1 Abstract
The low velocity impact behavior of laminates made of glass fibre and phenolic resin was studied. Two different samples typologies were compared: orthotropic and quasi-isotropic different in thickness (3, 4, 5, and 6 mm). Impact test were carried out up to penetration and at variable energy values. The aim of the latter tests is to correlate the dimension of the indentation left by the indenter on the surface with the impact energy. The complete tests up to penetration were useful to obtain the whole load-displacement curve and the penetration energy value. Impact results obtained on basalt fibre reinforced epoxy resin were compared too. About the external damage, the quasi-isotropic specimens showed higher resistance than the orthotropic ones, in all the different thicknesses tested. An interesting result was obtained for basalt laminates that showed indentation depths lower than all the material systems analyzed up to now. The stacking sequence was found to have no influence on the penetration energy. The measured energy values, from the area under the complete load-displacement curve, were used to validate an existing power law in which the fibre content assumes the most important role.

2 Introduction
In many advanced industrial fields, such as aeronautics, naval and transportation, the study of impact resistance of the composite materials is very important. In particular, it could be useful to appreciate the damage induced in the material by an accidental impact, during manufacturing process, in service or maintenance operations. Many studies were done in literature about impact [1-12], in particular different reinforcements (glass fibre, carbon fibre and aramid fibre) and resin typologies (epoxy and polyester) were studied. One of the requirements to be fulfilled is the ability to know the internal damage from a simple inspection of the visual damage. The parameter almost universally used to quantify this property is the indentation, i.e. the depth of the dent resulting from the contact of the material surface with a foreign object travelling at low, medium, or high velocity and, so, the only external indication of an impact. Of course, the critical indentation could be selected in a sound way, if a reliable correlation would be established between its geometry and the residual mechanical properties of the material. Indeed, such correlation would be particularly useful in inspection as well, because it would allow decisions on the necessity of repair utilizing a damage parameter easy to be measured. The procedure is complicated since, in general, the dent depth is strongly dependent on many parameters, like the particular laminate under concern, its thickness, the constraint conditions, tup geometry, and impact speed. Analytical tools for the prediction of indentation under known impact conditions can, of course, simplify the problem. In [13], a simple power-law equation was assessed, correlating the dent depth with impact energy, negligibly affected by the laminate type and thickness and impact velocity. Of course, in this way, the unknown impact energy resulting in a known indentation could be found with ease. Since in the literature, some models have been proposed [14, 15], aiming to predict the residual strength of a composite laminate as a function of the impact energy, in principle the possibility to predict the residual strength from indentation is devised. To do this, the penetration energy has to be known and it can be calculated through a model developed in [6, 16], accounting only for the reinforcement volume and tup diameter.
In literature, extensive researches are available on this topic, concerning impact dynamics [9-12], mechanisms of failure initiation and propagation [12, 17-20], and correlation between impact energy, damage, and residual material properties [12, 14, 17, 21-23] on different reinforcements and resin typology. From the previous considerations, the present work had the fundamental objective to ascertain whether the relationship between indentation and low velocity impact energy could be validated for other material systems.

3 Materials and test methods

In the present research, the low velocity impact behavior of laminates made of glass fibres, fabric 256 g/m², and phenolic resin was studied. The laminates were produced by autoclave forming process in two different typologies: orthotropic, O, and quasi-isotropic, I. For both samples, different thickness, 3, 4, 5, and 6 mm, were obtained overlapping different numbers of layers following the stacking sequences [(0/90)]ₙ, [((0/90),(+45/-45))ₙ] s, n = 3 to 24.

Low velocity impact tests were carried out on basalt fibre reinforced plastics (BFRP) too. Laminates with 300 mm x 300 mm in plane dimensions were obtained through infusion technology. The reinforcement employed is basalt dry fabrics, 200 g/m², plain-weave (warp 10F/10 mm, weft 10F/10 mm), tex 100. In order to produce plates with the desired thickness, a sufficient number of plies were overlapped on a release film placed on a glass tool. Then, they were covered with the peel ply and the plastic bag. After that, the plies were impregnated through resin infusion by an epoxy matrix (Becor I-SX10 + hardener SX10M). The curing stage at room temperature and at a vacuum level of -990 mbar was performed for 24 hours. The following stacking sequence was obtained: [((0,90)/(+45,-45)/(+45,-45)/(0,90))ₙ], with n=2 to 4, leading to nominal thickness of 1, 2 and 3 mm and a fibre volume fraction Vₕ = 50%. From the plates, square specimens 70 mm in side, destined to the experimentation, were cut by a diamond saw.

