# Size and scale effects in composites: III. Woven-roving laminates

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## Abstract

This paper is concerned with scale and size effects in the strength characterisation of composite materials with particular reference to woven-roving laminates. Attention has been focused on the tensile and flexural strengths of glass/polyester laminates fabricated by hand lay-up techniques. Factorial experiments have been designed to allow investigation of the joint influence of different factors on strength. The work highlights the importance of fabrication factors and the distinguishing difference between scale effects and size effects.

## Keywords

Scale effects, FRP, Composite, Dimensional analysis, Weibull analysis, Factorial experiments

## 1. Introduction

For some time a strength 'size effect' has been thought to exist for some composites, which is usually (but not exclusively) detrimental with increasing size. This is believed to be due to the increased probability of a larger specimen containing a flaw great enough to lead to failure. However, an accurate quantitative description of such effects, or even concrete evidence of their existence, has proved elusive. A review of this literature is given by Sutherland et al. [1].

An investigation of possible strength size effects for composite materials concerns a number of pertinent variables, and also experimental data subject to considerable scatter. The methods of statistically designed experimentation [2] have been applied to benefit this type of problem, and used to study size effects in glass-fibre and carbon-fibre unidirectional laminates.

The purpose of this paper is to investigate size and scale effects in woven roving (WR) laminates of glass reinforced polyester (GRP) fabricated by a hand lay-up technique. This is studied with respect to the tensile and flexural strength characteristics. Two principal classes of factors for the variations are considered, namely influence of different glass suppliers and typical fabrication parameters encountered in constructing large structures.

## 2. Influence of the glass supplier

### 2.1. Experimental programme

This part of the study addresses the issue of variability in strength with size by considering three particular suppliers of glass reinforcements. The reinforcements comprised a balanced twill-weave woven roving of nominal areal density of 780 g/m$^2$. Specimen length, width and thickness were varied in the experiment and a nested structure of width and length within thickness was adopted for the flexural tests. Because of restrictions in the maximum load attainable by the test rig, the length and width levels for both thicknesses of tensile specimens were identical.

The list of factors considered for both test methods is thus:

1. Thickness
2. Woven-roving manufacturer (reinforcement)
3. Length
4. Width

Laminate panels were supplied in two thicknesses, four and eight plies. To explore further the use of experimental design methods in this context, and to give more detailed information on any possible size-related effects, the length and width factors were assigned three levels.

For both test methods a 15-run central composite design as described by Grove and Davis [3] was selected for each thickness. This design is shown schematically in Fig. 1, where each filled circle represents a test coupon in our application. Since the three woven rovings used were nominally identical, interactions with the reinforcement factors were expected to be small. Hence the design was judged sufficient to allow the important factor effects to be estimated without the need for replication of the specimens. A schematic illustration of the structure of the test series is shown in Fig. 2 and the coded design of the 15-run central composite plan is given in Table 1.

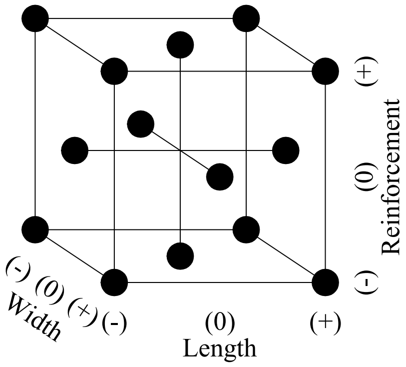

Fig. 1. 15-run, central composite design.

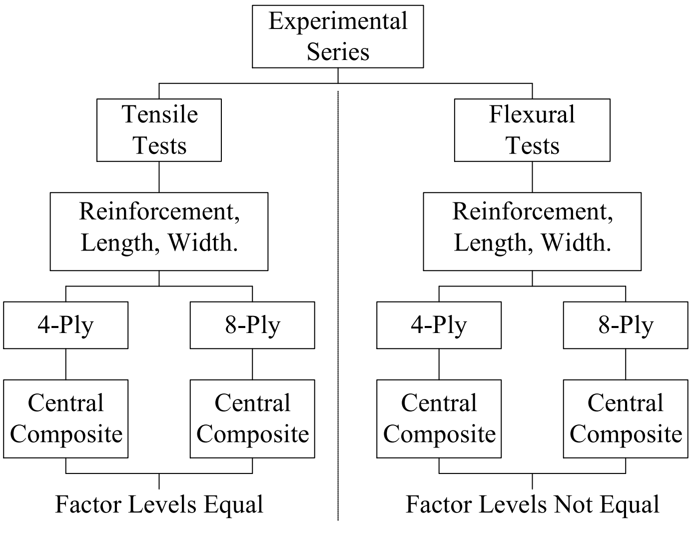

Fig. 2. W.R. manufacturer experimental series.

| Specimen | Reinforcement | Length | Width |
|---|---|---|---|
| 1 | Low | Low | Low |
| 2 | High | Low | Low |
| 3 | Low | High | Low |
| 4 | High | High | Low |
| 5 | Low | Low | High |
| 6 | High | Low | High |
| 7 | Low | High | High |
| 8 | High | High | High |
| 9 | Medium | Medium | Medium |
| 10 | Low | Medium | Medium |
| 11 | High | Medium | Medium |
| 12 | Medium | Low | Medium |
| 13 | Medium | High | Medium |
| 14 | Medium | Medium | Low |
| 15 | Medium | Medium | High |

Table 1. 15-run, central composite design

The ASTM standards for flexural and tensile testing of fibre-reinforced plastics [4, 5], were used here as guidelines. The resin 'burn-off' method described in ASTM standard D2584 [6] was used to obtain fibre volume fractions for each specimen. The levels of the reinforcement factor consisted of three different suppliers of nominally identical E-glass woven roving of weight 780 g/m$^2$. The three levels are labelled 'AUS8', 'AUS11' and 'AUS12' (after the original Vosper Thornycroft notation). Panels fabricated from each of these reinforcements were available at thicknesses of four and eight plies; 12 mm load and support rollers were used throughout. The factor levels for the flexural and tensile tests are given in Table 2 and Table 3, respectively. The total coupon lengths for the tensile specimens were larger than those quoted in the tables, including an additional grip length of 40 mm at each end.

| Thickness | Depth (mm) | Level | Length (mm) | Width (mm) |
|---|---|---|---|---|
| **4-Ply** | 3 | **Low** | 50 | 10 |
| | | **Medium** | 75 | 20 |
| | | **High** | 100 | 30 |
| **8-Ply** | 6 | **Low** | 100 | 20 |
| | | **Medium** | 150 | 40 |
| | | **High** | 200 | 60 |

Table 2. Flexural test geometric factor levels

| Thickness | Depth (mm) | Level | Length | Width |
|---|---|---|---|---|
| **4-Ply** | 3 | **Low** | 50 | 10 |
| **8-Ply** | 6 | **Medium** | 100 | 17.5 |
| | | **High** | 150 | 25 |

Table 3. Tensile test geometric factor levels

### 2.2. Specimen preparation

The panels were hand laminated under factory-floor conditions at Vosper Thornycroft's Woolston shipyard. The resin system used was DSM Synolite 73-2785, a medium-reactivity isopthalic polyester resin described by the manufacturers as “suitable for the construction of large marine structures”; 0.75% NL 49 P accelerator and 1.5% Butanox M50 catalyst were used to cure the resin. A nominal fibre weight fraction of 0.5 was stipulated. The four-ply laminates were fabricated to be one cloth width square, and the eight-ply panels were fabricated to be two cloth-widths square, requiring a system of butting together two cloth widths. The laminates were post-cured for 24 to 72 h at a temperature not exceeding 25°C, followed by 16 h at 40°C±2°C. The specimens were then cut from the panels with a diamond edged saw. The moulding surface produced a smooth and flat surface on one side of the panels but the coarseness of the weave meant that the other surface was very uneven. Hence the strain gauges were attached to the moulded surface.

### 2.3. Results

The full data set of results for these tests is given in Appendix A. The failure of the tensile specimens was sudden and resulted in extensive delamination and bulging over the length of the coupon. Flexural specimens failed due to delamination of the top compressive ply between the loading rollers.

### 2.4. Statistical analysis

As for the unidirectional tests of Sutherland et al. [7], this experiment has a split-plot structure. In this case, thickness has only two levels and hence no quadratic effects may be estimated. However, the reinforcement manufacturer, length and width factors each have three levels, and hence quadratic effects may be estimated for these factors and their interactions. The three levels of the woven roving manufacturer, M, were assigned the coded values 1, 2 and 3 for the Colan W.R./Chinese Roving (AUS8), the Asahi Fiber Glass Co. (AUS11) and the Key Trading Corp. (AUS12) reinforcements, respectively. Hence the linear and quadratic components of the manufacturer main effect are interpreted respectively as a comparison of the average response for the first and third manufacturers, and the average for these two compared with the second manufacturer. See Grove and Davis [3] for a discussion of qualitative factors examined in this way. Interactions between three or more factors were assumed to be negligible. It should be stressed that this does not mean that the contrasts corresponding to these interactions played no part in the analysis; they were used to give a more accurate estimate of the experimental error.

If the components of the interaction between manufacturer and thickness were assumed negligible then their estimates would be solely due to the whole-plot variation and they could be used to give an estimate of the whole-plot error. However, there was little confidence in this assumption, and hence no estimate of the whole-plot error was available. As for the unidirectional tests, simple qualitative comparisons were made between the whole-plot terms and the sub-plot terms using the whole- and sub-plot sums of squares expressed as a percentage of the total sums of squares.

For the flexural tests, the length and width factors are nested under the thickness factor. This structure and the corresponding analysis are described in Sutherland et al. [2]. For the tensile tests the length and width factors were not nested under thickness; all factors had identical level settings at each of the other factor levels. The software package SAS was used to perform the analyses by the General Linear Model (GLM) procedure which carries out an analysis of variance which uses a least-squares approach [8].

A feature of the 15-run central composite design is that it is not fully orthogonal with respect to the second order model [3]. This means that the estimates of the quadratic terms are not independent of each other. In practical terms this results in the estimates of the quadratic terms varying according to the order in which they are fitted in the statistical model. Hence, to allow meaningful comparisons to be made, each sums of squares used to give the *p* values for each term is calculated after all the other terms have already been fitted in the model.

It was thought that possible indications of the quality of the specimens could be given by the initial Young's modulus and the fibre volume fraction. Hence, these measurements were included in the model as covariates. Both were found to be statistically just significant at the 5% level for the tensile stress measurements, and hence were kept in the model. However, these variables were found to be important for the tensile stress measurements only.

The statistical model postulated for the failure strain of the tensile tests and the failure stress and strain of the flexural tests can be expressed:

$$\begin{aligned} &Strength = \alpha_0 + \alpha_1 M_l + \alpha_2 M_q + \alpha_3 T + \alpha_4 M_l xT + \alpha_5 M_q xT + \mathrm{E} \\ &+\alpha_6 M_l xCL_l + \alpha_7 M_q xCL_l + \alpha_8 CL_l + \alpha_9 CL_q \\ &+\alpha_{10} M_l xCW_l + \alpha_{11} M_q xCW_l + \alpha_{12} CW_l + \alpha_{13} CW_q \\ &+\alpha_{14} CL_l xCW_l + \alpha_{15} TxCL_l + \alpha_{16} TxCW_l + \varepsilon \end{aligned} \tag{1}$$

where the *α* terms are unknown coefficients, *M* denotes manufacturer, *T* denotes thickness, *E* is the whole-plot error, *CL* and *CW* are the coded length and coded width (within the appropriate thickness), *ε*, is the sub-plot error, and the subscripts *l* and *q* refer to linear and quadratic effects respectively. The two error terms are assumed independent with normal distributions, means 0 and constant variances. The model for the tensile failure stress was similar to Eq. (1) with the addition of linear terms for the initial modulus and fibre volume fraction.

Table 4 gives an indication of the relative importance of the whole-plot and sub-plot terms using the respective sums of squares expressed as a percentage of the total sums of squares.

| | **Whole-Plot SS (%)** | **Sub-Plot SS (%)** |
|---|---|---|
| Tensile Stress | 57.7 | 22.8 |
| Tensile Stress with mod. & $V_f$ | 22.5 | 40.2 |
| Tensile Strain | 24.6 | 20.8 |
| Flexural Stress | 55.7 | 19.1 |
| Flexural Strain | 52.6 | 20.2 |

Table 4. Whole-plot and sub-plot sums of squares (as percentages of the total sum of squares)

The sums of squares normalised with respect to the sub-plot error, given in Table 5, are now used to compare the relative importance of the whole-plot factors. Here it should be stressed that these ratios are purely comparative and that no statistical inferences should be made from them. The trends may be seen in the appropriate main effects and interaction plots, given in Figures 3 to 8.

| | Tensile | | Flexural | |
|---|---|---|---|---|
| **Source** | **Stress** | **Stress** (Mod & Vf) | **Stress** | **Strain** |
| Man. | 4 | 0 | 1 | 1 |
| QMan. | 21 | 1 | 13 | 2 |
| Thick | 7 | 12 | 13 | 22 |
| Man*Thick | 1 | 0 | 2 | 0 |
| QMan*Thick | 5 | 0 | 0 | 0 |

Table 5. Whole-plot sums of squares normalized with respect to sub-plot error

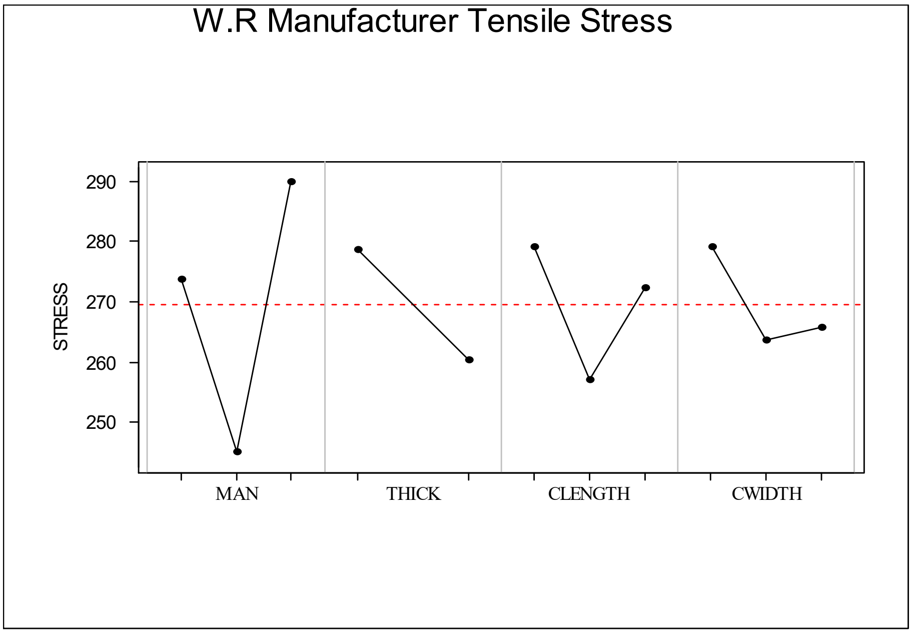

Fig. 3. Tensile stress (MPa) main effects plots.

