# PENETRATION AND INDENTATION ON BASALT FIBRE REINFORCED PLASTIC LAMINATES UNDER LOW VELOCITY IMPACTS

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## Abstract

*Low-velocity impact tests were carried out on basalt-fibre-reinforced plastic panels, varying the impact energy and the laminate thickness. A previous modified model, valid for CFRP and GFRP laminates, for the prediction of the indentation as a function of impact energy, was applied: a different behaviour was observed denoting a different damage mechanism of the basalt fibre laminate. About the prediction of the penetration energy, the previous model largely applied in the literature showing the importance of the total fibre content, was adopted and a good agreement between the theoretical predictions and the experimental results was found. In analyzing previous experimental data, concerning carbon-fibre-reinforced plastics an higher impact energy was found to be necessary to penetrate the basalt laminates whereas the indentation depth at the same impact energy is lower*

## 1 Introduction

The relatively recent use of basalt fibre as reinforcement for polymer matrix is due to its good mechanical performance together with the low cost. The idea could offer very interesting perspectives that have not been sufficiently investigated yet. In the last decades, much works were devoted to the study of the response of composite materials to impact loads, paying attention to the damage mechanisms occurring [1,2], as well as to their effect on residual properties [3,4]. However, many questions remain to be answered.

At the aim to investigate about the impact behaviour of a new interesting material system, in this work, low-velocity impact tests were carried out on basalt-fibre-reinforced plastic panels varying impact energy and laminate thickness. Penetration tests were carried out to obtain the complete load-displacement curve and the penetration energy whereas indentation tests were useful for the indentation depth measurements.

Indentation depth, penetration and absorbed energies, maximum forces and displacements were measured and compared with what obtained in literature about glass and carbon laminates.

A modified model for the prediction of the indentation was assessed in the present case and a correlation between the dent depth and the absorbed energy was studied. Analyzing previous experimental data concerning carbon and glass-fibre-reinforced plastics, the different behaviour of BFRP in absorbing energy and undergoing indentation was revealed. The existing model [5] for the prediction of the penetration energy valid for classical laminates was validated too. The results were compared with what obtained about classical composites and an higher energy was revealed necessary to completely penetrate the basalt laminate whereas a lower indentation depth was measured.

## 2 Background

In [6], after impact tests on CFRP laminates, the measured indentation was plotted against the impact energy, U, for all the laminates: a more than linear increase with the increasing of the impact energy was found. Besides, for given energy and material system, the dent depth was the higher, the lower the plate thickness. The same data, plotted against the non-dimensional energy $U/U_p$, where $U_p$ is the penetration energy, all converged to a master curve irrespective of the actual thickness.

All the experimental points analysed were fitted by a power law equation:

$$I = I_o \cdot \left( \frac{U}{U_p} \right)^{\beta} \tag{1}$$

By the best fit method, the values Io = 6.77 mm and β = 2.535 were calculated. However, the latter formulation was found to be valid up to an impact energy 60% of the penetration one.

Caprino and co-workers in [7] proposed a modified formula correlating the impact energy, U, with indentation, I, through the experimental constants k’ and γ’:

$$I = k' \cdot [10^{\gamma'(U/Up)} - 1] \tag{2}$$

valid in low-velocity impact conditions on Carbon-Fibre-Reinforced Plastic (CFRP) laminates.

The data in [7] showed that k’ and γ’ are dependent on the fibre type under concern, being insensitive to the panel thickness and constraint conditions, reinforcement architecture, orientation of the layers in the laminate, and matrix type.

Eq. (1) was used to assess the indentation model, plotting all the experimental data on a $\text{Log}(I/k'+1) \cdot U_a/U_p$ diagram, and varying k’ until the best-fit straight line passed through the origin. k=1.06 mm and γ=0.931 were found for GFRP [8] and they were revealed insensitive to the panel thickness and tup diameter. Of course, it is important to know $U_p$.

Recent data [6, 9-10] demonstrate that $U_p$ increases more than linearly with thickness. In particular, it was found that the dependence of the penetration energy on the material thickness, t, for CFRP and GFRP laminates could be well described by a power law having exponent 1.5 and 1.35 respectively.

