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Enhanced rules-of-mixture for natural fibre reinforced polymer matrix (NFRP) composites (comment on Lau *et al* in volume 136)

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Abstract: The use of rules-of-mixture to predict the elastic modulus and strength of natural fibre-reinforced composites is often compromised by the fibre properties used in the calculations being derived with an assumption of circular cross-section, when real fibres have polygonal cross-section. A fibre area correction factor (FACF) has been proposed to address this inaccuracy and has been demonstrated to improve the predictions.

Letter: Lau *et al* [1] have stated that "it is challenging to develop a generic formula to predict the structural and mechanical properties of NFRP [natural fibre reinforced polymer matrix] composites" and that the traditional shear-lag "model is not applicable to NFRP composites due to the imperfect shape of nature fibres along their longitudinal direction and irregular shape of fibres' cross section".

Virk *et al* [2] (the authors of this letter) introduced a "fibre area correction factor (FACF)" to address this issue in the context of the rules-of-mixture (RoM) for natural fibre reinforced composites. The FACF, denoted κ, is determined as the ratio of the apparent fibre cross-section area (CSA) divided by the true fibre CSA for a set of observations. While it is impractical to determine this value for each individual fibre test, a sensible κ value can be determined from the mean values for a set of measurements using "apparent diameters" (obtained prior to experimental fibre tests), and by measuring the true fibre polygonal CSA from polished fibres/composites mounted parallel to the microscope axis, respectively.

The modified RoM [2] become Equation (1) for elastic modulus of any composite, and Equation (2) for strength (limited to quasi-unidirectional composites) by extending the Kelly-Tyson model [3]:

$$E_c = \kappa\, \eta_d\, \eta_l\, \eta_o\, E_f\, V_f + E_m\, V_m \tag{1}$$
$$\sigma'_c = \kappa\, \sigma'_f\, V_f + \sigma^*_m\, V_m \tag{2}$$

where E = elastic modulus, η_d = fibre diameter distribution factor, η_l = fibre length distribution factor, η_o = fibre orientation distribution factor, V_f = component volume fraction, σ' = strength, σ^*_m = stress in the matrix at the failure strain of the fibre, and subscripts c, f and m denote composite, fibre and matrix respectively. The assumptions underlying the rules of mixtures are not changed by the introduction of the FACF.

Virk et al [2] reported experimental data for well-characterised quasi-unidirectional technical jute fibre reinforced epoxy resin matrix composites, manufactured by resin infusion under flexible tooling (RIFT) with a flow medium, and for the respective constituents. The experimental mean moduli and strengths were 8.19±0.6 GPa and 100.0±5.7 MPa respectively for dyed fibre/pigmented resin composites and **8.47**±1.18 **GPa** and **101.0**±17.2 **MPa** for undyed/unpigmented composites respectively (i.e. the difference between the pairs of respective mean values was <50% of the lower standard deviation). The predicted modulus using Equation (1) without κ was 6.44 GPa (-24.0% from the experimental data for the undyed/unpigmented composites) and with κ was **8.24 GPa** (-2.7%).

The experimental fibre strengths were analysed using natural logarithm interpolation (NLI) [4, 5], and multiple data set (MDS) weak link scaling (WLS) [6], models. The predicted strengths using Equation (2) without κ were 79.2 MPa (NLIM, -21.6% from the experimental data for the undyed/unpigmented composites) and 73.1 MPa (MDS, -25.4%) and with κ = 1.42 (2697/1896) were **102.9** (NLI, +1.9%) and **95 MPa** (MDS, -5.9%) respectively (Figure 1).

Further, Virk *et al* [2] assumed that the FACF would be appropriate for other batches of jute fibres and analysed 14 sets of experiments conducted by other researchers with sliver, yarn, chopped strand or fabric reinforcements. The error in those predicted composite moduli was reduced when the FACF was used for all but two cases (Figure 2). Soatthiyanon et al [7] determined a fibre area correction factor of 2.70 for flax. By back-calculation from tensile tests on unidirectional composites, the modulus of the flax fibres was within 6%, and the strength was within 7%, of that for single fibre tests.

