EXPERIMENTAL VALIDATION OF DELAMINATION CRITERION FOR SMALL MASS IMPACT

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Abstract

Impact on a plate by small masses, e.g. runway debris or hailstones, results in a wave controlled response which is independent of the dimensions and boundary conditions of the plate. This paper presents an experimental validation of a recently presented criterion for delamination onset during small mass impact. A gas gun was used to fire 2.1 and 8.4 g steel balls against 2.1 and 4.2 mm thick quasi-isotropic carbon/epoxy laminates.

The theoretically predicted delamination threshold velocities range from 30 to 50 m/s and are in good agreement with the experimental observations. The influence of the impactor mass is shown to be relatively small.

1 Introduction

Impact is a common cause for delamination and reductions in strength and stiffness of composite laminates, particularly in compression [1, 2]. Causes for in-service damage of composites in aircraft range from low-velocity large mass impact such as dropped tools, to medium velocity impacts by small masses such as runway debris and high velocity impact by ballistic projectiles. Most impact testing of composites is done using large mass drop weight tests, but it has been shown that small mass impacts cause more severe damage for a given energy, Fig. 1 [2].

Fig. 1. Example of delaminations due to a 10 J with a 10 g (left) and 1.5 kg (right) impactor.

Previously a delamination threshold load has been derived and validated for quasi-static conditions [3], i.e. large mass impact. Recently this criterion was extended to dynamic conditions by considering the deflections and inertial terms under small mass medium velocity (20-100 m/s) impact [4]. The criterion was validated by comparison with dynamic finite element simulations for a single delamination in homogeneous plates and by comparison with published experimental data from small mass impact tests on multi-directional laminates. The available experimental studies were generally not targeted at finding delamination threshold velocities and frequently lacked reliable material data.

The current work presents a more systematic experimental validation of the delamination criterion for medium velocity impact on realistic laminates.

2 Theoretical background

2.1 Impact response types

An impact generally initiates various types of transient wave phenomena. In plates these include tensile-compressive waves, shear waves and flexural waves. These waves propagate at different speeds and gradually decay due to material damping and various geometrical effects associated with wave propagation. For long impact times the transient waves have essentially died away and the response is quasi-static, i.e. the load-deflection relation is similar to a static case. For short impact times the response is governed by wave propagation and remains independent of the plate boundary conditions as long as no major wave has reached a boundary.

It can be shown that the response type is governed by the mass ratio between the impactor and the plate area affected by the impact [5], Fig. 2. Relatively large impactor masses cause a quasi-static response and small masses cause a wave controlled response. A typical example of large mass impact response is dropping of heavy tools during maintenance, which may be simulated by traditional drop tests. A typical example of small mass impact response is an aircraft hit by runway debris, which can be simulated by non-penetrating gas gun tests and certain spring actuated tests.

The condition for a pure small mass impact response is that no major flexural waves are reflected from the boundaries during the time of impact. For central impact on a square quasi-isotropic plate the mass criterion becomes [5]:

$$M/M_p \leq 1/4 \qquad (1)$$

where M is the mass of the impactor and M_p is the mass of the impacted plate. For non-central impacts the quantity M_p refers to a square region centred at the impact and having one side coinciding with the closest plate edge. The mass ratio obviously becomes irrelevant when the impact velocity is sufficient for penetration.

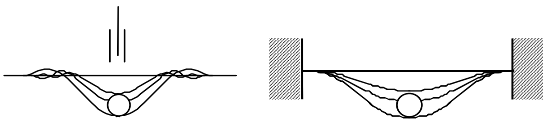

Fig. 2. Response during small mass (left) and large mass (right) impact

The current paper is entirely focused on the prediction of delamination onset during small mass (wave controlled) impact.

