RELIABILITY OF COMPOSITE STRUCTURES
- IMPACT LOADING -

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SUMMARY: This paper deals with a method to study the responses of laminated composite structures under impact loading. A preliminary study takes into account the influence of the coupling mass-velocity on some responses such as the contact force between striker and structure, the displacement of the projectile, and the damage induced inside the composite. The importance of the dimensions of composite beams and plates is shown for the same responses. Experimental design based technique is used. This method is powerful to provide to designer some empirical polynomials giving the evolution of mechanical responses as a function of the variables of the system. A factorial and Doehlert matrix were used for the laminated composites.

KEYWORDS : impact, experimental design, modelling, damage, delamination, cracks, size effect, metrology.

INTRODUCTION

Design of structures is often made with a deterministic approach. But, this kind of design is not always efficient for composite materials because of variability of their mechanical behaviour. In fact, some tools exist to take into account the scatter of both the mechanical characteristics and loading. For this, it is necessary to well know the failure processes of the structure. The two main loading which are applied on a industrial structure can be accidental impacts and fatigue solicitation.

The first step of this work is the analysis of mechanical responses of composite structures loaded in low velocity (from 3 up to 5 ms^{-1}) - high mass (from 2,5 up to 7 kg) impact. Impact solicitation is a multiparameter problem. It can be defined in terms of the geometry, mass and velocity of the impacter, the dimensions of the composite plate, and the boundary conditions [1-3]. The main question is how to identify the critical parameters. One way of quantifying the influence of factors on one or more responses is to use experimental design method. This enable different variables to be assessed and the most influential ones to be identified with a minimum of experiments. A factorial and Doehlert matrix were used for the laminated composites.

The evolution of responses as a function of variables is modelled by simple mathematical expressions (empirical polynomials) but these are not based on physical mechanisms. The aim is to present tools for dimensioning composite structures, but it should be underlined that these will only be valid within the experimental domain studied, and extrapolation is risky. Nevertheless, by identifying models the optimisation of impact response of composite structures may be achieved.

The influence of plate dimensions and the influence of the mass-velocity combination are studied because the critical parameter used to characterise an impact is the kinetic energy of the impacter.

SET - UP

The impact tests were performed using drop weight set-ups (Fig. 1).

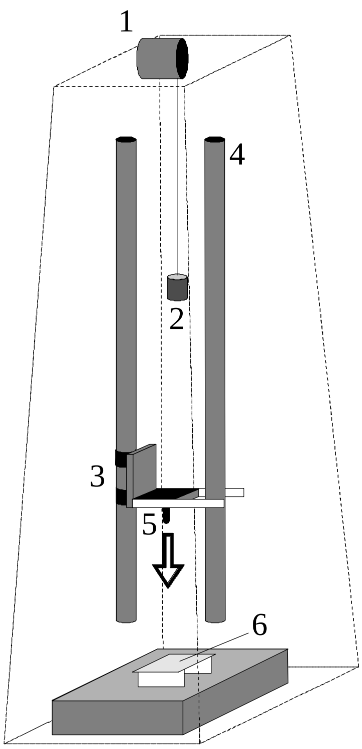
An electric motor is used with a magnet to raise the mass. The drop height is determined by the position of a first infra-red captor which stops the motor at the desired level. A second captor located on the set-up close to the specimen activates a mechanism which avoids a second impact on the structure.

The contact load between the striker and the composite specimen as a function of time is measured by means of an accelerometer and a piezoelectric captor which are attached to the drop weight.

Two laser captors provide the striker displacement and the deflection at the centre of the composite structure versus time.

The tests have been filmed by a high speed camera system Camsys+ (2,000 to 11,000 frames/sec).

The structure is put on two steel opposite supports. Two flexible sheets made of metal with a rubber end maintain it (Fig. 2). These boundary conditions allow rotation and vertical movement.



1 : electric motor
2 : magnet
3 : drop weight
4 : column
5 : end of the stricker
6 : structure

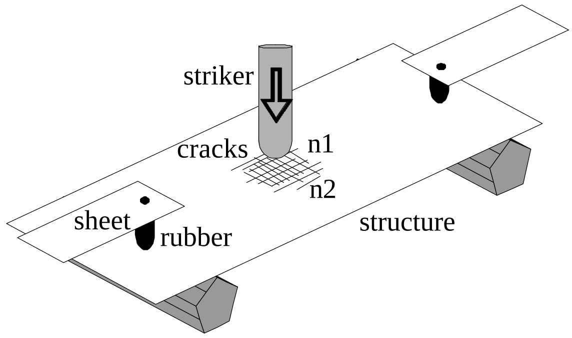


Fig. 1: Drop tower.