In conclusion, the modified generic RoM formulae do permit sensible prediction of the elastic moduli and strengths of NFRP, and hence address the challenge issued by Lau *et al* [1]. Further work is required to (a) determine the validity of the model for natural fibre composites from a broader range of sources, (b) establish if κ varies with the range of "apparent" fibre diameters, (c) determine κ for other natural fibres (and for non-circular [8] or hollow [9] synthetic fibres), and (d) confirm the validity of the new equations for a wider set of data.
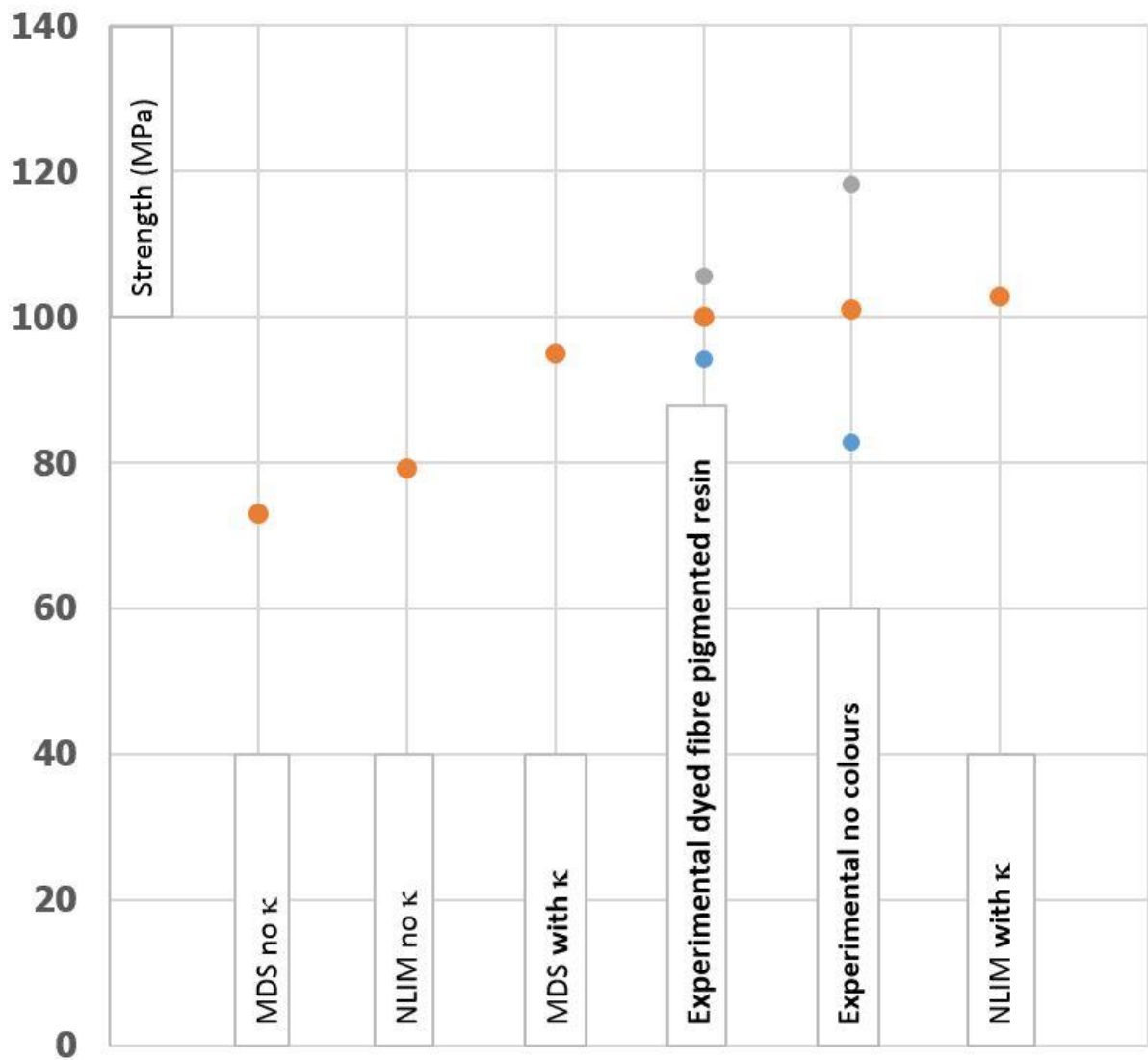