2.2 Impact response equations

In this paper we will consider small mass impact by a spherical isotropic impactor on a quasi-isotropic plate. The impactor has radius R, mass M, initial velocity V_0, Young's modulus E_i, Poisson's ratio ν_i, and effective contact modulus $Q_{ci}=E_i/(1-\nu_i^2)$. The plate has the following properties:

- Density ρ
- Thickness h
- Mass per unit area $m=\rho h$
- Bending stiffness D
- Out-of-plane contact modulus Q_{cp}
- Out-of-plane shear modulus G_{rz}
- Shear factor K
- Out-of-plane shear stiffness $S=KG_{rz}h$

For homogeneous plates $K\approx5/6$. The calculation of Q_c for homogeneous quasi-isotropic plates is described in [4], and both Q_{cp} and G_{rz} must be defined as suitable average values for a homogenized laminate. For orthotropic laminates D and S may be replaced by effective stiffnesses D^* and S^* [4] and the mass M_p of a square region by M_p of a rectangular region [5].

The approach ("indentation") between the impactor and the plate is governed by a contact relation. For Hertzian (elastic) contact the relation becomes:

$$F = k_H^*\left(w_i - w_p\right)^{3/2} \qquad (2)$$

where w_i and w_p are the displacements of the impactor and plate at the point of impact. The indentation stiffness k_H^* is approximately given by:

$$k_H = \frac{4}{3} Q_c \sqrt{R} \quad \text{where} \quad 1/Q_c \approx 1/Q_{cp} + 1/Q_{ci} \qquad (3)$$

A more accurate calculation of k_H^* requires consideration of the finite plate thickness, which results in slightly higher values [4]. The effective contact modulus Q_{cp} of multidirectional laminates is somewhat higher than E_{33} of the individual plies [6]. Both these corrections are normally in the order of 10-20% and can usually be neglected without any major effect on the peak load. For sandwich plates the shear factor K and the contact relation, Eq. (2) must be modified as described in [7].

The wave controlled response associated with an elastic small mass impact may be predicted by a stepwise solution of the non-linear dynamic equations of the plate-impactor system [7]. A fairly accurate approximation of the peak load can be obtained by superposition of the solutions to the following three asymptotic impact cases [8]:

- Pure bending of plate without indentation
- Pure shearing of plate without indentation
- Pure contact indentation of inflexible plate

The resulting peak load for pure bending is:

$$F_b = 8V_0\sqrt{mD} \qquad (4)$$

Similarly the peak load for pure shearing is:

$$F_s = 2V_0\sqrt{\pi MS} \qquad (5)$$

The peak load in pure contact indentation depends on the contact law. For Hertzian (elastic) indentation of a monolithic (not sandwich) plate the peak contact load may be approximated by:

$$F_c = k_H^{*\,2/5}\left(\tfrac{5}{4} M V_0^2\right)^{3/5} \tag{6}$$

The resulting approximation for the peak load during small mass elastic impact becomes:

$$1/F_{\max} = 1/F_b + 1/F_s + 1/F_c \tag{7}$$

2.3 Delamination threshold criterion

The load for growth of n delaminations during small mass impact derived in [4] is given by:

$$F_{dn} \approx 1.213\pi\sqrt{32DG_{IIc}/(n+2)} \tag{8}$$

where GIIc is the interlaminar toughness in mode II. The load in Eq. 8 was obtained by multiplying the quasi-static delamination load by a factor 1.213, which accounts for the inertial effects during small mass impact. In the following analysis it is assumed that a single delamination initiates at the interface with the highest shear stresses, and that additional delaminations develop afterwards. Thus, the delamination threshold load during small mass impact is given by:

$$F_{dth} \approx 1.213\pi\sqrt{32DG_{IIc}/3} \tag{9}$$

The delamination threshold velocity V_{dth} for a certain impactor and plate may be found by equating the expression for the peak load in Eq. 7 with the delamination threshold load in Eq. 9. The resulting equation for V_{dth} is:

$$V_{dth} = 1.213\pi\sqrt{DG_{IIc}/6}\times \\ \times\left[\frac{1}{\sqrt{mD}} + \frac{4}{\sqrt{\pi MS}} + \frac{8(4/5)^{3/5}}{k_H^{*\,2/5} M^{3/5} V_{dth}^{1/5}}\right] \tag{10}$$

The solution for V_{dth} may be found by iteration. A suitable initial guess is obtained by neglecting the last term in the first iteration. Finite plate thickness was considered in the following calculations of k_H*, Thus, it becomes a function of the load, as the latter has a direct influence on the contact radius.

