# EFFECTS OF THE VELOCITY IN THE DELAMINATION OF CARBON-EPOXY PLATES SUBJECTED TO LOW-VELOCITY IMPACT LOAD

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## Abstract

Impact is one of the most severe loading cases a material may be subjected to. Especially within the automotive industry, where products must be developed to fulfill very demanding specifications concerning impact. Nowadays the use of light and high performance materials such as composite is becoming more and more important that allows the reduction of weight and de $CO_2$ emissions. In this communication a previously developed characterization method [15] is applied to a carbon epoxy bidirectional composite. This method is based on the instrumented drop weight impact experimental technique. Tests at different impact velocities are performed for the same level of impact energy by varying the striker mass. The impact curves and energies were analyzed from these instrumented tests. The delaminated areas generated in each impact test are studied carrying out C-scan ultrasonic analysis before and after each test. In this article it is shown the influence of the impact velocity on the damage area of a composite plate submitted to low velocity impact tests.

## 1 Introduction

Nowadays lightweight is considered to be one of the most important criteria when selecting materials to design transport vehicles such as cars, trains or planes. In these industries where vehicles weight directly depends on its consumption and emissions, polymers are replacing metallic materials due to their low cost and lightness. Nevertheless, it is not possible to use them in structural applications because of their low mechanical properties, and it is precisely in those applications (chassis, bumpers, etc.) where there are more improvement possibilities in terms of weight reduction. The solution for these applications is to use fiber reinforced polymeric materials, although they are more expensive, but as light as polymers and capable of providing excellent specific mechanical properties.

Impact loads are the most restrictive type of solicitations a transport vehicle or its components can be subjected to. Under these kind of loading cases vehicles must absorb as much energy as possible in order to protect their occupants or cargo. Composites exhibit less impact resistance than traditional metallic materials; Nevertheless, in certain circumstances they are able to dissipate more energy during an impact because their failure is produced due to the combination of different modes of degradation; in long fiber reinforced polymeric materials the energy dissipation is caused by the failure of the plies under different solicitations and by interlaminar failure or delamination, and both material degradation mechanisms contribute to the dissipation of energy during an impact.

Impact loads that happen in transport applications are considered to be low energy impacts, because they usually do not achieve impact velocities above of 180 km/h. Delamination is the most critical failure mode when a composite structure is subjected to a transverse impact, because under this solicitation delamination is the failure mode that determines the moment in which the composite undergoes an irreversible damage [1]. This kind of failure also has another problem; the damage does not appear on the surface of the structure, so it is not possible to detect it by naked eye.

Impact loads imply that the material or structure is subjected to different strain rates depending on the applied impact condition, and polymeric materials exhibit a strain rate dependent behavior due to its viscoelasticity [2]. Delamination occurs in the matrix rich areas, so the behavior of the composite interlayer depends upon its strain rate. This implies that the global behavior of a composite structure subjected to a transverse impact load will depend on the strain rate and consequently the velocity of the impact [3].

The excellent specific mechanical properties and high capacity to dissipate energy are making composite materials acquire a great relevance to the detriment of the materials traditionally used in the transport industry. However, the design of these composite components involves difficulties (deciding what type and how much reinforcement must be used and its exact location in the structure) that cannot be overcome without the help of complex material models and powerful computational tools like finite element method (FEM). Moreover, the need of analyzing their behavior under impact makes even more necessary the use of these if the effects of the impact velocity on the material must be taken into account. The aim of this study, first part of another longer project, is to analyze the effect of the impact velocity in the delamination phenomenon of the composite materials, in order to take it into account afterwards in finite element models.

### *1.1 Impact behavior of composite materials*

Impacts, dynamic solicitations of short duration and high intensity, on structures can cause important damage to the components [4]. While designing automotive parts or structures subjected to impact loads it is necessary to try to achieve two objectives: On the one hand the structure has to be resistant enough to avoid collapsing. On the other hand the structure has to dissipate the highest amount of impact energy so the occupant or cargo of the vehicle suffers lighter the consequences of any impact.

