Received: 30 April 2021 | Revised: 28 June 2021 | Accepted: 29 June 2021

DOI: 10.1002/mdp2.260

SPECIAL ISSUE ARTICLE

WILEY

Charpy impact properties and numerical modeling of polycarbonate composites

Tamas Krausz | **Iulian-Ionut Ailinei** | **Sergiu Valentin Galatanu** | **Liviu Marsavina**

Faculty of Mechanics, Politehnica University of Timişoara, Timisoara, Romania

Correspondence
Tamas Krausz, Faculty of Mechanics, Politehnica University of Timişoara, 1 Mihai Viteazu Blvd., Timisoara 300222, Romania.
Email: tamas.krausz@student.upt.ro

Abstract

Polycarbonate composites are widely spread in many industries, for product manufacturing. Although these materials are being used with high fidelity, their mechanical properties will highly depend on manufacturing processes, fiber orientations with respect to external loads, type of loading, environmental conditions, and so forth. This paper presents the Charpy impact behavior of three polycarbonate grades, in notched and unnotched conditions, as follows: *Makrolon 2405*—unreinforced polycarbonate, *Makrolon 9415*—polycarbonate with 10% glass fiber, and *Makrolon 8035*—polycarbonate with 30% glass fiber. The experimental measurements clearly demonstrated the effect of the fiber content on the impact strength of the material: as the fiber ratio increases, the impact strength decreases, exhibiting brittle behavior. The impact characterization of the notched specimens can facilitate the material selection for applications with higher geometrical complexities, where stress concentrators cannot be eliminated. In addition, the material models obtained through correlations could help increase simulation accuracy and speed up product development cycles.

KEYWORDS

Charpy impact, composite, impact strength, Makrolon, simulation

1 | INTRODUCTION

Impact testing has been developed in order to measure experimentally a product or material's resistance to high-rate loadings. During the life cycle of many of the products, these can be exposed to specific external loads like shocks, collisions, or drops, which might require rapid energy absorbance. Therefore, the materials of the individual, mainly injection molded parts, must be selected by taking into account all the possible circumstances that may occur in the service life of a product, for guaranteeing continuous functionality. One of the most difficult tasks is the assurance of mechanical properties, with a high weighting of impact strength, as these parameters are highly dependent on geometrical effects.[1]

The Charpy impact test, or Charpy V-notch test, is a classical, standardized, high strain rate test, used to measure the energy absorbed by a notched or unnotched specimen, during fracture, caused by an impact load.

This material testing procedure has emerged as one of the most commonly used impact strength or quality control methods for notch sensitivity, impact toughness, and failure mode determination of different engineering materials,[2] due to the several advantages, such as low difficulty test preparation and performance and rapidly and cheaply obtained results,[3] comparable to the ones attained by other common testing methods—for example, the short beam shear test in case of composite materials.[4]

Similar to other testing methods, the classical Charpy impact test is also characterized by a few disadvantages, out of which we should mention its qualitative aspect: the obtained results by testing can only be used for comparative reasons; measurements can be compared to each other or to a specific requirement but cannot be utilized for subsequent calculations.

Instrumented Charpy impact testing, on the other hand, was developed to go beyond the limitations of the classical impact testing, by offering more than just the energy that the specimen absorbs. Maximum force, loading as a function of specimen deflection, general yielding, potential fast fracture response, or a better overview of the ductile to brittle transition response by the evaluation of the impact behavior at different temperatures[5,6] are only some of the major abilities which the instrumented Charpy impact testing possesses. Beside these material characteristics, others were also derived by the several investigations concerning instrumented impact testing, out of which to be mentioned the proposal of Server,[7] regarding the estimation of the dynamic yield strength based on the characteristic force at general yield, representing a particular importance for loading-rate sensitive materials, for example, low strength steels and composites.

The objective of this paper is to present the impact behavior of three commercially available polycarbonate grades, for both unnotched and notched specimens, and proposes to elaborate a material model for numerical simulations, based on a correlation process, supposed to facilitate material selection and design concept processes.

2 | EXPERIMENTAL INVESTIGATIONS

2.1 | Preparation of test specimens

As for any of the standardized material characterization methods, Charpy impact testing also prescribes the manufacturing process and dimensions of the specimens to be used for experimental investigation reasons. In case of plastics, the standard to be followed is the ISO 179,[8] which is meant to cover the testing procedure for both noninstrumented and instrumented method types, described in two separate parts (Parts 1 and 2).

The test specimens used in this study were derived from classical, dog bone test samples (Figure 1A), manufactured by injection molding technique, according to the ISO 527-2 tensile testing standard's[9] type 1B test specimens, which were then cut off to the required rectangular shape and dimensions (Figure 1B) imposed by the Charpy impact testing standard, as follows: length of 80 ± 2 mm, width of 10.0 ± 0.2 mm, and thickness of 4.0 ± 0.2 mm.