3 Experiments

A detailed description of the specimens, equipment and procedures in the experiments may be found in [9].

3.1 Specimens and impactors

2.1 and 4.1 mm thick 100x100 mm laminates were made from AS4/8552 carbon-epoxy prepreg with the layup $[(0/90/\pm45)_s/(90/0/\mp45)_s]_n$ n=1 or 2. This specific layup lacks bending-twisting and bending-membrane coupling and has *equal* flexural and membrane modulus independent of laminate thickness and in-plane direction. The specimen size was selected to satisfy the condition for small mass impact response, Eq. 1. Assumed ply properties are:

Table 1. Assumed ply properties

Poisson's ratio	Young's modulus [GPa]	Shear modulus [GPa]	G_{IIc}= 829 J/m^2
$\nu_{12}=\nu_{13}=0.3$	E_1=135	$G_{12}=G_{13}$=4.5	ρ=1560 kg/m^3
ν_{23}=0.5	$E_2=E_3$=10	$G_{23}=E_2/(2+2\nu_{23})$	t_{ply}= 0.130 mm

Homogenised laminate properties were calculated using geometric averages as follows:

$$\nu_{rz} = \sqrt{\nu_{13}\nu_{23}} \quad \nu_r = \sqrt{A_{12}A_{21}}\Big/\sqrt{A_{11}A_{22}} \\ G_{rz} = \sqrt{G_{13}G_{23}} \quad E_r = \left(1-\nu_r^2\right)\sqrt{A_{11}A_{22}}\Big/h \tag{11}$$

where A_{ij} agrees with the conventional notation for laminates.

The impactors consisted of 8 and 12.7 mm diameter hardened steel ball bearings with a mass of 2.1 and 8.4 g respectively. The impactor properties were E=210 GPa, ν=0.3 and ρ=7830 kg/m^3.

Table 2. Number of specimens in each test case

	Laminate thickness	
Impactor mass	2.1 mm	4.1 mm
2.1 g	6	6
8.4 g	6	6

3.2 Experimental equipment

The experimental equipment included a gas gun to fire plastic plugs (sabots) with steel balls and ultrasonic equipment to monitor delaminations.

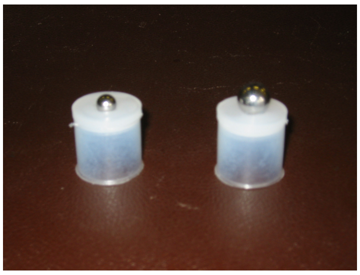

Fig. 3. Plastic sabots with steel ball impactors

The gas gun, of in-house design, consisted of a pressure vessel equipped with a pressure meter connected to a bursting membrane and subsequently to an acceleration pipe, a sabot catcher, a velocity measuring device and a sealed impactor catcher containing the specimens. The velocity was measured in a time-of-flight unit consisting of two optical gates connected to a time counter.

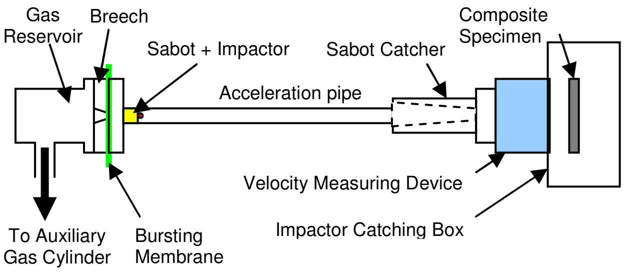

Fig. 4. Schematic drawing of gas gun

The plastic burst membranes were equipped with electrically heated wires to control the burst pressure. Thus, a suitable pressure was obtained by opening the valve to the gas gun pressure vessel until the pressure meter reached the required value. The burst membrane was then broken by switching on the electrical heating wires.

Initial tests indicated a significant scatter in velocities which were believed to be partly caused by tumbling of the sabot. For this reason the regular cylindrical sabot catcher was replaced by a conical catcher, which somewhat reduced the scatter.