However since the effect of both the thickness (t) and the impactor ($D_t$) diameter could be modelled by power laws having practically the same exponent, it was suggested in [5, 10] that the empirical relationship

$$U_p = K \cdot (t \cdot V_f \cdot D_t)^{\alpha} \tag{3}$$

where K and α are two material parameters to be experimentally determined, could help to predict the penetration energy (of GFRP). The experimental tests supported eq. (1): all the data obtained substantially fall on a single master curve when plotted against the quantity $(t \cdot V_f \cdot D_t)$ irrespective of the adopted tup diameter and fibre architecture and orientations. The authors as hereafter presented, ascertained that eq. (1) could be applied to BFRP too. The formula proposed has a quite wide applicability, and can be probably further simplified, allowing a simple comparison of different materials. The possibility to predict the penetration energy allows to know the impact energy, through the indentation measurements. Since the residual material properties after an impact is correlated with the impact energy and the damage mechanisms [11, 12], the importance of the above mentioned correlations is clear.

## 3 Materials and test methods

Low-velocity impact tests were carried out on basalt-fibre-reinforced plastic panels varying the impact energy and the laminate thickness. The specimens were cut by a diamond saw from square plates 300x300 mm obtained by the infusion technology. From 8 to 24 numbers of layers were overlapped following the stacking sequences: $[(0,90)/(+45,-45)/(+45,-45)/(0,90)]_n$, with n=2 to 4, to obtain thickness in the range 1-3 mm and $[(0,90)]_n$, n=12-24, for the 2-4 mm of nominal thickness. The epoxy matrix (Becor I-SX10 + hardener SX10M) was employed to impregnate basalt dry fabrics, 200 g/m$^2$, plain-weave (warp 10F/10 mm, weft 10F/10 mm), tex 100, from ZLBM (De) and the final fibre volume fraction in the range 50-60 % was obtained.

Impact tests were carried out on a Ceast Fractovis MK4 falling weight machine varying the impactor mass and the falling height. The latter device allowed to vary the impact energy for the indentation tests and to investigate about the damage start and propagation. In these tests, the energy was set by suitably combining the falling eight and three different masses (M=3.6, 5.6, 7.6 Kg) available in the testing machine. Impact tests were carried out also up to the complete penetration of the coupons using a mass M=10.6 Kg falling from 1 m height.

The instrumented impactors was cylindrical in shape with hemispherical nose 19.8 mm in diameter. The square (100x100mm) specimens were simply supported on a ring with a 50 mm internal diameter. The indentation depths were measured on each impacted specimen following the EN6038 standard. All the force-displacement curves were recorded during the tests by the DAS4000 acquisition program and successively studied to evidence the main impact parameters involved in the phenomenon. Penetration energies and maximum forces were measured and compared with data from literature about glass and carbon laminates. In all, at least three impact tests were performed for each experimental condition.

## 4 Results and discussion

### *4.1 Penetration energy*

The same procedure described above about the possibility to predict the penetration energy of a composite under impact conditions was followed here about basalt fibre laminates. In figure 1, the experimental data about penetration energy of the material under exam measured as the area under the complete load curve, were reported (open symbols) as a function of the product $(t \cdot D_t \cdot V_f)$. The model assessed for CFRP and GFRP laminates (eq. (3)) was confirmed and the constant $\alpha = 1.32$ and $K = 0.69$ J/mm$^2$ were found with $\alpha$ very close to what previously found. In the same figure, the theoretical prediction of the penetration energy of GFRP laminates is reported too (dashed line). A good agreement was observed confirming the validity of eq. (3) in predict the penetration energy independently of the fibre, stacking sequence and particular impact conditions.

