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Studies of Scale Effects for Crash on Laminated Structures

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Abstract. This work proposes the study of the influence of scaled down ply layout techniques applied in a laminated composite structure submitted to fast dynamics. By its wide-ranging advantages, scale reduction represents a significant stake for engineers. An experimental campaign is carried out on an omega-shaped structure. The energies absorbed, as well as the efforts applied in the composite structure are then compared between the scale 1 prototype with the various models established (scales 1/2 and 1/4). The conclusions generated are numerous. Firstly, in this geometrical configuration, dynamic loading does not have the same effects on the results and, secondly, the relations of similitude used seem to be able to give some solutions, if the same ruin damage modes appear.

Key words: composite material, dynamic, scale reduction, experimental campaign.

1. Introduction

Transportation vehicles security nowadays represents a fundamental parameter in the design of the latter. For that purpose, several major industrial groups and research laboratories have met in order to capitalize their know-how and experimental means in order to work on passive security developments. Various projects have therefore been set-up, especially on the similitude techniques applied in composite materials. Indeed, the similitude or scale reduction is a major stake for industrialists in the field of structure testing; some of them can reach considerable dimensions in aeronautics. However, if numerous similitude laws have already been developed for more conventional materials, no similitude law has been established for the study of non-linear dynamic composite behaviour. Yet, these materials assure an increasingly important part in aeronautical design, as well as in the field of primary structures, such as in assemblies. A lack of knowledge is also obvious, as regards the influence of the loading speeds onto these materials. Nevertheless, some studies are in the pipeline [1–3]. We undertook to examine some solutions that will permit us to define preliminary answers to the problem of laminated composite structures scale reduction. Therefore, a study dealing with the evaluation of different ply

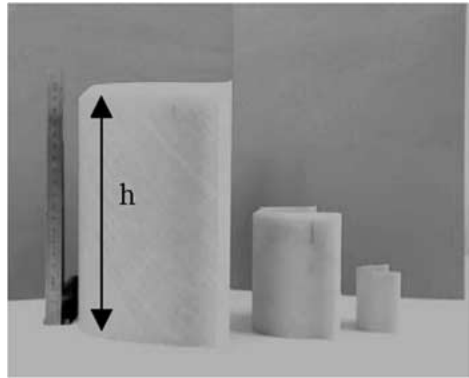


Figure 1. Side view.

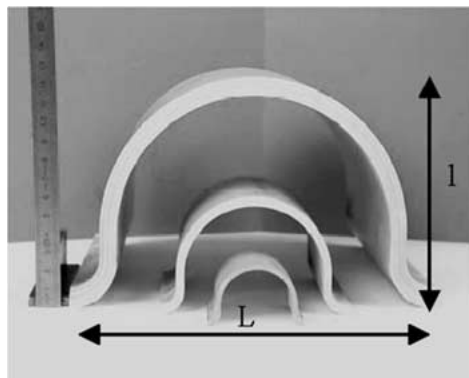


Figure 2. Front view.

arrangement techniques has been achieved on an ‘omega type’ structure at different scales, all made up of an E/epoxy glass material.

2. Dimension of the Test Specimens

The ‘omega’ test specimens presented for different scales here (Figures 1 and 2) have the following dimensions (Table I):

Table I. Dimensions of the test-tubes omega.

	Scale 1/4	Scale 1/2	Scale 1
L (mm)	50	100	200
l (mm)	30	60	120
h (mm)	50	100	200
Number of plies	4	8	16
Thickness (mm)	2.4	4.8	9.6

For manufacturing and manipulation reasons, a ‘Cauchy’ geometric similitude has been applied in the dimensional parameters of the selected structure. In this type of scale effect method, the materials are identical. The ‘Cauchy’ number is constant which implies the impact speed conservation. With this approach, there is an identity of stresses and strains both in the model and the prototype. The masses appear with a β^3 factor, the forces are of a β^2 factor, the energies are with a β^3 factor, the displacements are with a β factor, and the accelerations are with a β^{-1} factor. The relation between the prototype and the models is operated thanks to the factor β (the β scale ratio in our case = 1/2 or 1/4). To initialise the ruin of the structure, a chamfer (angle = 45°) is manufactured on top of the test piece.