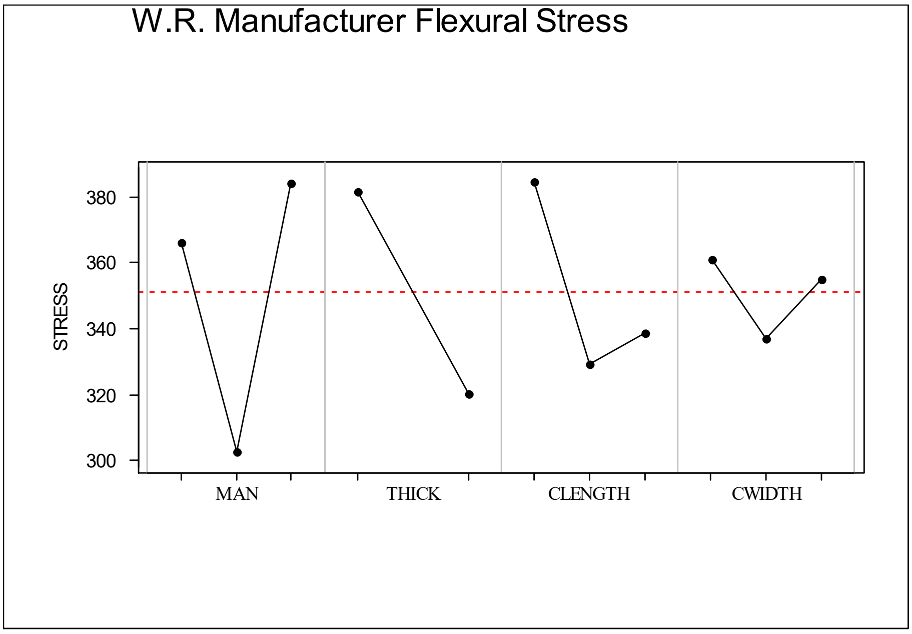

Fig. 4. Flexural stress (MPa) main effects plots.

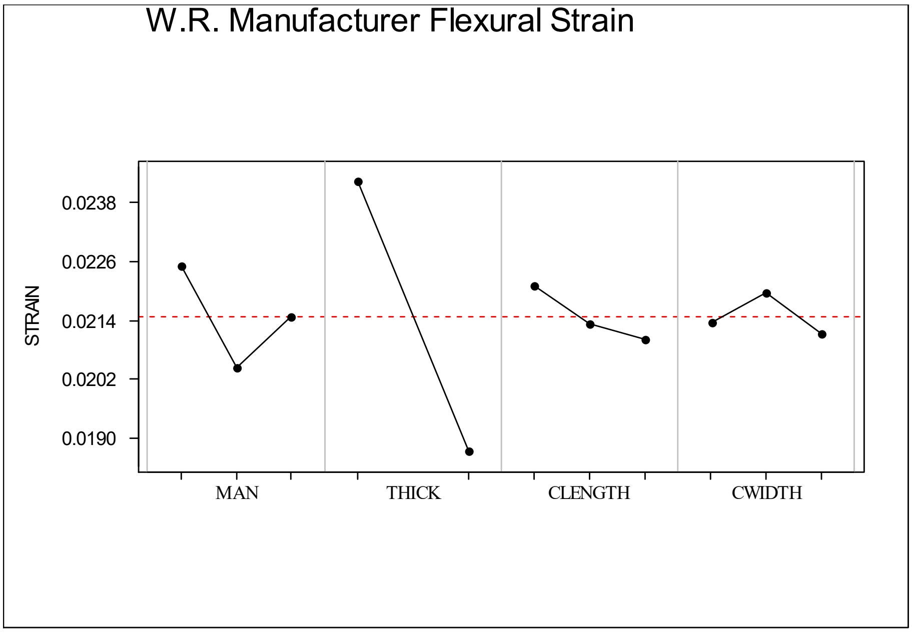

Fig. 5. Flexural strain (%) main effects plots.

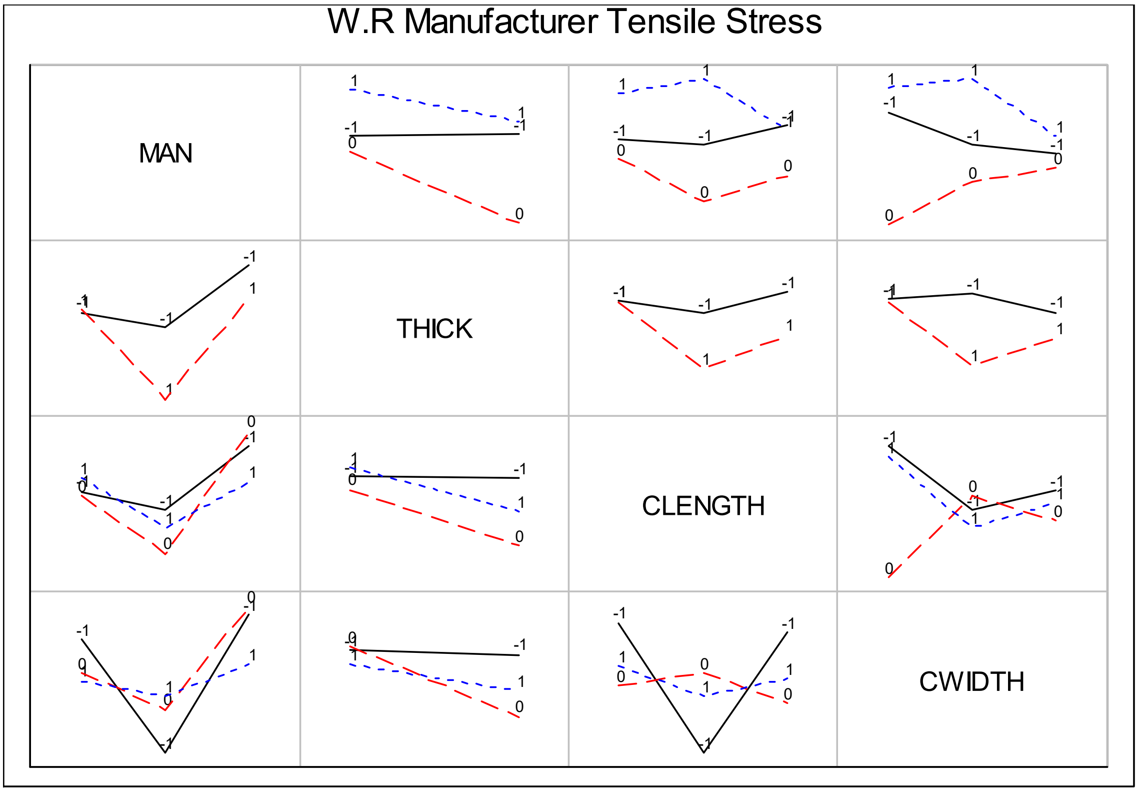

Fig. 6. Tensile stress interactions plots.

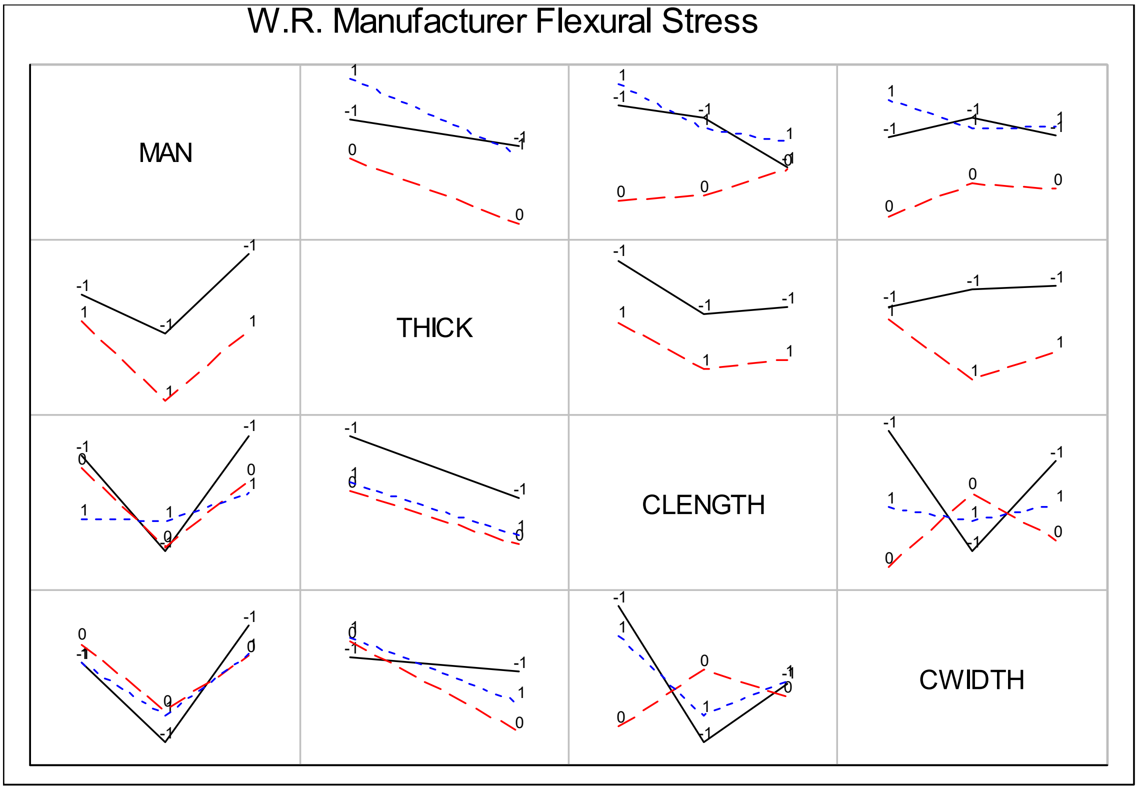

Fig. 7. Flexural stress interactions plots.

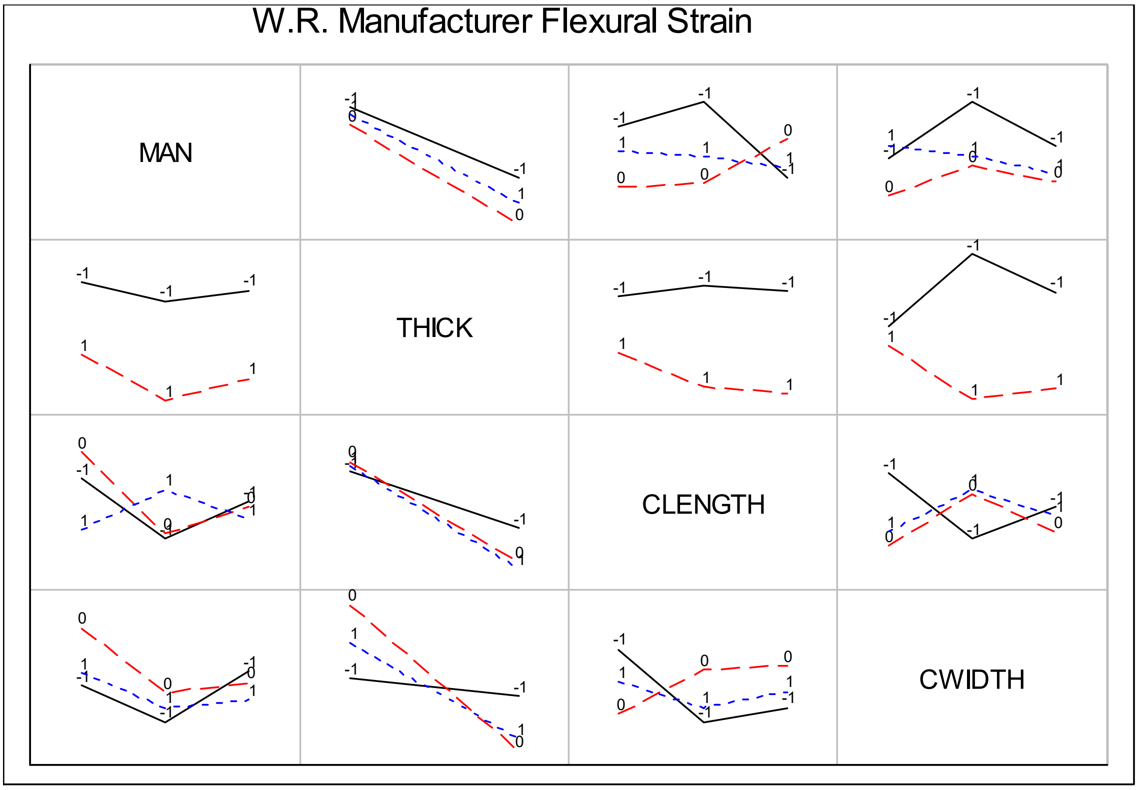

Fig. 8. Flexural strain interactions plots.

