EXPERIMENTAL METHODOLOGY TO DETERMINE THE ABSORBED ENERGY IN AN AERONAUTICAL STRUCTURE UNDER IMPACT LOADS USING DIGITAL IMAGE CORRELATION

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Keywords: Impact, Digital Image Correlation, Energy absorbed, composite

Abstract

In this work and energy balance for an aeronautical structure under impact loads were evaluated [1]. An experimental methodology was developed to quantify the transformation of the transmitted energy into the different damages produced at the specimen, such us contact and bending deformation [2]. The employed loading system to perform the impact tests allows a control of the impact load during the test and the displacement measurement of the indenter at each instant, using a high speed camera. In the rear face of the structure, digital image correlation was used to measure the displacements field during the impact.

Different energies were applied on the panel; the results show how the energy transmitted is transformed to produce contact damage and bending deformation during the test. The energy balance results obtained from the impact tests on a real structure highlight the importance of the bending effect during the impact and the less influence of contact damage. The thickness of the structure is an important parameter and in some cases defines the functionality of the structure in the service life.

1. Introduction

The mechanical behavior of a structure when a contact or impact load is exerted is an important phenomenon to study due to the influence on its properties and working conditions. During the service life of a structural component, this could be affected by undesirable loads. For instance in the case of an airplane, it could suffer impact loads during maintenance processes, such a drop of a tool. During landing and taking off operation some part of the fuselage could receive impact from external objects damaging the component. Furthermore, the increasing improvement in the development and accuracy of different optical techniques such as DIC [3-6] make it possible its use to investigate the phenomenon of impact, obtaining valuable information that could contribute to a better understanding of structural component behavior.

In a real contact between two bodies, Hertz`s hypothesis may not be achieved [6] when a static or an impact load is applied. However, if the materials have a perfectly elastic behavior the permanent deformation should be zero after the force returns to zero. Nevertheless, during experiments a permanent deformation it is generated after the application of the force and only part of the de deformation is recovered.

The first step to understand the impact problem is to develop models, able to predict the applied force by the projectile or indenter over the structure when it is dynamically loaded. These models should be focused on the motion of the structure, the indenter and the local deformation occurring at the contact

Excerpt from ISBN 978-3-00-053387-7

area. Thus, it is required a contact law that relate the force and the indentation occurring during the motion of the indenter relative to the specimen. As it is assumed by some researchers [8], the static and dynamic contact laws are identical, thus the contact law statically determined can be used in dynamics analysis.
In the present work, it was studied the extrapolation to dynamics events of the novel experimental methodology to determined de contact law and the energy balance during preliminary tests obtained in an aerospace structure. The experimental set up for impact analysis is capable to generate different ranges of energy, at the same time that it is obtained the contact law and the bending experienced by the structure during the dynamics events. For this porpose, 3D-DIC was used to obtained the displacements fields. The results show a first aproximation to obtained the energy balance during the deformation considering the transmitted energy and its transformation to generate bending and contact damage on the structure.

2. Theory

2.1. Impact phenomenon

The behavior of plates made by different materials under impact loading has been extensively study. Most of the investigations are based on the response of the material, trying to model the relation between the applied force and the indentation a on a plate described by static contact laws. The approach proposed by Rayleigh [9] shows that if the contact duration between the impactor and the target is very long in comparison with their natural periods, the system vibrations can be neglected, and therefore the used of Hertz`s law can be assumed.

For a flexible target, the surface pressure area of contact and the impact duration depend on the impact velocity. The dynamic force will decrease as the target flexibility increases (or the thickness of the specimen decreases). The target will experiment indentation, and a force-deflection relationship will be present due to the deformation of the target, as figure 1 shows [10].

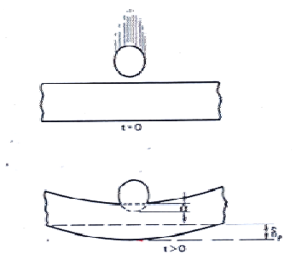

Figure 1.. Local and overall deformation of flexible target [10]

If deformations shown in figure 1 are considered at the point of contact (α and δp), it must be considered the Hertzian contact law at this point. Moreover, on the plate is generated a deflection δp. The Hertzian force-indentation relationship was it is given by (Eq.1):

$$F_c = K\alpha^n \quad (1)$$

Whereas the force-deflection relation for a plate subjected to a concentrated load has the following equation (Eq.2):

$$F_p = K_p \delta_p \quad (2)$$

Where subscripts c and p are referred to the contact problem and plate respectively and Kp is the spring constant for the plate.

