8 CONCLUSIONS

Structural composites are required to reliably sustain external loads in addition to self-support or play a principal role in supporting the structure of the final component. The overall objective of this research was to investigate the potential of plant fibre reinforced composites (PFRPs), as a prospective alternative to E-glass composites (GFRPs), in structural applications. This would not only demand that the macro-mechanical behaviour of PFRPs is well-studied/documented for various composite parameters, but also obliges that the mechanical properties of PFRPs are well-predicted under various loading conditions. Hence, this thesis is mainly concerned with characterising, optimising, and achieving an improved understanding, of the macro-mechanical properties of aligned PFRPs.

The aim of this chapter is to present the major conclusions established from the work described in this thesis, with reference to the overall theme described in *Chapter 1*. In addition, several recommendations are made for future work.

8.1 THESIS CONCLUSIONS

Through an up-to-date critical review of the literature in *Chapter 2*, an overview of key aspects that need consideration when developing PFRPs for structural applications was obtained. This included recommendation on the selection of *i)* the fibre type, fibre extraction process and fibre surface modification technique, *ii)* fibre volume fraction, *iii)* reinforcement geometry and interfacial properties, *iv)* reinforcement packing arrangement and orientation and *v)* matrix type and composite manufacturing technique, was achieved. The review identified long bast fibres converted into minimally-processed well-aligned semi-products as the most suitable composite reinforcement, prepregging, compression moulding and vacuum infusion were identified as the most suitable composite manufacturing techniques, and thermosets were identified as the most suitable matrix material.

In this section, the contents of each chapter are summarised and assessed to evaluate their implications on the mechanical performance of aligned PFRPs, and eventually their suitability for load-bearing applications.

8.1.1 *Chapter 3*: Effect of reinforcing fibre/yarn and matrix type

Screening the mechanical properties of various unidirectional plant bast fibre yarn reinforced thermoset matrix composites, it is found that they offer three to five times better tensile stiffness and strength in comparison to conventional non-woven randomly-oriented short-fibre PFRPs (Fig. 8.1). The marked improvements in mechanical properties are not only attributable to enhanced reinforcement alignment but also to increased reinforcement length efficiency factors. It is shown that due to low critical fibre lengths (l_c = 0.28-0.52 mm) and high fibre aspect ratios ($l_f/d_f > 100$), length efficiency factors for plant fibre yarns/rovings are effectively unity. This indicates good load transferring capability in yarn reinforced PFRPs, without any fibre surface modification to enhance interfacial properties. Indeed, even multiaxial PFRPs exhibit better mechanical properties than conventional non-woven randomly-oriented short-fibre PFRPs (Fig. 8.1) due to the higher efficiency factor (particularly related to length) in the former.

Aligned PFRPs were manufactured through a vacuum infusion process. The yarn bundles in the PFRPs were found to be uniformly distributed and well-impregnated, and the fabricated laminates have low void content (typically in the range of 0.5-2%). No correlation is found between yarn structure and composite void content. However, yarn construction does seem to affect the type of voids that form; for instance, high-twist yarn reinforced PFRPs are susceptible to impregnation-related intra-yarn voids. While single plant fibres have highly variable mechanical properties, PFRPs reinforced with yarns were found to have consistent quality, indicated by the small coefficient of variation in mechanical properties (typically less than 6%). Hence, aligned PFRPs can provide highly controlled properties, which is essential for structural applications.

Considering the effect of matrix type, it is found that epoxies form a stronger interface with plant fibres than polyesters do. While the fracture surfaces of epoxy-based PFRPs are flat (indicating brittle failure), polyester-based PFRP specimens present a serrated fracture surface with greater fibre pull-out lengths and even delamination. However, the effect of matrix type on the longitudinal tensile properties of aligned PFRPs is unclear.