3. Ply Arrangement Techniques

The objective of these techniques is a structure scale reduction; however, within our study, these techniques have been used inversely, that is to say, applied gradually to the 1/4-scaled models then to the 1/2-scaled models and, finally, to the prototype. The similitudes developed initially by E. Jackson [4] (Figures 3-1 and 3-3) are the following ones:

- the first one, (Figure 3-1), consists in defining a first stacking sequence made of n plies $[+\theta/-\theta]$, then defining the following one by doubling each ply in order to obtain a final laminate made of $2n$ plies $[+\theta_2/-\theta_2]_s$. This similitude is very interesting because it permits us directly to keep stiffness (in-plane tension and compression) and bending modulus,
- in the second one, (Figure 3-2) the initial stacking sequence is duplicated by a symmetry,
- the third one (Figure 3-3), leading from the laminate $[+\theta/-\theta]_s$ to the final laminate $[+\theta/-\theta]_{2s}$, is performed by a symmetry of the initial sequence twice. As for the first technique, it allows a correct setting of the in-plane modulus, but not of the bending modulus.

For the rest of the study, laminates will be differentiated by the number of interfaces which, within this study, represent the separation between two differently orientated plies.

4. Experimental Test Facilities

4.1. STATIC TESTS

A static INSTRON machine can be used in tension as well as in compression. Its load capacities are adaptable (2, 5, 10, 20, 50, 100 kN) according to the testing speeds applied (0.1 mm/min until 500 mm/min). An in-house developed hydraulic press has been used for the 1/2- and 1-scaled specimens. This machine has a 1000 kN compression load capacity and is composed of a hydraulic jack with

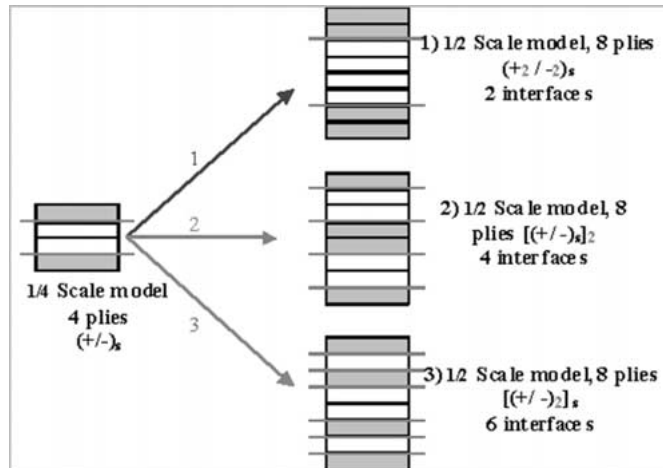


Figure 3. Similitude techniques.

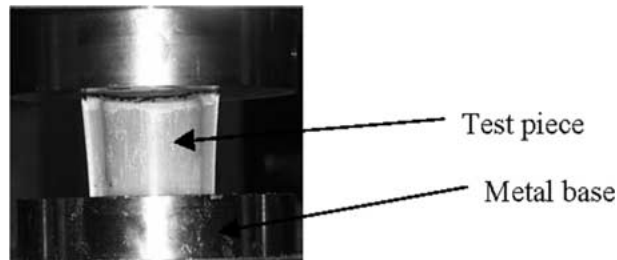


Figure 4. Test assembly.

a maximum 100 mm displacement; that explains why the total crush displacement is limited to this value. Its speed range extends from 10 mm/min to 100 mm/min.