The ultrasonic equipment consisted of a portable manual “Andscan”-system for quick control of damage initiation, and an automatic C-scan “Midas” system for detailed measurement of delamination area.

3.3 Experimental procedures

Prior to testing all specimens were C-scanned to confirm that they were free from defects. The thickness of each specimen was measured at nine locations using a micrometer.

For each impactor mass calibration curves were generated for impact velocity versus burst pressure.

The impact tests were performed by gradually increasing the burst pressure for a given specimen until a delamination was detected with the “Andscan”. In subsequent impacts the aim was to impact virgin specimens at a marginally higher velocity to confirm that delamination initiation in the first specimen had not been affected by the repeated impacts.

Specimens with delaminations were taken for measurement of the projected delamination size using the automatic C-scan system.

4 Results and discussion

The theoretical delamination threshold velocities were calculated using Eq. 10 and the material data in Section 3.1. Experimentally it proved difficult to accurately control the impact velocity, and the goal to gradually increase the impact velocity was only partly achieved. Thus, delamination sizes were obtained for a range of velocities around the threshold velocity. Comparisons between measured delamination sizes and predicted threshold velocities (dashed lines) are shown in Figs 5 to 8.

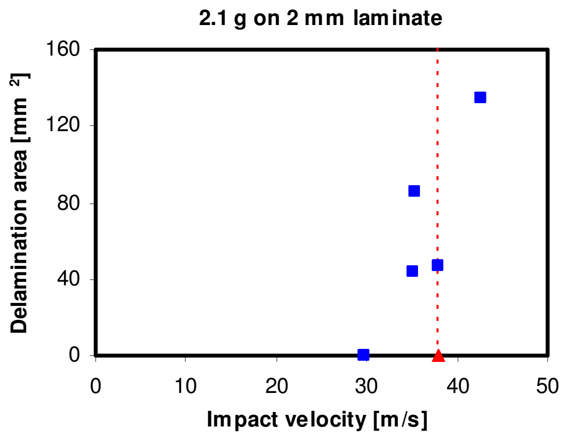

Fig. 5. Delamination size vs velocity for 2.1 g impactor on 2 mm laminate

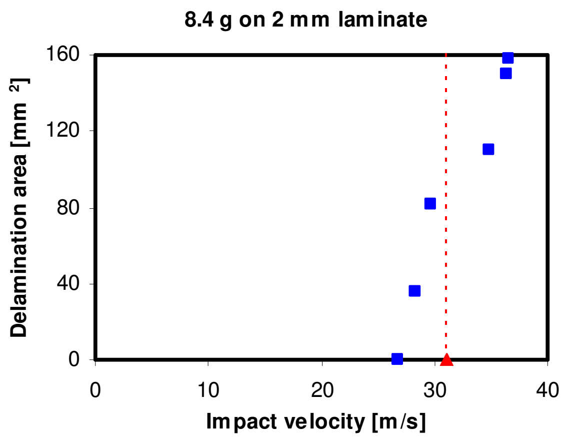

Fig. 6. Delamination size vs velocity for 8.4 g impactor on 2 mm laminate

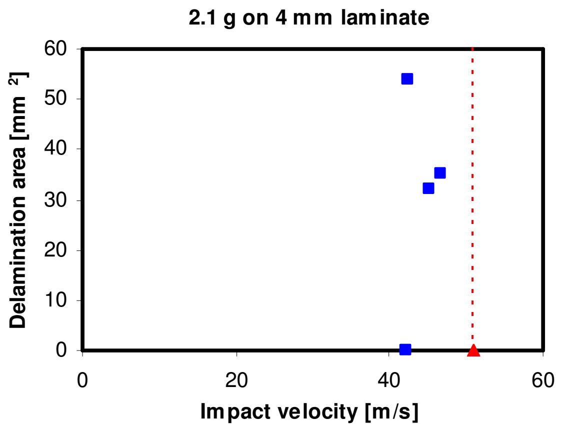

Fig. 7. Delamination size vs velocity for 2.1 g impactor on 4 mm laminate

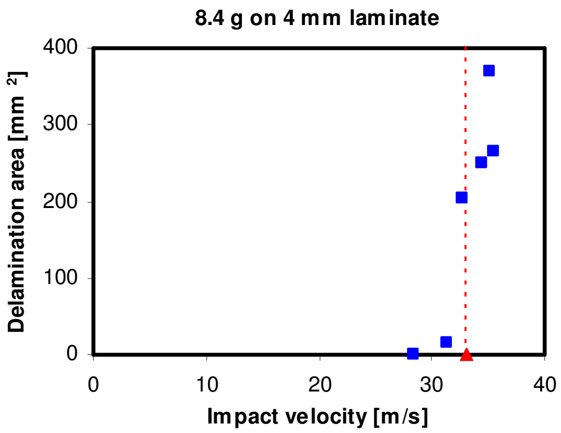

Fig. 8. Delamination size vs velocity for 8.4 g impactor on 4 mm laminate

The square bracket of Eq. 10 is dominated by the first term (i.e. bending) which is independent of the impactor mass. As a result the delamination threshold velocity is relatively independent of the impactor mass, which is illustrated by Figs 5 to 8.

There is a fairly good agreement between theory and experiments. The assumed interlaminar toughness G_{IIc} strongly influences the threshold load and may be a cause for the slight overestimation of the threshold velocity. Delaminations during impact typically occur between plies of different orientation and the assumed G_{IIc}=825 J/m^2 was based on measurements on 0º/45º interfaces in AS4/8852 material [10]. It is, however, worth noting that noticeable delamination growth is