Constitutive Shell Model Calibration for Low-Velocity Impact on Basalt Fibre Reinforced Composites

Felipe Vannucchi de Camargo[1], Ana Pavlovic[1], Cristiano Fragassa[1], Raffaele Ponzini[2]

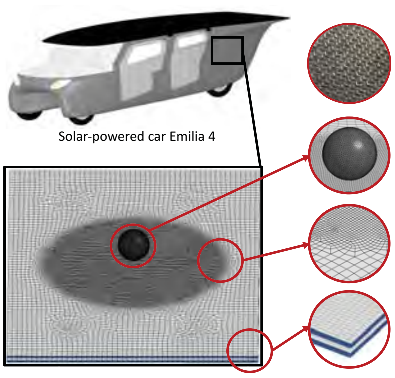
[1]Department of Industrial Engineering, Alma Mater Studiorum Università di Bologna, Viale del Risorgimento 2, 40136 Bologna, Italy
[2] CINECA, Super Computing Applications and Innovation Department - SCAI, Milan Operational Site, Via Raffaello Sanzio 4, 20090 Segrate, Milan, Italy

SCOPE

Acknowledging composite plastics as the most adequate materials for structural applications where light-weight components are required and encouraging the usage of natural reinforcements for more sustainable designs, the present study aims at calibrating a numerical model of a basalt fibre/vinylester laminate to allow a more practical assessment of the low-velocity impact behaviour of such material than through extensive experimental tests. In this work, the composite was considered for application on the monocoque chassis of a solar-powered electric vehicle, being an essential step to evaluate the possibility of using basalt in its structure. However, the simulation guidelines described can be considered in any case involving low-energy impact for the material considered.

MATERIALS AND METHODS

Reproducing the experimental low-velocity impact test performed according to ASTM D7136[1], the specimen of dimensions 150x100x4 mm impacted on a drop-weight tower by a hemispherical-tip steel impactor was drawn and meshed in Ansys Workbench and then exported to LS-DYNA for material properties set-up. All the computations were performed on the CINECA HPC facility "Galileo", a Linux Infiniband Cluster computing system (CentOS 7.0 OS) made of 516 nodes, each one equipped with two 8-cores (16 cores/node, 8256 cores in total) Intel Haswell with a clock frequency of 2.40 GHz per node and a RAM of 128 GB/node. Thanks to the parallel computing resources using 16 cores, the average run time usage was less than 30 minutes on a mesh of 218,897 elements, although the scalability of the LS-DYNA was previously analyzed and tuned to get the best computational performances and time saving on up to 128 cores.



Basalt plies modeled with MAT_54 adopting the Chang-Chang[2] failure criterion where the elements fail by fiber or matrix tensile or compressive modes.

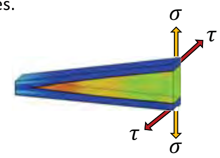
Ridig MAT_20 hemispherical-tip indenter represented with density correspondent to the testing machine weight of 1.25 kg.

Mesh refinement on the impact region to assure stable interbody contact and fracture formation.

Ply representation with 4 shell element layers with 2 integration points each.

Numerical shell representation of the laminate to be used in monocoque, and tested for low-velocity impact.

Delamination: modeled with the interply contact definition AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE_TIEBREAK providing resistance inputs to delamination by tension (NFLS = 60 MPa) and shear (SFLS = 35 MPa).



Calibration of failure parameters especifically for basalt:

$$2\varepsilon_{12} = \frac{1}{G_{12}}\sigma_{12} - \boldsymbol{\alpha}\sigma_{12}^{\;3}$$
weighing factor for the nonlinear shear stress term in the stress-strain equation for the through-the-thickness direction.

$$e_f^2 = \left(\frac{\sigma_{aa}}{X_t}\right)^2 + \boldsymbol{\beta}\left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1$$
$$e_m^2 = \left(\frac{\sigma_{bb}}{Y_t}\right)^2 + \boldsymbol{\beta}\left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1$$
weighing factor for shear in tensile fiber and matrix failure modes, varying from 0 (assuming Hashin's failure criterion) and 1 (assuming Maximum Shear Stress criterion).

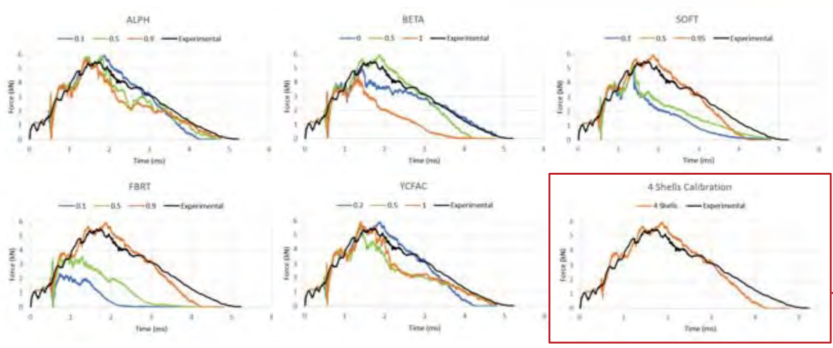
$$\{XT, XC, YT, YC\} = \{XT', XC', YT', YC'\} * \boldsymbol{SOFT}$$
reduction in overall strength of the elements ensuing to those in the crush front.

$$XT = XT' * \boldsymbol{FBRT}$$
reduction in fiber tensile strength of the elements ensuing to those in the crush front.

$$XC = YC' * \boldsymbol{YCFAC}$$
reduction in compressive strength of the fibers after matrix compressive failure occurs.