The sub-plot *p* values in Table 6 are now used to identify the dominant sub-plot terms. The $R^2$ values given in Table 6 show that the model postulated for the tensile failure stress measurements fits the data well, and that the model is improved further through the inclusion of the two covariates. However, the fit of the tensile failure strain model is poor, with an $R^2$ value less than 50%. Such a poor fit means that the results of the statistical analysis are unreliable and hence further inferences are not made from this analysis of the tensile failure strain response. Both models of the failure measurements for the flexural tests show reasonable fits to the experimental data with $R^2$ values of around 75%.

| | **Tensile** | | **Flexural** | |
|---|---|---|---|---|
| **Source** | **Stress** | **Stress** (Mod & Vf) | **Stress** | **Strain** |
| Man*Clength | 0.164 | 0.653 | 0.908 | 0.508 |
| QMan*Clength | 0.873 | 0.313 | 0.080 | 0.168 |
| Clength | 0.420 | 0.829 | 0.352 | 0.584 |
| Qlength | 0.388 | 0.147 | 0.734 | 0.997 |
| Man*Cwidth | 0.822 | 0.785 | 0.525 | 0.436 |
| QMan*Cwidth | 0.018 | 0.005 | 0.412 | 0.700 |
| Cwidth | 0.497 | 0.374 | 0.433 | 0.265 |
| Qwidth | 0.291 | 0.472 | 0.574 | 0.280 |
| Clength*Cwidth | 0.947 | 0.618 | 0.461 | 0.355 |
| Thick*Clength | 0.184 | 0.060 | ~ | ~ |
| Thick*Cwidth | 0.473 | 0.285 | ~ | ~ |
| **Covariates:** | | | | |
| Mod | ~ | 0.044 | ~ | ~ |
| Vf | ~ | 0.042 | ~ | ~ |
| **R-Squared** | 82.4% | 91.3% | 77.3% | 72.7% |
| **Sub-Plot C.V.** | 0.0685 | 0.0523 | 0.1330 | 0.1504 |

Table 6. Sub-plot *p*-values for W.R. manufacturer tests

### 2.5. Discussion

Inclusion of the initial Young's modulus and fibre volume fraction of the tensile specimens in the statistical model gives an improved description of the failure stresses observed. The fibre volume fraction gives a measure of the 'quality' of the specimen in terms of the ratio of fibre to matrix materials within the composite. Variations from this specified value will contribute to the experimental variation, since the strength of a composite material is strongly dependent on this ratio. Some of the experimental variation has been accounted for through consideration of the fibre volume fraction. Similarly, the initial Young's modulus can give an indirect measure of other variations in specimen 'quality'. Imperfections in the laminate, such as fibre misalignment, fibre crimp and void inclusion, will lead to changes in the initial stiffness. Hence inclusion of this covariate further accounts for some of the experimental variation. The fact that these covariates are not statistically significant for the flexural failure stress is puzzling considering the known sensitivity of compressive strength to such imperfections as described above. However, the fact that the woven roving manufacturer term has already been included in the statistical model may account for this.

The load versus tensile strain plots obtained using the strain gauges did not show smooth traces. Sections of the graphs showed an increase in strain with very little or no increase in load. It was often necessary to estimate the failure strain by ignoring these sections and/or extrapolating the line to the failure load in order to give the failure strain. This is an obvious explanation for the poor fit of the statistical model to the tensile failure strain data. The length of the strain gauges, 10 mm, is of a comparable dimension to that of the weave of the roving reinforcement. This means that the local positioning of the gauges with respect to the weave becomes important.

The flexural failure stress values were, by necessity, obtained indirectly by a calculation involving the failure load and test dimensions [4]:

$$\sigma_f = \frac{P_f L}{bd^2} \tag{2}$$

where $P_f$ is the failure load, and $L$, $b$ and $d$ are the specimen length, width and thickness, respectively.

Also, an approximation was made to allow for the effects of large central deflections of the specimens seen [4]:

$$\sigma_f = \left(\frac{P_f L}{bd^2}\right)\left[1 + \left(4.70\frac{D^2}{L^2}\right) - \left(7.04\frac{Dd}{L^2}\right)\right] \tag{3}$$

where $D$ is the central deflection. Both of these procedures introduce errors into the stress values.

This accounts for the fact that the fit of the model to the flexural stress values is slightly lower than that for the tensile tests.

The whole-plot factors are seen to be more influential than the sub-plot factors, indicating that the manufacturing related effects are important. The only exception to this is when initial modulus and volume fraction are included in the analysis, and account for a large proportion of the variation in the failure strain previously attributed to the whole-plot factors. Since laminates of differing reinforcement and thickness must be laminated as separate panels, and since there was no replication of each laminated panel, it is impossible to distinguish between the effects of the whole-plot factors and the effects of panel to panel variation.

The coefficient of variation of the experimental error for the tensile stress measurements, at 7%, is comparable to the values obtained by Vosper Thornycroft (5–8%) in their in-house study [9] and slightly less than the value of 12% quoted by Smith [10]. Inclusion of the covariates reduces the coefficient to 5%, again since they provide some indication of the laminate quality.

The inaccuracies associated with the calculations of flexural stress and the localised flexural strain measurement are reflected in the flexural failure stress and strain coefficients of 13 and 15%, respectively. These values are comparable to Vosper Thornycroft's results of around 10%, but are around half the figures quoted by Smith of 29%. However, the data used by Smith is from many sources and hence material and test set-up differences would explain why his coefficients are relatively large.

The importance of the whole-plot quadratic woven roving manufacturer for both tensile and flexural failure stress simply means that the laminates fabricated using the AUS11 woven roving were weaker than those constructed using either of the other woven rovings. This could be due to a number of reasons such as difficulty in wetting out when laminating, poor stacking of laminates, inferior bonding between matrix and fibre and increased fibre damage incurred by the weave process used. The first two examples would be reflected in a variation in the fibre volume fraction, and this hypothesis is reinforced by the removal of the importance of the quadratic manufacturer effect when fibre volume fraction is considered as a covariate for the tensile tests.

The strengths of the eight-ply specimens are lower than those of the four-ply specimens for both test methods and for both stress and strain measurements. The four ply panels were laminated one continuous sheet of woven roving in each ply. However, the eight-ply panels were fabricated with more than one sheet of woven roving in each ply by using a butting system. This gives discontinuities in the reinforcement and would account for the decrease in material strength.

Another explanation for this trend is that a lower quality specimen is obtained when a thicker laminate is produced. A plausible explanation for this would be that, when there are more wet, and hence unstable, plies, the fibres of the top lamina are more difficult to keep straight as they are wetted-out. Compressive failure of the flexural specimens was initiated in the top laminate and since fibre waviness is critical for compressive failure, this would explain why the thicker laminates were weaker. A similar trend was seen for the tensile tests, where the straightening of crimped fibres may lead to localised matrix failure and subsequent failure of the specimen.

The tensile stress interaction between the quadratic manufacturer and width terms is mainly due to the low strength obtained for the low width (10 mm wide) AUS11 reinforced specimen. An explanation for this behaviour may be derived from the values for the number of ends (of warp rovings) per 100 mm: 20 for AUS8 and 12 reinforcements, and 17.8 for the AUS11 reinforcement. Hence, for a 10 mm wide specimen there would be on average, two warp rovings in the AUS8 and 12 coupons but only 1.78 rovings in the AUS11 coupons. This would lead to a higher number of cut or damaged warp rovings in the AUS11 10 mm wide specimens and would account for their reduced strength.

## 3. Investigation into fabrication factors

### 3.1. Experimental programme

The action of laminating by hand often produces distortions in the orthogonal structure of the warp and weft of a woven-roving composite. A similar effect is seen when the cloth has to be worked into a three dimensional shape. This was modelled by skewing the warp and weft in the woven roving to give the levels of a fibre-orientation factor. Two levels were allocated to this factor, orthogonal warp and weft and skewed warp. The angle of skew had to be large enough to be practically achieved and controlled. An angle of 15° was considered to be appropriate. The two levels of this factor are illustrated in Fig. 9.

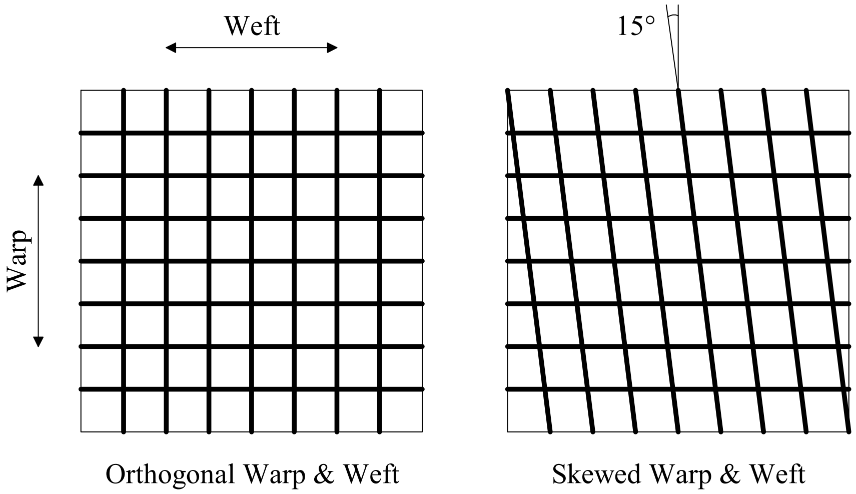

Fig. 9. Skewed warp and weft.

In practice woven-roving cloth is usually supplied in rolls of a given width. Hence to fabricate large structures these widths of cloth are laid up side by side, introducing a butt joint where the two cloths meet. A system of butts was introduced to simulate that used in practice. A butt was introduced into every fourth ply, as shown in Fig. 10. The butts were positioned perpendicular to the warp along the centre-line of each panel fabricated. The two levels of this factor consisted of the absence and the presence of this ‘butting system’.

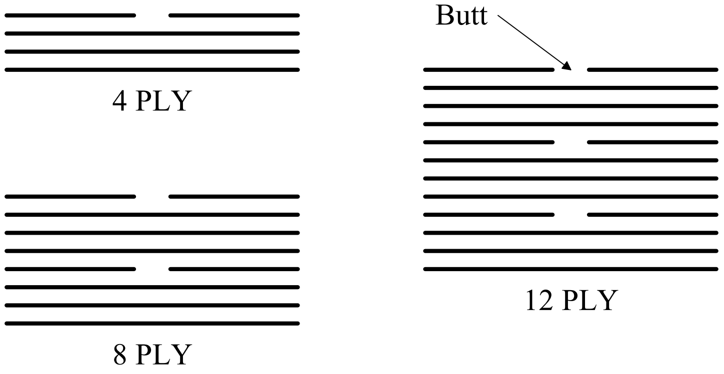

Fig. 10. Butting system.

Three levels of panel thickness were selected: four and eight plies to correspond to those in the W.R. manufacturer tests, and also 12 plies to try to induce any effects associated with thicker laminates. To ensure continuity in the test programme as a whole, the tensile and four-point flexural test methods were again employed.

The large amount of scatter in the results observed for the results of the W.R. manufacturer tests led to a fairly conservative approach to the design of the experimental plan for the final test programme. A full factorial design was selected for the factors thickness, butts and skew, leading to the fabrication of the 12 panels described in Table 7. The full factorial combination of the length and width factor levels, with one replication of each coupon gave 16 specimens from each panel (eight for each of the two test methods). This gave a total of 192 coupons for this test series. The structure of the test programme is shown in Fig. 11, where the panel numbers refer to the last digit of the panel code given in Table 7.

| **Panel Code** | **Thickness (Plies)** | **Butts** | **Skewed Warp** |
|---|---|---|---|
| VOS / 41 | 4 | No | No |
| VOS / 42 | 4 | No | Yes |
| VOS / 43 | 4 | Yes | No |
| VOS / 44 | 4 | Yes | Yes |
| VOS / 81 | 8 | No | No |
| VOS / 82 | 8 | No | Yes |
| VOS / 83 | 8 | Yes | No |
| VOS / 84 | 8 | Yes | Yes |
| VOS / 121 | 12 | No | No |
| VOS / 122 | 12 | No | Yes |
| VOS / 123 | 12 | Yes | No |
| VOS / 124 | 12 | Yes | Yes |

Table 7. Panel codes

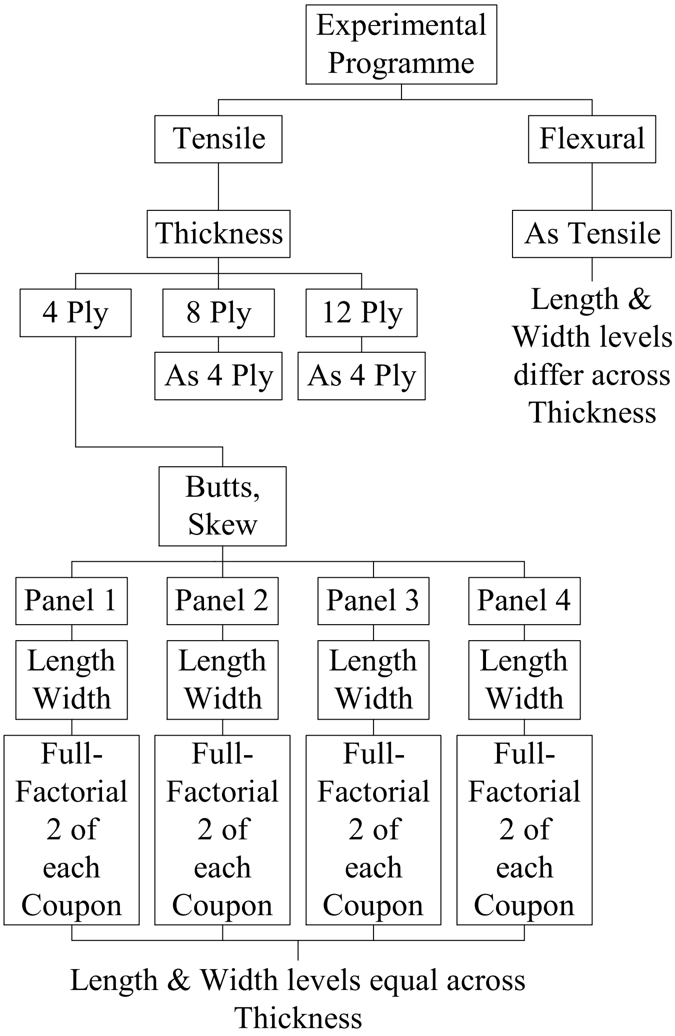

Fig. 11. Final W.R. test series structure.

The experience gained from the W.R. manufacturer test programme was used to set the specimen dimensions for the flexural and tensile tests and these are given in Table 8 and Table 9. Additionally, an extensometer was used for the tensile tests, and this dictated that the minimum specimen length be 100 mm. A grip length of 50 mm at each end of the tensile specimens was introduced to minimise the likelihood of slippage.

| Units: mm | Depth (Approx.) | Level | Length | Width |
|---|---|---|---|---|
| 4-Ply | 4 | Low | 54 | 10 |
| | | High | 100 | 30 |
| 8-Ply | 7 | Low | 105 | 20 |
| | | High | 200 | 60 |
| 12-Ply | 11 | Low | 162 | 30 |
| | | High | 300 | 90 |

Table 8. Flexural test factor levels

| Units: mm | Depth (Approx.) | Level | Length | Width |
|---|---|---|---|---|
| 4-Ply | 4 | Low | 100 | 10 |
| | | High | 300 | 25 |
| 8-Ply | 7 | Low | 100 | 10 |
| | | High | 300 | 25 |
| 12-Ply | 11 | Low | 100 | 10 |
| | | High | 300 | 25 |

Table 9. Tensile test factor levels

### 3.2. Materials

All panels were again hand laminated at Vosper Thornycroft’s Woolston shipyard. The panels were of dimensions 1 m by 1 m. The reinforcement consisted of Fothergill Engineering Fabrics YO 530 plain weave, woven roving E-glass of weight 780 gm$^{-2}$ . The matrix phase was Scott Bader Crystic 489 PA isophthalic boat-building polyester resin with 1.5% Butanox M50 catalyst. A nominal fibre weight fraction of 0.5 (equivalent to a fibre volume fraction of approximately 0.35) was stipulated and the laminates were cured at room temperature for 2 months.

