SCALE AND SIZE EFFECTS IN THE MECHANICAL CHARACTERIZATION OF COMPOSITE AND SANDWICH MATERIALS

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SUMMARY : This paper presents experimental results from tests performed on three types of materials widely used in marine applications: glass reinforced polyester laminate panels produced by hand lay-up, foam core sandwich panels, and filament wound glass and carbon/epoxy cylinders. For all three types of material static tests have been carried out at different scales; results from some scaled impact tests are also reported.

KEYWORDS: Scale effect, Size effect, Mechanical Testing, Impact, Sandwich, Cylinder

INTRODUCTION

The characterization of the quasi-static mechanical properties of laminated composites and sandwich materials is generally performed by tests on small coupons, of length up to 25 cm. The data obtained, stiffness and strength properties, are then applied to the design and dimensioning of large structures. The coupon tests employed are now mostly standardized, but specimen size independence of the measured properties is rarely checked. Indeed, when studies have been performed on composites with different dimensions both size and scale effects have been observed. Size effects are defined as resulting from changes in one or more specimen dimension, while to detect scale effects it is necessary to scale up or down all the dimensions and test conditions in order to establish the correlation between a subscale model and a full scale component. λ is used here to indicate the ratio of full scale to model dimensions. It is not always easy to determine the causes of apparent size or scale effects, as there are often differences in fabrication method or test techniques for the thicker specimens which leave doubts as to the origins of measured differences. Zweben has reviewed this subject recently and concluded that 'there is significant but inconclusive experimental evidence for the existence of a size effect in composites' [1]. Jackson et al [2] studied a scale range of 1 to 6 (8 to 48 plies) and showed lower strengths with increasing scale for tension and flexure tests on certain carbon/epoxy lay-ups. Other stacking sequences, and notably unidirectional and quasi-isotropic specimens, were much less sensitive. Wisnom [3] also studied flexure of unidirectional carbon/epoxy scaled from 1 to 4 (25 to 100 plies) and found a small but significant decrease in strength with size. For glass reinforced composites some indications of lower flexural strengths for thicker unidirectional specimens exist [4] and of lower tensile strengths in thick woven composites [5]. On the other hand, a recent series of tests on composites reinforced with more isotropic (woven and mat) reinforcement showed an effect only in tension at 45° to the weave directions [6]. The latter study is discussed below.

Establishing whether size effects do exist in composites is of great practical importance for safety in structural design. In marine applications, in the offshore or shipbuilding industries for example, structures may be tens of metres long, so some dimensions are increased by two or three orders of magnitude compared to test coupon size. The 'material' scale change, rather than the structure size is usually less however, as tests are performed on coupons a few millimetres thick while full size monolithic structures rarely exceed thicknesses of 40 or 50 mm. The scale size of interest is thus in the range of 1 to 10. For such large structures sandwich materials are often used, in order to save weight. There is much current interest in test methods for sandwich materials, and local effects can dominate the global response, so scaling of tests on structures becomes very complex. Little work has been published in this area. A third type of structure, filament wound cylinders, extensively employed for internal pressure applications are also attracting interest for underwater applications. Here the loading is hydrostatic pressure and very little work is available on scaling effects in such structures. The failure mode may be material failure or buckling and tests are not easy to perform, but recent results suggest thicker cylinders may give higher crushing failure strengths [7]. Again, few results are available to confirm or deny the existence of size effects.

In the case of impact few standard tests exist but again for cost reasons small panels tend to be tested during material selection, and results are assumed to apply to larger structures. Studies of scale effects in impact are extremely complex but some published results suggest that scaling rules may be applicable to predict the undamaged response, and that there is an absolute size effect for damage which can be analyzed using fracture mechanics [8-10].

It is of fundamental importance to the proper design of structural elements that the influence of specimen size on material properties be established and understood. It is further essential that scale effects be thoroughly studied, as validated scaling laws for composites and sandwich structures would enable considerable cost savings in many test programmes. This paper describes some experimental studies performed to examine whether scale effects exist.

MATERIALS and TESTS

The materials tested are widely used in marine applications, but are also of interest for many other large industrial components. The materials and tests which will be described are presented in the Table below.