RESULTS

Calibration of constitutive and degradation parameters: constitution of a basalt/vinylester numerical model applicable to general low-energy impact conditions, with a correlation coefficient to experimets of 97,6%.

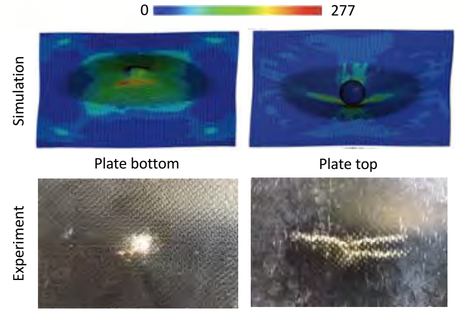


ALPH → low influence of shear in the elastic region for the through-the-thickness direction.
BETA → partial influence of shear on tensile fiber failure mode - between Hashin and MSS criteria.
SOFT, FBRT → reproduction of damage propagation should not be very accentuated, although it should be taken into account.
YCFAC → compressive strength reduction of fibers after matrix compressive failure is elevated.

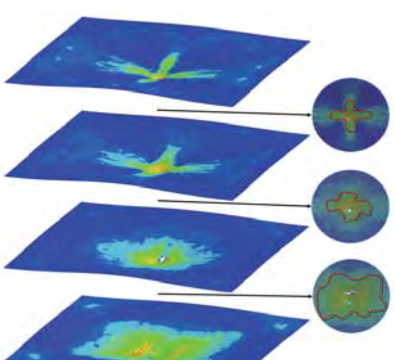
ALPH	BETA	SOFT	FBRT	YCFAC
0.1	0.5	0.95	0.9	0.2

$$r = \frac{\sum(F_{exp} - \bar{F}_{\text{exp}})(F_{sim} - \bar{F}_{\text{sim}})}{\sqrt{\sum(F_{exp} - \bar{F}_{\text{exp}})^2 \sum(F_{sim} - \bar{F}_{\text{sim}})^2}} = 97{,}6\%$$

Maximum Principal Stress (MPa)

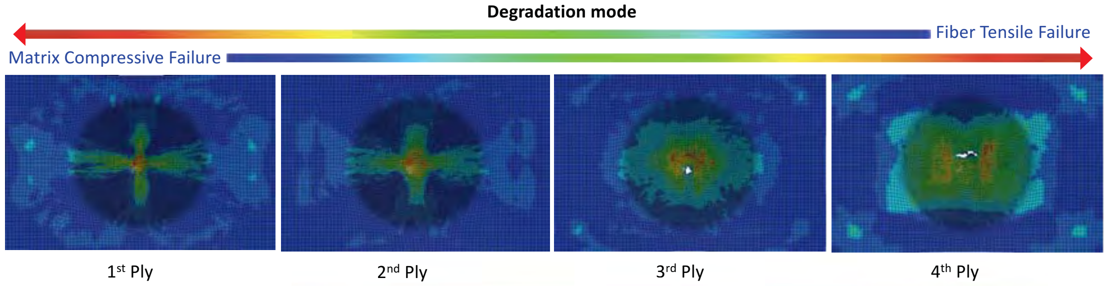


Providing the possibility to understand how the damage propagates through the laminate, a faithful reproduction of the failure mechanisms is observed, characterized by a round-shaped fiber tensile breakage indentation in the bottom, and matrix compressive directional cracks in the top.



Delaminated areas: defined by the superposition of neighbour layers and identification of common stress zones with superior magnitude to NFLS (60 MPa) on tensile stress in the through-the-thickness *z* direction and SFLS (35 MPa) on shear stress in the in-plane *xy* direction.

Degradation mode



CONCLUSIONS

The adjustment of unmeasurable explicit parameters has shown to be of utmost importance not only to build a numerical model of a basalt composite subjected to impact, but also to understand in a quantifiable way the influence of each failure mechanism described by the Chang-Chang constitutive material model (the influence of shear and the degradation of the material near the indentation zone being key factors). Therefore, a precise virtual representation of the damage caused by low-energy shocks on basalt/vinylester composites was successfully attained, providing both an accurate stress-strain response and a visual depiction of the failed regions consistent with experimental tests.

ACKNOWLEDGEMENTS

This research was realized inside the Onda Solare collaborative project, an action with the aim at developing an innovative solar vehicle. The authors acknowledge support of the European Union and the Region Emilia-Romagna (inside the POR-FESR 2014-2020, Axis 1, Research and Innovation).

REFERENCES

[1] ASTM D7136/D7136M: Standard test method for measuring the damage resistance of a fiber-reinforced polymer matrix composite to a drop-weight impact event (2005).
[2] Chang FK, Chang KY. Post-Failure Analysis of Bolted Composite Joints in Tension or Shear-Out Mode Failure. Journal of Composite Materials 21, pp. 809-833 (1987).