The specimens were then cut from the panels using a diamond-edged saw, with the warp in the length direction. Those specimens with butts were cut out of the panels so as to position the butt half way along the length of the specimen. Strain gauges were adhered to the centre of the moulded, tensile face of each flexural specimen.

### 3.3. Results

The full data set of results for these tests is given in Appendix B. Tensile failure of the orthogonal warp/weft specimens with no butts was initiated at the jaws, with fibre failure across the specimen and extensive delamination predominately down one edge. The tensile failure of the orthogonal warp/weft specimens with butts was initiated at the butt with extensive delamination and fibre pullout. Flexural failure of the specimens with orthogonal warp/weft was compressive delamination of the top ply between the loading rollers. The coupons with skewed warp and weft failed in tension with white diagonal lines of shear failures, more concentrated near the butt where these joins were present. Flexural failure of the skewed warp/weft specimens is again compressive and between the loading rollers.

### 3.4. Statistical analysis

The experimental design used here again has a split plot structure. Additionally, the length and width factors are nested within the thickness factor for the flexural tests. The SAS software [8] was again used to analyse the data, and the interaction between thickness, butts and skew was used to give an estimate of the whole-plot error.

Both fibre volume fraction and initial modulus were considered as covariates, but the only statistically significant covariates were found to be initial modulus for tensile and flexural failure stress. Additionally, initial modulus was shown to be weakly significant for the flexural failure strain analysis (*p* value 0.09).

The statistical models postulated for the tensile and flexural failure strain can be represented by:

$$\begin{aligned} Failure\ Strain = {} & \alpha_0 + \alpha_1 T_l + \alpha_2 T_q + \alpha_3 B + \alpha_4 S + \alpha_5 T_l xB \\ & + \alpha_6 T_q xB + \alpha_7 T_l xS + \alpha_8 T_q xS + \alpha_9 BxS + \mathrm{E} \\ & + \alpha_{10} CL + \alpha_{11} T_l xCL + \alpha_{12} T_q xCL + \alpha_{13} CW \\ & + \alpha_{14} T_l xCW + \alpha_{15} T_q xCW + \alpha_{16} CLxCW \\ & + \alpha_{17} BxCL + \alpha_{18} BxCW + \alpha_{19} SxCL + \alpha_{20} SxCW + \varepsilon \end{aligned} \qquad (4)$$

where the α terms are the coefficients corresponding to the effects, $T_l$ is linear thickness, $T_q$ is quadratic thickness, *B* and *S* are the coded values of butts and skew, *E* is the whole-plot error, *CL* and *CW* are the coded length and width (within thickness) and ε is the sub-plot error. The error assumptions were the same as for model (1). For the tensile and flexural failure stress, the initial modulus was also included in the statistical models.

The whole-plot coefficients of variation are presented, together with the sub-plot values, in Table 10. An analysis of the residuals showed evidence of non-constant variance. Statistically, this point required further investigation, in particular whether a transformation of the data would rectify the situation. The procedure is comprehensively discussed by Box et al. [11], and essentially consists of applying a mathematical transformation to the data before statistical analyses are carried out. The statistical analysis of the suitably transformed data, however, produced almost identical results to those obtained using the raw data. As such a transformation had no physical justification, the results for the raw data are presented. However, it should be borne in mind that the *p* values presented are hence approximations.

| | **Whole-Plot C.V. (%)** | **Sub-Plot C.V. (%)** |
|---|---|---|
| Tensile Stress | 12.5 | 9.5 |
| Tensile Stress with Modulus | 12 | 9.5 |
| Tensile Strain | 10 | 9 |
| Flexural Stress | 20.5 | 12 |
| Flexural Stress with Modulus | 20 | 11 |
| Flexural Strain | 11 | 12.5 |

Table 10. Whole-plot and sub-plot coefficient of variation comparisons

These *p* values, shown in Table 11, are now used to highlight the important main effects and interactions. The important values are underlined. The trends may be seen in the appropriate main effects and interaction plots in Figures 12 to 19.

| | **Tensile** | | | **Flexural** | | |
|---|---|---|---|---|---|---|
| **Source** | **Stress** | **Stress** (With Mod.) | **Strain** | **Stress** | **Stress** (With Mod.) | **Strain** |
| **Whole-Plot:** | | | | | | |
| Thick | | | | | | |
| Linear | 0.277 | 0.289 | 0.024 | 0.607 | 0.107 | 0.014 |
| Quadratic | 0.066 | 0.291 | 0.770 | 0.467 | 0.751 | 0.267 |
| Butts | 0.006 | 0.018 | 0.076 | 0.517 | 0.303 | 0.188 |
| Skew | 0.003 | 0.017 | 0.077 | 0.036 | 0.456 | 0.166 |
| Thick*Butts | | | | | | |
| Linear | 0.902 | 0.560 | 0.210 | 0.994 | 0.609 | 0.794 |
| Quadratic | 0.006 | 0.013 | 0.201 | 0.511 | 0.767 | 0.892 |
| Thick*Skew | | | | | | |
| Linear | 0.777 | 0.896 | 0.139 | 0.829 | 0.716 | 0.974 |
| Quadratic | 0.008 | 0.019 | 0.051 | 0.242 | 0.282 | 0.213 |
| Butts*Skew | 0.045 | 0.048 | 0.288 | 0.133 | 0.277 | 0.376 |
| **Sub-Plot:** | | | | | | |
| Clength | 0.764 | 0.698 | 0.108 | 0.056 | 0.399 | 0.586 |
| Thick*Clength | | | | | | |
| Linear | 0.352 | 0.876 | 0.247 | ~ | ~ | ~ |
| Quadratic | 0.150 | 0.724 | 0.273 | ~ | ~ | ~ |
| Cwidth | 0.004 | 0.005 | 0.721 | 0.398 | 0.922 | 0.426 |
| Thick*Cwidth | | | | | | |
| Linear | 0.005 | 0.001 | 0.366 | ~ | ~ | ~ |
| Quadratic | 0.305 | 0.218 | 0.741 | ~ | ~ | ~ |
| Clength*Cwidth | 0.442 | 0.262 | 0.016 | 0.668 | 0.526 | 0.999 |
| Butts*Clength | 0.148 | 0.282 | 0.541 | 0.698 | 0.645 | 0.089 |
| Butts*Cwidth | 0.101 | 0.070 | 0.003 | 0.202 | 0.022 | 0.471 |
| Skew*Clength | 0.771 | 0.916 | 0.000 | 0.121 | 0.231 | 0.124 |
| Skew*Cwidth | 0.000 | 0.000 | 0.044 | 0.031 | 0.434 | 0.277 |
| **Covariates:** | | | | | | |
| Initial Modulus | ~ | 0.0307 | ~ | ~ | 0.000 | ~ |
| **R-Square (%):** | 95 | 95 | 71 | 72 | 72 | 58 |

Table 11. Summary of *p*-values for final W.R. tests

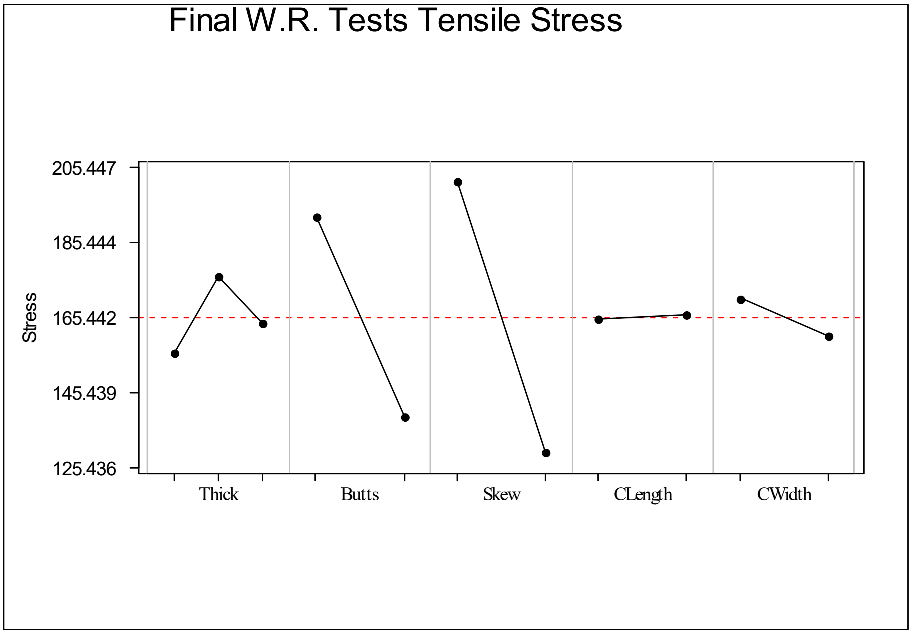

Fig. 12. Tensile stress (MPa) main effects plots.

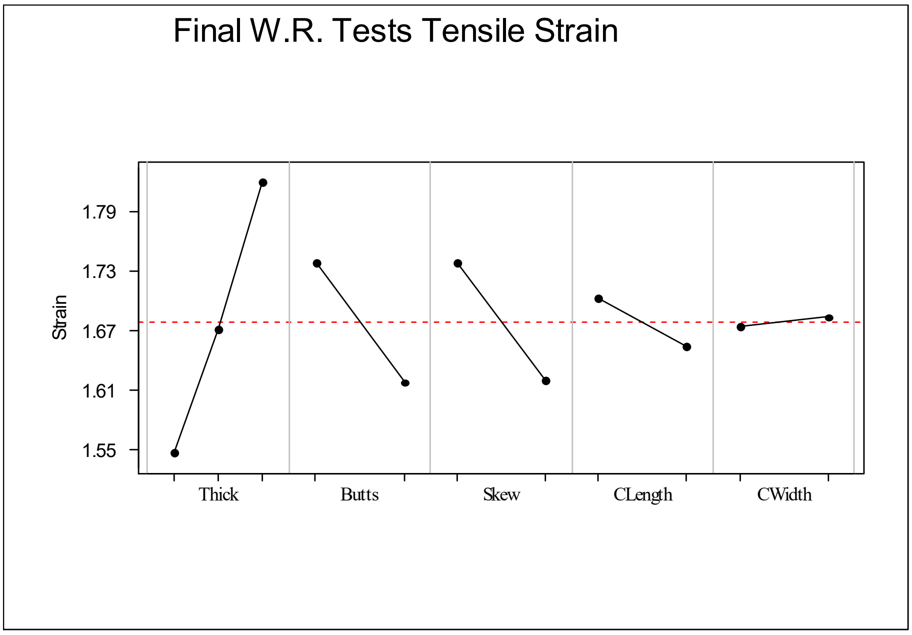

Fig. 13. Tensile strain (%) main effects plots.

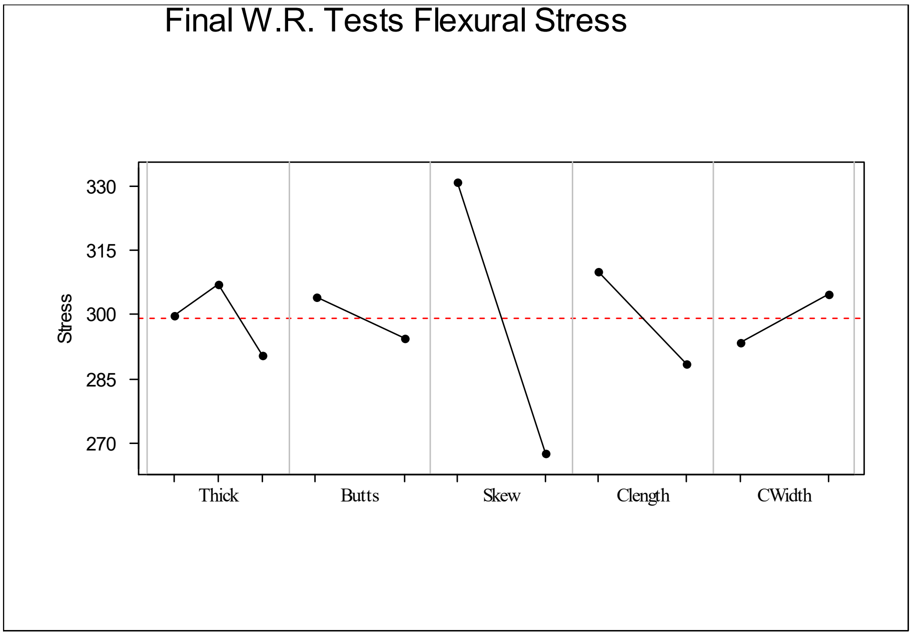

Fig. 14. Flexural stress (MPa) main effects plots.

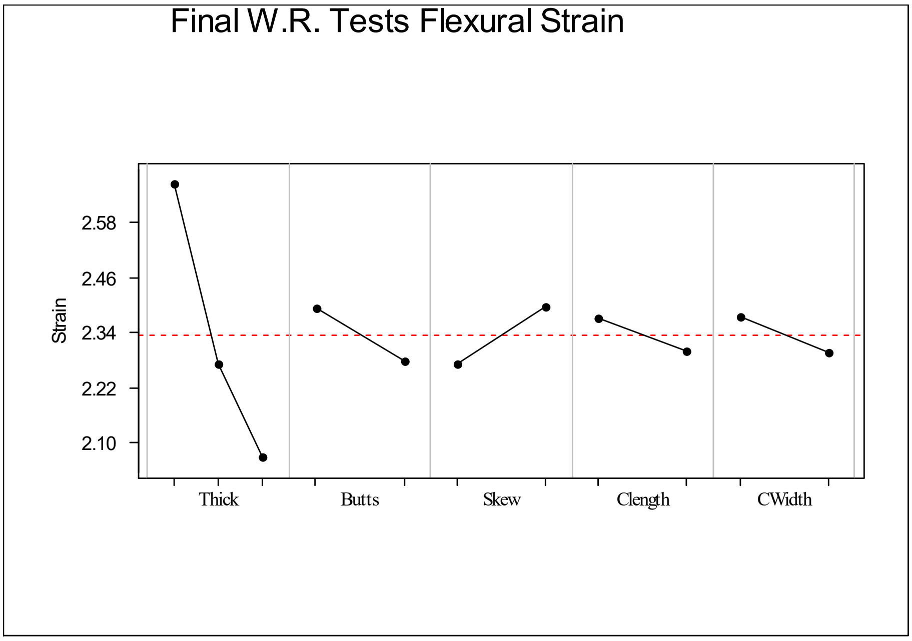

Fig. 15. Flexural strain (%) main effects plots.