Fig. 2: Boundary conditions.

TEXT MATRIX

In the present study an analysis of the influence of the mass and the velocity of the striker was first performed with a first type of laminated composite. Then, a second type of laminated composite was used to establish polynomial models linking the dimensions of plates and beams to the mechanical responses in a given experimental domain.

In order to demonstrate mechanical, physical or chemical phenomena tests are frequently performed, in small or large numbers. The experimental design method enables test campaigns to be set up to minimise variance in results while reducing the number of tests.

By analysing the results from such tests empirical polynomial models (Y) can be established relating the variables of the mechanical system to the structural responses. The basis of this approach lies in the fact that the model variance (Eqn 1) can be expressed as the product of the experimental variance (σ^2) with a term which depends only on the organisation of the tests (A).

$$\text{var}\,(Y)=A\,\sigma^2 \qquad (1)$$

σ^2 is estimated by repetition of one of the tests. This estimation is more accurate if the number of repeats is increased. This indicates that the variance of the model can be minimised by choice of an optimal experimental distribution of the tests.

Setting up an experimental design method involves several steps. The nature and limit values of the variables must first be fixed. The degree of the polynomial must then be chosen. Then the matrix is established according to strict rules [4]. In order to facilitate the determination of the relative influence of the different parameters, the variables are expressed in centred, reduced co-ordinates. Their amplitude of variation is confined to the interval [-1,+1].

The first phase of this study used a factorial test matrix to analyse some basic responses of simple laminated composite beams under impact loading (Table 1). This phase was not intended to establish models of mechanical behaviour but particular attention was directed towards the combination of the two variables mass and velocity.

Table 1: Two-variable factorial matrix.

Test n°	X_1	X_2
1	-1	-1
2	+1	-1
3	-1	+1
4	+1	+1

The model corresponding to this matrix is a first order polynomial (Eqn 2).

$$Y=b_0+b_1.X_1+b_2.X_2+b_{12}.X_1X_2 \tag{2}$$

The parameter X_1 represents the drop velocity and X_2 is the mass. The coefficient b_{12} quantifies the coupling between them.

For the second phase, a Doehlert matrix [5] is used to study the influence of beams and plates dimensions. It is a test matrix known as a response surface. The basic principle is to position oneself at one point in an experimental domain and to examine the neighbouring area. These matrices have spherical symmetry. The factors are assumed to be quantitative and known. The Doehlert matrix has the advantage of the ability to be translated in the variables space with a minimum of new tests. The two variables in this study are the span (X_1) and the width (X_2). The test matrix associated with these variables requires 9 tests (Table 2) :

Table 2: Doehlert test matrix.

Test n°	1	2	3	4	5	6	7	8	9
x_1	1	0,5	-0,5	-1	-0,5	0,5	0	0	0
x_2	0	0,866	0,866	0	-0,866	-0,866	0	0	0

Test number 7, 8 and 9 are used to establish the σ^2 (Eqn 1). The value of A (Eqn 1) is calculated from the matrix given in Table 2.

In addition, the polynomial associated is of second order. This assumes that the responses are maybe non-linear :

$$Y=b_0+b_1X_1+b_2X_2 +b_{11}X_1X_1+b_{22}X_2X_2+b_{12}X_1X_2 \tag{3}$$

MATERIALS

Two composites are used here. Both are composed of glass fibres reinforced in an isophthalic polyester resin. Several plates of about 1 m^2 were made by the hand lay-up process. All the plates are constituted of 8 layers which give a total thickness of about 3.5 mm. The stacking sequence for the first plate called material 1 is : $[0,90]_4$ and for the second plate called material 2 : $[0_3,90]_s$. The specimens of this study have been cut from this plates.

TEST CAMPAIGN

From a first phase on the laminated material 1, the influence of the mass and the velocity on different responses was determined, such as contact time, contact force, central plate displacement, delaminated area between plies, number of cracks parallel to plate width (n_1) and number parallel to the length (n_2) (Fig. 2). From the test matrix (Table 1) the test programme is defined (Table 3) for the material 1.

Table 3: Test programme.

Test n°	Drop height (m)	Mass (kg)
1	0,5	1
2	1,5	1
3	0,5	2
4	1,5	2

The specimen size was 350 mm long and 66 mm wide.