4.2. DYNAMIC TESTS

For the 1/4-scaled specimens, dynamic tests have been performed on an in-house designed hydraulic machine composed of a dynamic jack fed by 350 bar pressure and a 150 l/h flow rate. Its load capacities are 50 kN in dynamics and 69 kN in statics; its maximal speed reaches 10 m/s for a maximum 250 mm displacement. For the larger dimension specimens (scale 1/2 and 1), tests have been carried out in a drop tower designed by C3T (Centre de Transfert en Transport Terrestre of Valenciennes University) and permits us to test in free fall conditions, the maximum mass ranging from 100 to 700 Kg, with a variable height ranging from 80 cm to 4 m.

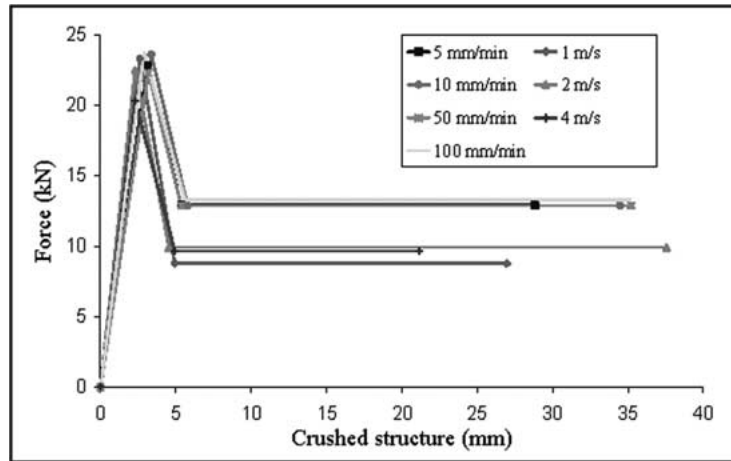


Figure 5. Comparison of the average results for the 1/4-scaled specimens at different speeds.

4.3. TEST ASSEMBLY

For the experimental program, the test pieces are embedded with an extra glue in a metal base so as to avoid any structural bending (Figure 4). The loading is applied in the chamfer on top of the composite structure.

5. Experimental Programme

For each laminate or test-speed tested, at least three tests have been performed. In order to ensure an easy comparison of results, the following figures present the mean load peaks and load plateaus obtained during the compression specimen.

5.1. COMPARISON OF RESULTS FOR 1/4-SCALED SPECIMENS

As a first step in our study, some tests have been performed on different stacking sequences and have led to a final choice of the $[\pm 45]_s$ laminate whose main advantage was to feature a more stable compression load plateau and manufacturing case.

The major aim to be obtained by these tests at a 1/4 scale was to evaluate the influence of the loading speed on the specimens structural behaviour. Our material indeed had already been proved to be strain rate dependent within the previous characterization studies, carried out on simple tube specimens [5] and there was an interest to evaluate to what extent this dependence may still remain at the structure level. Therefore, the speed range from 5 mm/min to 4 m/s has been applied. The comparison between these different cases and the data obtained have been plotted in Figure 5 and Table II.

In view of the results obtained, the analysis shows that the influence of this solicitation speed does not exist a priori on the different tests achieved in this

Table II. Comparison of the average data for the 1/4-scaled specimens.

Test speed	Max peak load (kN)	Average load (kN)
5 mm/min	22.78	12.876
10 mm/min	23.58	12.840
50 mm/min	22.27	12.843
100 mm/min	23.71	13.264
1 m/s	23.28	8.780
2 m/s	22.46	9.911
4 m/s	20.27	9.658

structural configuration, even if the load plateau differs by 3 kN between the static and dynamic tests. This difference can be explained by a higher amount of debris remaining at the contact between the impactor and the structure in statics (in dynamics, debris are projected away from the contact surface, thus reducing significantly the effort).