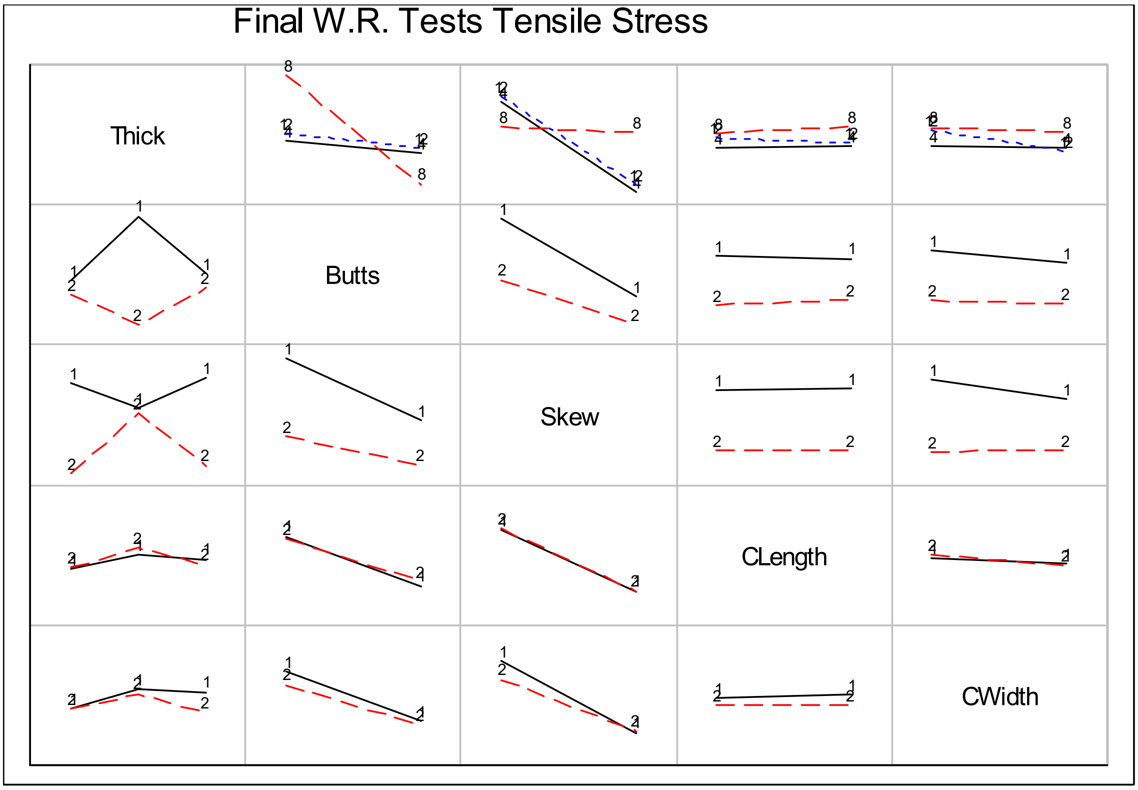

Fig. 16. Tensile stress interactions plots.

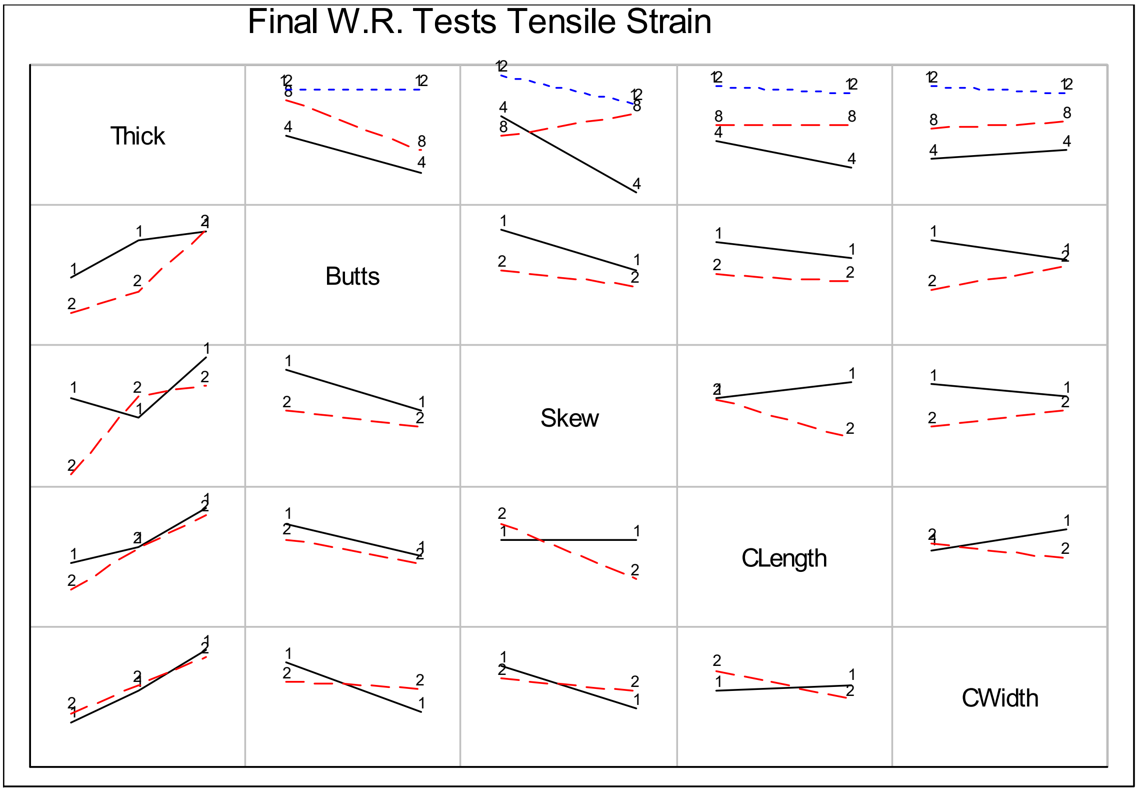

Fig. 17. Tensile strain interactions plots.

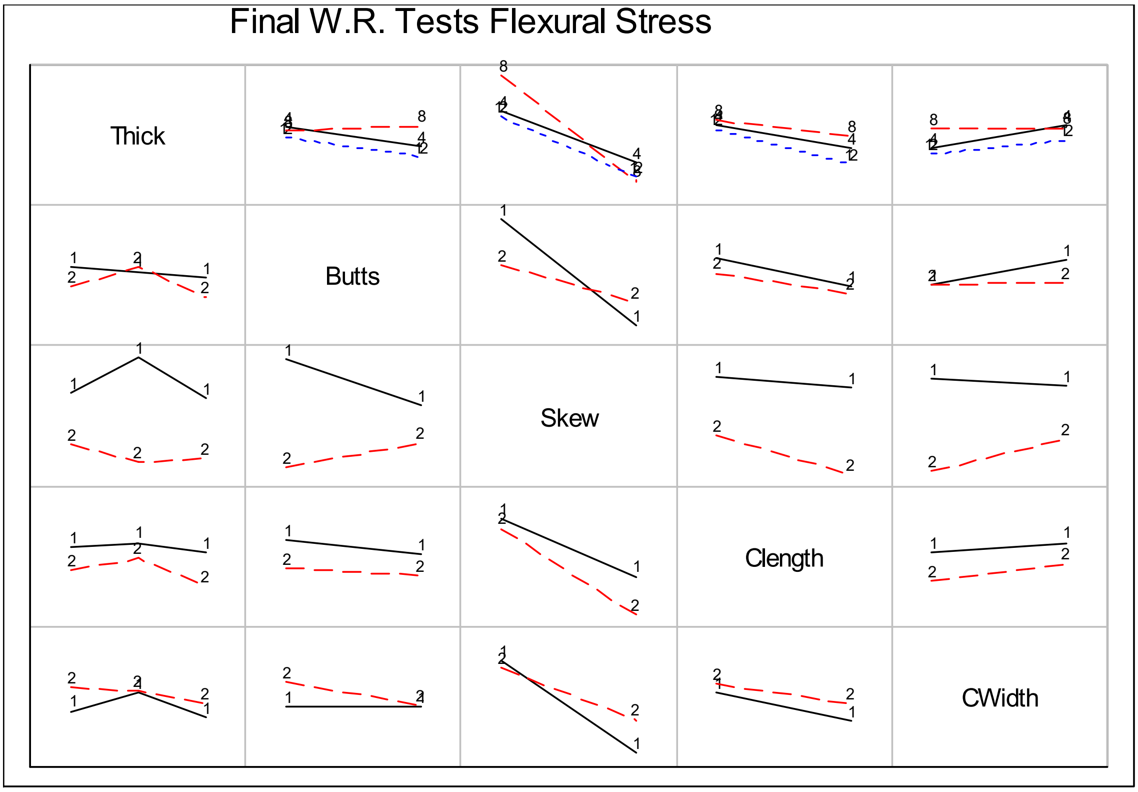

Fig. 18. Flexural stress interactions plots.

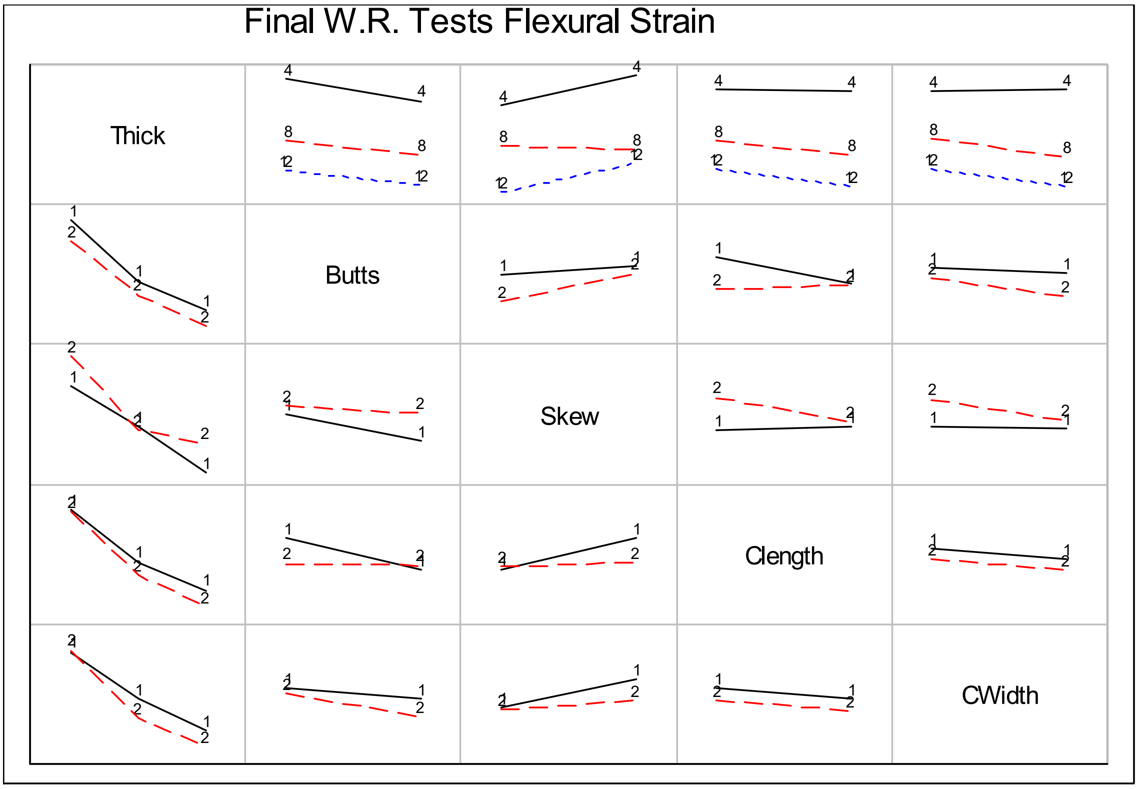

Fig. 19. Flexural strain interactions plots.

### 3.5. Discussion

The high $R^2$ value of 95% obtained for the tensile failure stress analysis shows that the model proposed accounts for most of the experimental variation. It also indicates that the ultimate tensile stress is a pertinent measurement of the tensile strength of these woven-roving composites. The $R^2$ value for the ultimate tensile strains (71%) suggests that the use of an extensometer provides a reasonable measure of this material property.

The flexural failure stress values were obtained indirectly by a calculation involving the failure load and test dimensions, Eq. (2). Also, an approximation was made to allow for the central deflections of the specimens seen, Eq. (3)). These procedures introduce errors into the stress values. This accounts for the fact that the fit of the model to the flexural stress values is lower than that for the tensile tests, although at 72% this is still reasonable.

The fit to the flexural failure strain data, collected using 10 mm long foil type strain gauges, is not good. This is because localised strain variations in the coupon may affect the readings due to the positioning of the gauges with respect to the relatively coarse weave. This is exacerbated by the presence of butts. Also, for the skewed specimens, the strain gauges were not aligned with the warp.

The whole-plot coefficients of variation show that the experimental error variation between panels Is important, especially for the flexural tests. This indicates that variability in the manufacture of the specimens is influential. The compressive failure of the flexural specimens would be more sensitive to such variability.

The significance of the modulus covariate for the failure stresses shows that this material property may give an indication of the quality of the laminate. For the flexural tests, effects concerning skew become much less significant when initial modulus is included in the statistical model. This is because the skewing of the warp directly affects the stiffness of the specimen.

The statistically significant whole-plot main and interaction effects are now considered. The strength of the tensile test specimens is lowered for both stress and strain by the skewing of the warp. This is due to the observed change in failure mode from fibre-dominated tensile failure to one of matrix and fibre-matrix interface dominated shear failure.