Table 1. Tests performed

Material	Tension	Flexure	Drop weight Impact
Laminates			
Rovimat/polyester Chomarat 500/300g/m² Scott Bader 491PA Iso.	2,3,4,6,8,10 plies	2,3,4,6,8,10 plies	-
UD glass/polyester Cotech 300 g/m² Cray Valley T7039 Iso.	4,8,16 plies	4,8,16,24,32 plies	-
Sandwich			
Rovimat/polyester/PVC Airex 80 kg/m^3	Core shear 10, 20 mm	1ply/10mm/1 ply 2 plies/20mm/2plies	1ply/10mm/1 ply 2 plies/20mm/2plies
Cylinders			
Glass, carbon/epoxy ±55° PPG Eglass/MY750 T700 carbon/MY750	Biaxial compression D/t = 9 175/20, 55/6	-	D/t = 9 175/20, 55/6

RESULTS FROM STATIC TESTS

Rovimat/polyester

Glass rovimat reinforced polyester is a very popular material for pleasure boat applications and many other larger industrial structures. Results from quasistatic tests on glass/rovimat specimens (woven plus mat layers, fibre content 50% by mass) have been presented elsewhere [6] and will not be detailed here. All specimen dimensions were scaled (width, span length and thickness), as well as the loading rate. Two examples are given below. Figure 1a shows tensile strengths measured at 0° and 45° to the woven axes. While no scale effects were noted in testing at 0°, apart from lower values for the thinnest specimens due to low fibre content, at 45° the strength increases with increasing specimen scale. From published results and statistical analysis of brittle materials a scale effect would be expected to decrease the strength. This effect was shown to result from the increased ability of larger specimens to accomodate local damage before final failure. Figure 1b shows quasistatic flexural strengths at different scales. For this relatively isotropic laminate a small decrease in 0° strength above 3 plies was noted but this remained within experimental scatter, 45° flexural strengths were quite constant.

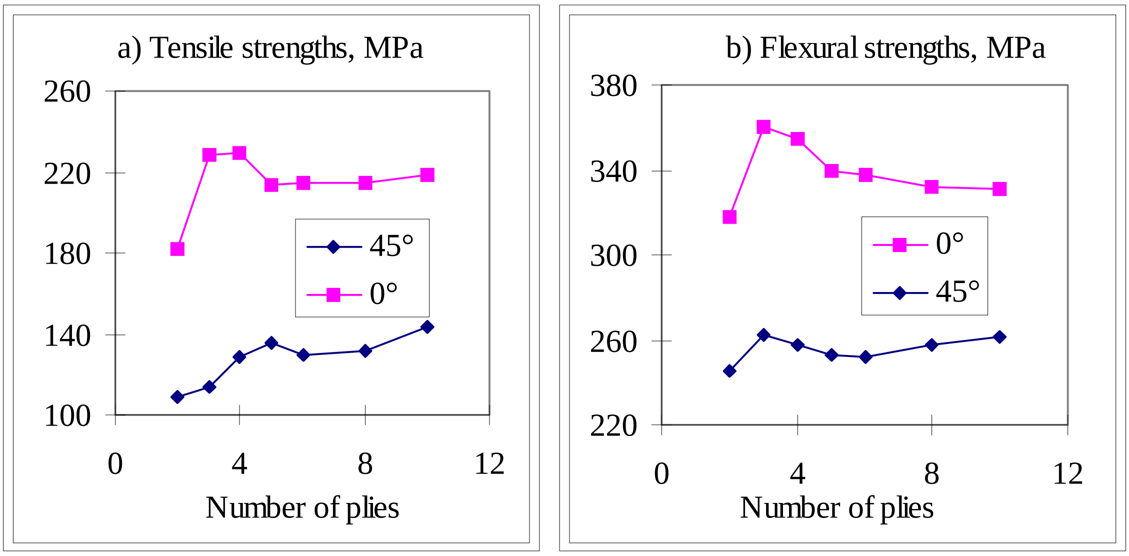

Fig. 1. a) Tensile strength, b) Flexural strength, both plotted versus specimen scale, glass rovimat/polyester [6]

Unidirectional specimens

In order to examine whether scale effects would be observed in more anisotropic materials tensile and flexural strengths were measured on unidirectional (hand lay-up, fibre content 66% by mass) specimens with the long axis in the fibre direction. The test conditions were again scaled, Table 2, and tension and flexure results are given. Figure 2 shows the flexure results graphically. At least 5 specimens were tested for each condition. The radius of the loading nose can be critical in flexural tests, ASTM standard D790 recommends a radius from 3.2 mm minimum up to a maximum of 1.5 times the specimen depth, to avoid excessive indentation or compressive failure. These recommended values are shown in Table 2. This radius was varied for 8 and 32 ply specimens as small radii were seen to cause local damage.

Table 2. Test conditions, unidirectional speciimens.