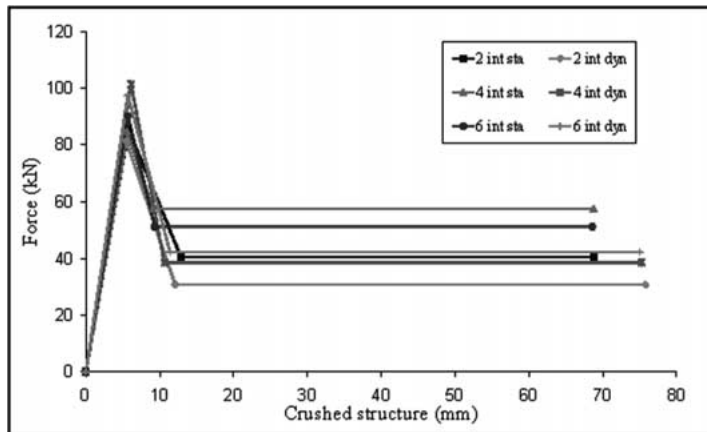


Figure 6. Comparison of the average results according to the static and dynamic tests for the 1/2-scaled specimens.

5.2. COMPARISON OF RESULTS FOR 1/2-SCALED SPECIMENS

For this scale, three speeds have been tested, two in statics (10 and 100 mm/min) and one in dynamics (4 m/s). The stacking sequences are obtained by applying the ply arrangement techniques previously presented (Figure 3).

As for the 1/4-scaled specimens, a comparison of the results is proposed between the static tests and the dynamic ones (Figure 6 and Table IV).

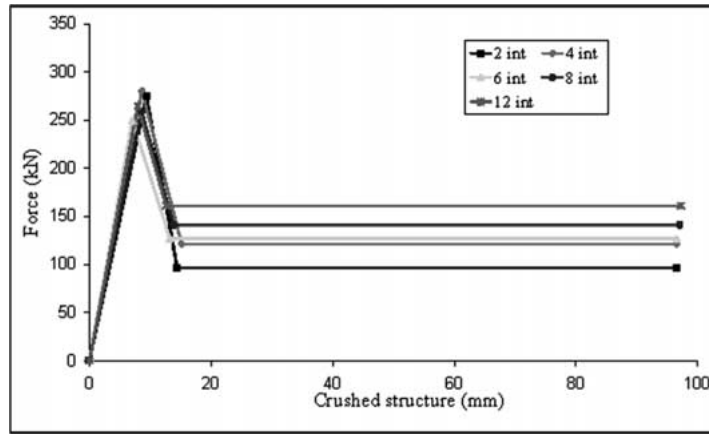


Figure 7. Comparison of the average data for the 1-scaled specimens in statics.

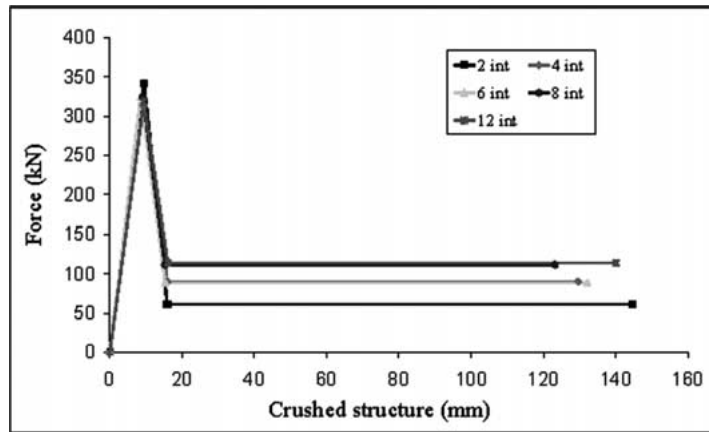


Figure 8. Comparison of the average data for the 1-scaled specimens in dynamics.

A first conclusion between the different stacking sequences for a similar specimen shows that the load plateau seems to depend on the number of interfaces included in the structure studied.

5.3. COMPARISON OF RESULTS FOR 1-SCALED SPECIMENS

By the same procedure as defined previously, we obtained 6 configurations of stacking sequences that differ in number of interfaces they feature:

- $[+45_4/-45_4]_s$ 2 interfaces
- $[+45_2/-45_4/+45_2]_s$ 4 interfaces
- $[+45_2/-45_2/+45_2/-45_2]_s$ 6 interfaces
- $[+45/-45_2/+45_2/-45_2/+45]_s$ 8 interfaces
- $[+45/-45/+45/-45_2/+45/-45/+45]_s$ 12 interfaces

Table III. ‘Cauchy’ relations for the displacement, strength and energy absorption.