The thicker tensile specimens have a higher strain to failure, and Fig. 17 shows this to be mainly due to the behaviour of the skewed specimens. The shear failure of the skewed tensile coupons is possibly more damage tolerant for thicker specimens.

The lower tensile failure stress and strain for the coupons containing butts is due to the discontinuity of a quarter of the reinforcing plies. The interaction between the butt and skew factors for both tensile failure measurements shows that the effects of these two factors are not additive, the weakest failure mode is due to the skew and is the dominant of the two. The indication, from Fig. 17, that the reduction in the tensile failure strain with the inclusion of butts is greatest for eight-ply specimens (and not the 4- or 12-ply specimens) suggests that this interaction effect between thickness and butts is not directly related to the thickness, per se. It is more probable that the butts in the eight-ply panels were of a lower quality than those in the four- or 12-ply equivalents. Similarly, the interaction between thickness and skew for both failure criteria is thought to be due to a lower skew angle in the eight-ply specimens.

The reduction of flexural failure stress with the skewing of the warp is also due to the change to a mixed failure mode including shear as well as compressive failure. The flexural failure strain is lower for a thicker laminate. A plausible reason for this would be that, when there are more wet, and hence unstable, plies, the fibres of the top lamina are more difficult to keep straight as they are wetted-out.

The dominant sub-plot main effects and interactions are now considered. The effect of width on the tensile failure stress is mainly due to a reduction in strength with increasing width for the 12-ply specimens only. The width of the wider 12-ply coupons is close to that of the jaws, and hence the possibility of the edge of the jaws affecting the failure is greatest here.

For both tensile failure stress and strain, the weakening effect of skew is greatest for the narrow specimens. For a given angle of skew, the narrower a coupon, the greater number of warp fibres which will traverse the whole coupon, hence leading to a reduction in strength. Similarly, the longer a coupon, the greater number of warp fibres which will traverse the width of the coupon, leading to a reduction in strength and explaining the similar interaction of skew with length. Similarly, there will be a small number of shear failure planes in the wide, short specimens compared to the other three plan shapes, leading to a greater effect of length for the wider coupons.

The effect of the presence of butts on the tensile failure strain is greater for the narrower specimens. The stress concentrations at the edges of the butt would affect a greater proportion of the coupon width for the narrow specimens. This trend is also weakly significant for the tensile failure stress.

The weak effect of length on the flexural failure stress could be a purely chance occurrence. Alternatively, for the skewed specimens, the longer specimens would have more warp fibres crossing the width of the specimen, thus reducing the strength. Similarly the flexural stress interaction between skew and width can be explained as described above for the tensile specimens.

The strengthening effect on the flexural failure stress of an increase in width seen for the specimens with no butts is removed by the inclusion of such joins. This could be because the butts provide an initiation site for compressive delamination that is independent of the coupon width.

## 4. General discussion

Previous work in the field of composites size effects has either made no statistical inferences about any apparent size effects, or has made simple statistical tests assuming the experimental variance to be constant throughout the experiment. Here the experimental error has been split into two pertinent parts, that due to the variation between the properties of separate panels (the whole-plot variation), and that due to the variation between coupons cut from the same panel (the sub-plot variation). For all three test series the variation between panel properties is seen to be important, and is generally greater than that within a panel. The implications of this are that the laminate properties are sensitive to variations at the fabrication stage, and hence that size effects due to the scale of production are important.

If this large panel-to-panel variation is not recognised, then the design of the experiment will not take this into account. Hence the effects of the factors which change between panels will be inseparable from this variation. This may lead to overestimation of these effects, and false trends.

The trends seen are not always consistent between the tensile and flexural test methods used. This is because the different failure modes present in each method make direct comparisons meaningless. Even considering the same test method, different configurations, in this case flexural roller diameter, have lead to different material behaviour. Similarly, varying behaviour was seen for the different materials considered, even between the three nominally identical woven roving laminates as considered in the W.R. manufacturer tests. Extending this, different results are seen depending on the failure criteria considered (stress or strain in this case) and on the method of its measurement. Hence it is not sufficient to describe a composites size effect or many other effects in such a generic manner; the behaviour may well depend upon the specific material, methods and failure criteria used. By far the best indication of the tensile failure of the W.R. laminates was given by the stress calculated from the failure load and coupon cross-sectional area. The equivalent flexural stress measurements were also the best option for these tests, although the less direct calculations and the central deflection approximation reduce the accuracy of this failure measurement.

One of the reasons for the greater variability of the strength of the W.R. reinforced materials considered, compared to those considered in the bulk of the literature, is that the production methods and the nature of the materials lead to laminates of more variable quality. By this it is meant that defects such as air bubbles (voids), misalignment of the fibres (waviness and skew) are more prevalent in such laminates and, since they are not easily controlled, lead to greater variation in the material properties. These variables are often reflected in variations in the stiffness of the material, and the consideration of the initial modulus for the stress measurements, especially for the tensile tests, reduced such variation and improved the description of the data. Similarly, the consideration of the fibre volume fraction of the coupons also improved the description of the data, but only for the flexural W.R. manufacturer tests. These points again show the importance of keeping the fabrication methods at the test scale as similar to those at the ship scale as possible.

The skew and butts factors considered in the final W.R. tests were designed to reproduce more macroscopic defects introduced in the laminating of an actual ship. These were found to be important, but the behaviour at the coupon scale was found to be dependent on other factors including the length and width of the specimen. This indicates that the influence of such features may be different at the coupon and ship scales, although the accuracy of such an extrapolation is obviously limited by the range of coupon sizes considered in this study. The strength variability of the laminates is also seen to be dependent on these factors.

Narrower specimens have been found to be influenced by the cutting of the fibre rovings at the edges. This is thought to be exacerbated by the skew or waviness of these rovings. This means that a suitable lower limit to the coupon will depend on both the width of the rovings and their alignment. It also means that whilst this may be important at the coupon scale, for a ship with few such edges it may not. This is another effect of the scale of the material considered.

One explanation offered for the effect of thickness is that thicker specimens are harder to lay-up by hand and hence are weaker. This is thought to be the main reason for the effect seen for the W.R. materials considered, since no corresponding effect of length or width is seen. This also corresponds to a size effect, but in the sense of scale of production.

## 5. Conclusions

For the shipbuilding-grade, woven roving reinforced marine composites studied here, the effects of factors related to manufacturing were found to be important. These effects include variations between the properties of nominally identical panels, the use of nominally identical woven rovings from different manufacturers, warp-weft distortions and the inclusion of butts in the reinforcement layers. These effects were often seen to depend on other factors, including the size of the test coupon. In terms of an influence of scale, this shows that discrepancies between coupon and ship scale material properties are influenced by the effects of the scale of production, and hence that the manufacturing processes used for the coupons should be as close to those used at the ship scale. The size effects reported for the mainly aerospace grade composites of the literature were not observed for the W.R. composites studied here. The unidirectional tests also showed that the variability in the marine composite properties was greater than that in the carefully prepared unidirectional composites often studied in the literature. In terms of an effect of scale this shows that the manufacturing processes used for the coupon should not only be as close to, but should also be as variable as, those used at the ship scale. For the woven roving E-glass/polyester composite materials considered here the scale effect is of far more concern than is the size effect.

## Acknowledgements

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# Appendix A. Woven roving manufacturer test data

The specimen codes begin with the woven roving identity (e.g. AUS8), then ‘T’ for tensile or ‘F’ for flexural. The length and width levels are then identified by a letter and a number, respectively, and finally the number of plies is given.

Tensile results

| **Specimen Code** | **Length (mm)** | **Width (mm)** | **Depth (mm)** | **Fibre Volume Fract.n** | **Initial Mod. (GPa)** | **Deflect.n at Failure (mm)** | **Failure Stress (MPa)** | **Failure Strain (%)** |
|---|---|---|---|---|---|---|---|---|
| AUS8TA1/4 | 50 | 10.04 | 3.27 | 0.40 | 19.5 | 4.2 | 291 | 1.840 |
| AUS8TC1/4 | 150 | 9.89 | 3.35 | 0.38 | 17.5 | 5.7 | 272 | 1.775 |
| AUS8TA3/4 | 50 | 25.00 | 3.83 | 0.34 | 16.6 | 5.6 | 232 | 1.675 |
| AUS8TC3/4 | 150 | 24.90 | 3.43 | 0.39 | 18.1 | 7.4 | 287 | 1.913 |
| AUS12TA1/4 | 50 | 9.99 | 3.06 | 0.42 | 20.7 | 3.3 | 294 | 1.650 |
| AUS12TC1/4 | 150 | 9.85 | 3.22 | 0.41 | 18.8 | 5.4 | 307 | 1.740 |
| AUS12TA3/4 | 50 | 25.03 | 3.16 | 0.42 | 22.5 | 4.7 | 296 | 1.490 |
| AUS12TC3/4 | 150 | 25.18 | 3.21 | 0.38 | 16.7 | 6.4 | 277 | 1.800 |
| AUS11TB2/4 | 100 | 17.41 | 3.47 | 0.39 | 18.6 | 4.8 | 247 | 1.775 |
| AUS11TA2/4 | 50 | 17.35 | 3.28 | 0.40 | 17.5 | 4.4 | 285 | 2.150 |
| AUS11TC2/4 | 150 | 17.43 | 3.29 | 0.40 | 19.1 | 6.2 | 279 | 1.830 |
| AUS11TB1/4 | 100 | 9.84 | 3.38 | 0.40 | 17.4 | 4.1 | 238 | 2.025 |
| AUS11TB3/4 | 100 | 25.00 | 3.37 | 0.39 | 16.9 | 5.9 | 273 | 1.790 |
| AUS8TB2/4 | 100 | 17.49 | 3.36 | 0.41 | 17.2 | 4.9 | 283 | 1.975 |
| AUS12TB2/4 | 100 | 17.42 | 3.1 | 0.39 | 24.0 | 5.1 | 320 | 1.750 |
| AUS8TA1/8 | 50 | 10.00 | 6.22 | 0.41 | 20.1 | 5.1 | 293 | 1.625 |
| AUS8TC1/8 | 150 | 9.82 | 6.23 | 0.41 | 18.8 | 6.9 | 289 | 1.975 |
| AUS8TA3/8 | 50 | 25.46 | 6.31 | 0.38 | 20.2 | 7.0 | 269 | 1.700 |
| AUS8TC3/8 | 150 | 25.56 | 6.44 | 0.41 | 20.7 | 7.8 | 267 | 1.650 |
| AUS12TA1/8 | 50 | 9.93 | 6.19 | 0.42 | 21.3 | 5.1 | 305 | 2.000 |
| AUS12TC1/8 | 150 | 10.03 | 6.29 | 0.41 | 20.8 | 6.2 | 293 | 1.750 |
| AUS12TA3/8 | 50 | 25.02 | 6.27 | 0.42 | 20.7 | 6.8 | 290 | 1.700 |
| AUS12TC3/8 | 150 | 25.00 | 7.20 | 0.39 | 17.6 | 8.2 | 229 | 1.650 |
| AUS11TB2/8 | 100 | 17.48 | 7.03 | 0.36 | 15.3 | 5.8 | 218 | 1.825 |
| AUS11TA2/8 | 50 | 17.56 | 7.08 | 0.35 | 18.6 | 6.0 | 237 | 1.725 |
| AUS11TC2/8 | 150 | 17.52 | 7.26 | 0.36 | 17.2 | 7.8 | 224 | 1.600 |
| AUS11TB1/8 | 100 | 9.66 | 7.00 | 0.36 | 20.3 | 4.9 | 211 | 1.700 |
| AUS11TB3/8 | 100 | 24.96 | 6.99 | 0.36 | 16.3 | 7.7 | 238 | 2.025 |
| AUS8TB2/8 | 100 | 17.50 | 6.46 | 0.41 | 20.3 | 6.4 | 254 | 1.575 |
| AUS12TB2/8 | 100 | 17.47 | 6.29 | 0.41 | 20.7 | 6.7 | 289 | 1.775 |

Flexural results

| Specimen Code | Length (mm) | Width (mm) | Depth (mm) | Fibre Volume Fract.n | Initial Mod. (GPa) | Deflect.n at Fail (mm) | Failure Stress (MPa) | Failure Strain (%) |
|---|---|---|---|---|---|---|---|---|
| AUS8FA1/4 | 50 | 10.07 | 3.47 | 0.40 | 16.7 | 3.0 | 346 | 2.200 |
| AUS8FC1/4 | 100 | 10.12 | 3.28 | 0.38 | 18.0 | 16.2 | 369 | 2.275 |
| AUS8FA3/4 | 50 | 29.76 | 3.39 | 0.40 | 16.1 | 4.3 | 476 | 2.650 |
| AUS8FC3/4 | 100 | 29.91 | 3.54 | 0.38 | 14.9 | 14.3 | 323 | 2.400 |
| AUS12FA1/4 | 50 | 10.03 | 3.13 | 0.40 | 21.8 | 3.7 | 495 | 2.225 |
| AUS12FC1/4 | 100 | 10.05 | 3.19 | 0.38 | 21.1 | 14.5 | 365 | 2.425 |
| AUS12FA3/4 | 50 | 29.96 | 3.31 | 0.38 | 18.3 | 3.7 | 408 | 2.225 |
| AUS12FC3/4 | 100 | 30.05 | 3.09 | 0.42 | 18.7 | 15.6 | 422 | 2.525 |
| AUS11FB2/4 | 75 | 19.95 | 3.35 | 0.40 | 17.2 | 8.5 | 378 | 2.550 |
| AUS11FA2/4 | 50 | 20.01 | 3.50 | 0.40 | 15.5 | 3.2 | 367 | 2.650 |
| AUS11FC2/4 | 100 | 20.04 | 3.38 | 0.40 | 17.5 | 16.7 | 358 | 2.500 |
| AUS11FB1/4 | 75 | 10.00 | 3.36 | 0.41 | 15.4 | 6.1 | 267 | 1.825 |
| AUS11FB3/4 | 75 | 29.92 | 3.37 | 0.40 | 14.9 | 6.5 | 323 | 2.275 |
| AUS8FB2/4 | 75 | 20.09 | 3.46 | 0.37 | 15.3 | 8.6 | 390 | 2.875 |
| AUS12FB2/4 | 75 | 20.07 | 3.17 | 0.40 | 16.8 | 9.7 | 437 | 2.725 |
| AUS8FA1/8 | 100 | 20.02 | 6.27 | 0.41 | 20.1 | 8.0 | 433 | 2.550 |
| AUS8FC1/8 | 200 | 20.11 | 6.16 | 0.41 | 21.0 | 21.2 | 300 | 1.563 |
| AUS8FA3/8 | 100 | 59.75 | 6.58 | 0.40 | 18.8 | 6.6 | 331 | 2.000 |
| AUS8FC3/8 | 200 | 59.99 | 6.24 | 0.40 | 19.0 | 23.0 | 320 | 1.850 |
| AUS12FA1/8 | 100 | 20.06 | 6.29 | 0.43 | 19.5 | 7.4 | 422 | 2.525 |
| AUS12FC1/8 | 200 | 19.41 | 6.39 | 0.41 | 21.0 | 22.0 | 328 | 1.750 |
| AUS12FA3/8 | 100 | 60.03 | 6.25 | 0.41 | 21.1 | 6.0 | 351 | 1.800 |
| AUS12FC3/8 | 200 | 59.91 | 6.50 | 0.41 | 19.9 | 21.0 | 309 | 1.650 |
| AUS11FB2/8 | 150 | 39.96 | 6.89 | 0.37 | 17.5 | 9.6 | 247 | 1.575 |
| AUS11FA2/8 | 100 | 39.92 | 7.04 | 0.37 | 17.7 | 4.0 | 218 | 1.275 |
| AUS11FC2/8 | 200 | 39.96 | 7.07 | 0.36 | 16.9 | 21.8 | 294 | 2.050 |
| AUS11FB1/8 | 150 | 19.89 | 6.90 | 0.36 | 15.1 | 11.4 | 284 | 2.000 |
| AUS11FB3/8 | 150 | 60.02 | 6.87 | 0.37 | 17.5 | 11.2 | 287 | 1.725 |
| AUS8FB2/8 | 150 | 40.03 | 6.33 | 0.40 | 19.0 | 13.8 | 376 | 2.150 |
| AUS12FB2/8 | 150 | 39.88 | 6.44 | 0.42 | 22.7 | 10.8 | 305 | 1.600 |