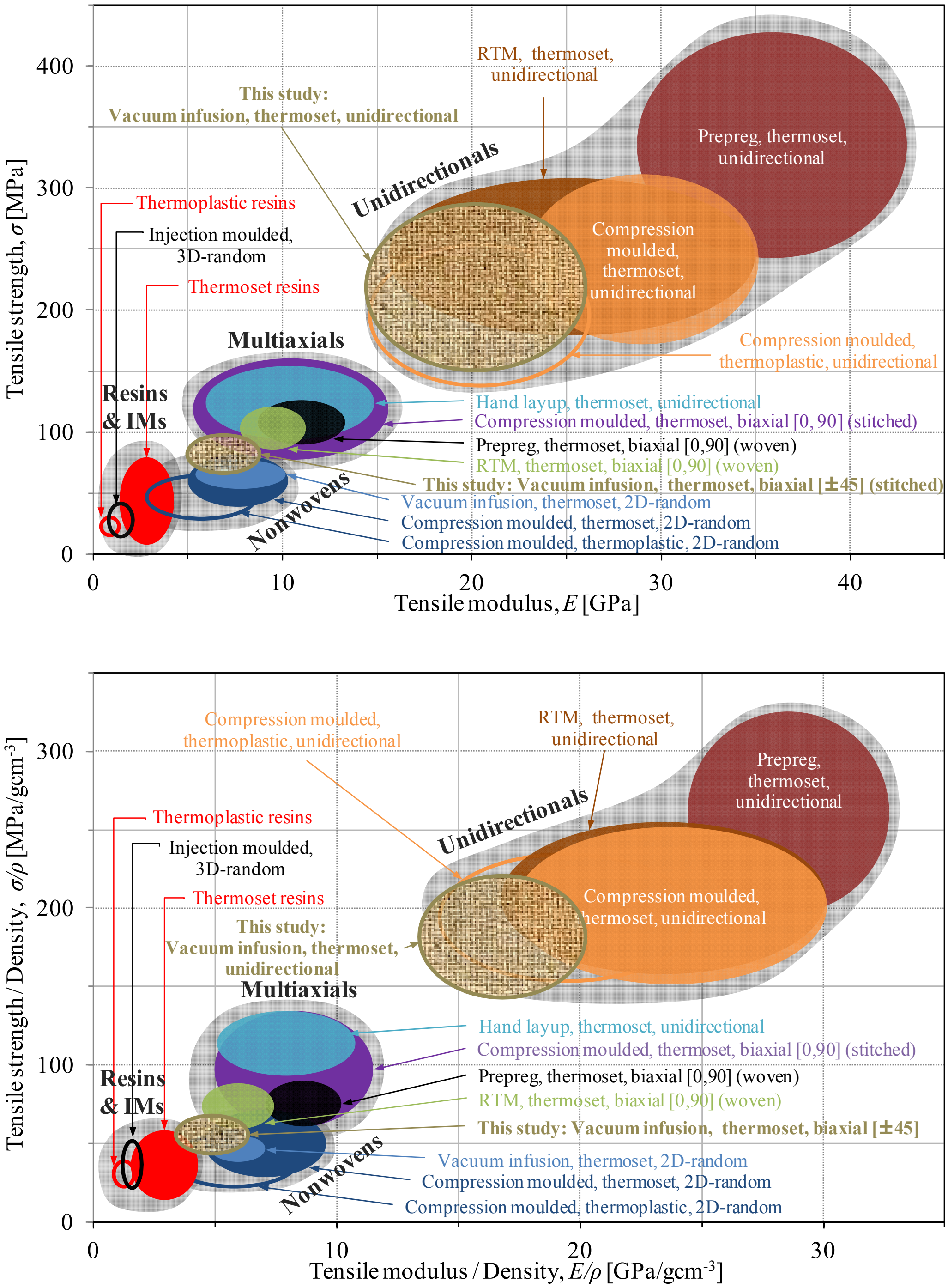

Fig. 8.1. Materials selection chart (reconstructed from Fig. 2.6 in *Chapter 2*) comparing the mechanical properties of various PFRPs studied in literature and this thesis.

The low void content and consistency in properties of aligned PFRPs is comparable to that of aligned GFRPs. However, PFRPs exhibit considerably lower fibre volume fractions than GFRPs, due to the low packing-ability of plant fibre preforms. This is thought to be a critical set-back for PFRPs as composite mechanical properties generally improve with fibre volume fraction. Apart from the expected (30-40%) lower density of PFRPs, they have 20-30% lower interlaminar shear strength, 5-10 times lower impact strength, 60-80% lower tensile strength and 30-60% lower tensile stiffness than GFRPs. Hence, unidirectional GFRPs clearly outperform unidirectional PFRPs in terms of absolute mechanical properties. Nonetheless, the specific tensile stiffness performance of high-quality aligned PFRPs is found to be comparable to aligned GFRPs. Hence, where high stiffness and low weight are the key materials selection criteria, high-quality plant fibre rovings can replace E-glass reinforcements in composites.