Plies	Thickness, mm	Width, mm	Free/Support length, mm	Loading rate mm/min.	Load nose diameter, (ASTM)mm	Strength, MPa (Std dev.)
Tension						
4	1.2	10	110	1	-	463 (31)
8	2.5	20	220	2	-	449 (17)

16	4.8	40	440	4	-	553 (10)
Plies	Thickness, mm	Width, mm	Free/Support length, mm	Loading rate mm/min.	Load nose diameter, (ASTM)mm	Strength, MPa (Std dev.)
3 point Flexure						
4	1.1	7.5	20	0.5	5 (3.5)	1036 (94)
8	2.5	15	40	1	5 (7.5)	861 (30)
8	2.5	15	40	1	20 (7.5)	982 (61)
16	4.8	30	80	2	10 (14.5)	975 (45)
24	6.6	45	120	3	20 (20)	994 (52)
32*	9.8	60	160	4	20 (30)	798 (31)
32*	9.8	60	160	4	30 (30)	811 (28)
32	8.5	60	160	4	30 (30)	917 (79)

* discontinuous fabrication

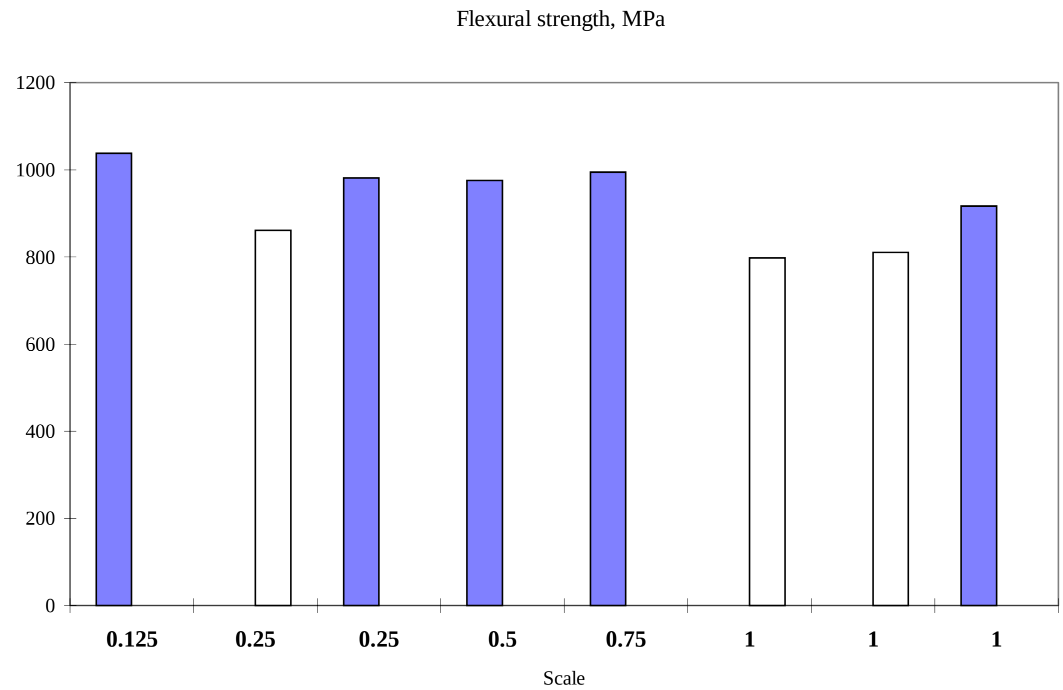

Figure 2. Flexural strength (MPa) versus specimen scale, UD glass/polyester

These results suggest that, as for the more isotropic rovimat specimens, there is no decrease in strength with scale as specimen size is increased from 1 to 6 (4 to 24 plies). There is a slight decrease for the largest (32 ply) specimens. This was first thought to be due to the loading nose diameter, which caused local damage, but when the diameter was increased the value remained low. Another possibility was that the manufacturing method for the thick laminates was different and indeed it is common practice to stop after half the plies have been laid up, apply a peel ply and let the laminate cool to avoid excessive exotherm before restarting. This can result in a weak central layer although interlaminar shear tests did not reveal a significant drop compared to the other panels. Another panel was therefore produced continuously, and the results were improved markedly, but fibre content is higher for this final panel as can be seen from thicknesses in Table 2. Strengths are still slightly lower than those from smaller specimens, despite the higher fibre content. There is more scatter for this last series and the size of the difference is around 10% but this may indicate a genuine size effect.

