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Experimental study of a woven fiberglass composite delamination under impact shock

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ABSTRACT

This work is devoted to the experimental study of a glass/polyester composite laminate under impact shock. Based on a thermodynamic approach, the objective is the evaluation of specific interlaminar delamination energy in a multi-layer composite material under impact loading causing damage to it by cracking. For modeling impact loading, it is used an experimental device based on the principle of Charpy test which is to measure residual energy of a mass movement following a shock at speeds generally between 1 and 4 m/s, on a test piece cut of standardized dimensions requested in bending. Some of available energy is consumed by the rupture of the test piece. The results of this work showed that for impact test, mode I fracture energy is function of impact speed and the load fall energy. These results could be useful in the design of multilayer structures in composite materials subjected to impact loads.

1. Introduction

The resistance of composites to delamination is an important character which is widely studied by researchers. Indeed, the delamination phenomenon (cracking at the interface between plies different orientations) is one of the predominant modes of damage in composite laminates. The development of delamination causes a gradual decrease in stiffness followed by the complete breakdown of the structure. Failure under static loading of composite materials was widely studied by several authors (Bruno et al., 2005; Mattews & Swanson, 2007; Morais & Pereira, 2006; Prombut et al., 2006). On the other hand, the dynamic behavior of phenomenon of cracking of this type of material has not yet received sufficient attention. However numbers of models linked to the spread of cracks under dynamic loading have been proposed in recent years (Greco et al., 2013; Lonetti, 2010; Bruno et al.,

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2009). Even less when these structures are subject to impact loads. In this area, interesting experimental models are presented by Pegoretti et al. (2008). The breaking of the composite laminates can occur in very complex ways. As is known, the failure modes depend on stratification and loading direction relative orientation of fibers. The description of failure across the plies is relatively efficient for the classification of the failure mechanisms. We are interested in this work in mode I fracture i.e. interlaminar rupture that occurs in the interface between two plies of a laminate. This type of failure in fact studied by (Pereira & Morais, 2004; Kenane at al., 2010) for the case of epoxy matrix composites.

Some studies on investigation of impact performance of laminates are conducted by (Chakraborty 2007; Kersys et al. 2010; Karakuzu et al., 2010 Aarthy & Velmurugan 2013). On the other hand many studies on the behavior of composites under impact were conducted, e.g. by Saghafi et al. (2013), Salavati and Berto (2013). Quick stress are often referred to as "dynamic" when the effects of inertia can no longer be neglected, and that the kinetic energy involved is no negligible with regard to the energy of deformation. The sizing of structures becomes much more difficult to perform. Under these conditions, an experimental analysis for the understanding of phenomena of impact fracture becomes evident. There are enough systematically deformation speeds under $10s^{-1}$ for which testing machines have a close enough architecture that are used to characterize the behaviour and fracture of materials under quasi-static loading, although the inertia of the testing machine makes difficult the discharge. Secondly, for loads greater than $100s^{-1}$, typically used a montage of Hopkinson-Kolsky bar that allows, according to the device, apply a compression, tensile or torsional loading. Beyond $1000s^{-1}$, one of the privileged means of investigation is loaded by shock obtained either by impact of plates using powder or gas launchers, explosive. However the small number of experimental data related to rupture and evaluation of resistance characteristics to cracking of composites under impact loading slows the development of standards for composite structure damages. The present work proposes an experimental method for evaluation of specific delamination energy of a glass/polyester composite under impact by mode I fracture.

2. Materials and methods

2.1. Description of the test

The impact tests were executed with a device used to measure energy leading to breakdown of sample by impact, which the brand is *Tinius Olsen* and model *Impact 104* (Fig.1 and Fig.2). Tests were executed according to the standard ASTM D256 (American Society for Testing and Materials). Furthermore, it is the device trademark Dynisco model ASN 120 m, which was used to hack the samples. This step should also meet the standard ASTM D256. Since the test is performed using the Charpy method, the parts are placed horizontally and pendulum must hit the opposite side of sample.