Amongst the various yarn reinforced PFRPs studied, composites reinforced with flax rovings demonstrated exceptional mechanical properties, with a back-calculated fibre tensile modulus in the range of 65-75 GPa (comparable to that of E-glass) and fibre tensile strength of about 800 MPa (almost half that of E-glass). This is proof of the reinforcing potential of plant fibres for structural composites, without the use of any active fibre surface treatment. Not only the bast fibre type, but yarn structure (twist level and packing fraction) and fibre/yarn quality were also found to have a significant effect on the mechanical properties of the resulting composite.

Reinforcing the recommendations from the critical review in *Chapter 2* and the constructed materials selection chart in Fig. 8.1 (or Fig. 2.6), through the findings of this chapter it is proposed that using minimally-processed flax rovings/slivers, processed specifically for composites applications rather than textile applications, as reinforcements in an epoxy matrix is a good starting point for producing high-quality PFRPs. Furthermore, employing prepregging technology or vacuum-assisted resin transfer moulding could enable the production of PFRPs with higher fibre content and thus better mechanical performance. Alternatively, using (press) consolidation upon resin impregnation may be necessary to produce higher fibre volume fractions.

8.1.2 *Chapter 4*: Effect of fibre volume fraction

To identify the processing window which produces PFRPs with useful properties, the effect of fibre volume fraction on the physical and tensile properties of aligned PFRPs has been investigated. Vacuum-infused PFRPs were producible with low local variations in fibre/matrix volume fractions and low void content (typically in the range of 0.3-1.4%). Importantly, there is no clear correlation between fibre content and void content. Furthermore, a void content of up to 4% is found to have negligible effect on the tensile properties of PFRPs. Fibre content and tensile properties are found to be linearly related, as per the rule of mixtures, similar to conventional brittle-fibre ductile-matrix fibre reinforced plastics (FRPs).

It is demonstrated that plant fibre assemblies (particularly in the form of twisted yarns) will inherently produce lower fibre volume fractions than conventional synthetic fibre assemblies. Aligned synthetic fibre reinforced composites have a low critical fibre volume fraction (~2.5% for carbon/polyester) and a high maximum (practical and theoretical) fibre volume fraction (of the order of 75-80%), implying that the range of fibre volume fractions that produce composites with useful properties is 70-75%. The study finds that PFRPs utilising staple fibre twisted yarns as reinforcements have a small window of fibre volume fractions which produce composites with useful properties. A high critical fibre volume fraction (on the order of 10%), low maximum (practical) fibre volume fraction (of the order of 45-55%) and low maximum (theoretical) fibre volume fraction (of the order of 45-60%) implies that the possible range of employable fibre volume fractions for such PFRPs is only 35-50%. Importantly, randomly-oriented short-fibre PFRPs have a much higher critical fibre volume fraction (of the order of 25%) and lower maximum (practical) fibre volume fraction (of the order of 30-45%) implying that the useable range of fibre volume fractions is even lower. This significantly limits the maximum exploitation of the mechanical properties of plant fibres in FRPs.

8.1.3 *Chapter 5*: Effect of reinforcement orientation

In aligned PFRPs, (mis)orientation manifests itself in various forms at every length scale: *a)* microfibril angle in a single plant fibre, *b)* twist angle in a processed staple fibre yarn, and *c)* off-axis loading angle in a composite laminate. The effect of these misorientations on the tensile properties of plant fibres and their composites is reviewed and studied.

8.1.3.1 Yarn structure

Due to the discontinuous length of technical plant fibres, the manufacture of aligned PFRPs requires the reinforcement to be in the form of staple fibre yarns/rovings, which have a twisted structure. Although twist facilitates yarn processability, it has several detrimental effects on the composites produced from such twisted yarn reinforcements; one of which is fibre obliquity and misalignment. This results in a drastic drop in composite mechanical properties.