	Prototype	Model
Displacement	δ	$\beta\delta$
Load	F	β^2F
Energy	E_c	β^3E_c

- $[+45/-45/+45/-45/+45/-45/+45/-45]_s$ 14 interfaces (the last configuration was not manufactured for time reasons).

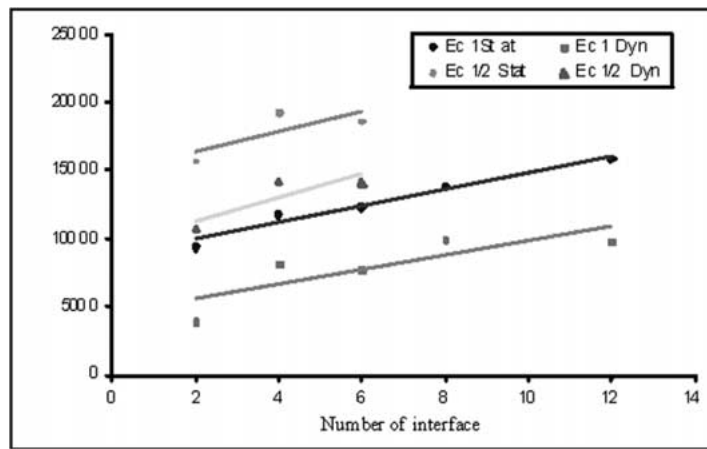


Figure 9. Evolution of the energy absorption according to the number of interfaces (in statics and dynamics) for the 1/2- and 1-scaled specimens.

The speed for the static tests is 10 mm/min, and that for the dynamic tests to be carried out in the drop tower has been calculated close to 4 m/s. Figures 7 and 8 present a comparison for each stacking sequence, respectively, in statics and dynamics.

The analysis of results at the 1 scale shows the same phenomenon as the one that was observed for the lower scale. Indeed, for the static and the dynamic studies, we obtain an evolution of the load plateau according to the number of interfaces.

5.4. ANALYSIS OF RESULTS OF DIFFERENT SCALES

5.4.1. Comparison of Efforts

Due to the fact that the crush displacement for the 1-scaled specimens was limited to 100 mm (while the ‘Cauchy’ similitude relation should have led to 200 mm), displacement data have been modified in consequence of the 1/4- and 1/2-scaled

Table IV. Equivalent results in statics and in dynamics.

	Number of interfaces	Test speed	Max peak load (kN)	Load plateau (kN)	Energy (J)
Scale 1/4	2 int	static	368	190	18286
		dynamic	365	132	13422
Scale 1/2	2 int	static	331	162	15605
		dynamic	325	107	10670
	4 int	static	350	198	19186
		dynamic	406	142	14194
	6 int	static	366	192	18545
		dynamic	390	141	14089
Scale 1	2 int	static	275	97	9359
		dynamic	341	38	3845
	4 int	static	280	121	11701
		dynamic	313	81	8115
	6 int	static	250	127	12241
		dynamic	324	77	7673
	8 int	static	258	141	13806
		dynamic	324	99	9902
	12 int	static	260	161	15776
		dynamic	318	98	9784
14 int*	static	–	177	17300	
	dynamic	–	119	12000	

specimens in order to work with consistent displacement, strength and energy values in terms of similitude (Table III). Once this step has been verified, the results could be compared among the different scales (Figure 9).

Note that the evolutions of the energy absorption according to the number of interfaces are linear with the same gradient for statics and dynamics.

The values for the non-manufactured stacking sequence containing 14 interfaces have been estimated according to this linear energy evolution shown previously. In Table IV the equivalent data are displayed.