Sandwich specimens

Sandwich construction is widely used where weight saving is critical, and foam core sandwich materials are employed in many fast passenger ferries.

The sandwich specimens studied here consist of glass rovimat facings, (either one or two layers), identical to those described above, and PVC foam core (10 or 20mm thick). Before testing the sandwich some shear tests were run on the core materials (ASTM C273) to check that there was no difference in behaviour between 10 mm and 20 mm thick foam panels. Results indicated that there is a small difference in static shear moduli, which is caused by small differences in density. Although these cores have the same nominal density of 80 kg/m^3, measured densities were 91 and 81 for 10 and 20mm samples respectively. The facing fibre contents were also measured, by resin burn-off, and found to be 45% by weight in both cases.
In order to examine the static response of sandwich specimens three point flexural tests were performed to failure. Distance between supports was 16 times the sandwich thickness, specimen width, loading rate and load point diameter were all halved for the subscale tests. Strain gauges recorded the lower facing strain and results are presented in the form of force v strain plots, Figure 3, for three specimens of each size.

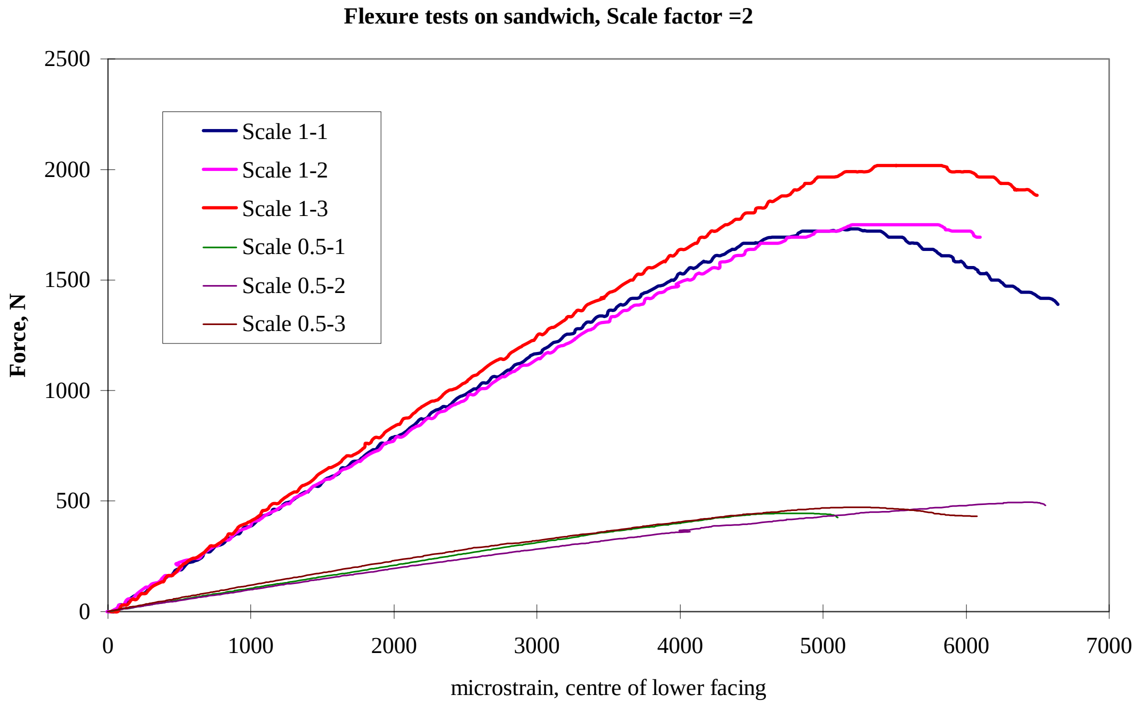

Figure 3. Sandwich beams, static flexure tests, scale factor 2.

When the mean force-strain slopes and the mean maximum loads for the two sizes are compared a ratio of 3.9, is found for both cases, which given the hand lay-up fabrication is very close to the expected ratio of 4 based on sandwich beam theory [11].

Cylinder specimens

The use of thin wall composite tubes for cooling water systems is now widespread, but thick wall composites are also very attractive for underwater applications. Some unmanned underwater vessels are already using filament wound composites. However, if manned submersibles and submarine hulls are to adopt this technology two of the aspects which need to be studied are resistance to external pressure and to impact loads. These aspects have been examined in some detail in a recently completed EUCLID project (see Acknowledgements), and here only some additional tests to examine the influence of scale will be discussed. Cylinders were manufactured to obtain the same diameter/wall thickness ratio (9) as closely as possible, but with different diameters. This ratio should ensure that material failure precedes buckling. They were tested to failure in a 2400 bar pressure vessel. Strain gauges on the inner walls of the cylinder allowed hoop and axial strains to be measured during test. Cylinder length was twice the diameter. Tests were performed on glass and carbon reinforced epoxy cylinders with ±55° reinforcement, examples of results for both materials are shown in

Table 3 below.