The degradation process of a composite material subjected to a transverse impact is the following: First of all matrix cracking occurs in direction parallel to the fibers [4], this cracking makes the structure not suffer a loss of mechanical properties, but it becomes easier to start the following phenomenon of degradation, delamination. Delamination onset determines when the material undergoes an irreversible damage supposing the most critical failure mode for these materials under these solicitations [1]. The third phenomenon is fiber breakage due to localized stress concentration in the contact zone, this failure occurs after a total or local delamination of the laminate. The latter phenomenon of failure is penetration, which consists in that the impactor breaks through the sample.

### *1.2 Strain rate effects on composite materials*

The material of a structure under an impact load undergoes different strain rate conditions, which can suppose a change in the mechanical behavior of the same material. In the case of composite materials numerous authors have analyzed the strain rate effect on the constituents: Most authors note that the strain rate affects the mechanical behavior of the matrix of the composite [5]. However, in the case of reinforcements, there is insufficient information to quantify this effect [2]. Different studies associating the mechanical behavior of the matrix and the interlaminar behavior of the composite conclude that the interlaminar properties of the composites are rate dependent too: It has been found that the interlaminar toughness of a carbon-epoxy composite may depend on the strain rate, although there is no consensus on how does it affect [6]. In Table 1, some of the articles that analyze the strain rate effect on interlaminar fracture toughness are shown.

| **Articles** | **Interlaminar delamination mode** | **Effect of the strain rate on the interlaminar toughness** |
|---|---|---|
| 7-10 | I | No dependent |
| 11 | | Increases with the strain rate |
| 7, 12 | II | Increases with the strain rate |
| 13 | | Decreases with the strain rate |

**Table 1.** Studies on the effect of loading rate on the interlaminar toughness**.**

## 2 Materials and testing methods

### *2.1 Material*

Composite plates made of carbon fiber reinforce and epoxy matrix were manufactured by infusion. A $[0/90]_{10s}$ layup was developed from a unidirectional standard modulus carbon fiber (Toray's GV 170 U) and an epoxy resin for infusion (SiComin's SR 8100 / SD 8822). Plates of 250 x 250 mm were manufactured leading to a nominal thickness of 3.75 mm and a 51 ±1% fiber volume fraction. These plates were cut by water jet process into circular samples of 60 mm diameter.

### *2.2 Impact testing*

Impact tests were carried out in a falling weight impact machine (Fractovis Plus, Ceast) instrumented with 20 kN strain gauge load cell, and the contact force history was registered during impact. Then the recorded force time history was converted into impact parameters, such as acceleration, velocity, displacement and energy histories, based on Newton´s second law and the assumption that the nose of the impactor is perfectly rigid [14]. The hemispherical impactor headstock had a diameter of 20 mm.

The tests were conducted under different impact energy levels ranging from 0.9 to 49 J to determine the impact behavior of the composite under different velocities with the same striker mass (2.045 kg). Afterwards, three energy levels (10, 15 and 20J) over the damage threshold were chosen to analyze the effect of impact velocity; changing the mass of the striker by additional 1 kg masses (2.045, 3.045, 4.045 and 5.045 kg striker mass can be obtained) it is possible to achieve the same impact energy with different impact velocities.

The circular samples were simply supported on an annular ring with an inner and outer diameter of 40 mm and 60 mm respectively.

### *2.3 Non destructive Inspection*

The portable sound encoder OmniScan® MXU M and a two axes encoded scanner were used to perform ultrasonic measurements with a broadband phased array probe of 64 elements (10 x 0.6 mm each) and a center frequency of 5 MHz. A gel was applied to the composite and the measurements were performed at normal incidence in pulse echo mode.

## 2 Results and discussion

Based on the delamination threshold energy, also called critical energy amount when the delamination threshold happens, impact events can be divided into two main categories: subcritical for values of impact energy below this threshold or supercritical for those above. Representative plots of force and energy versus time of the impact tests are shown in the Fig. 1. Consecutive impact tests varying impact energy were carried out to calculate an approximate the delamination threshold energy.