In this study, a novel mathematical model is developed to predict the influence of yarn structural parameters (twist level, compaction, density) on composite tensile strength. The model is based on *i)* the modified rule of mixtures for PFRPs, *ii)* well-defined structure-property relationships in an idealised twisted staple fibre yarn, and *iii)* the Krenchel reinforcement orientation efficiency factor. The developed model includes a corrected orientation efficiency factor of $\cos^2(2\alpha)$, where α is the yarn surface twist angle. The model has been validated with extensive experimental data from Goutianos and Peijs [1] and is found to be a near-perfect fit (with $R^2 = 0.950$). Experimental data from other studies (namely [2]) on aligned yarn reinforced PFRPs are also used for further verification. An interesting inference of the derived model is that employing yarns with $\alpha > 26°$ or $\alpha > 32°$ as composite reinforcements will reduce the reinforcement orientation efficiency factor as in a 2D-random and 3D-random composite, respectively.

8.1.3.2 Ply orientation

While unidirectional composites provide optimum mechanical properties in one direction, the highly anisotropic nature of plant fibres and their aligned composites implies that off-axis loads have a significant influence on the mechanical behaviour of aligned PFRPs.

Investigating the response of PFRPs to off-axis tensile loads, conventional composite micro-mechanical models are found to be in good agreement with the experimental data, suggesting that reliable prediction of PFRP off-axis properties is possible. The application of such models has also enabled the determination of, otherwise difficult to measure, material properties, such as the fibre shear and transverse modulus. As observed in conventional FRP's, off-axis loaded PFRPs fail by three distinct fracture modes in three different off-axis ranges, where each fracture mode produces a unique fracture surface.

A key finding of this study is that due to the non-linear stress-strain response of PFRPs, the apparent stiffness of the composite reduces by ~30% in the strain range of 0.05–0.25%. In addition, through cyclic tests on the composites, the elastic strain limit is found to be only ~0.15%. This has major implications on the strain range to be used for the determination of the composite elastic Young's modulus. Consequently, it is proposed that the tensile modulus for PFRPs should be measured in the strain range of 0.025–0.100%. It is argued that the non-linear stress-strain response (decreasing 'apparent' stiffness with increasing strain) of single plant fibres has been transferred to the resulting PFRPs.

8.1.4 *Chapter 6*: Evaluation of fatigue performance

There is a noticeable lack of fatigue data on PFRPs which seriously limits their prospective use in fatigue-critical structural components. To provide a complete set of fatigue data on aligned PFRPs, S-N lifetime diagrams were constructed to specifically investigate the effect of *i)* plant fibre type/quality, *ii)* fibre volume fraction, *iii)* textile architecture, and *iv)* stress ratio, on PFRP cyclic-loading behaviour. At each stage, the fatigue performance of PFRPs has been compared to that of GFRPs. To facilitate fatigue design and life prediction of a PFRP component, a complete constant-life diagram has also been generated.

It has been demonstrated that power-law regression lines are a good fit to S-N fatigue data for PFRPs ($R^2 > 0.95$), and thus useful in predicting the fatigue life of PFRPs. While plant fibre type, plant fibre quality, textile architecture and composite fibre content have a significant impact on the static (tensile) properties of the PFRP, they have little impact on the material fatigue strength coefficient *b* (which dictates the slope of the S-N curve). In essence, higher static properties are a sign of superior fatigue loading capacities throughout the lifetime of PFRPs. Increasing stress ratios lead to improved fatigue performance (increasing *b*) in PFRPs. Fatigue fracture mechanisms and modes are the same for all plant fibre types, but depend on fibre content, textile architecture and load regimes (stress ratios). Although the absolute fatigue performance of GFRPs is far superior to PFRPs, it is a revelation to find that fatigue strength degradation rates are lower in PFRPs than in GFRPs.