For the notched specimen type, A notches have been considered, as specified by the ISO 179-1 standard. These are characterized by a $45 \pm 1°$ notch, having a radius at the apex of 0.25 ± 0.05 mm. The remaining width of the specimen at the notch tip is 8.0 ± 0.2 mm.

Due to the fact that the test specimens were obtained from 1B type tensile test samples, as a result having a parallel sided portion shorter than the required length from the Charpy standard, the specimens used for the investigations had

(A) (B)

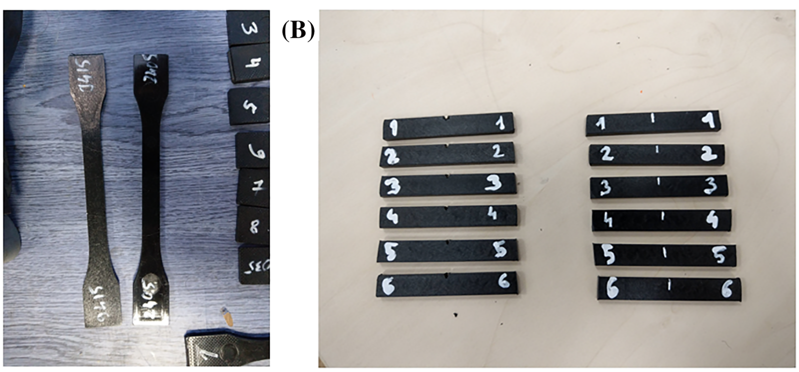

FIGURE 1 (A) Tensile "dog bone" specimens according to ISO 527-2; (B) Charpy impact notched and unnotched test probes according to ISO 179-1

a deviation of 20 mm in length, compared to the prescribed dimensions. Nevertheless, this shortening did not influence the impact behavior of the samples, as the span between the specimen supports, characteristic of the equipment used, was measured to be 40 mm.

2.2 | Test setup

For the Charpy impact characterization of the selected three polycarbonate grades, an Instron CEAST 9050 instrumented test equipment has been used (Figure 2A). The machine consists of a 394.5-mm-long impact pendulum combined with a 3.46-kg hammer at the striker end, possessing a potential energy of 25 J and an impact speed of 3.8 m/s. The recorded force signal measurements were forwarded to the equipment's computer software via a data acquisition system connected to the hammer (Figure 2B).

In order to conduct the tests, the specimens were placed horizontally, in the edgewise manner, on the supports of the test rig and pushed against the anvils. In addition, a centering pin has been used for aligning the notch between the anvils. In case of the unnotched test specimens, a marking has been applied for reference reasons.

2.3 | Results

For the determination of the impact characteristics, experimental tests have been performed for six notched and six unnotched specimens out of each material category.

In case of the unnotched specimens, different post-impact behaviors could be observed. Makrolon 2405 (unreinforced material) did not suffer material breakage; instead, the test probes were found permanently deformed (Figure 3A); Makrolon 9415 (10% fiber volume ratio) exhibited partially fractured impact behavior (Figure 3B); whereas, Makrolon 8035 (polycarbonate with 30% glass fiber) showed full fracture along the impact direction (Figure 3C).

On the other hand, in case of the notched specimens, for all the samples, for all material types, except for very few numbers of cases for the neat polycarbonate material (Makrolon 2405), brittle fracture impact behavior has been observed, triggered by the hammer's impact load. The broken test probes are shown in Figure 4A–C.

Taking the opportunities offered by the instrumented Charpy impact testing, and in order to prepare a material model for the subsequent numerical investigations, further result analyses have been carried out, concerning the recorded force–time data.

For evaluation and comparison purposes, force–displacement and energy–displacement curves were plotted, for both unnotched and notched specimen sets, presented in Figures 5 and 6.

Similar to quasi-static tensile test results, on the force– displacement curve of the unreinforced polycarbonate, all three characteristic regions could be observed: elastic deformation region followed by the region of the plastic deformations and ending in the crack-propagation region (Figure 5A). In terms of energy as a function of displacement, the effect of the plastic deformations can be derived from the displacement increase at constant energy levels.