Table 3. Implosion tests on cylinders, λ = 3

Material	Inner Diameter, mm	Thickness, mm	r_{inner}/t	Failure pressure, bars	Nominal hoop strength, MPa
E glass/epoxy	55 175	6.3, 6.2 19.4	4.5 4.5	922, 859 939	493, 464 517
T700/epoxy	55 175	6.7, 6.7 18.3	4.1 4.8	1128, 1115 980	579, 572 570

From these first tests it appears that within experimental scatter there is no influence of scale on pressure response, at least in this size range. However, when the strain responses at the mid-section are examined for small and large diameter glass/epoxy specimens, Figure 4; it is apparent that there are differences in the behaviour.

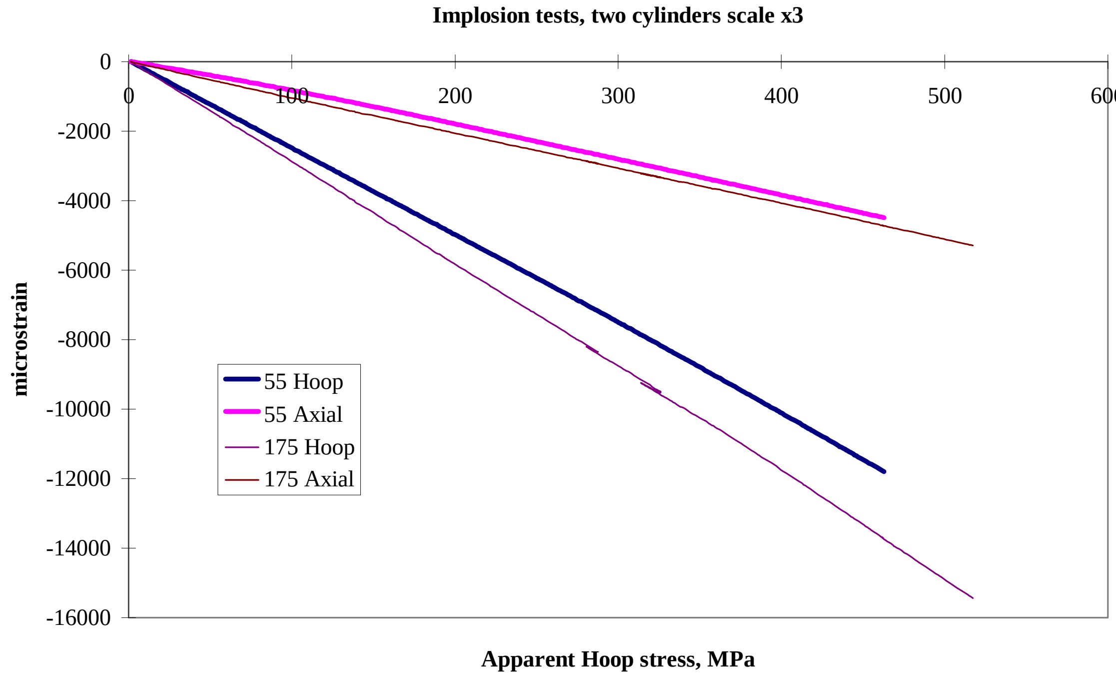

Figure 4. Pressure versus hoop strain, two cylinder dimensions with same r/t ratio, glass/epoxy ±55°

The smaller cylinders appear stiffer than the large ones in the hoop direction (strains 15% higher) suggesting a difference in fibre content or winding angle. Fibre volume contents were estimated to be 67 and 63.5% by weight, for the small and large cylinders respectively, which will certainly cause a difference in hoop strains as $E_{\theta\theta}$ will be increased about 7%. However there may be other reasons for the differences as although the fibre and resin constituents are the same, there are differences in fabrication parameters. Test boundary conditions are also not scaled, no end reinforcement was used but the smaller cylinders had simpler end closures than the large ones, which further complicate the interpretation and are being investigated. Tests on larger scale cylinders are also needed in order to be able to extrapolate this behaviour to larger structures.