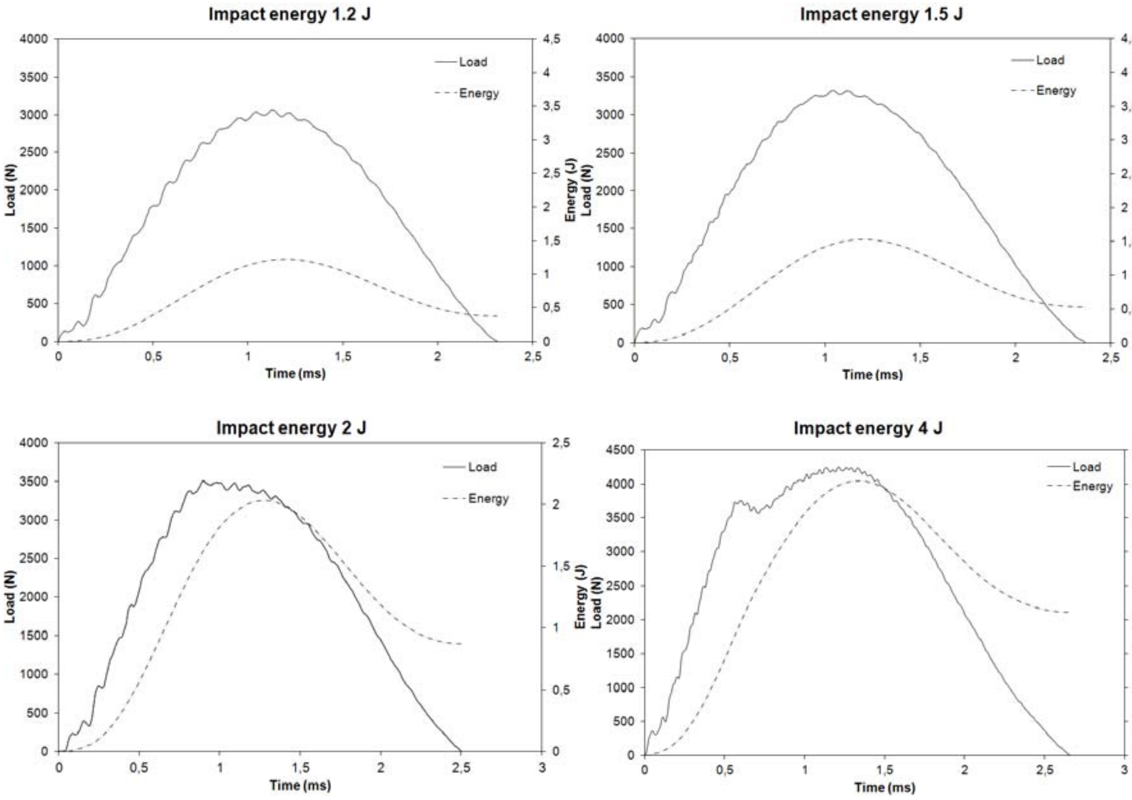

**Figure 1.** Force and energy versus time curves for drop tests with a 2.045 kg striker and impact energies of 1.2 J, 1.5 J, 2 J and 4 J.

These tests show that the delamination damage threshold energy would be between 2 J and 4 J. The subcritical impact tests (the first three curves) show a symmetric force versus time curve even at this low energy impact energy loss can be significant, this energy loss can be measured analyzing the maximum and the final energies on each test [15]. For supercritical values of impact energy the force versus time curve is not symmetric because delamination growth, and also other damage modes as indentation or fiber cracking, provoke a fall of the force and the unloading slope is different because the material losses its initial stiffness. The final energy/maximum energy ratio also decreases once the delamination damage force or energy is overcome.

The damage produced to the samples at each energy level has been analyzed visually; the samples in Fig. 2 show the damage in four energy levels.