Figure 1: Strength of quasi-unidirectional jute/epoxy composites predicted using Equation 2 with and without the fibre area correction factor (FACF: κ) compared to experimental values for materials with dyed fibres in pigmented resins or without colourants [2]. The experimental data points are the mean and ± one standard deviation.
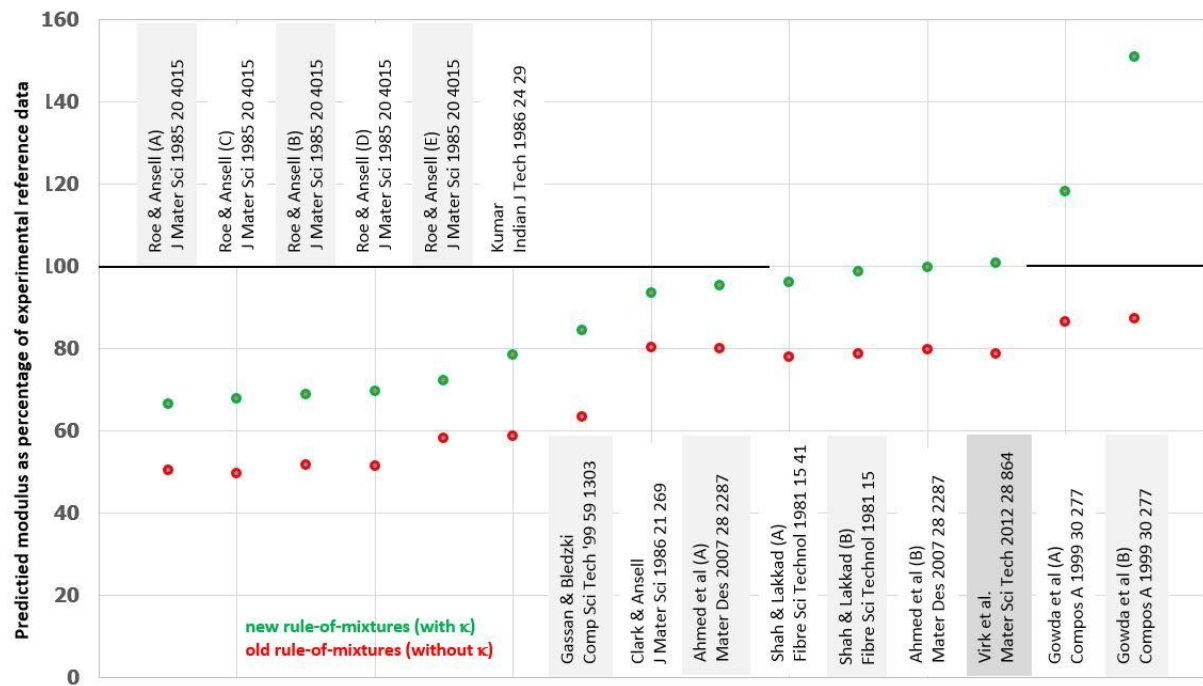
Figure 2: Comparison of rule-of-mixtures predicted moduli for jute fibre composites without (below/red) and with (above/green) the fibre area correction factor [2, 10-16].

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Supplementary information

1: spreadsheet for modulus
2: spreadsheet for strength