Impact test were carried out on a drop weight testing machine using a cylindrical indenter with a semi-spherical nose, 19.8 mm in diameter. Tests up to penetration were carried out at the aim to obtain the complete load-displacement curve and the strength at penetration. On the recorded load curves, different energy values, in correspondence of characteristic points related to the damages, were selected and indentation tests were carried out at the selected energy values. The aim of these tests was to correlate the dimension of the indentation left by the indenter on the surface of the laminate with the impact energy. The indentation depth resulting from the impactor-material contact was measured by a micrometric dial gauge, Mytutoio, according to EN 6038 standard. At the final aim, but out of the scope of the present paper, to predict the residual strength, the penetration energy, Uₚ, was measured as the area under the complete load–displacement curve obtained in the impact tests up to perforation. The results were used to validate a previous assessed model [6]. That allows to predict Uₚ taking into account only the fibre volume fraction and the tup diameter.

4 Results

4.1 Load curves

In Fig. 1, the complete load-displacement curves recorded during the experimental tests up to penetration on the quasi-isotropic laminates, I, were overlapped for all the thickness tested. It is appreciable an initial region in which the force increases due to the impact; then, reached the maximum value, the impact force has a significant reduction correspondent to a strength loss for the significant damage, finally followed by the beginning of the penetration in the laminate. As expected [4], the load increases at the increasing of the thickness.

![Fig. 1. Load-displacement curves, different thickness. Isotropic laminates.](image-url)
In Fig. 2, a comparison between the load-displacement curves obtained on the quasi-isotropic and orthotropic laminates, is proposed. To avoid crowding of data, only two thicknesses, the lowest and the highest ones, were reported. It is possible to observe the similar behavior of the two different stratifications since the perfect overlapping of the curves.

Fig. 2. Load-displacement curves: isotropic (thin line) and orthotropic (thick line) laminates. \( t = 3 \) mm and \( t = 6 \) mm.

### 4.2 First failure and maximum force

In Fig. 3, the first failure load, obtained on the load-displacement curve in correspondence of the first load drop or the first changing in the slope [4] (see the thick and short arrows in Fig. 2), was plotted against the panel thickness for the quasi-isotropic, I, laminates. The trend is well represented by the following power law:

\[
F_i = 317.5t^{1.5}
\]  

(1)

The exponent 1.5 verify the Hertzian contact law [4, 24]. In the figure, the points represent the mean values of at least three values obtained in the same test conditions. The perfect overlapping of the load curves, denoted the perfect reproducibility of the experimental tests and no significant standard deviations are evidenced on the data.

In Fig. 4, the influence of the panel thickness on the first failure load, was reported for the orthotropic laminates.

Also in this case the trend is well evidenced by a power law:

\[
F_i = 735.8 t^{1.03}
\]  

(2)

More dispersions in the data, evidenced by the standard deviation bars in the figure, were noted. Moreover, the exponent in Eq. (2) is significantly lower than 1.5 of the Hertzian law. However, comparing Figs. 3 and 4, it is possible to note that the values about the two different stacking sequences are quite similar, denoting similar response of the laminates about the beginning of the damage. It confirms what showed in Fig. 2 since the perfect overlapping of the curves also in the first increasing part.

In Fig. 5, the influence of the panel thickness on the maximum force for both quasi-isotropic, I, and
orthotropic, O, panels, was analysed: in both cases, no power laws were able to describe the trend that is clearly linear and very similar.

![Graph showing Fmax vs t](image)

Fig. 5. Maximum load, $F_{\text{max}}$, against the panel thickness, $t$.

The very similar behavior of the two systems under attention, was confirmed by the following linear equations, the first one for quasi-isotropic and the second for orthotropic laminates, representing the linear trends in Fig. 5:

\begin{align*}
F_{\text{max}} &= 3127.3t + 8094.5 \\
F_{\text{max}} &= 3274.5t + 8204
\end{align*}

(3) (4)

Similar coefficients were obtained.

4.3 Indentation

In [4], a variety of CFRP laminates, different in thickness, lay-up, and material system, were subjected to low-velocity impact tests using a hemispherical tup of diameter $D_t = 12.7$ mm. The indentation at increasing energy levels was measured and plotted against the impact energy, $U$ [13]. Different trends were found for each single thickness even if all the indentation data concerning a single material system, irrespective of $t$, was found to converge to a single curve when $I$ was plotted against the non-dimensional energy $U/U_p$. This indicated that the same indentation law can be valid for a quite large class of laminates. It was noted in [13] that, for a given tup diameter, the impact energy could be calculated from an indentation measurement.

In [7], a new indentation law was found to fit well the experimental point for higher impact non dimensional energy values.

In Fig. 6, all the indentation depths obtained here for both I (full symbols) and O (open symbols) panels were plotted against the impact energy, $U$. It was not possible to represent the trend with power nor exponential laws, as done in [7, 13], in neither of the two cases. Only straight lines seem to better approximate the behavior. However, the two lines about the two different materials are separated and the data don’t follow a single trend. In general, from the figure, it is possible to assert that in correspondence of the same impact energy, a deeper indentation was measured on the orthotropic laminates.