RESULTS FROM IMPACT TESTS

In many cases it is the impact behaviour of composites which is the most difficult to characterize. Drop weight impact tests have been performed on many monolithic and sandwich panels in recent studies and size effects were studied [12]. Here some additional tests have been carried out on the same two materials as those tested in static flexure above to look at scale effects. Simply-supported square sandwich panels were impacted with the conditions shown in Table 4, based on the work of Swanson and co-authors [9].

Table 4. Parameters for study of scale effect on sandwich impact

	Scale λ	t mm	x mm	y mm	Impact diam. mm	Impact Mass kg	Drop height mm
Case 1 (shear)							
	1	11.8	150	150	50	1.375	60-300
	2	23.6	300	300	100	11.0	60-300
Case 2 (flexure)							
	1	11.8	300	300	50	1.375	60-300
	2	23.6	600	600	100	11.0	60-300

A series of impact tests was performed with drop heights from 60 to 300 mm. Force was measured by an accelerometer in the impacter and plots versus time for examples of Case 1 and Case 2 impacts are shown in Figure 5. If scaling laws are followed the contact force should scale as λ^2, i.e. in the present case the contact force should be 4 times higher for the larger panel. The contact time to maximum force or strain should increase with λ, i.e. here it should be twice as long for the larger panel.

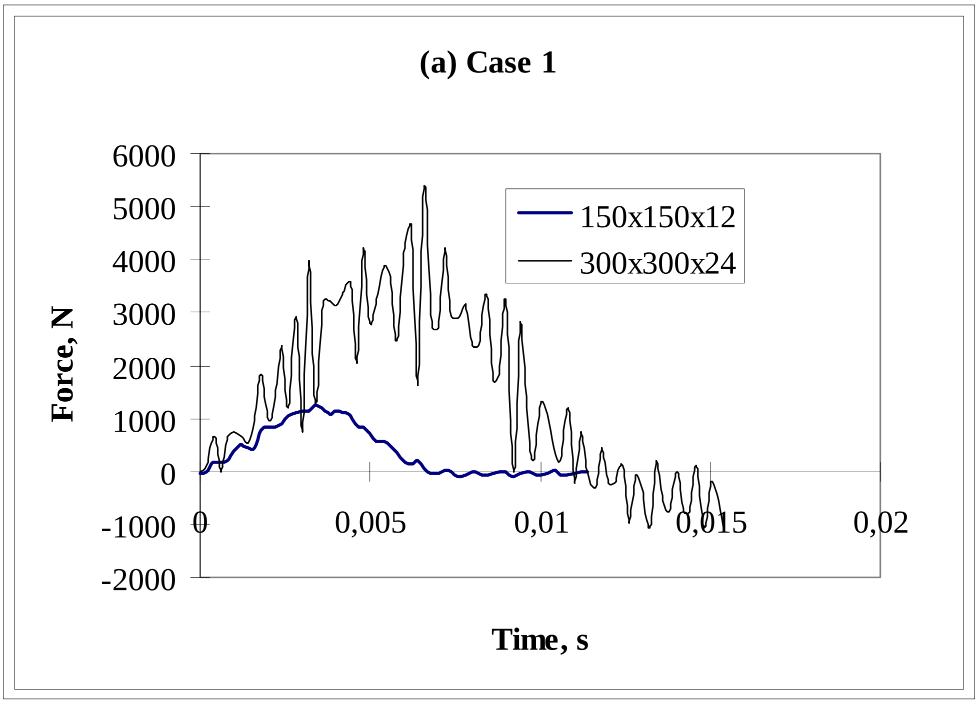

Figure 5a. Unfiltered force v time plots, 18 cm drop height.

These plots do seem to follow this expected behaviour, the forces are about 4 times as large for the larger panels and the contact time is roughly twice as long. In addition, if scaling laws are followed, the peak strains in scaled down panels should be the same as in full size panels.