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2.2. Energy balance in dynamics events

Another approach for the analysis of the impact dynamics is to analyze the energy balance concerned in the system during the quasi-static or dynamics event. The kinetic energy applied by the indenter is transformed into deformation of the structure. During static or impact tests, when the structure suffers its maximum deflection, the velocity of the indenter become to zero. Thus, all the kinetic energy, at this particular instance, is transformed into deformation and damage of the structure. The deformation created has different effect involving bending, shear deformation and vibration of the structure. Moreover, the local deformation at the contact zone also has to be considered. Therefore the energy-balance equation can be written as [1] (Eq.3):

$$\frac{1}{2}MV^2 = E_b + E_s + E_m + E_c \tag{3}$$

Where subscripts b, s, and m refer to bending, shear and membrane components of the structure and Ec is the energy stored at the contact area due to the indentation. It is possible to express the force-deflection relation as (Eq. 4):

$$E_b + E_s + E_m = \frac{1}{2}K_{bs}W_{\max}^2 + \frac{1}{4}K_m W_{\max}^4 \tag{4}$$

Where K_{bs} is the linear stiffness including bending and the transverse shear deformation effects, K_m is the membrane stiffness and W is the deflection at the impact point. Ec can be expressed for the following equation (Eq. 5):

$$E_c = \int_0^{\alpha\max} P d\alpha = \frac{2}{5} n \alpha_{\max}^2 \tag{5}$$

Where n is a parameter for Hertz´s law representing the contact stiffness.
Therefore it could be concluded that it is possible to measure the energy balance involved in a specimen under loading condition, determining the contact load and the total deflection occurred during the test.

3. Experimental set up

To generate different energy impacts an impact device was specially designed and manufactured. The impact device consisted on a 25 liters pressurized chamber connected to a pneumatic cylinder thought a trigger valve. Depending on energy conditions of the air pressure at the chamber was adjusted to a particular value ranging from 1 to 8 bar. When the pressure set point was reached, the trigger valve was opened. Thus, the pressurized air inside of the deposit enters from the rear chamber of the cylinder accelerating the shaft inside of the cylinder. At the front part of the shaft the indenter together with a 20 kN piezoelectric load cell was previously screwed. Thus, depending on the pressure at the chamber and the mass of the shaft and the indented the impact velocity could be estimated (figure 2).

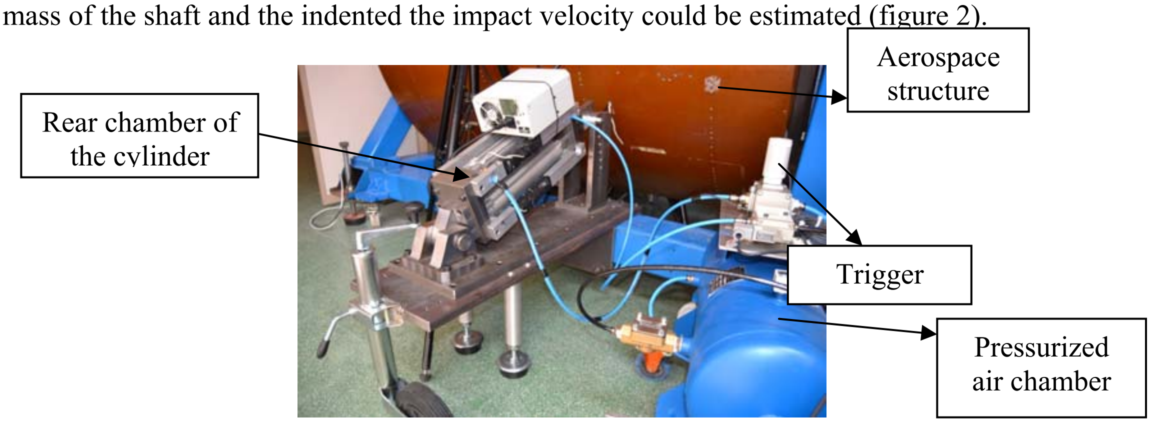

Figure 2. Impact device developed for experiments on a real aerospace demonstrator

The described impact system was calibrated by performing a set of impact experiments in order to relate the chamber pressure with the impact energy.