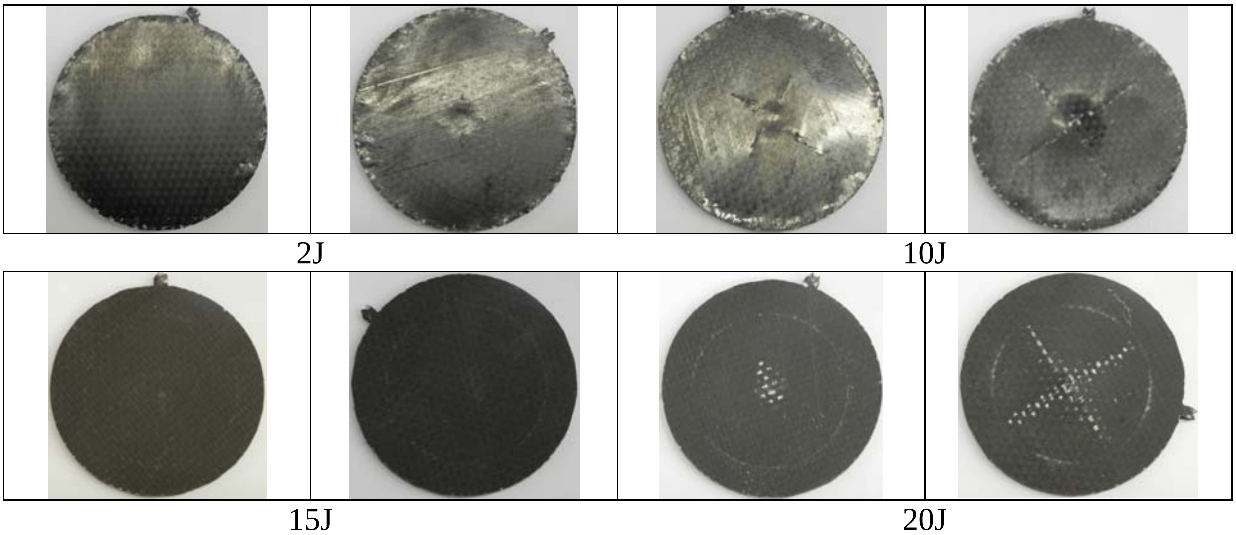

**Figure 2.** Impact face and back face of impacted samples for impact energies of 2 J, 10 J, 15 J and 20 J.

Before the critical energy is reached no damage is shown in the tested samples (2 J). After that critical energy level different damage levels appear on the samples. Samples submitted to the second energy level (10 J) show an indentation phenomenon in the impact surface, but damage does not affect to the back surface, fiber breakage is only shown in the indentation, so it can be considered that only delamination its given. For higher energy levels (15 and 20 J) indentation phenomenon and fiber cracking damage modes are shown both for impact and back surfaces. In the highest energy level the samples are so damaged that they lose their flatness so it would not be possible to analyze them by C-scan technique.

Once this preliminary analysis of the behavior of the composite samples under drop weight tests is done, three levels of energy were chosen over the damage threshold. The effect of the impact velocity on the damaged areas and the impact response of the composite material will be analyzed. Testing conditions are described in Table 2.

| Sample nº | Striker mass (kg) | Impact velocity (m/s) | Impact energy (J) |
|---|---|---|---|
| 1 | 2.045 | 3.13 | 10.02 |
| 2 | 3.045 | 2.57 | 10.03 |
| 3 | 4.045 | 2.23 | 10.03 |
| 4 | 5.045 | 1.99 | 10.04 |
| 5 | 2.045 | 3.83 | 15.03 |
| 6 | 3.045 | 3.15 | 15.06 |
| 7 | 4.045 | 2.73 | 15.06 |
| 8 | 5.045 | 2.44 | 15.07 |
| 9 | 2.045 | 4.43 | 20.15 |
| 10 | 3.045 | 3.63 | 20.19 |
| 11 | 4.045 | 3.15 | 20.21 |
| 12 | 5.045 | 2.82 | 20.18 |

**Table 2.** Testing conditions for each sample.

The results of the force and energy versus time of all these impact tests are shown in the Fig. 4, 5 and 6.