![Graph showing I vs U](image)

Fig. 6. Indentation against impact energy. Comparison between quasi-isotropic (full symbols), I, and orthotropic (open symbols), O, laminates.

The same data from Fig. 6 are reported in Fig. 7 against the non-dimensional energy, $U/U_p$. The data seem to more closely follow a single exponential trend, irrespective of the thickness, material and stacking sequence.

![Graph showing I vs U/U_p](image)

Fig. 7. Indentation, I, against the non dimensional energy,
U/U_p. Comparison between isotropic, I, and orthotropic, O, laminates.

Using experimental data available in literature, the existing indentation law [7], allowing for the prediction of the impact energy from the depth of indentation, was validated with the results obtained in this research:

\[
I = k \cdot (10 \frac{U}{U_p} - 1) \tag{5}
\]

\(U\) is the impact energy, \(U_p\) the perforation energy, \(k\) and \(\gamma\) constants to be experimentally determined. Following the same procedure adopted in [7], the data from Fig. 7 were rearranged in a log scale (Figs. 8 and 9) separately for I and O laminates.

The solid lines in the figures are the graphic representation of the following relationship, simply obtained from Eq. (5):

\[
\log\left(\frac{U}{U_p} - 1\right) = \frac{1}{\gamma} \cdot I
\]

that allow to know the constant \(\gamma\) from the slope. The value \(k = 1.6\) mm allowed to have a line passing through the origin in both cases and \(\gamma\) = 0.6881 was found for isotropic laminates with a very good approximation \((R^2 = 0.95)\) whereas \(\gamma\) = 0.7473 was found for the orthotropic ones with \(R^2 = 0.82\). Even if these values are different from \(k = 0.288\) mm and \(\gamma\) = 1.269 found for carbon and glass fibres in epoxy matrix, the indentation law seems to confirm the quite general applicability, being scarcely affected by the fibre type and orientations, and matrix type.

In Fig. 10, all the indentation data obtained in the present research are compared with classical data from literature. In addition, the indentation depths measured on the basalt fibre laminates introduced in the “Material and tests methods” paragraph, were reported too.

It is clear that the trend is similar for all the material systems, but about the external damage, at the same penetration energy, an impact energy causes deeper indentations on the specimens made by phenolic matrix whereas basalt laminates showed the better behavior.

Of course, it could be very interesting to have the same information about the internal damage. It will be done in a future step.
4.4 Penetration energy

Since the relationship between impact energy and residual strength [13], the indentation law can be very useful in the prediction of the residual properties of a structure: through a simple measurement of a surface damage after impact, it is possible to know the correspondent energy level and so the residual strength. However, the penetration energy of the laminates has to be known.

By comparing the penetration energies of the two different glass fibre laminates tested, as anticipated by the observation of Fig. 2, the stacking sequence has no influence on the energy necessary to complete penetrate the laminates. In Fig. 11, the measured penetration energies are plotted against the product between thickness, t, fibre volume fraction, Vf, and tup diameter, Dp, for all the laminates tested in the present research.

![Graph showing penetration energy against product of thickness, Vf, and tup diameter](image)

Fig. 11. Penetration energy, Up, against t*Vf*Dp.

The data validate a previous power law presented in [6] for the prediction of the penetration energy. The law represented by the continuous line in Fig. 11, has the following expression:

\[ U_p = 1.37 (t*V_f*D_p)^{1.16} \]  

(7)

in which the exponent is close to what obtained in [6]. In the same figure, data from literature [25], only about glass fibre to avoid crowding of symbols, were add to compare the data and to confirm the trend.

5 Conclusions

Existing indentation and penetration models were validated with data from low velocity impact tests on composite laminates different in materials, thickness and stacking sequence.

In particular, two glass fibre in phenolic matrix laminates in two different configurations, quasi-isotropic and orthotropic ones, and in different thicknesses, were tested at the aim to verify the influence of the fibre orientation on the impact behaviour. Experimental data from basal fibre in epoxy matrix specimens were add too to investigate about the influence of the materials.

From the results, it was possible to write the following main conclusions:

- no significant differences were found about the general impact behaviour, in terms of first failure and maximum load, and penetration energy, between the two different stacking sequences of the glass specimens;
- however, about the external damage, the quasi-isotropic specimens showed an higher resistance than the orthotropic ones in all the different thicknesses tested;
- basalt laminates showed indentation depths lower than all the material systems analyzed up to now;
- the existing indentation and penetration laws were verified with success.

5 References

INDENTATION AND PENETRATION LAWS VALIDATED FOR COMPOSITE LAMINATES DIFFERENT IN FIBRES AND MATRIX


