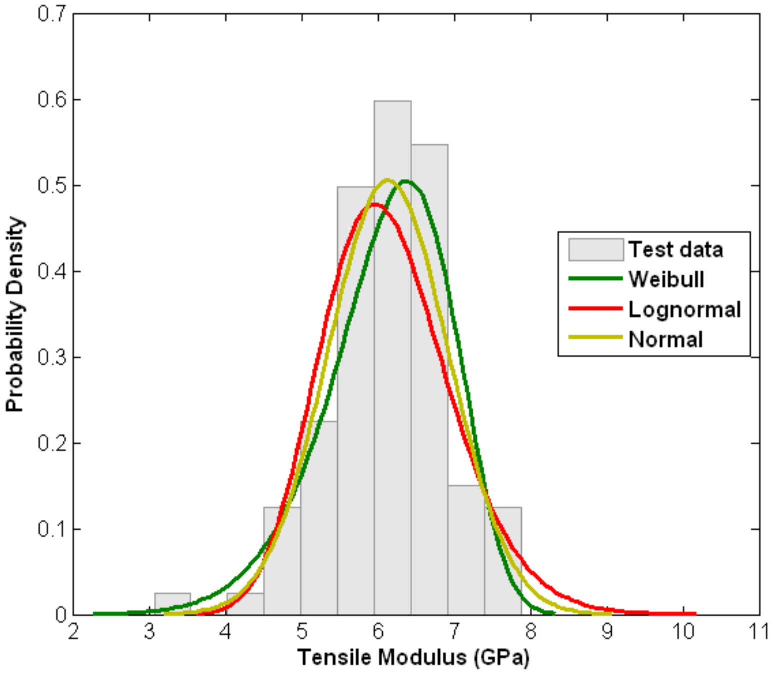

Figure 14: Probability density of tensile modulus

5. CONCLUSIONS

Stochastic models of GFRP composite characteristics are developed by an experimental analysis of the tensile and compressive properties of composite panels that were in service for 32 years. Visual inspection of these panels suggested very limited structural damage and minimal weathering to the gel coat surface. Similar observations were made on these cladding panels by previous researchers suggesting GFRP is a very durable building material. Statistical analysis methods support the hypothesis of CSM composite material properties at the intra and inter panel level being isotropic. The relative variability of CSM, pultruded and carbon/epoxy prepregs suggests the variation in X_T to be of same order for all types, while for X_C and E, CSM has higher variation than other composite material systems.

At the intra panel level, mean values of random variables are in same range while the coefficients of variation differ. A significant negative dependence exists between X_T and t in terms of the parametric and nonparametric correlation measures. The compressive and tensile strengths are found be statistically independent for intra panel and inter panel analysis due to the different failure mechanism involved. Weibull probability distribution is suggested for modelling the CSM material properties based on the hypothesis fit and supported from a historical and theoretical perspective. Even though the present study concentrates on a specific GFRP type material, it should be stressed that CSM composites are frequently used in various structural forms and applications.

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