Fig.1. Sheep pendulum Charpy

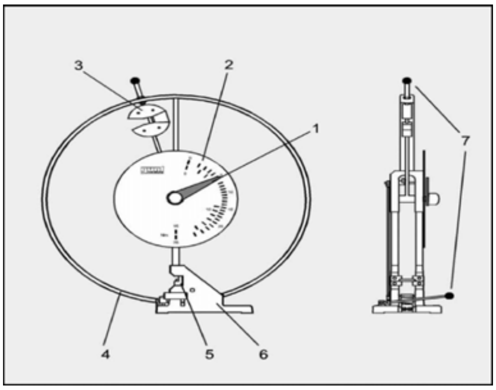


Fig.2. Device design: 1 needle; 2 measurement scale; 3 Hammer with removable additional weight; 4 protection ring; 5 sample lodging; 6 base; 7 trigger two hands and brake

The purpose of the test material is a glass/polyester composite (Fig.3) whose mechanical properties under static and long term loadings were the subject of a study by (Olodo et al., 2013).

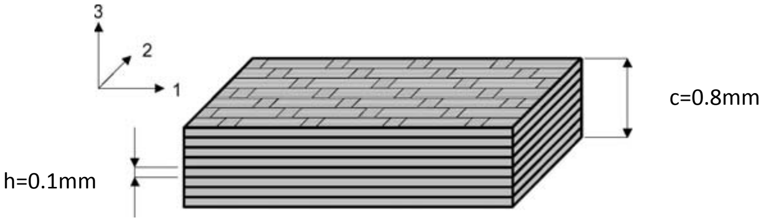


Fig.3. Studied woven glass/polyester laminate

Tablecloths are woven in a texture called Satin 5 balanced in the warp and frame directions. The laminate consists in a stacking of eight plies all oriented in same way. Stacking gives a final thickness approximately 0.8 mm.

The studied material is a woven glass/polyester laminate which the Table 1 below summarizes some characteristics of prepared plies HEXPLY PR10. These data come from the prepared supplier HEXCEL Composites.

Table 1. Prepared plies characteristics

Fiber diameter	d_f	$7\mu m$
Fiber volume mass	ρ	1760kg/m^3
Number of fibers by wick		3000
Fiber section		$0.11 mm^2$
Fiber linear mass	m_l	1g/1000m
Fabric structure		Satin 5
Fabric mass per unit area		285g/m^2
prepared ply mass per unit area	m_s	491g/m^2
Polymerized ply thickness	h	0.1mm
Stacking sequence		$[0]_8$
Fiber mass fraction in prepared ply	f_m	42%
Fiber volume fraction in prepared ply	f_v	50%

Principle of the test

This test is intended to measure energy required to break a previously notched specimen. It uses pendulum sheep at its end a knife that allows developing given energy at time of clash. Absorbed energy is obtained by comparing the difference in potential energy between the pendulum starting and the end of test. The machine is equipped with index to know pendulum height the starting, and highest position that pendulum will reach after rupture of test piece.

Energy obtained (neglecting friction) is equal to:

$K = m \cdot g \cdot h - m \cdot g \cdot h'$

$K = m \cdot g \cdot (h - h')$

m = sheep-pendulum mass [kg]

g = ground acceleration. [m s^{-2}] *(9.80665)*

h = sheep-pendulum height to its starting position [m]

h' = sheep-pendulum height to its arrival position [m]

Machine scale typically provides directly a value in joule. Impact energy for the sample deformation is shown on a display equipped with scale large dimensions. Trigger with both hands increases the user security. Moreover, a protective cover for the workspace and an acquisition of data measured on PC is available as accessory.