The second step used the Doehlert test programme matrix (Table 4) from the test matrix (Table 2) for the material 2.

Table 4: Doehlert test programme matrix.

	Centre	Step	n° 1	2	3	4	5	6	7	8	9
Width (mm)	250	150	400	325	175	100	175	325	250	250	250
Span(mm)	250	150	250	379,9	379,9	250	120	120	250	250	250

The responses investigated are contact time, maximum contact load, the deflection of the plate centre and the delaminated area.

Two series of test were performed using the same test programme matrix at isoenergie : the first one with a mass of 2.5 kg and a velocity of 5.2 ms^{-1} and the second one with a mass of 7.5 kg and a velocity of 2;9 ms^{-1}.

RESULTS

Material 1

The Fig. 3 shows a typical evolution of the contact load versus time measured by the accelerometer and the load captor. In fact, to obtain only the interaction between the striker and the structure the accelerometer signal must be filtered (500Hz) to eliminate the vibratory response of the drop weight.

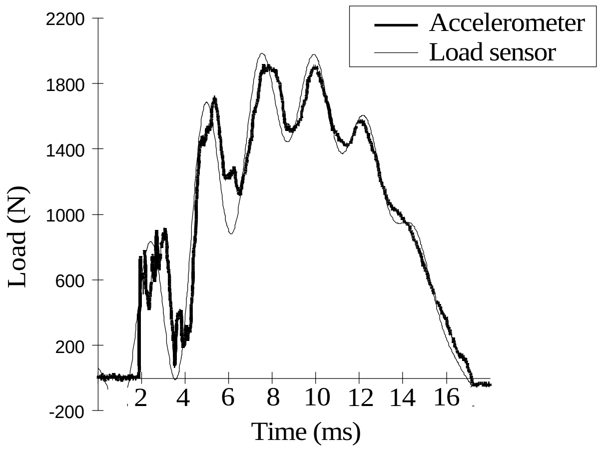


Fig. 3: Relationship between contact force and time from both accelerometer and load sensor.

The films given by the high speed camera shows that the undulations on the curve load versus time (Fig. 3) can be attributed to a transverse eigen mode induced by the stricker during the impact loading. A finite elements analysis confirms this assumption by giving at about 500 Hz the first transverse eigen mode.

The following results of the experimental design for the material 1 were obtained (Table 5) :

Table 5: Results from impact test on laminate 1.

test n°	load (N)	deflection (mm)	contact time(ms)	delaminated area (cm^2)	n_1	n_2
1	1000	8,4	10,0	0	20	37
2	1500	13,3	10,8	0,58	22	70
3	1266	12,9	15,0	1	27	90
4	1900	22,1	15,5	2,28	32	106

From these data the coefficients (Table 6) related to the mass and velocity variables can be determined together with their coupling from Eqn 2.

Table 6: Representation of coefficients related to each variable.

	load (N)	deflection (mm)	contact time (ms)	delaminated area (cm^2)	n1	n2
b0	1416	14,18	12,8	0,97	25,	75
b1	283	3,52	0,3	0,47	1,7	12
b2	166	3,33	2,4	0,67	4,2	22
b12	**33**	**1,1**	-0,1	**0,18**	**0,7**	**4,3**

It can be noticed that the coupling (b_{12}) is significant for all the variables related to the mechanical behaviour of the structure (load, deflection and damage). Therefore, it is risky for these responses to consider only the kinetic energy as the main parameter.

In addition, the damage observed is made up essentially of delaminations at several interfaces and cracks oriented parallel to the width and length of the panel.

Moreover, from the films of the camera we can establish a chronological evolution of the damage during the impact loading (Fig. 4). At the point 1 the matrix cracking begins. At the point 2 the delamination appears. Next, we observe the evolution of the delamination area as following : point 3 - 0.75 cm^2, point 4 - 1.46 cm^2, point 5 - 1.83 cm^2.

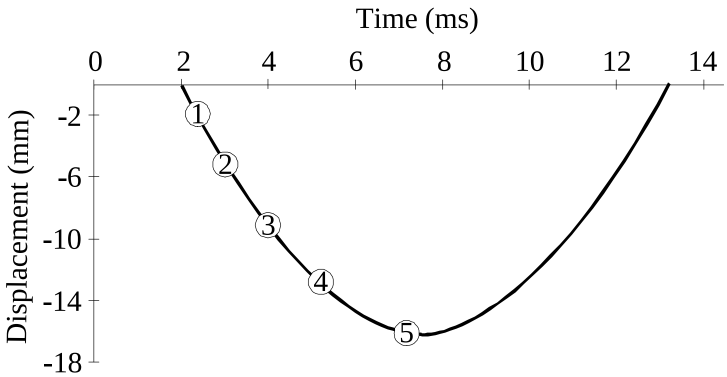


Fig. 4: Chronological evolution of the material 1 damage.