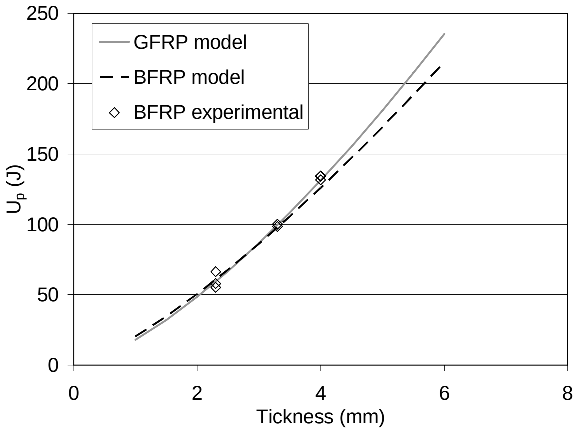

**Figure 1.** Penetration energy model.

A very simple equation was found by Sutherland and Guedes Soares [13] in low-velocity impact tests on GFRP laminates made of different woven roving architectures, thicknesses, and resins. Plotting the absorbed energy against U, a bi-linear trend was observed: the knee was found to correspond to the onset of fibre damage. Correlating the impact energy, U, and the absorbed one, $U_a$, through the perforation energy for GFRP laminates and CFRP [8] a similar correlation between U and $U_a$ was found by the authors. The knee in the case of GFRP was found located in the range $U/U_p$=0.08 to 0.11 whereas U~0.2$U_p$ for CFRP laminates.

In figure 2, the measured non-dimensional value $U_a/U_p$ was plotted against $U/U_p$ for basalt. It is possible to clearly distinguish the bi-linear trend highlighted by Sutherland and Guedes Soares [13]. According to the interpretation given, the onset of fibre damage would here occur for U~0.16$U_p$ earlier than CFRP laminates but later than glass fibre ones. The dashed line in figure 2 has equation $U_a/U_p$= $U/U_p$ and represents the condition for which all the available energy is absorbed. It is interesting to note the very big distance between the dashed and the continuous line denoting a bigger amount of energy stored elastically, amount that seems to increase at the increasing of the impact energy.

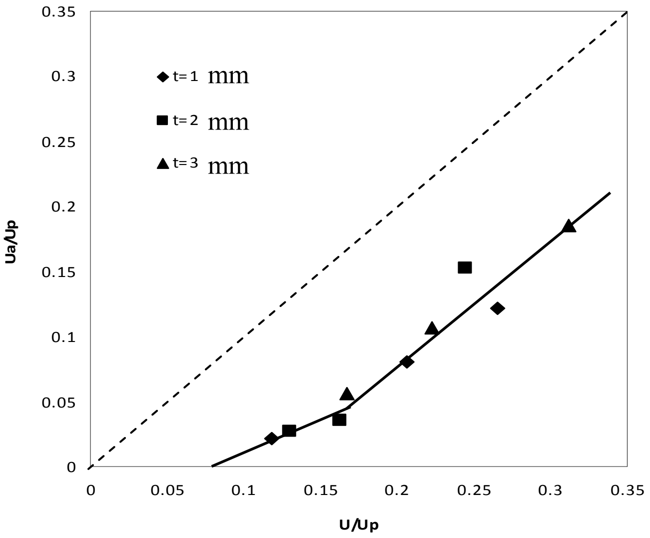

**Figure 2.** Non dimensional absorbed energy, $U_a/U_p$, against non dimensional impact energy, $U/U_p$. Material: BFRP. Mean values.

### *4.1 Indentation*

At the aim to find an independent parameter to compare the obtained experimental values, the measured indentation depth was plotted against the non dimensional energy, $U/U_p$. Contrarily to what happened for classical composites, the basalt laminates did not fall into a single master curve. Very surprisingly, as is possible to see in figure 3, the impact energy was revealed the parameter independent on the particular thickness: all the data when plotted against the energy that caused the specific indentation on the surface of the laminates, follow the same linear trend (figure 3).