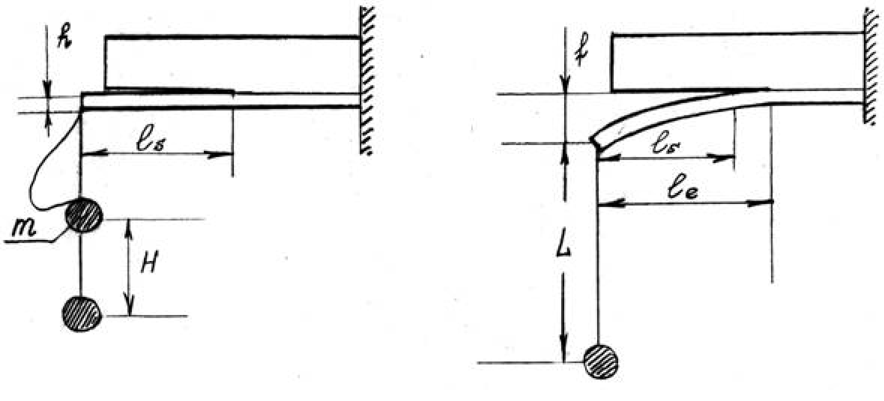
Modeling of impact loading, it is used an experimental device based on the principle of the Charpy test which consists in measuring the residual energy of a mass moving from shock at speeds generally between 1 and 4 m/s, on test piece cut to standardized dimensions requested flexural. Some available energy is consumed by the rupture of test piece. Test schematization is shown in Fig. 4.

Specific energy of breaking U_g is defined as enregy A_g necessary to emergence of a new cracking area D_s:

$$U_g = \frac{A_g}{D_s}. \quad (1)$$

For composites, the specific energy of quasi-static test failure has value between 10^2 and 10^3 j/m^2. Test piece is a laminate glass/polyester composite dimensions $a * b * c$, respectively the length, width and thickness of test piece. Numerical values of ''a'' and ''b'' are reported in Tables 2 and 3. Test piece thickness c =0.8 mm. The test piece embedded in the test machine has initial cracking and undergoes a load with free fall of the mass movement, leading to increase of interfacial crack.

Before starting the test, an initial cracking of length l_s is made on test piece (Fig. 4a) which is then embedded in testing machine. At the left end of the bottom layer is fixed a load of mass m with a wire length L. This experimental device allows considering that the wire is imponderable and absolutely rigid. The mass m is set so that the bar deformation is zero. This position of the mass corresponds to the zero potential. For loading, the mass is at height H above the zero level (corresponding to the zero potential). The height H corresponds to the lower limit of stored potential energy leading to the crack propagation. The balance of the system after loading is shown in Fig. 4 where the mass m position is given by the arrow f of lower layer and the crack length increases from l_s to value l_e.



a) b)

Fig.4. Diagram of the experimental device for impact loading

2.2. Modeling

Potential energy of the mass at the time t_0 will be:

$$U_H = mgH, \; g = 9.81 m/s^2. \quad (2)$$

Expression (2) corresponds to energy deployed to increase cracked surface D_s.

So be it:

U_b = Potential energy accumulated by inflected layer;

A = Energy dissipation during lower layer vibration;

$U_f = m.g.f$ - Change in the mass potential energy (f is the arrow on the bottom layer).

We consider that energy dissipation A is comparable to U_b.

Energy balance before and after loading will be written in the following form:

$$U_H = U_b + A - U_f + g_{dyn} D_s. \tag{3}$$

Considering that the crack propagation speed is quasi constant (with the exception of the beginning and the end of cracking), we obtain the expression of the delamination specific energy in following form:

$$U_{g_{dyn}} = \frac{(U_H + U_f - U_b - A)}{D_s} \tag{4}$$

3. Results and discussion

Experimental results are presented in Table 2 for load of mass m = 2.6g and in Table 3 for load of mass m = 10.5g. The loading speed has the expression $v = (2gH)^{0.5}$. g is the acceleration due to gravity, H is the fall distance (Fig. 4) and I is the inertia moment of delamination surface.