If the velocity of the indenter is measured just before the impact the kinetic energy can be calculated if mass of the mobile part of the indenter is known (0.5kg) and therefore the impact energy.

For this purpose, a high speed camera (brandt Photron, model FASTCAM SA3) was employed to film to movement of the indenter previously and during the impact. Since the the indenter velocity was high a powerful illumination was required, thus two flexible optic fiber lamps were employed (figure 3).

Figure 3. Adopted experimental set up placed at the front face of the aerospace panel

Moreover, two high speed cameras (brandt Photron, model FASTCAM SA4) were positioned at the back part of the aerospace panel to film the damage area during the impact. As in previous experiments the surface was previously treated to apply 3D DIC technique. The area of interest was properly illuminated to capture images during the out of plane deformation experienced by the structured during the impact. (Figure 4).

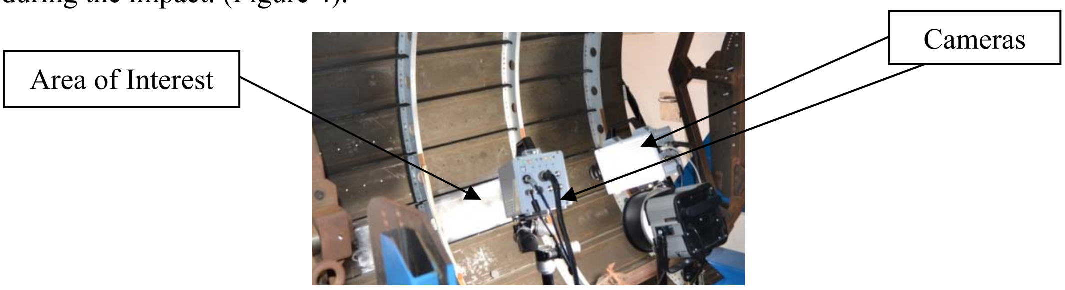

Figure 4. Adopted experimental set up placed at the rear face of the aerospace panel

To correctly perform the proposed impact experiments the three high speed cameras had to be perfectly synchronized. One of the cameras was set as master camera and the other two were considered as slaves of the master. The synchronization of the two back cameras was crucial to obtain out of plane deformation results using 3D DIC technique. Moreover, the third camera placed at the front focusing to the indenter had to be also synchronized with the other two to correlate the real time reading of provided by the load cell with indenter displacement. Thus, the recording speed for the two back cameras was set to 5000 fps, with a shutter time of 1/5000 s. In addition, two F-mount 55 mm focal length lenses were employed. For the front camera, the frame rate was set to 10000 fps and the shutter time fixed to 1/5000s. In this case a F-mount 85 mm focal length lenses was mounted. The synchronization signal from the master camera was introduced into a National Instrument Acquisition Card (model USB-6251 BNC) to simultaneously record the load cell readings. For this purpose Lab-

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View routine was programed to change the internal clock of the data acquisition card by the master camera clock (external).

The three cameras and the DAQ system were triggered when the impact device was released. From this instant, the cameras started recording all required information to analyze the panel behavior. The displacement of the indenter was determined by measuring its position in pixels at the image over a sequence of images. Thus, for a known pixels/mm relation and the time at which images were captured it was possible to quantify the indenter velocity

Finally, once the test finished images from the back of the panel were processed using 3D DIC to obtain the out of plane deformation during the impact. Moreover, images from the front camera were processed using a written Matlab routine to quantify the displacement of the indenter. Finally, load cell readings were employed to monitor the load evolution along the impact event.

The difference between the maximum out of plane displacements measured by 3D DIC technique at the back of panel during the impact and the indenter displacements measured according to the previously described procedure was the indentation experienced by the structure over time.