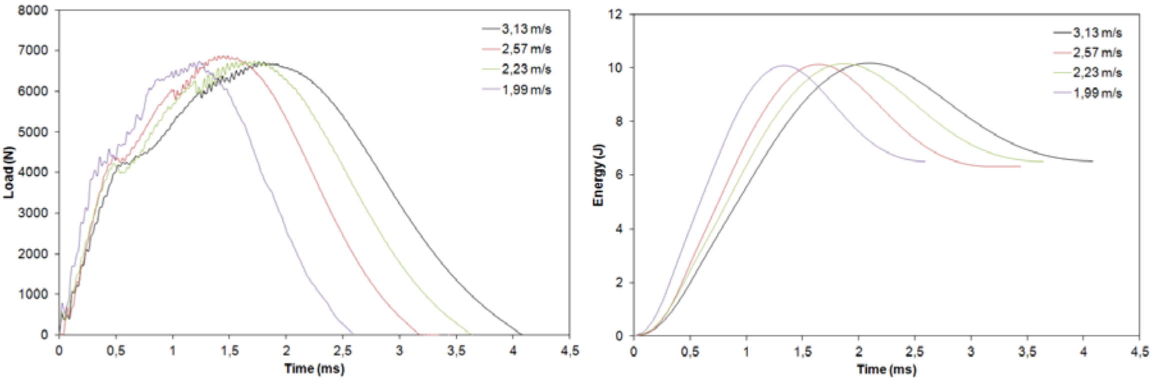

**Figure 4.** Load vs. time and energy vs. time test curves for different impact velocities and same impact energy of 10 J.

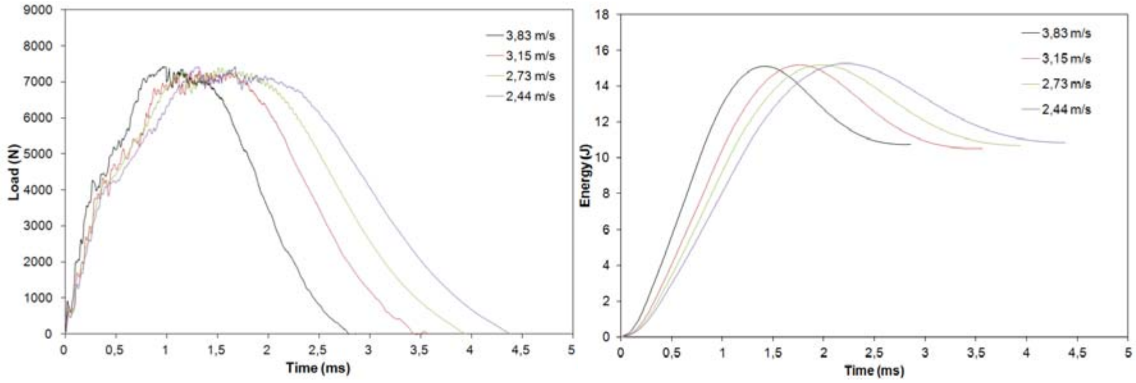

**Figure 5.** Load vs. time and energy vs. time test curves for different impact velocities and same impact energy of 15 J.

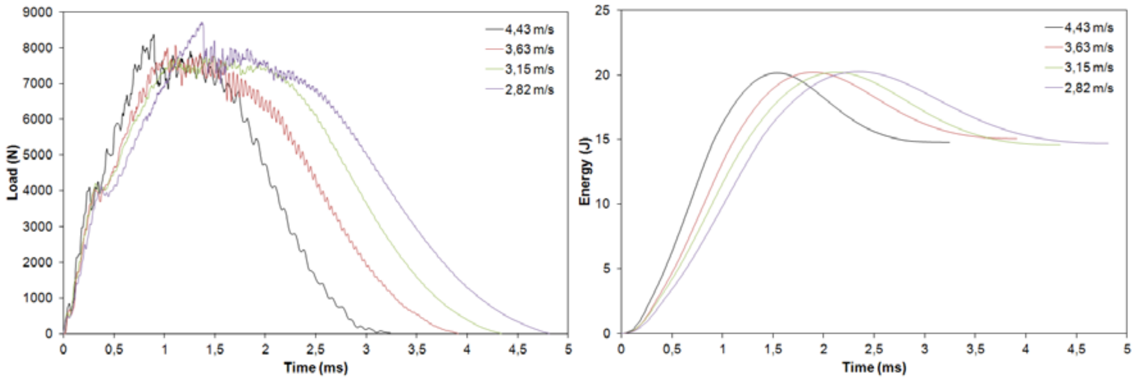

**Figure 6.** Load vs. time and energy vs. time test curves for different impact velocities and same impact energy of 20 J.