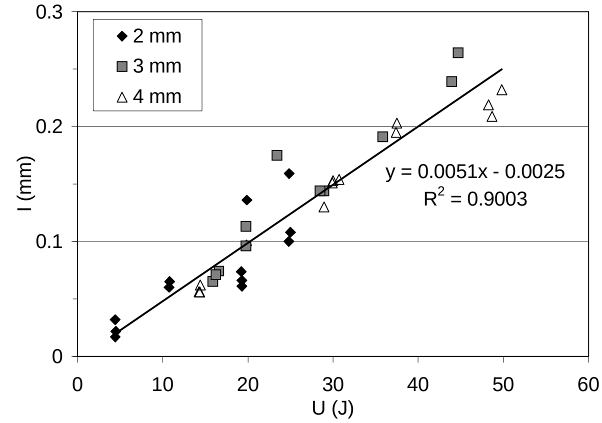

**Figure 3.** Indentation depth, I, versus impact energy, U. BFRP.

Since in literature there is an open debate about the role played by the impact energy and the maximum force in predicting the impact behaviour of a composite laminates, the same data analyzed above are reported in figure 4 as a function of the maximum force ($F_{max}$): all the experimental measurements follow a single linear trend.

Also, plotting I as a function of the absorbed energy $U_a$ the data are quite gathered along a single trend irrespective of the thickness.

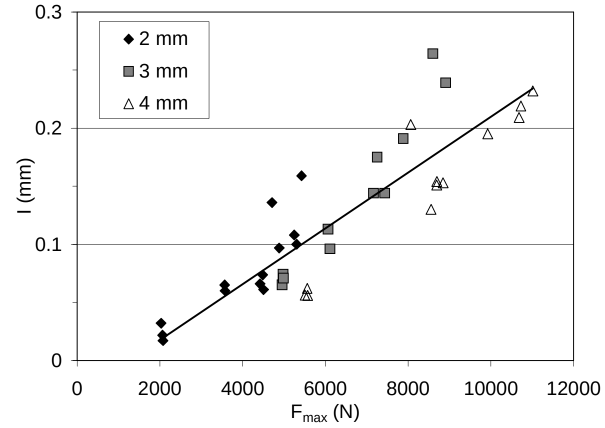

**Figure 4.** Indentation depth, I, versus maximum force, $F_{max}$. BFRP.

Moreover, as done for GFRP laminates [8] and discussed above to find the constant in Eq. (1), figure 5 shows the Log(I/k+1) as a function of the non dimensional energy $U_a/U_p$ for BFRP. The k value was varied until the straight line passed through the origin for k = 1.5 . In any case, the superposition of the points associated with different thicknesses was found not good for all the thickness. The 2 mm, excluded by the research of the k value, showed, in fact, a different behaviour that is going to be interesting to investigate under the damage mechanisms aspect.

The different behaviour respect to the classical laminates could mean a different mechanism of damage confirmed hereafter by the lower indentation values. Of course the assertion needs to be validated by a bigger number of experimental points and internal damage investigation.

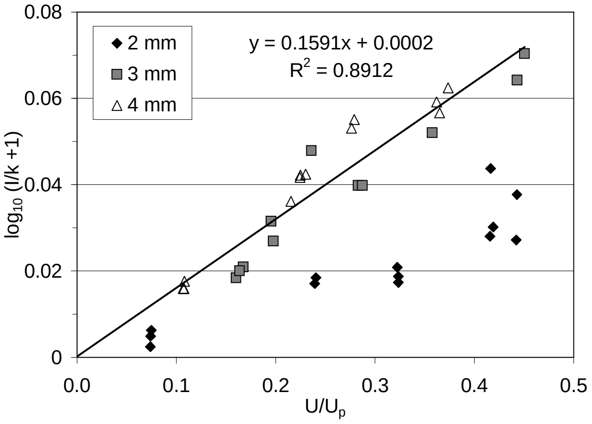

**Figure 5.** Diagram for the assessment of the indentation model. Material: BFRP.

Moreover, comparing the I data, lower indentations were found for BFRP laminates. It denotes, as anticipated, a different behaviour: when the same indentation is measured on the three material systems, the basalt fibre laminates absorb a higher portion of energy, if the perforation energy is assumed as a benchmark.

In figure 6, a comparison with classical composites was reported: all the experimental data about the measured indentation on basalt laminates are below the theoretical curve (continuous line) obtained for CFRP laminates. It is possible to observe that it is necessary a higher energy to obtain the same indentation depth or that at a fixed non dimensional impact energy ratio, the indentation is lower for basalt laminates. This means a higher criticity for the basalt laminates in having information about internal damages from external signs.