8.1.5 *Chapter 7*: The potential of plant fibres in structural applications

Using composite small wind turbine blades as a case study, the question is directly addressed: Are PFRPs potential alternatives to GFRPs for structural applications? Two identical 3.5-meter composite rotor blades (suitable for an 11 kW turbine) were built from flax/polyester and E-glass/polyester. It is found that although the flax/polyester blade is 10% lighter than the E-glass/polyester blade (fibre mass saving of 45%), the materials cost of the former is almost 3 times more than the latter. It begs mention that under current market conditions, plant fibre reinforcements, in the form of yarns/rovings, are not a cost-viable alternative to E-glass. Furthermore, comparing the estimated cumulative embodied energy of the flax and E-glass blade, it is found that the flax blade has an up to 15% larger eco-impact than the E-glass blade. This is due to the high embodied energy of aligned flax reinforcements; while the energy required in the cultivation of plant fibres is low (4-15 MJ/kg [3-7]), further processing steps (*e.g.* retting and spinning) can significantly increase the cumulative energy demand to 54-118 MJ/kg for flax sliver and 81-146 MJ/kg for flax yarn [4-6, 8]. Note that conversion from slivers/yarns to fabrics would require further energy inputs. It is also suggested that to truly reduce the eco-impact of the final product, noting the large negative contribution of the matrix and core materials to the eco-impact, developing high-performance bio-based (or at least bio-sourced) matrix and core materials is a critical step in the wide acceptance of PFRPs as sustainable materials.

Through static flap-bending testing of the blades (in accordance to certification standards), the mechanical properties of the two blades were compared. It is confirmed that like the E-glass/polyester blade, the flax/polyester blade satisfies the design and structural integrity requirements for an 11 kW turbine, under normal operation and worst case loading. Hence, flax rovings are a potential structural replacement to E-glass, particularly for small wind turbine blade applications. While the displacement-load curve is linear for the E-glass blade, it is non-linear for the flax blade. This is consistent with the fact that plant fibres and their composites have a non-linear stress-strain curve, while E-glass and its composites have a linear stress-strain curve. This highlights the differing stress-strain accumulation mechanisms in natural materials. The failure load and corresponding tip displacement of the flax blade are ~80% and ~250% that of the E-glass blade, respectively. The substantially higher tip deflection of the flax blade is proof of its flexibility and almost a concern. The mean flexural rigidity of the flax and E-glass blades is 24.6 kNm^2 and 43.4 kNm^2. While it is demonstrated that the absolute and specific properties of the composites (*i.e.* flat laminate plaque) are transferred to the blade (*i.e.* component/structure), it is argued that there is a critical trade-off between component weight savings and component stiffness; for similar stiffness performance of a flax blade to an E-glass blade, weight savings cannot be achieved. Furthermore, while increasing the flax fibre content to enhance the stiffness of the flax blade stiffness may be an attractive option, this would have a substantial detrimental impact on the economic cost and eco-impact of the flax blade.

It is concluded that currently aligned flax reinforcements are a light weight and structural, but not low-cost or sustainable, alternative to conventional aligned E-glass reinforcements. Hence, despite the fact that yarn reinforced PFRPs demonstrate good potential for structural applications and their properties are well-predicted through (conventional and novel) micro-mechanical models, the development of low-cost sustainable aligned plant fibre intermediate products (yarns/rovings/fabrics) is critical to the commercialisation of the material technologies and its wide acceptance as a high-performance green material in industry and the wider society.

8.2 RECOMMENDATIONS FOR FUTURE WORK

In light of the work performed, a number of topics are proposed for future work. Some important improvements or studies that could be undertaken in terms of material and manufacturing process development and characterisation are:

- Develop cost-viable aligned plant fibre intermediate products (such as wrap-spun yarns and prepreg tapes) that are more suitable for composites applications rather than textile applications. Consider the potential of utilising fibres that are extracted from non-standard retting processes (*e.g.* biotechnical retting [9]) with minimal processing. It would also be of interest to conduct life-cycle analyses (such as those conducted by [4, 8, 10, 11]) to determine if processed plant fibre reinforcements (in the forms of yarns, fabrics and so on) are sustainable alternatives to traditional E-glass reinforcements.

- Investigate alternative composite manufacturing techniques (suitable for small wind turbine blade manufacture) that enable production of PFRPs with higher fibre volume fractions, such as vacuum-assisted resin transfer moulding and prepregging technology (as initiated recently by other researchers [12, 13]).

- Investigate the properties of aligned plant yarn/roving reinforced bio-based thermoset matrix composites. Examples of bio-resins that could be considered include plant seed-oil–based epoxies (such as those developed by Prof. Wool's group [14, 15]) and hemicellulose–based furan (polyfurfural alcohol) [16].

- Investigate the properties of hybrid composites (*e.g* carbon/flax reinforcements) to meet certain structural integrity requirements, as demonstrated by Mikkelsen *et al.* [17] in developing a flax/carbon wind turbine blade.