Table 2. (Part a) Treatment of experimental data for load of mass m = 2.6g

№ test	E (Pa)	a(m)	b(m)	h(m)	I (m^4)	m (kg)	H (m)	ls (m)	le (m)
1	4.00E+09	0.0999	0.0511	0.001	4.26E-12	0.0026	0.66	0.025	0.031
2	4.00E+09	0.0999	0.0511	0.001	4.26E-12	0.0026	0.76	0.031	0.035
3	4.00E+09	0.0999	0.0511	0.001	4.26E-12	0.0026	0.96	0.035	0.04
4	4.00E+09	0.0999	0.0511	0.001	4.26E-12	0.0026	1.16	0.04	0.045
5	4.00E+09	0.0999	0.0511	0.0	0.0	0.0026	0.0	0.0	0.045

Table 2. (Part b) Treatment of experimental data for load of mass m = 2.6g

№ test.	D_l(m)	f(m)	U_b (J)	P_{stat} (N)	U_{rup} (J)	Ds (m^2)	$U_{g\,dyn}$ $(J/m)^2$	v (m/s)	$U_{g\,dyn}/U_{g\,stat}$
1	0.006	1.49E-05	1.89E-07	0.0	1.68E-02	0.000307	54.8	3.59	8.76
2	0.004	2.14E-05	2.73E-07	0.0	1.94E-02	0.000205	94.7	3.86	15.1
3	0.005	3.19E-05	4.07E-07	0.0	2.45E-02	0.000256	95.7	4.33	15.3
4	0.005	4.54E-05	5.79E-07	0.0	2.96E-02	0.000256	115.0	4.77	18.4
5	0.0	0.008	0.0	1.2	0.0	0.0	$U_{g\,stat}$=6.25	0.0	0.0

Table 3. (Part a) Treatment of experimental data for load of mass m = 10.5g

№ test	E (Pa)	a(m)	b(m)	h(m)	I (m^4)	m (kg)	H (m)	ls (m)	le (m)
1	4.00E+09	0.1004	0.0414	0.001	3.45E-12	0.0105	0.1	0.004	0.02
2	4.00E+09	0.1004	0.0414	0.001	3.45E-12	0.0105	0.12	0.02	0.036
3	4.00E+09	0.1004	0.0414	0.001	3.45E-12	0.0105	0.2	0.036	0.052
4	4.00E+09	0.1004	0.0414	0.001	3.45E-12	0.0105	0.25	0.052	0.067
5	4.00E+09	0.1004	0.0414	0.001	3.45E-12	0.0105	0.3	0.067	0.084
6	4.00E+09	0.0999	0.0511	0.0	0.0	0.0105	0.0	0.05	0.0

Table 3. (Part b) Treatment of experimental data for load of mass m = 10.5g

№ test	$D_l(m)$	$f(m)$	$U_b(J)$	$P_{stat}(N)$	$U_{rup}(J)$	$Ds\ (m^2)$	$U_{g_{dyn}}\ (J/m)^2$	$v\ (m/s)$	$U_{g_{dyn}}/U_{g_{stat}}$
1	0.016	1.99E-05	1.03E-06	0.0	1.03E-02	0,000662	15.5	1.40	2.41
2	0.016	1.16E-04	5.98E-06	0.0	1.24E-02	0,000662	18.6	1.53	2.89
3	0.016	3.50E-04	1.80E-05	0.0	2.06E-02	0,000662	31.1	1.98	4.82
4	0.015	7.48E-04	3.85E-05	0.0	2.58E-02	0,000621	41.5	2.21	6.43
5	0.017	1.47E-03	7.59E-05	0.0	3.10E-02	0,000704	44.0	2.42	6.8257
6	0.0	0.01	0.0	1.1	0.0	0.0	$U_{g\text{stat}}$ =6.45	0.0	0.0

In Table 2 and Table 3, E is Young's modulus in bending of used polyester resin matrix for studied composite. It is a polyester resin for lamination NORPOL420-732 of company POLYESTER 93. Among the mechanical characteristics given by the manufacturer we have:

- Flexural Young's modulus E = 4 GPa, ISO 178
- CHARPY impact strength R_c =2.5 kJ/m^2 ISO 179
- Traction strength R_t=50 MPa ISO 527-1993
- Elastic modulus in traction E_t=3.2 GPa ISO527-1993
- Elongation at break : 1.8% ISO 527-1993

It is an unsaturated orthophthalic polyester resin with short polymerization time.