## Appendix B. Fabrication factors test data

The specimen codes begin with the panel identity (see Table 7), then 1 for low length and width, 2 for low length and high width, 3 for high length and low width and 4 for high length and width. A letter then indicates which replication the specimen is.

Tensile tests

| **Specimen Code** | **Length (mm)** | **Width (mm)** | **Depth (mm)** | **Fibre Volume Fract.n** | **Initial Mod. (GPa)** | **Deflect.n at Fail (mm)** | **Failure Stress (MPa)** | **Failure Strain (%)** |
|---|---|---|---|---|---|---|---|---|
| VT/41/1A | 100 | 10.28 | 3.88 | 0.33 | 14.8 | 4.3 | 213 | 1.810 |
| VT/41/1B | 100 | 9.79 | 4.00 | 0.34 | 15.5 | 4.9 | 243 | 1.932 |
| VT/41/2A | 100 | 25.01 | 3.88 | 0.34 | 15.0 | 5.6 | 219 | 1.656 |
| VT/41/2B | 100 | 24.42 | 4.19 | 0.33 | 14.6 | 5.6 | 215 | 1.733 |
| VT/41/3A | 300 | 9.77 | 3.96 | 0.33 | 16.5 | 8.1 | 249 | 1.902 |
| VT/41/3B | 300 | 9.34 | 4.04 | 0.36 | 15.2 | 8.8 | 240 | 1.948 |
| VT/41/4A | 300 | 25.07 | 4.18 | 0.36 | 15.3 | 8.9 | 218 | 1.672 |
| VT/41/4B | 300 | 25.36 | 4.22 | 0.32 | 15.1 | 8.8 | 216 | 1.718 |
| VT/42/1A | 100 | 10.31 | 3.80 | 0.36 | 15.5 | 3.6 | 199 | 1.687 |
| VT/42/1B | 100 | 10.30 | 3.91 | 0.36 | 15.2 | 3.6 | 181 | 1.472 |
| VT/42/2A | 100 | 25.16 | 3.92 | 0.35 | 15.2 | 4.9 | 191 | 1.580 |
| VT/42/2B | 100 | 25.29 | 3.74 | 0.36 | 16.6 | 4.8 | 188 | 1.472 |
| VT/42/3A | 300 | 10.55 | 3.79 | 0.36 | 16.2 | 6.3 | 188 | 1.472 |
| VT/42/3B | 300 | 10.33 | 3.80 | 0.38 | 15.4 | 5.6 | 178 | 1.656 |
| VT/42/4A | 300 | 25.03 | 3.82 | 0.38 | 15.9 | 8.6 | 214 | 1.840 |
| VT/42/4B | 300 | 25.33 | 4.01 | 0.36 | 15.7 | 8.6 | 203 | 1.810 |
| VT/43/1A | 100 | 10.06 | 4.32 | 0.31 | 12.0 | 2.7 | 100 | 1.381 |
| VT/43/1B | 100 | 10.19 | 4.36 | 0.33 | 12.4 | 2.7 | 98 | 1.319 |
| VT/43/2A | 100 | 24.87 | 4.43 | 0.31 | 11.7 | 4.0 | 101 | 1.764 |
| VT/43/2B | 100 | 24.51 | 4.37 | 0.34 | 11.3 | 4.2 | 101 | 1.595 |
| VT/43/3A | 300 | 10.10 | 4.29 | 0.31 | 12.7 | 5.4 | 103 | 1.350 |
| VT/43/3B | 300 | 10.31 | 4.24 | 0.32 | 12.3 | 4.8 | 102 | 1.411 |
| VT/43/4A | 300 | 24.77 | 4.41 | 0.33 | 12.6 | 6.6 | 102 | 1.411 |
| VT/43/4B | 300 | 24.77 | 4.44 | 0.32 | 12.8 | 6.3 | 102 | 1.350 |
| VT/44/1A | 100 | 9.88 | 4.16 | 0.35 | 12.7 | 2.9 | 108 | 1.411 |
| VT/44/1B | 100 | 10.02 | 4.38 | 0.36 | 12.2 | 3.1 | 106 | 1.626 |
| VT/44/2A | 100 | 24.90 | 4.17 | 0.34 | 12.5 | 4.2 | 115 | 1.549 |
| VT/44/2B | 100 | 25.03 | 4.35 | 0.32 | 9.7 | 4.5 | 110 | 1.672 |
| VT/44/3A | 300 | 10.09 | 4.15 | 0.35 | 11.9 | 3.8 | 91 | 0.890 |
| VT/44/3B | 300 | 10.32 | 4.04 | 0.36 | 13.6 | 4.8 | 104 | 1.166 |
| VT/44/4A | 300 | 25.02 | 4.33 | 0.35 | 12.5 | 6.0 | 99 | 1.074 |
| VT/44/4B | 300 | 4.19 | 24.91 | 0.36 | 11.8 | 5.8 | 101 | 1.135 |
| VT/81/1A | 100 | 10.00 | 7.27 | 0.36 | 16.5 | 5.8 | 249 | 1.779 |
| VT/81/1B | 100 | 10.27 | 7.25 | 0.34 | 16.7 | 6.0 | 254 | 1.810 |
| VT/81/2A | 100 | 24.77 | 7.36 | 0.36 | 16.7 | 8.1 | 256 | 1.794 |
| VT/81/2B | 100 | 25.50 | 7.32 | 0.35 | 16.1 | 8.1 | 255 | 1.856 |
| VT/81/3A | 300 | 10.82 | 6.97 | 0.33 | 17.2 | 10.6 | 267 | 1.902 |
| VT/81/3B | 300 | 10.46 | 6.85 | 0.35 | 17.9 | 10.3 | 281 | 1.886 |
| VT/81/4A | 300 | 25.44 | 7.02 | 0.35 | 17.8 | 10.1 | 244 | 1.610 |
| VT/81/4B | 300 | 25.76 | 6.97 | 0.32 | 17.9 | 11.5 | 257 | 1.702 |
| VT/82/1A | 100 | 10.33 | 7.72 | 0.37 | 14.2 | 3.3 | 98 | 1.195 |
| VT/82/1B | 100 | 10.54 | 7.87 | 0.38 | 13.3 | 3.8 | 93 | 1.166 |
| VT/82/2A | 100 | 24.77 | 7.93 | 0.38 | 10.4 | 4.8 | 104 | 1.595 |
| VT/82/2B | 100 | 24.94 | 7.76 | 0.38 | 13.9 | 4.6 | 103 | 1.595 |

| **Specimen Code** | **Length (mm)** | **Width (mm)** | **Depth (mm)** | **Fibre Volume Fract.n** | **Initial Mod. (GPa)** | **Deflect.n at Fail (mm)** | **Failure Stress (MPa)** | **Failure Strain (%)** |
|---|---|---|---|---|---|---|---|---|
| VT/82/3A | 300 | 10.18 | 7.44 | 0.38 | 14.7 | 5.4 | 103 | 1.472 |
| VT/82/3B | 300 | 10.05 | 7.40 | 0.37 | 14.6 | 5.8 | 109 | 1.564 |
| VT/82/4A | 300 | 24.96 | 7.64 | 0.37 | 13.8 | 7.0 | 101 | 1.442 |
| VT/82/4B | 300 | 25.19 | 7.50 | 0.38 | 15.1 | 7.2 | 106 | 1.626 |
| VT/83/1A | 100 | 10.28 | 7.60 | 0.34 | 15.1 | 5.2 | 211 | 1.748 |
| VT/83/1B | 100 | 10.37 | 7.40 | 0.35 | 16.6 | 5.5 | 238 | 1.779 |
| VT/83/2A | 100 | 25.25 | 7.53 | 0.35 | 15.5 | 5.6 | 214 | 1.718 |
| VT/83/2B | 100 | 24.99 | 8.03 | 0.35 | 14.9 | 6.7 | 209 | 1.687 |
| VT/83/3A | 300 | 10.52 | 6.61 | 0.35 | 17.8 | 9.4 | 252 | 2.086 |
| VT/83/3B | 300 | 10.72 | 6.65 | 0.34 | 16.2 | 9.4 | 241 | 1.932 |
| VT/83/4A | 300 | 25.44 | 7.09 | 0.35 | 16.9 | 9.6 | 216 | 1.595 |
| VT/83/4B | 300 | 25.60 | 7.25 | 0.35 | 16.6 | 9.8 | 207 | 1.564 |
| VT/84/1A | 100 | 10.21 | 7.71 | 0.36 | 12.9 | 3.8 | 107 | 1.534 |
| VT/84/1B | 100 | 10.18 | 7.47 | 0.37 | 13.7 | 4.0 | 122 | 1.595 |
| VT/84/2A | 100 | 24.66 | 7.86 | 0.36 | 12.7 | 6.0 | 124 | 1.902 |
| VT/84/2B | 100 | 24.76 | 7.88 | 0.37 | 13.9 | 5.6 | 124 | 1.994 |
| VT/84/3A | 300 | 10.27 | 7.38 | 0.36 | 12.7 | 6.2 | 117 | 1.595 |
| VT/84/3B | 300 | 10.24 | 7.35 | 0.38 | 15.3 | 5.4 | 125 | 1.488 |
| VT/84/4A | 300 | 24.66 | 7.55 | 0.38 | 14.6 | 8.5 | 134 | 1.748 |
| VT/84/4B | 300 | 24.80 | 7.45 | 0.35 | 14.7 | 8.5 | 129 | 1.503 |
| VT/121/1A | 100 | 10.60 | 10.10 | 0.37 | 16.7 | 9.5 | 283 | 1.948 |
| VT/121/1B | 100 | 10.36 | 10.16 | 0.37 | 16.1 | 6.9 | 260 | 1.871 |
| VT/121/2A | 100 | 25.45 | 10.13 | 0.36 | 17.0 | 7.2 | 222 | 1.932 |
| VT/121/2B | 100 | 25.59 | 10.07 | 0.37 | 17.0 | 9.6 | 236 | 2.024 |
| VT/121/3A | 300 | 10.47 | 11.21 | 0.36 | 14.3 | 12.6 | 256 | 2.147 |
| VT/121/3B | 300 | 10.46 | 11.04 | 0.37 | 16.0 | 11.1 | 224 | 1.748 |
| VT/121/4A | 300 | 25.42 | 11.28 | 0.37 | 15.8 | 11.2 | 176 | 1.656 |
| VT/121/4B | 300 | 25.49 | 11.17 | 0.37 | 15.4 | 13.4 | 188 | 1.748 |
| VT/122/1A | 100 | 10.34 | 11.70 | 0.34 | 13.7 | 9.6 | 258 | 1.871 |
| VT/122/1B | 100 | 10.76 | 11.79 | 0.35 | 13.4 | 9.6 | 197 | 1.902 |
| VT/122/2A | 100 | 25.59 | 11.62 | 0.33 | 14.0 | 11.0 | 145 | 1.472 |
| VT/122/2B | 100 | 25.33 | 11.90 | 0.34 | 13.9 | 12.7 | 157 | 1.748 |
| VT/122/3A | 300 | 10.55 | 11.21 | 0.34 | 14.5 | 11.1 | 228 | 2.086 |
| VT/122/3B | 300 | 10.33 | 10.93 | 0.33 | 14.7 | 14.8 | 262 | 2.116 |
| VT/122/4A | 300 | 25.55 | 11.36 | 0.34 | 14.9 | 14.0 | 174 | 1.871 |
| VT/122/4B | 300 | 25.46 | 11.54 | 0.34 | 14.5 | 15.1 | 187 | 1.963 |
| VT/123/1A | 100 | 10.37 | 10.17 | 0.34 | 13.3 | 4.3 | 118 | 1.840 |
| VT/123/1B | 100 | 10.35 | 10.15 | 0.32 | 14.4 | 4.4 | 117 | 1.840 |
| VT/123/2A | 100 | 25.47 | 10.29 | 0.34 | 14.1 | 6.6 | 124 | 1.902 |
| VT/123/2B | 100 | 25.57 | 10.28 | 0.33 | 13.8 | 6.6 | 126 | 1.840 |
| VT/123/3A | 300 | 10.58 | 11.07 | 0.34 | 12.1 | 6.7 | 101 | 1.534 |
| VT/123/3B | 300 | 10.51 | 11.10 | 0.35 | 12.0 | 7.2 | 103 | 1.810 |
| VT/123/4A | 300 | 25.58 | 11.36 | 0.33 | 13.0 | 9.0 | 111 | 1.656 |
| VT/123/4B | 300 | 25.37 | 11.12 | 0.33 | 13.0 | 9.2 | 113 | 1.595 |
| VT/124/1A | 100 | 10.62 | 11.69 | 0.36 | 12.9 | 4.5 | 101 | 1.687 |
| VT/124/1B | 100 | 10.50 | 11.72 | 0.37 | 12.1 | 4.3 | 97 | 1.656 |
| VT/124/2A | 100 | 25.36 | 11.84 | 0.35 | 12.1 | 6.8 | 114 | 2.055 |
| VT/124/2B | 100 | 25.28 | 11.75 | 0.34 | 12.5 | 6.2 | 118 | 1.779 |
| VT/124/3A | 300 | 10.52 | 11.20 | 0.58 | 11.7 | 7.1 | 105 | 1.687 |
| VT/124/3B | 300 | 10.33 | 10.94 | 0.36 | 11.8 | 6.8 | 107 | 1.626 |
| VT/124/4A | 300 | 25.58 | 11.39 | 0.34 | 12.3 | 9.9 | 119 | 1.810 |
| VT/124/4B | 300 | 25.55 | 11.61 | 0.35 | 11.6 | 10.0 | 118 | 1.840 |