In this thesis, the tensile and fatigue behaviour of aligned PFRPs has been thoroughly investigated for various composite parameters and the structural potential of a plant fibre small wind turbine blade has also been demonstrated. However, to consider PFRPs for structural applications, specifically small wind turbine blades, some aspects that need further research include:

- Water sorption properties of PFRPs and particularly its effect on *i)* component dimensional stability, *ii)* tensile mechanical properties, and *iii)* cyclic-loading behaviour. While there are several studies, including [18-25], have investigated the mechanism of water sorption in PFRPs and its (dubious but) generally detrimental effects on the physio-mechanical properties, it is suggested that future studies should consider the effect of protective coatings that are conventionally applied on components (*e.g.* gel-coats and paints) and the effect of one-sided exposure, to truly assess the impact on the design life of a PFRP component.
- The compressive properties of PFRPs are not well-researched, and where studied [26-28] the properties are found to be impressive for the plant fibre (mean compressive strength of 1200 ± 370 MPa [26]) but poor for the composites (on the order of 80 MPa, similar to the compressive strength of the matrix [27]). These need to be investigated and characterised, particularly as a function of fibre content and textile architecture.
- Due to variations in wind velocity, rotor blades typically experience variable-amplitude (rather than constant-amplitude) fatigue loading. In addition, the fatigue loads are not only acting along the blade length (*i.e.* tension and compression), but are also torsional and flexural. Hence, it is of interest to evaluate the multi-axial fatigue behaviour of PFRPs, particularly under variable-amplitude loading. This has not been studied in literature so far.
- Talreja [29] argued and demonstrated that conventional FRPs follow a strain-controlled model of fatigue (rather than a stress-controlled model). Talreja clarified that the strain-life curves of FRPs, where strain is defined as the maximum strain attained in the first cycle of a load-controlled fatigue test, may be thought of in terms of three regimes (relating to the fibre, interface and the matrix) within which separate mechanisms control fatigue failure. The three regimes are: Region I (low-cycle fatigue) where catastrophic fibre breakage leads to failure within the experimental scatter-band for composite failure strain in a static test; Region II (intermediate cycles) where progressive fibre-bridged

matrix cracking and/or interfacial shear failure is dominant; Region 3 (high-cycle fatigue) where failure initiates in the matrix but is arrested by the fibres. To date, the limited studies on fatigue of PFRPs (including the one conducted in *Chapter 6*) employ a stress-controlled fatigue model. It would be of interest to study the fatigue behaviour of PFRPs through strain-life curves, which may provide more appropriate and accurate fatigue life predictions.

- For structures manufactured through infusion processes, flow modelling is also very relevant. It is of interest to investigate the effect of plant yarn structure on flow front evolution and fill time. Employing various yarn construction and fibre volume fractions (and thus yarn and preform permeability) would also allow studying the formation of voids in PFRPs. This has not been studied for PFRPs specifically, but similar studies have been conducted on conventional FRPs.

For structural applications, it becomes necessary to be able to reliably predict the response of a material/component to specific load scenarios. While this thesis does attempt to develop and validate predictive models (based on the rule of mixtures and conventional micro-mechanical models) on the tensile and fatigue properties of aligned yarn reinforced PFRPs, some aspects that require further research include:

- Developing finite element models to predict PFRP mechanical properties based on the properties of the individual constituents derived from experiments, and comparing it with rule of mixture predictions to validate the applicability of the micromechanics to PFRPs.
- In combination with the above, it may be useful to model the effect of reinforcing yarn construction and mechanical properties on composite mechanical properties. As the effect of fibre mechanical properties on yarn mechanical properties has been studied by several studies, and the effect of yarn mechanical properties on impregnated yarn mechanical properties has also been studied, if a mathematical model is developed to understand the effect of reinforcing yarn properties on composite properties, a complete integrated model can be built, which links the fibre, yarn and composite mechanical properties. Certainly, the models would need to be validated with experimental data.

- Fatigue testing with statistical analysis (and thus many more samples). This will not only improve the accuracy of the S-N regression curves but also improve the confidence in using constant-life diagrams for component fatigue life prediction. The DOE matrix for fatigue testing should also include more test frequencies, stress ratios and composite parameters. It would also be of interest to conduct a fatigue test on the actual component (*i.e.* small wind turbine blade) and compare with the estimated fatigue life obtained from the constant-life diagram.

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