In last line of Tables 2 and 3 are shown results of static tests. The coefficient of variation for such tests does not exceed 15%. As it is shown in these Tables, the dynamic work of rupture is higher than static work value and depends largely on load impact speed, its mass and energy accumulated at the time of the impact. Thus, for impact test, the fracture energy is function of the speed and impact energy of the load fall.

$$U_{g_{dyn}}=U_{g_{stst}}F(m,v,U), \tag{5}$$

Here, F is a function of correction that can be evaluated as a first approximation by statistical means. In Fig. 5, it presents the relationship between the fracture energy and the load falling energy at the time of the impact.

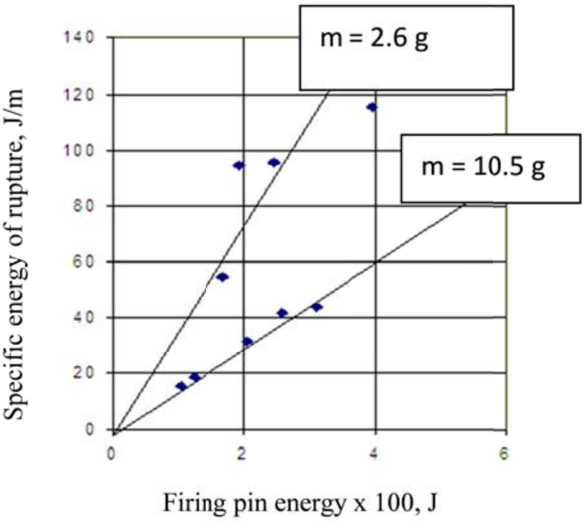


Fig.5. Diagram breaking specific energy - firing pin energy

Two cases are studied: load of mass m = 2.6 g and m = 10.5 g. For the same energy accumulated by the firing pins, loading by the small mass leads to a higher fracture energy value which is correlated with the firing pin speed at load time. As first approximation we can consider that the relationship between fracture energy and firing pin energy is quasi nonlinear. This is valid both for the small charge for the great (Fig. 5).

The relationship between fracture energy and the loading speed is presented in Fig. 6. The static value of the fracture energy corresponds to the speed zero. To the right of the same figure was the results of firing pin of mass *m* =10.5 g; top those mass *m* =2.6 g. Regarding the small mass, the energy is more important (Fig.5). It should be noted that at each point in the chart, the firing pin energy is different.

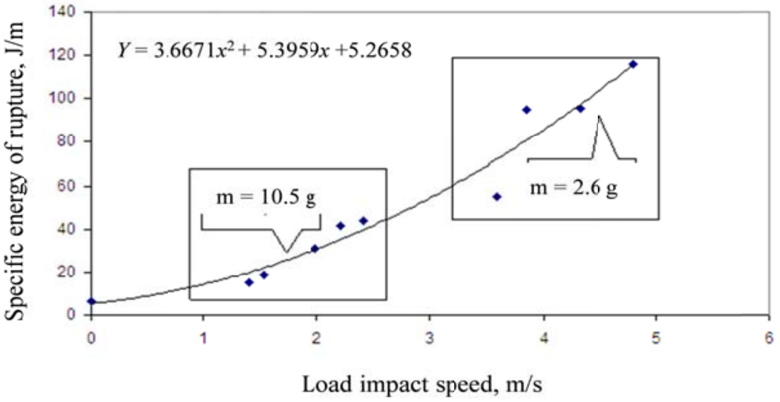


Fig. 6. Curve fracture specific energy - impact speed

As seen from Fig. 6, the experimental data are approximated by a quadratic function satisfactorily. Visibly, in an acceptable interval (slow loading) results for the large mass will be in a range of small loading speeds. Energy thresholds necessary for cracking propagation are presented in Figs. 7 and 8. Figure 7 corresponds to mass *m* = 2.6g while that Figure 8 corresponds to mass m=10.5g. To evolve the crack, it will take the firing pin's small mass accumulation of largest energy need more large mass. In Fig. 9 the micrographs of damages induced by the impact of test specimens are shown. The red arrow indicates impact point.