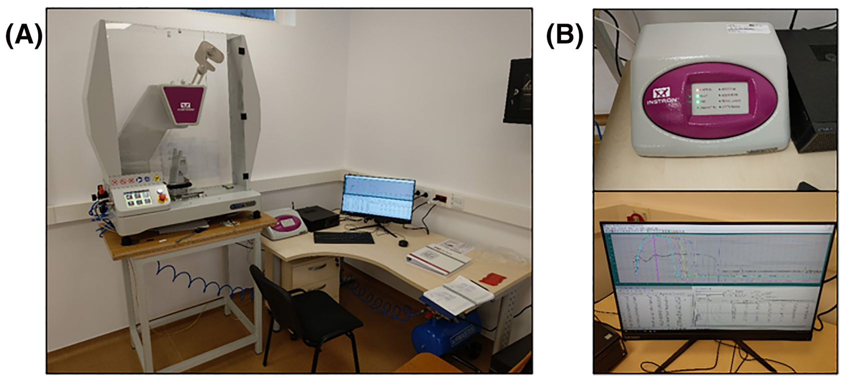

FIGURE 2 (A) Instron CEAST 9050 instrumented impact test equipment; (B) data acquisition system

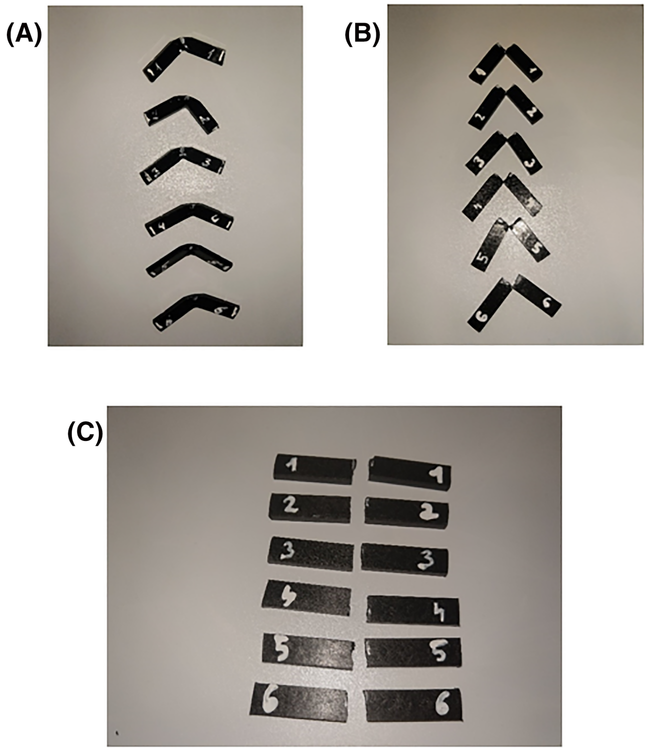

FIGURE 3 Unnotched test specimens after impact: (A) Makrolon 2405; (B) Makrolon 9415; (C) Makrolon 8035

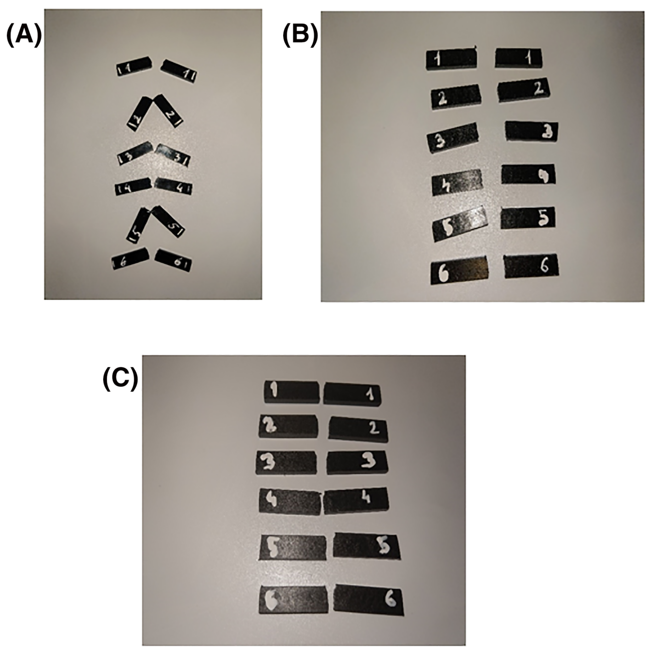

FIGURE 4 Notched test specimens after impact: (A) Makrolon 2405; (B) Makrolon 9415; (C) Makrolon 8035

For the 10% fiber volume fraction material, the third region is characterized by a more brittle behavior, although ductile deformations are still present before the occurrence of fracture (Figure 5B). The impact energy is found to be decreased with the reinforcement.