The conclusions generated by this table are very interesting. In the case of structures including the maximum number of interfaces (2 interfaces for scale 1/4, 6 for scale 1/2, and 14 for scale 1), the energy and effort evolutions are nearly identical among the different scales. Scale reduction techniques are therefore valid, in this case, and do not affect the ‘Cauchy’ relation. Deviations are acceptable in this study case, dealing with the dynamic crush behaviour of composite structures (Table V).

Table V. Deviations.

% of difference with as reference scale 1	Scale 1/2	Scale 1/4
In static	6.8%	5.4%
In dynamic	14.9%	10.2%



Figure 10. Comparison of rupture modes at different scales.

Another analysis shows that the ‘Cauchy’ relation also applies to the evolution of energy and force of different stacking sequences. It is therefore possible, while knowing the evolution of a value of the different feasible scale stacking, to estimate the evolution of this same value for a model, while applying a relative relation coefficient to the size studied.

5.4.2. Comparison of the Rupture Modes

The main rupture mode observed in the tests performed consists of a peeling mode. Plies progressively and symmetrically split in most cases, on both sides of the middle-plan of the structure. This mode has already been described in previous studies [6–9]. This rupture mode, specific to composites, has been shown not to be influenced either by the structure dimensions, or by the loading speed and by the stacking sequence tested. Figure 10 presents a comparison at different scales.

Table VI. Equivalent results in statics and dynamics for three stacking sequences.

Scale	Number of interfaces	Test speed	Max peak load (kN)	Load plateau (kN)	Energy (J)
Scale 1/2	4 int	static	457	288	28517
		dynamic	451	126	14879
Scale 1	4 int	static	333	110	10919
		dynamic	422	91	10668
	8 int	static	346	119	11679
		dynamic	368	95	11101
	10 int	static	344	164	16212
		dynamic	375	109	12876

5.5. STUDY OF STACKING SEQUENCES CONTAINING THREE DIFFERENT FIBRE ORIENTATIONS

The analysis now concerns structures made of 3 different orientations. As a consequence, the study began with 1/2-scaled specimens and the number of plies was defined equal to 8 plies $[\pm 45/0_2]$ to keep the same dimensions as the previous specimens (the minimum number of plies to consider a symmetrical stacking sequence is 6 theoretically). By applying the same previous techniques to the 1-scaled specimens, the following sequences are obtained:

- $[+45_2/-45_2/0_4]_s$ 4 interfaces
- $[+45/-45/0_4/-45/+45]_s$ 8 interfaces
- $[+45/-45/0_2/+45/-45/0_2]_s$ 10 interfaces

The comparison of the equivalent results for each dimension has been plotted in Table VI.

Despite the restricted number of tests performed at each different scale, the previously developed statements seem to apply once again to this type of stacking sequence in dynamics. In the case of the static study, the equivalent energy calculated for the 1/2 model is much more important than for the prototype. An explanation of this phenomenon can be found in the difference of rupture modes between the two scales studied.

In Figure 11, the 1/2 model presents a more developed ply peeling. This rupture mode is emphasized by a strong ply delamination oriented at 0° located in the heart of the structure in a higher number. For the prototype, this rupture mode is the same as previously observed. This part of study is very interesting because it shows that, if the ‘Cauchy’ relations cannot be applied, the rupture modes are not comparable.



Figure 11. Presentation of the different rupture modes in statics.

6. Conclusions

In terms of the results, this experimental campaign brings a considerable database. The output generated is wide-ranging and the phenomena observed are quite interesting.

This campaign shows the lack of influence, for this structural configuration, of the loading speed on the performed tests, while the dynamic characterization campaign had shown the opposite results. This can be due to structural geometrical effects and to the specific rupture modes.

The second important conclusion concerns close relation between the load plateau and the number of interfaces of the stacking sequences. It has been shown that the evolution of the energy and effort parameters was linear and that this evolution could be defined thanks to the “Cauchy” relations. It is therefore possible to estimate the average energy of a stacking sequence containing n interfaces for any scale, once the evolution of this variable for a different stacking sequence at different scales is previously known. But, and this point is important, these relations can only apply when the rupture modes are identical.

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