likely to first appear close to the mid-plane at interfaces with the lowest interlaminar toughness. In the current layup the midplane contains a 0º/90º interface. Measurements on 0º/45º and 0º/90º interfaces of a similar material (IM7/8852) indicated that 0º/90º interfaces have about 25% lower toughness [10]. If this also applies for AS4/8852 the predicted delamination threshold velocities would be reduced by about 12%, which is in good agreement with the observations. It is also worth mentioning that the material used in the current tests was expired, which may have contributed to a lower toughness than the one obtained in [10].

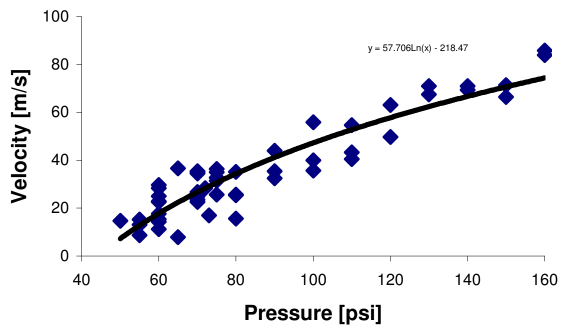

Fig. 9. Velocity scatter versus pressure for 8.2 g ball

The main reason for the difficulties in controlling the impact velocity was the large variations in velocity at a given burst pressure, Fig. 9. The causes for this seem to be friction and the uncontrolled flow conditions in the burst membranes, which both are of lesser concern at the velocities and pressures where the gas gun is normally used. The uncontrolled flow may partly have been caused by the presence of the heating wires, and partly by the irregular lip shape created in membranes bursting at low pressures. These problems could be reduced by replacing the burst membranes by a fast electrically controlled valve. The friction is an effect of the oversized sabot designed to eliminate pressure losses at higher velocities. Such losses are not a concern at the current test speeds, where friction could be reduced by using sabots made of light rigid foam cylinders with a slight play in the acceleration pipe, Fig. 4.

5 Conclusions

The present experimental study has dealt with delamination onset during small mass (wave controlled) impact on composite laminates, e.g. due to runway debris or hailstone impact on stationary structures. The results have been compared with predictions of the delamination threshold velocity obtained by combining a recently derived delamination criterion with expressions for the peak load during small mass impact. The experiments demonstrate the ability of the theory to predict the delamination onset and delamination threshold velocity in real quasi-isotropic laminates made of plies of different orientation. Comparison with published experimental data indicates that the approach can be extended to orthotropic laminates [4].

The ability to predict delamination threshold velocities should be highly useful in applications, and will allow designers to design for impact resistance or to evaluate the severity of different small mass impact threats.

Acknowledgements

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