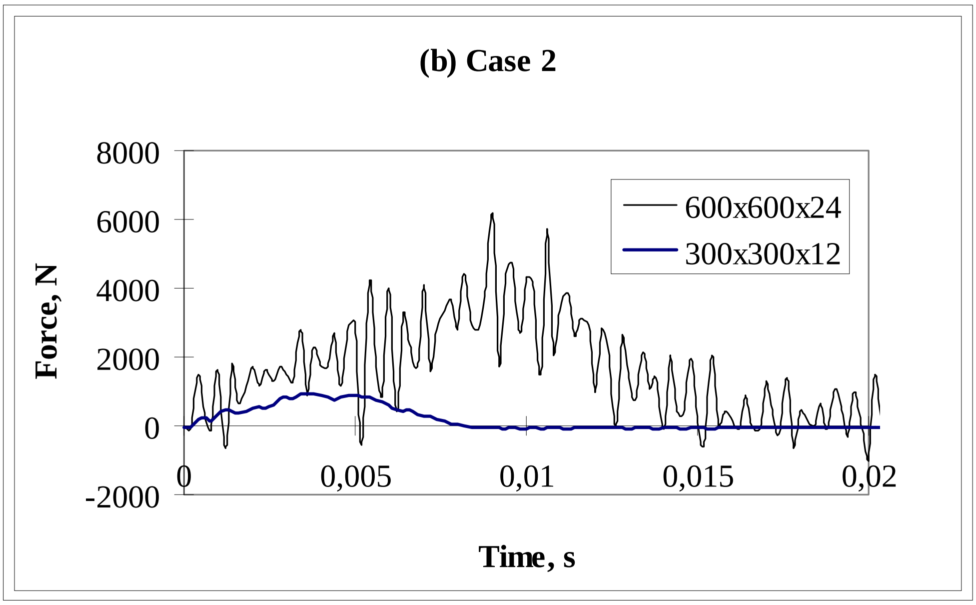

Figure 5b. Unfiltered force v time plots, 18 cm drop heights.

Figure 6 shows the maximum strain values measured on the lower sandwich facing below the impacter, for each case.

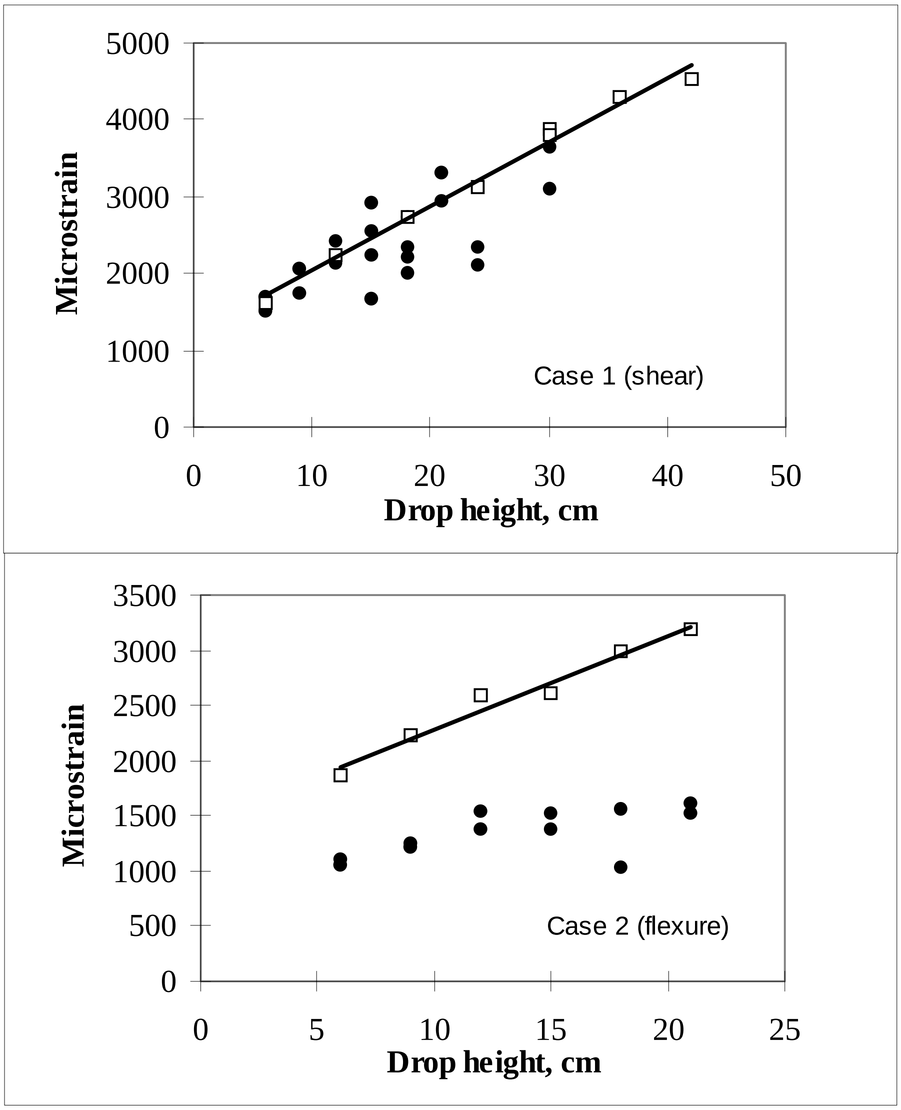

Figure 6. Maximum strain on lower facing below impact v drop height
a) Case 1, b) Case 2. Solid line full size, full symbols scaled down tests.