Material 2

The influence of the structure dimensions on the mechanical responses under impact loading is very important. For instance, for a large span (test n°2, Table 4) the evolution of the load versus time shows several loading and unloading (Fig. 5). In fact, we can notice from the film of the high speed camera a loss of contact between the striker and the structure each time the load is equal to zero (between two peak). But, for a small span (test n°5, Table 4) the response of the system is very different (Fig. 6). The oscillations corresponding to the transverse eigen mode are very small. Moreover, the duration of the test (6 ms) is smaller than the previous one (25 ms). In fact, for a small span the stiffness of the structure is higher than for a large span and of course the response is faster.

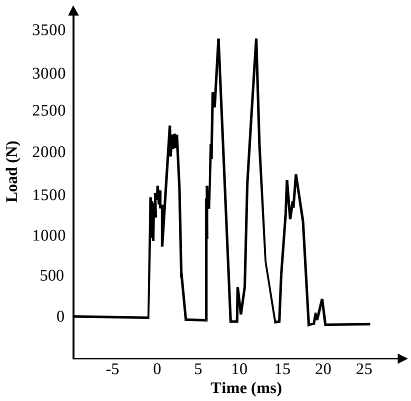


Fig. 5. Load versus time for the test 2.

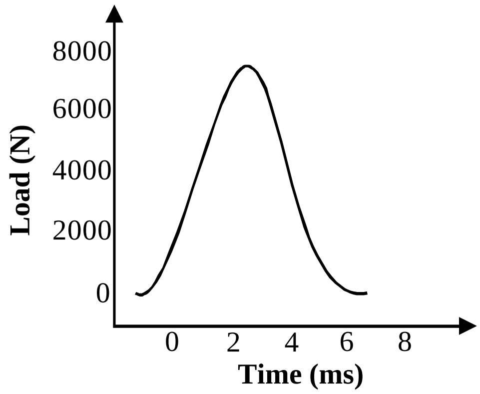
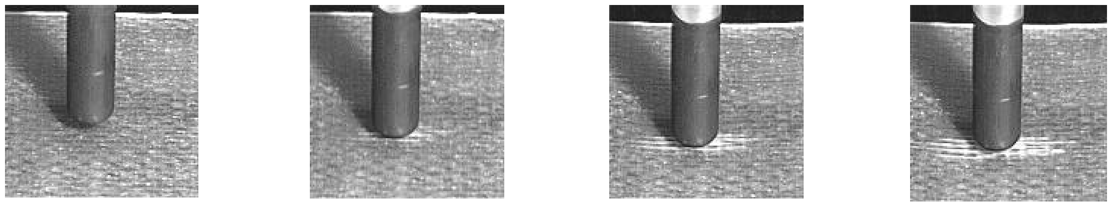


Fig. 6. Load versus time for the test 5.

For this part of the study the material damage is the same qualitatively for all the plates and the beams as discussed previously. First, we observe the matrix cracking (Fig. 7) and after the delamination appears and growths during the test.



0 ms + 2 ms + 4 ms + 4,5 ms

Fig. 7: Chronological evolution of the cracking.

Furthermore, the delamination is always inside the area where are located the matrix cracks. We can assume that a coupling exists between them. A 3D analysis of the delamination has been realised using the de-ply technique. This technique allowed direct observation of the delamination at each interface in the composite [6]. From all the observations of each interface of the laminate we can realise a 3D picture of the delamination. The assembling shows that delaminations exist nearly at all the interfaces. Moreover, the area increases towards the back surface of the laminate and is the largest in the furthest interface from the impact surface. The delamination propagated in the fibre direction of the layer below the interface. These phenomena are well known [7].

The following results of the polynomials calculated from the Doehlert test campaign were obtained :

- deflection of the plate centre (cm) for the first series (Eqn 4) and the second series (Eqn 5)

$$Y=2.23-0.74\ X_1+1.54\ X_2+0.26\ X_1^2+0.46\ X_2^2-1.06\ X_1\ X_2 \quad (4)$$
$$Y=2,41-0,69\ X_1+1,85\ X_2+0,38\ X_1^2+0,43\ X_2^2-0,73\ X_1\ X_2 \quad (5)$$

First we can notice that there is no significant difference for the two series. For this response and for our experimental domain there is no influence of the couple mass-velocity. Moreover, we can observe that the coefficient b2 is always higher than b1. It means that the deflection is rather dependent on the span. The coupling between the two variables can be considered as significant because of its value of coefficient which is close to the one of b1.