Flexural tests

| **Specimen Code** | **Length (mm)** | **Width (mm)** | **Depth (mm)** | **Fibre Volume Fract.n** | **Initial Mod. (GPa)** | **Deflect.n at Fail (mm)** | **Failure Stress (MPa)** | **Failure Strain (%)** |
|---|---|---|---|---|---|---|---|---|
| VF/41/1A | 55 | 10.31 | 4.01 | 0.35 | 14.5 | 3.5 | 303 | 2.250 |
| VF/41/1B | 55 | 9.66 | 3.70 | 0.34 | 14.0 | 4.5 | 429 | 2.750 |
| VF/41/2A | 55 | 29.89 | 4.01 | 0.32 | 15.3 | 3.5 | 295 | 1.963 |
| VF/41/2B | 55 | 30.39 | 4.01 | 0.36 | 13.7 | 5.1 | 398 | 3.275 |
| VF/41/3A | 100 | 9.87 | 3.87 | 0.36 | 14.7 | 15.0 | 389 | 2.850 |
| VF/41/3B | 100 | 9.74 | 3.98 | 0.34 | ~ | 11.8 | 331 | ~ |
| VF/41/4A | 100 | 30.06 | 3.78 | 0.31 | 14.2 | 15.0 | 387 | 3.050 |
| VF/41/4B | 100 | 30.35 | 4.20 | 0.35 | 13.5 | 15.2 | 336 | 2.200 |
| VF/42/1A | 55 | 10.17 | 3.75 | 0.34 | 15.3 | 3.3 | 296 | 2.250 |
| VF/42/1B | 55 | 10.18 | 3.70 | 0.34 | 12.6 | 3.7 | 297 | 2.475 |
| VF/42/2A | 55 | 29.78 | 3.79 | 0.38 | 15.8 | 3.7 | 302 | 2.275 |
| VF/42/2B | 55 | 29.80 | 3.63 | 0.37 | 15.8 | 4.6 | 334 | 2.863 |
| VF/42/3A | 100 | 10.21 | 3.67 | 0.36 | 10.8 | 9.2 | 214 | 2.550 |
| VF/42/3B | 100 | 10.31 | 3.58 | 0.34 | 14.5 | 9.8 | 290 | 2.450 |
| VF/42/4A | 100 | 29.86 | 4.09 | 0.36 | 13.8 | 12.8 | 281 | 2.450 |
| VF/42/4B | 100 | 29.82 | 4.04 | 0.35 | 13.3 | 12.0 | 280 | 2.525 |
| VF/43/1A | 55 | 9.41 | 4.24 | 0.33 | 11.0 | 3.1 | 214 | 2.300 |
| VF/43/1B | 55 | 10.33 | 4.25 | 0.32 | 12.7 | 3.7 | 241 | 3.400 |
| VF/43/2A | 55 | 29.22 | 4.41 | 0.33 | 10.7 | 4.9 | 299 | 3.325 |
| VF/43/2B | 55 | 29.98 | 4.39 | 0.33 | ~ | 4.5 | 286 | ~ |
| VF/43/3A | 100 | 10.09 | 4.32 | 0.32 | 12.0 | 10.5 | 227 | 2.225 |
| VF/43/3B | 100 | 10.20 | 4.32 | 0.33 | 11.2 | 12.4 | 223 | 2.600 |
| VF/43/4A | 100 | 29.99 | 4.41 | 0.33 | 11.1 | 12.6 | 281 | 2.713 |
| VF/43/4B | 100 | 29.09 | 4.30 | 0.33 | 11.9 | 12.8 | 295 | 2.750 |
| VF/44/1A | 55 | 9.85 | 3.70 | 0.32 | 15.7 | 3.4 | 395 | 2.650 |
| VF/44/1B | 55 | 10.18 | 4.26 | 0.33 | 11.1 | 4.4 | 282 | 2.575 |
| VF/44/2A | 55 | 29.67 | 4.37 | 0.34 | 14.7 | 4.3 | 287 | 2.875 |
| VF/44/2B | 55 | 29.81 | 4.36 | 0.35 | 13.9 | 4.1 | 300 | 2.225 |
| VF/44/3A | 100 | 10.09 | 4.25 | 0.32 | 10.5 | 11.6 | 257 | 2.800 |
| VF/44/3B | 100 | 9.97 | 4.28 | 0.34 | 9.6 | 12.2 | 246 | 3.600 |
| VF/44/4A | 100 | 29.64 | 4.09 | 0.35 | 14.6 | 14.0 | 312 | 2.675 |
| VF/44/4B | 100 | 29.78 | 4.09 | 0.36 | 14.8 | 10.2 | 291 | 2.250 |
| VF/81/1A | 105 | 20.0 | 7.4 | 0.34 | 17.4 | 7.4 | 380 | 2.400 |
| VF/81/1B | 105 | 20.1 | 7.7 | 0.34 | 16.3 | 7.2 | 353 | 2.475 |
| VF/81/2A | 105 | 59.9 | 8.0 | 0.32 | 15.7 | 13.5 | 375 | 2.700 |
| VF/81/2B | 105 | 59.5 | 7.8 | 0.33 | 16.6 | 13.9 | 414 | 2.575 |
| VF/81/3A | 200 | 19.5 | 7.5 | 0.35 | 15.4 | 26.8 | 333 | 2.325 |
| VF/81/3B | 200 | 19.8 | 7.4 | 0.35 | 15.8 | 30.2 | 329 | 2.200 |
| VF/81/4A | 200 | 59.8 | 7.5 | 0.33 | 16.0 | 26.4 | 336 | 2.350 |
| VF/81/4B | 200 | 59.7 | 7.5 | 0.34 | 15.2 | 29.2 | 343 | ~ |
| VF/82/1A | 105 | 19.8 | 7.5 | 0.34 | 15.4 | 6.2 | 228 | 1.750 |
| VF/82/1B | 105 | 20.0 | 6.7 | 0.34 | 19.0 | 6.0 | 392 | 2.125 |
| VF/82/2A | 105 | 60.5 | 7.6 | 0.37 | 17.2 | 6.2 | 297 | 1.950 |
| VF/82/2B | 105 | 60.0 | 7.4 | 0.35 | 15.8 | 5.6 | 266 | 1.850 |
| VF/82/3A | 200 | 19.7 | 6.8 | 0.33 | 19.1 | 25.2 | 440 | 2.450 |
| VF/82/3B | 200 | 19.8 | 6.7 | 0.35 | 19.0 | 25.8 | 459 | 2.525 |
| VF/82/4A | 200 | 60.4 | 7.3 | 0.36 | 17.9 | 26.0 | 368 | 2.425 |
| VF/82/4B | 200 | 60.5 | 7.3 | 0.35 | 17.0 | 23.6 | 342 | 2.050 |
| VF/83/1A | 105 | 19.7 | 7.1 | 0.37 | 15.2 | 7.8 | 326 | 2.500 |
| VF/83/1B | 105 | 19.7 | 7.8 | 0.40 | 13.1 | 7.6 | 232 | 2.825 |

| **Specimen Code** | **Length (mm)** | **Width (mm)** | **Depth (mm)** | **Fibre Volume Fract.n** | **Initial Mod. (GPa)** | **Deflect.n at Fail (mm)** | **Failure Stress (MPa)** | **Failure Strain (%)** |
|---|---|---|---|---|---|---|---|---|
| VF/83/2A | 105 | 60.5 | 7.6 | 0.36 | 15.9 | 6.2 | 256 | 1.813 |
| VF/83/2B | 105 | 60.5 | 7.6 | 0.35 | 15.4 | 6.8 | 293 | 2.125 |
| VF/83/3A | 200 | 19.6 | 7.9 | 0.39 | 11.3 | 24.2 | 190 | 2.175 |
| VF/83/3B | 200 | 19.8 | 7.6 | 0.41 | 12.0 | 25.4 | 203 | ~ |
| VF/83/4A | 200 | 60.5 | 7.5 | 0.38 | 14.1 | 24.4 | 264 | 2.050 |
| VF/83/4B | 200 | 60.3 | 7.5 | 0.35 | 13.9 | 23.4 | 253 | 2.050 |
| VF/84/1A | 105 | 19.5 | 7.4 | 0.37 | 15.0 | 7.2 | 292 | 2.500 |
| VF/84/1B | 105 | 19.6 | 7.4 | 0.36 | 13.3 | 7.2 | 292 | 2.538 |
| VF/84/2A | 105 | 60.7 | 7.7 | 0.34 | 13.1 | 7.2 | 303 | 2.625 |
| VF/84/2B | 105 | 60.6 | 7.4 | 0.36 | 15.7 | 8.0 | 325 | 2.275 |
| VF/84/3A | 200 | 19.8 | 7.7 | 0.37 | 12.9 | 18.0 | 222 | 2.325 |
| VF/84/3B | 200 | 19.4 | 7.5 | 0.38 | 13.2 | 18.8 | 235 | 2.063 |
| VF/84/4A | 200 | 61.0 | 7.7 | 0.37 | 15.0 | 20.2 | 245 | 2.075 |
| VF/84/4B | 200 | 61.2 | 7.7 | 0.36 | 14.6 | 19.0 | 242 | 1.988 |
| VF/121/1A | 162 | 31.10 | 10.61 | 0.36 | 19.1 | 10.8 | 353 | 2.175 |
| VF/121/1B | 162 | 30.65 | 10.40 | 0.36 | 19.2 | 11.8 | 383 | 2.475 |
| VF/121/2A | 162 | 90.50 | 10.59 | 0.36 | 20.3 | 12.0 | 352 | ~ |
| VF/121/2B | 162 | 89.56 | 10.45 | 0.36 | 18.8 | 9.6 | 324 | 1.900 |
| VF/121/3A | 300 | 30.46 | 10.51 | 0.36 | 19.1 | 34.8 | 332 | 2.075 |
| VF/121/3B | 300 | 30.31 | 10.39 | 0.36 | 19.8 | 32.4 | 314 | 1.700 |
| VF/121/4A | 300 | 90.03 | 10.38 | 0.37 | 19.3 | 34.8 | 314 | 1.875 |
| VF/121/4B | 300 | 90.08 | 10.48 | 0.36 | 18.7 | 33.6 | 328 | 2.025 |
| VF/122/1A | 162 | 30.75 | 11.21 | 0.34 | 17.5 | 9.8 | 302 | 1.825 |
| VF/122/1B | 162 | 30.64 | 11.24 | 0.34 | 16.9 | 10.4 | 333 | 2.200 |
| VF/122/2A | 162 | 89.93 | 10.58 | 0.35 | 19.1 | 11.0 | 351 | ~ |
| VF/122/2B | 162 | 89.93 | 11.46 | 0.33 | 17.5 | 10.4 | 295 | 1.925 |
| VF/122/3A | 300 | 30.67 | 11.29 | 0.32 | 17.4 | 28.8 | 260 | 1.700 |
| VF/122/3B | 300 | 30.63 | 11.42 | 0.33 | 17.4 | 32.4 | 281 | 1.825 |
| VF/122/4A | 300 | 90.20 | 11.37 | 0.34 | 15.3 | 30.4 | 273 | 2.050 |
| VF/122/4B | 300 | 90.08 | 11.54 | 0.34 | 17.6 | 30.8 | 279 | 1.900 |
| VF/123/1A | 162 | 30.74 | 12.08 | 0.33 | 14.7 | 10.2 | 253 | 2.388 |
| VF/123/1B | 162 | 30.90 | 11.83 | 0.34 | 13.8 | 9.8 | 234 | 2.250 |
| VF/123/2A | 162 | 90.51 | 11.36 | 0.34 | 16.3 | 11.0 | 308 | 2.150 |
| VF/123/2B | 162 | 89.90 | 11.29 | 0.35 | 15.4 | 10.8 | 293 | 2.275 |
| VF/123/3A | 300 | 30.71 | 11.45 | 0.34 | 13.4 | 34.4 | 240 | 2.225 |
| VF/123/3B | 300 | 30.53 | 11.43 | 0.35 | 14.5 | 31.6 | 227 | 2.225 |
| VF/123/4A | 300 | 90.32 | 11.87 | 0.34 | 14.3 | 32.0 | 259 | 2.025 |
| VF/123/4B | 300 | 89.67 | 11.94 | 0.34 | 14.6 | 32.8 | 270 | 2.225 |
| VF/124/1A | 162 | 30.65 | 11.60 | 0.35 | ~ | 9.6 | 260 | ~ |
| VF/124/1B | 162 | 30.64 | 11.53 | 0.34 | 14.8 | 10.6 | 275 | 2.375 |
| VF/124/2A | 162 | 90.20 | 11.39 | 0.34 | 18.1 | 10.6 | 297 | 1.925 |
| VF/124/2B | 162 | 89.93 | 11.34 | 0.34 | 17.3 | 9.8 | 284 | 1.900 |
| VF/124/3A | 300 | 30.87 | 11.36 | 0.35 | 15.2 | 31.2 | 250 | 1.913 |
| VF/124/3B | 300 | 30.34 | 11.43 | 0.34 | 15.4 | 33.2 | 255 | 2.250 |
| VF/124/4A | 300 | 90.41 | 11.44 | 0.34 | 15.8 | 33.2 | 284 | 2.075 |
| VF/124/4B | 300 | 90.15 | 11.57 | 0.34 | 15.7 | 26.8 | 239 | ~ |