4. Results

To perform the tests, pressures of 2.5, 3, 4.5 and 5.5 bar were set in the air compression chamber for each experiment. The pressure compressed air, after the triggering the opening valve, was released into the back cylinder chamber accelerating the cylinder rod to generate an energy impact of 4.6, 5.2, 11 and 18 J for each level of pressure. During the test, the displacement of the indenter was measured using a high speed camera placed at the front of the panel with a known pixel/mm ratio. Simultaneously the out of plane displacements at the back side of the panel during the impact were measured using 3D DIC. The load progression during the test was measured using a piezoelectric load cell attached to the indenters as it is presented in figure 5. The load data capture was synchronized with the images captured using synchronization software provided by Photron Inc. The maximum load reached during the impact is represented for each experiment in the table 1. In all cases de evolution of the load versus the time experimented were similar, producing several rebounds after the first impact.

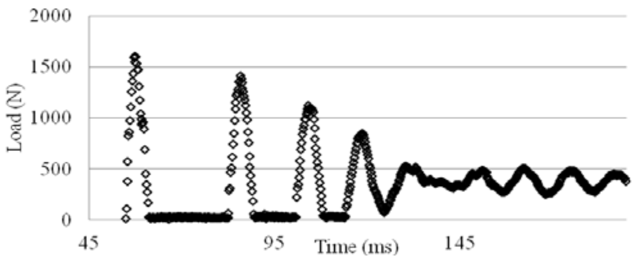

Figure 5. Load versus time for an 11 J (4.5 bar) impact with a semispherical indenter

Table 1. Energy applied to the structure for each experiments and the corresponding maximum load reached in the first impact

Pressure (bar)	Energy (J)	Maximum Load (N)
2,5	4,6	983
3	5,2	1186
4,5	11	1607
5,5	18	1894

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To estimate the contact law during the test, two cameras were used to record the event at the back face of the panel. To applied 3D DIC technique, the surface was prepared and images were synchronized with the rest of devices employed during the test as shown in figure 6.

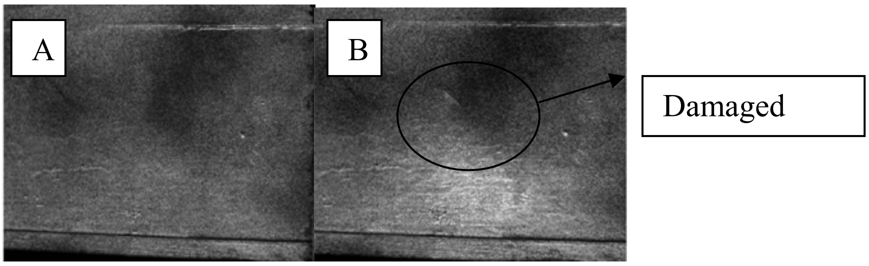

Figure 6. A) Reference image previous to the impact for a 11J experiment). B) Image during the impact for an 11J experiment.

The region of interest was divided into facet of 43x43 pixels and an overlap of 5 pixels. After the correlation, the out of plane displacements at the back surface were obtained. Figure 7 shows the registered load versus the measured out of plane displacements during the different tests. It is observed that the maximum displacement was 10.45mm. In addition, it is observed a stiffness reduction in two zones, a first one at around 1100 N and a second around one at maximum load. These stiffness reductions correspond with the load instant at which broken fibers are observed in the recorded images.

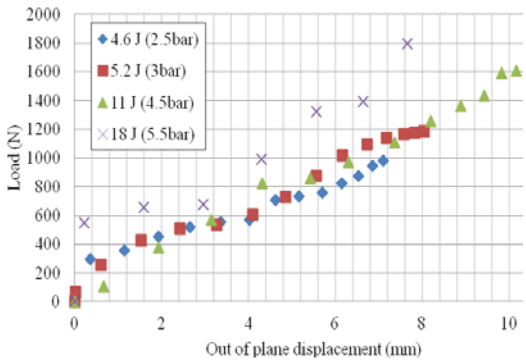

Figure 7. Out of plane displacements versus load during the different impact test performed using a semispherical indenter.