For case 1 there is reasonable agreement between the measured strains in full size and scaled down panels. For Case 2, however, the scaled down conditions result in much lower strains, roughly half those from tests on the full size panels. These preliminary results suggest that the scaling laws are not satisfied when flexure dominates the loading. More work is underway to examine this further.

Finally, some impact tests were performed on the glass/epoxy cylinder specimens described above. Again, the scaling rules described by Swanson [10] are applied, Table 5. (According to whether thickness or radius is taken as the baseline for scaling the value of λ varies from 3 to 3.2. The former was adopted for the majority of tests, but some additional tests were performed with $\lambda = 3.2$ (i.e. scaled mass of 0.33 kg) and no significant differences were noted.) The cylinders were placed in a cradle and subjected to a single impact. Specimens were then inspected ultrasonically to determine damage areas before sectioning and microscopic examination.

Table 5. Impact test conditions, glass/epoxy±55, $\lambda = 3$

	Diameter, mm	Thickness, mm	Length	Impacter diameter, mm	Impacter Mass, kg (λ^3)	Drop heights
Subscale	55	6.3	50	34	0.4	0.5 to 2.5 m
Full scale	175	19	150	100	10.9	0.5 to 2.5 m

The damage produced by different impacts for the two tubes is described in two ways. First the area detected ultrasonically was measured and is presented in Table 6 as a percentage of half the cylinder surface area. This is an arbitrary way of normalizing the damage in the two cylinders and takes no account of the nature of the damage. In order to characterize through the thickness damage longitudinal sections were taken and a penetrant dye was used to reveal cracks. The longest crack in the axial direction is presented as a percentage of cylinder length. Damage zones were almost circular. The sections enable a better evaluation of the extent of damage to be made, also presented in Table 6.

Overall, it appears that scaling of the impact conditions allows similar types of damage to be introduced into cylinders of two different sizes. For both cylinder sizes at 0.5metres drop height no damage is detected, while at 2.5 metres there is extensive cracking and delamination, with the classic cone shaped damage zone and a larger delamination close to the inner wall surface. For intermediate drop heights there are differences, in that at 1 metre there are more cracks in the smaller cylinder and in all cases there is an undamaged region at the centre of the damage cone for the large specimens, which is not present in the smaller cylinders Full through-thickness damage is observed from 1.5 metres drop height for both sizes.

Table 6. Damage in cylinders versus impact drop height, glass/epoxy, $\lambda = 3$.

	Small cylinder $\phi = 55$ mm			**Large cylinder $\phi = 175$ mm**		
Impact height, m	Projected Area, % Backlight	Length (Axial) % Total	Through-thickness aspect	Projected Area, % C-scan	Length (Axial), % Total	Through-thickness aspect
0.5	0	0	No damage	0	0	No damage
1.0	3	20	several isolated delaminations	0.5	10	single 'Hertzian' crack
1.5	20	50	Full damage cone	9.5	50	Full damage cone
2.0	20	50	Full damage cone	10	50	Full damage cone
2.5	35	66	Full damage cone	22	75*	Full damage cone

* extended to edge of specimen

CONCLUSIONS

- This paper presents results from several studies in which scaled specimens have been tested. Few scale effects were apparent in static tests over the range of scales examined. A small drop in flexural strength at increasing scale was observed (<10%) while tensile tests at 45° to woven fibres showed increasing rather than decreasing strength with increasing scale.
- Based on these results static tests on small laminate, sandwich and cylindrical specimens do not significantly overestimate mechanical properties of larger specimens. In the range of scales studied (up to a scale factor λ of 8) no strong evidence of a Weibull-type reduction in strength was apparent.
- Scaling of dynamic tests has been shown previously to be possible for carbon/epoxy laminates, here the scaling rules have been applied to sandwich and glass/epoxy cylinder specimens.. Despite the complexity of the damage mechanisms and the difficulties in producing completely scaled sandwich and cylindrical specimens the results obtained are promising though more larger scale experimental results are needed.
- This subject is of great practical importance for the prediction of the response of large composite structures and should be actively pursued.

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