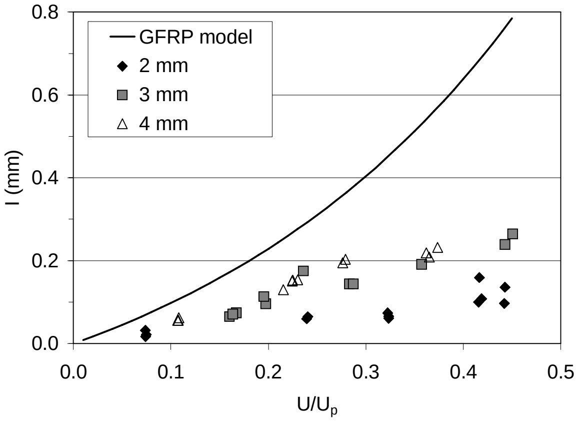

**Figure 6.** Comparison with GFRP and CFRP laminates.

## 5 Conclusions

From low-velocity impact tests performed on BFRP panels an existing law for the prediction of the penetration energy was validated. At sufficiently high impact energy, a relationship between initial energy and absorbed one can be reduced to a simple, linear law, independent of the laminate thickness.

A different behaviour about indentation depth was evidenced denoting a different damage mechanism: the comparison with classical laminates reveals some differences in the three materials, with reference to the energy absorbed in correspondence of a given dent depth.

More experimental data were generated about BFRP under low velocity impact conditions varying the matrix, the stacking sequence, the impactor diameter and the support dimension but the results won't be presented here for brevity.

## References

[1] Dorey G. An overview of impact damage in composites. *Inst. Phys. Conf. Series*; 102, pp. 395-02 (1989).

[2] David-West O.S., Nash D.H., Banks W.M. An experimental study of damage accumulation in balanced CFRP laminates due to repeated impact. *Compos. Struct*; 83, pp. 247-258 (2008).

[3] Richardson M.O.W., Wisheart M.J. Review of low-velocity impact properties of composite materials. *Composites Part A*, 27, pp. 1123-1131 (1996).

[4] Parvatareddy H , Wilson Tsang P.H., Dillard D.A. Impact damage resistance and tolerance of high-performance polymeric composites subjected to environmental aging. *Compos. Sci. Technol*, 56, pp. 1129-1140 (1996).

[5] Caprino G., Lopresto V. On the penetration energy of fibre-reinforced plastics under low-velocity impact conditions. *Compos. Sci. Technol*, 61, pp. 65-73 (2001).

[6] Caprino G., Lopresto V. The significance of indentation in the inspection of carbon fibre-reinforced plastic panels damaged by low-velocity impact' *Compos. Sci. Technol*, 60, pp.1003-1012 (2000).

[7] Caprino G, Langella A, Lopresto V. Indentation and penetration of carbon fibre reinforced plastic laminates. *Composites Part B*, 34, pp. 319-25 (2003).

[8] Lopresto V., Leone C., Caprino G., Low Velocity Impact Damage and Energy Absorption in Composites Laminates: Indentation Model. *Procedia Engineering,* 10, pp. 2298–2311 (2011).

[9] Delfosse D. and Poursartip A., Experimental parameter study of static and dynamic out-of-plane loading of CFRP laminates", in Proceeding of 10th Int. Conference on Composite Materials (ICCM 10), Whistler, Canada, pp. 583-590 (1985).

[10] Caprino G. and Lopresto V. Factors affecting the penetration energy of glass fibre reinforced plastics subjected to a concentrated transverse load. in Proceeding of European Conference on Composite Materials, (ECCM 9), Brighton, UK, 4 – 7 (2000).

[11] Cantwell W.J., Morton J. An assessment of the residual strength of an impact-damaged carbon fibre reinforced epoxy. *Compos. Struct*, 14, pp. 303-317 (1990).

[12] Caprino G. Residual strength prediction of impacted CFRP laminates. J. Composite. Materials, 18, pp. 508-518 (1984).

[13] Sutherland L.S., Guedes Soares C. Impact on low fibre-volume, glass/polyester rectangular plates. Compos. Struct., 68, pp. 13-22 (2005).