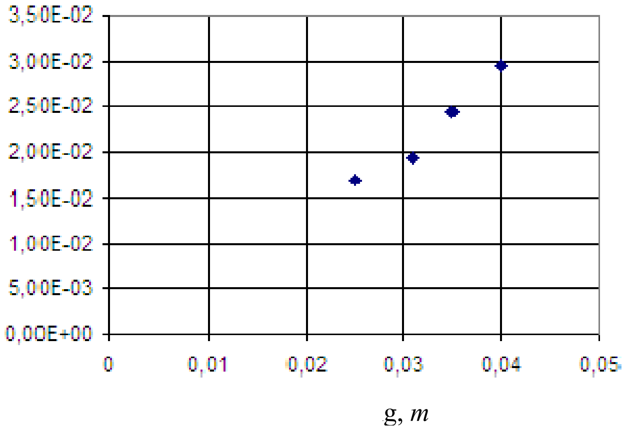


Fig.7. Energy necessary to the crack propagation (m=2.6g)

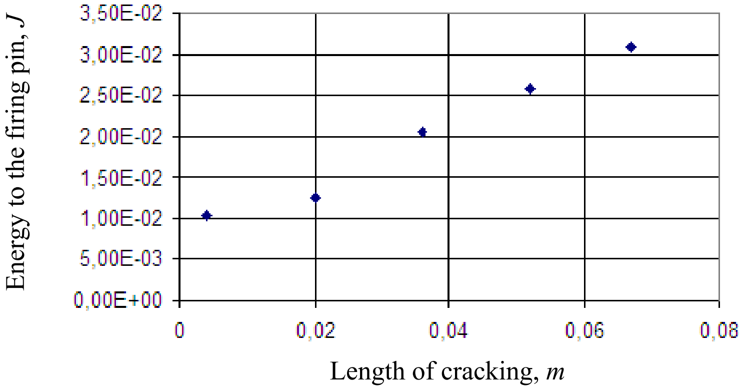
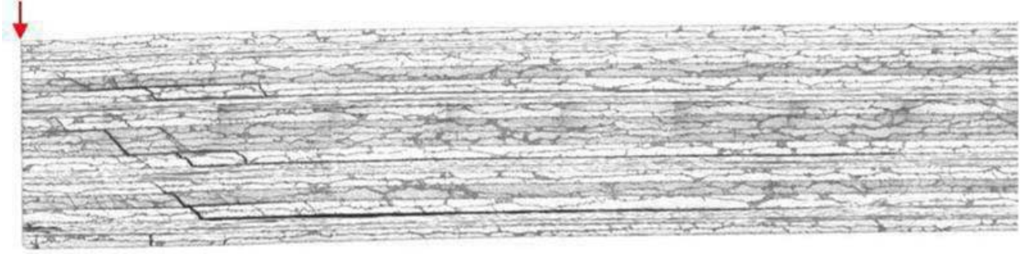
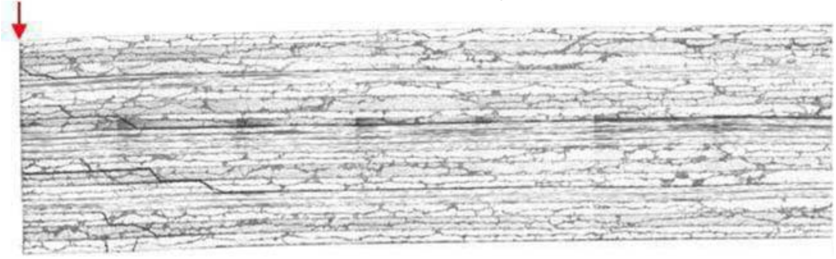


Fig. 8. Energy necessary to the crack propagation (*m*=10.2g).