- maximum contact load (V) for the second series (Eqn 6):

$$Y=3.23+0.8\ X_1-3.48\ X_2-0.16\ X_1^2+1.92\ X_2^2+0.02\ X_1.X_2 \qquad (6)$$

This response is related to the previous one. In fact, if the span is small the load will be very important because the stiffness of the structure is high. It is why there is a sign minus in front of X_2. Furthermore, the coupling is insignificant (0.02).

- contact time (ms) for the first series (Eqn 7) and the second series (Eqn 8):

$$Y=14.4-3.64\ X_1+13.72\ X_2+1.5\ X_1^2+5.35\ X_2^2-4.31\ X_1.X_2 \qquad (7)$$
$$Y=24-7.96\ X_1+20.76\ X_2+4{,}75\ X_1^2+5.11\ X_2^2-6.78\ X_1.X_2 \qquad (8)$$

The analysis of this polynomial shows that the contact time depends more on the span (b2) than the width (b1). As shown previously, the increase of the span decreases the stiffness of the structure and of course the striker remains more time on it. The two polynomials are different because we can confirm that the contact time is dependent on the couple mass-velocity and more especially on the mass as shown in the study of the material 1.

- delamination area (cm2) for the first series (Eqn 9) and the second series (Eqn 10):

$$Y=6.27-2.29\ X_1-9.8\ X_2-2.24\ X_1^2+8.53\ X_2^2+7.53\ X_1.X_2 \qquad (9)$$
$$Y=4.37+2.06\ X_1-13.41\ X_2-0.86\ X_1^2+12.77\ X_2^2+3.56\ X_1.X_2 \qquad (10)$$

These polynomials give the evolution of the second damage mode of the structure. Therefore, it has the same evolution as the load : there is a sign minus in front of X_2 too. The significant difference between the two polynomials could be attributed to the accuracy of the measurement method of the aera.

CONCLUSIONS

Finally, the results presented here show that more the span is high and the width small and less the structure is damaged by the impact loading for the same couple mass-velocity. In fact, the stiffness of the plate decreases, therefore, it can transform more kinetic energy of the drop weight in elastic energy.

The mechanical behaviour of composite structures varies widely according to their dimensions. For all the plates, the load versus time exhibits some undulations which are attributed to a transverse eigen mode of vibration.

The delamination growths only after the development of the matrix cracking suggesting a coupling between them. A 3D observation of the damage has shown, that the delamination exists nearly at each interface of the material.

The experimental design method enables :

i) quantitative informations to be obtained on the influence of impact parameters, and coupling between variables to be detected,

ii) empirical models for impact responses to be established.

The coupling coefficients for mass and velocity for laminated composites are significant for most responses studied. This implies that the energy parameter will not always be sufficient to describe an impact loading.

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REFERENCES

1. M.L. Bernard and P.A. Lagace, "Impact resistance of composite sandwich plates." Journal of Reinforced Plastics and Composites, vol 8, 1989, pp. 432-445.

2. P. Davies, D. Choqueuse and A. Pichon, "Influence of the foam core on composite sandwich static and impact response." European Conference on Composites Testing and Standardisation, Sept 13-15, Hamburg Germany, 1994, pp. 513-521.

3. R.A.W. Mines, C.M. Worrall and A.G. Gibson, "The static and impact behaviour of polymer composite sandwich beams." Composites, Vol 25, n° 2, 1994, pp. 95-110.

4. G.E.P. Box, W.H. Hunter, J.S. Hunter, "Statistics for experiments." Wiley and Sons., 1987.

5. D.H. Doehlert, "Uniform shell designs.", Applied Statistics, Vol 19, n°3, 1970, pp. 231-239.

6. S.M. Freeman, "Characterization of lamina and interlaminar damage in graphite/epoxy composites by the de-ply technique." A.S.T.M. S.T.P., 787,1980, pp. 50-64.

7. C.E. Harris, Damage evaluation by laminate de-ply. Manual on experimental methods for mechanical testing of composites, Soc. Exp. Mechanics, CN, USA, 1989, pp. 147-149.