Results show that the damage threshold of the material is always around 4000 N, and that is independent of impact conditions as energy or impact velocity. The maximum impact force is not velocity dependent, but increases while increasing the impact energy. Force versus time curve slope becomes higher for a higher impact velocity, which supposes that the damage energy threshold would be smaller for higher impact velocities. The contact time decreases as the impact velocity increases due to the impact phenomenon becomes shorter. The impact velocity does not affect in the final energy level, although if it can see that the energy is dissipated in a faster way and that the damage threshold energy is lower.In the highest energy level (20 J) and for the highest impact velocity (4.43 m/s) the force versus time curve shows dynamic effects that could suppose a problem in the energy calculation, this phenomenon should be analyzed for higher velocities and with more samples in this case.

The samples were analyzed before and after the impact by the C-scan method, Fig. 7. As result of this analysis damaged or delaminated areas are quantified by an image correlation system. Result can be shown in Fig. 8.

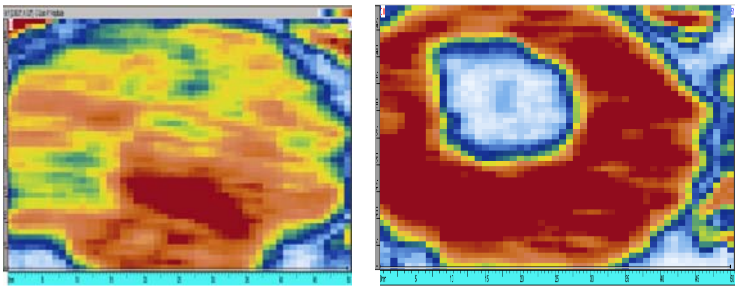

**Figure 7.** C-scan of a sample before and after a 15 J impact.

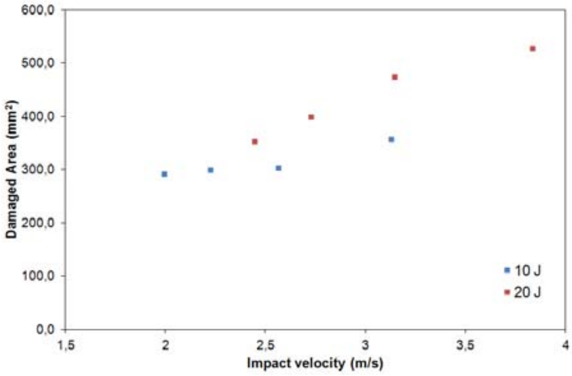

**Figure 8.** Damaged area versus impact velocity for the two levels of energy analyzed by the C-scan.

Results show that in a range between 2 and 4 m/s and for both energies analyzed (10 and 15 J), the damaged area grows as impact velocity increases. The damaged area in the tests of lower energy is less dependent on the speed of impact; this can be due to a change in the damage mode of the sample due to an increase of the impact energy. On these tests, there is no sign of fiber breaking, so it is supposed delamination and local indentation are the predominant damage modes on these samples. Samples of 15 J show delamination as well as fiber breaking in both of their surfaces, these damage mode changes can affect onto the higher increment of the damaged area while velocity changes.

## 4 Conclusions

Carbon-epoxy composite plates were manufactured and tested in a falling weight impact machine. Consecutive impact tests varying impact energy were carried out to calculate an approximate the delamination threshold energy. Three energy levels over this damage threshold were chosen to analyze the effect of the impact velocity on the impact response and damage produced to the samples. Four different impact velocities were performed for each energy level changing the mass of the impactor. Force and energy versus time and damaged areas were analyzed for the different impact conditions performed.

Results show that the damage threshold is independent of impact conditions as energy or impact velocity. The impact velocity does not affect in the final energy level, although if it can see that while velocity increases, the energy is dissipated in a faster way and that the damage threshold energy is lower. C-scan analysis shows that the damaged area grows as impact velocity increases. The damaged area in the tests of lower energy is less dependent on the speed of impact; this can be due to a change in the damage mode of the sample due to an increase of the impact energy.

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