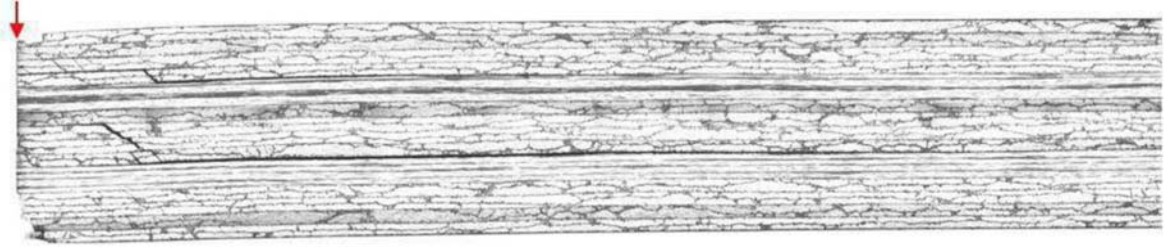
Specimen impacted to $1.68 \cdot 10^{-2} j$ by mass m = 2.6 g



Specimen impacted to $2.96 \cdot 10^{-2} j$ by mass m = 2.6 g



Specimen impacted to$1.03 \cdot 10^{-2} j$ by mass m = 10.5 g



Specimen impacted to $2.58 \cdot 10^{-2} j$ by mass m = 10.5 g

Fig. 9. Micrographs of damages induced by impact of test specimens.

Nowadays, analytical models are limited to simple geometries and often linked to particular impact configuration (boundary conditions, energy range). On the other hand, they are often limited to damage beginning or else provide a partial picture of damage extent. They do not know precisely the nature of created damage in the laminate. This is why impact numerical simulation is more and more sought after. Two types of finite element models are distinguished : finite element models with

‘’discreet’’ damage, where elements discretizing the laminate are joined by damaged interfaces on basis of cracks location and finite element models based on continuous damage mechanics.

For finite element modelling based on experimental results of this work, using continuous damage mechanics-based finite element model seems to be an essential complement to enrich the experimental campaigns. Doing so, it is planned to develop a dynamic implicit impact model for numerical simulation by finite element, able to predict induced damages. The first step in modelling will be to develop model using the ply behavior law ‘’Onera Progressive Failure Model’’(OPFM) (Laurin et al., 2007) and the bilinear model of cohesive zone proposed by Alfano and Crisfield (2001), then assess the different components sensitivity of behavior laws in response to an impact and expected damages. Impact and indentation tests on glass/polyester laminated must be carried out, analyzed and finally compared with the numerical results, in order to evaluate impact performance of OPFM model and its limits. This could lead to two main responses: first, the use of cohesive zone models seems necessary to predict the typical load drop. Secondly, one must take into account off-plan constraints, including shearing essential for predicting impact damages.

4. Conclusion

Following the experimental study on composite test piece, we can retain the below conclusions:

1. The specific energy of interlaminar delamination under impact loading is greater than that obtained under static load.

2. For a constant energy accumulated by a firing pin, firing pins of lower mass lead to a higher specific breaking energy value.

3. During an impact between solids of different masses, but having gained equal amounts of energy, the solid of greater mass are more dangerous because their energy from deployed delamination is less important and approximates the quasi-static value.

4. In order to determine energy restitution rate for representative load speeds of impact shock, a new experimental device has been implemented. According to a symmetrical opening movement to plane crack, this experimental approach allows to perform tests of impact shock at opening speeds from 1.40 to 5 *m/s* using the same experimental device.
5. Therefore the main contribution to the study of delamination is an experimental technique for determining critical energy restitution rate of a composite laminate depending on loading speed. The experimental setup was validated by a series of tests on a laminated glass/polyester.
6. In the optimization approach of the stratified composite, critical energy restitution rate is useful for mechanical behavior simulation and damage scenario of multi-layer laminated. This method also allows characterizing the material interfaces.

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