In the case of the experiment for a 18J, during the test it was experimented a matrix cracking and fiber breakage after a 7.65mm out of plane displacement. Therefore, the methodology could not be further employed due to a lack of information

Figure 8 A show a first approximation of the contact law for an 11 J experiment. The measured indentation was obtained by subtracting the indenter displacement to the measured out of plane displacement at the maximum displacement point at the back surface of the panel. It can be observed that at around 1100N a change in the trend occurs which is attributed to fiber breakage. After that, indentation increases and has a maximum value of -1.13mm, being the thickness reduction of the aeronautical structure during the loading path.

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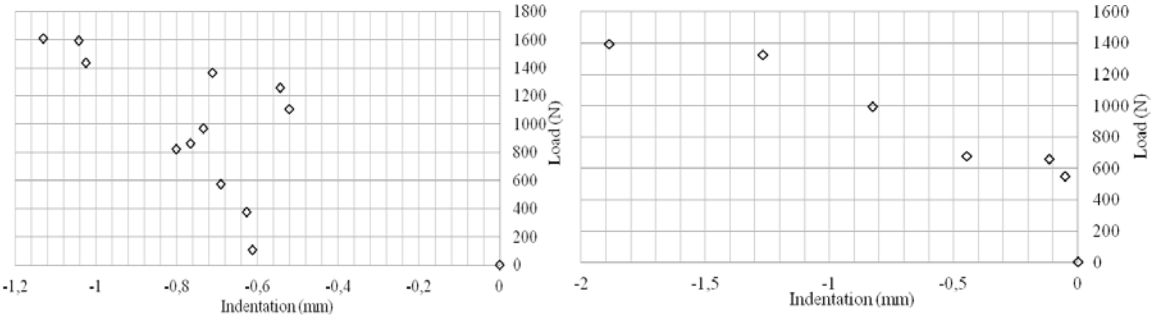

Figure 8. Contact law for an impact test using a semispherical indenter. A) 11 J. B) 18 J

In the case of impact energy of 18J, the contact law obtained is represented in the figure 8 B. As it is observed, the maximum indentation is -1.88mm at 1394N. After this load it is produced the specimen failure and it is not possible to evaluate the contact law.

It is important highlight, that for lower energies of 4.6 and 5.2 J not contact law was obtained, therefore non indentation was generate by the indenter and all applied energy was transmitted in produce bending deformation. However, a better accuracy of the methodology could be developed to quantify the displacement of the indenter during the test due to actually the precision is the relation pixel/mm from the images captured being 0.216mm/pixel.The energy balance results of the different experiments performed are shown in the table 2.

Table 2. Energy balance of the loading path for experiments of impact energy 4.6, 5.2, 11 and 18 J

Total Applied Energy (J)	Applied Energy: Bending (J)	Applied Energy: Contact (J)	Applied Energy: Failures (J)
4,6	3,5	0	1,1
5,2	4,75	0	0,45
11	9,32	0,62	1,07
18	x	x	x

5. Conclusions

A complex set up has been adopted to obtain the experimental contact law during an impact on a real aerospace component. Thus, a semispherical indenter was adopted to generate different impact energies. Results show how the major proportion of the energy is employed to deform the structure generating out of plane displacement due to bending. For each experiments, different energies and impact loads where measured. The maximum load depends on the location of the impact due to the presence of aluminium and carbon stiffener in the structure. The proximity of the impact to one of them could generate less out of plane deformation and a higher impact load for the same impact energy.

In the experiments for 4.6 and 5.2 J, not contact damage was observed during the loading path. The reason could be that more energy is demanded to create indentation in the structure. Moreover, it is assuming the presence of low accuracy in the determination of the indenter movement, being possible a loading contact low not observed during the experiments. For the test performed for an impact energy of 11J, only a small portion of energy generates contact damage (0.62J), while the rest of the energy is transmitted due to bending deformation evaluated in 4.75 J. Other part of the transmitted energy is attributed to the internal damage created in the structure, not being the objective of this studied. Included in this part of the transmitted energy is the transmitted energy to the indenter and the shaft, appreciating some bending deformation during the impact. The limitation of the experimental

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methodology was highlighted for the test to 18J, missing the information when the structure fails and not continuity is observed on the surface to applied DIC-3D.

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