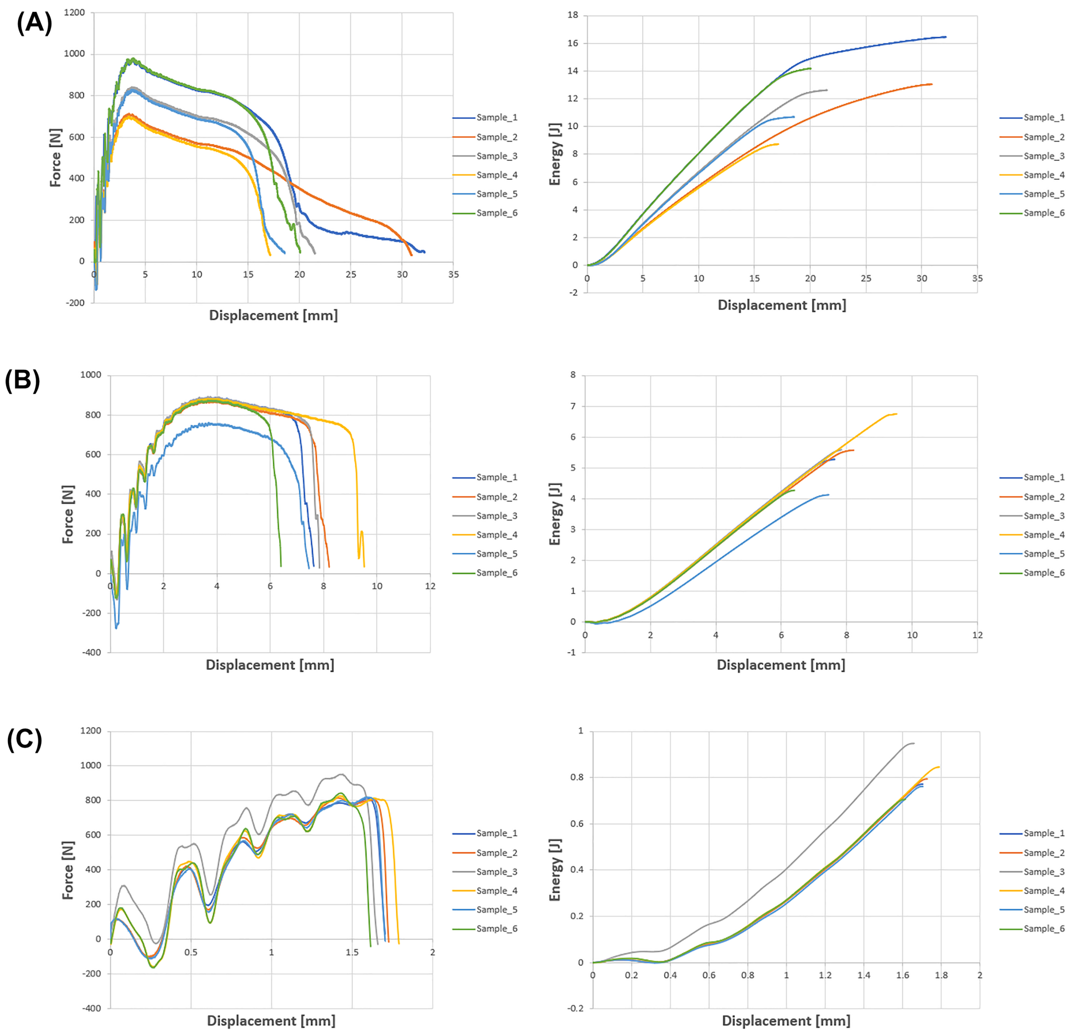

FIGURE 5 Force–displacement and energy–displacement curves—unnotched specimens: (A) Makrolon 2405; (B) Makrolon 9415; (C) Makrolon 8035

In case of the toughest material (30% glass fiber), the elastic region is directly followed by brittle rupture and is associated with the smallest amount of energy that the material can absorb before fracture (Figure 5C).

The results for the notched specimens are even more affected of variations than the ones for the unnotched samples, making it much more difficult to interpret the impact behavior of the individual materials. Some analogies with their unnotched counterparts can be observed in terms of characteristic regions; however, the brittle nature of the breakage is much more emphasized for all the material categories. As a result, the energies absorbed before impact are way less than in case of the unnotched specimens. The corresponding plots are shown in Figure 6A–C.

Besides the representation of the measured force and displacement values, the impact strength of the tested materials was also calculated and compared to the literature values. Table 1 summarizes the determined impact strength values for all three polycarbonate grades. For the unnotched Makrolon 2405, the impact strength value is not applicable as no material failure has occurred. On the other hand, due to the huge scattering of the measured data for the notched samples, the calculated standard deviations are very high; therefore, no reasonable conclusions can be drawn.

In the literature for the tested materials, only unnotched Charpy impact strength data could be found, showing a matching of the determined strength values as follows: for Makrolon 2405, no breakage was observed in either test or literature's side; for Makrolon 9415, a difference of 12.33% (131.5 kJ/m^2 measured vs. 150 kJ/m^2 in material database) has been detected; whereas for Makrolon 8035, a higher discrepancy of ∼50% between measured and datasheet values was observable (20.125 kJ/m^2 as tested vs. 40 kJ/m^2 in datasheets). Differences are possibly triggered by the manufacturing process of the specimens.

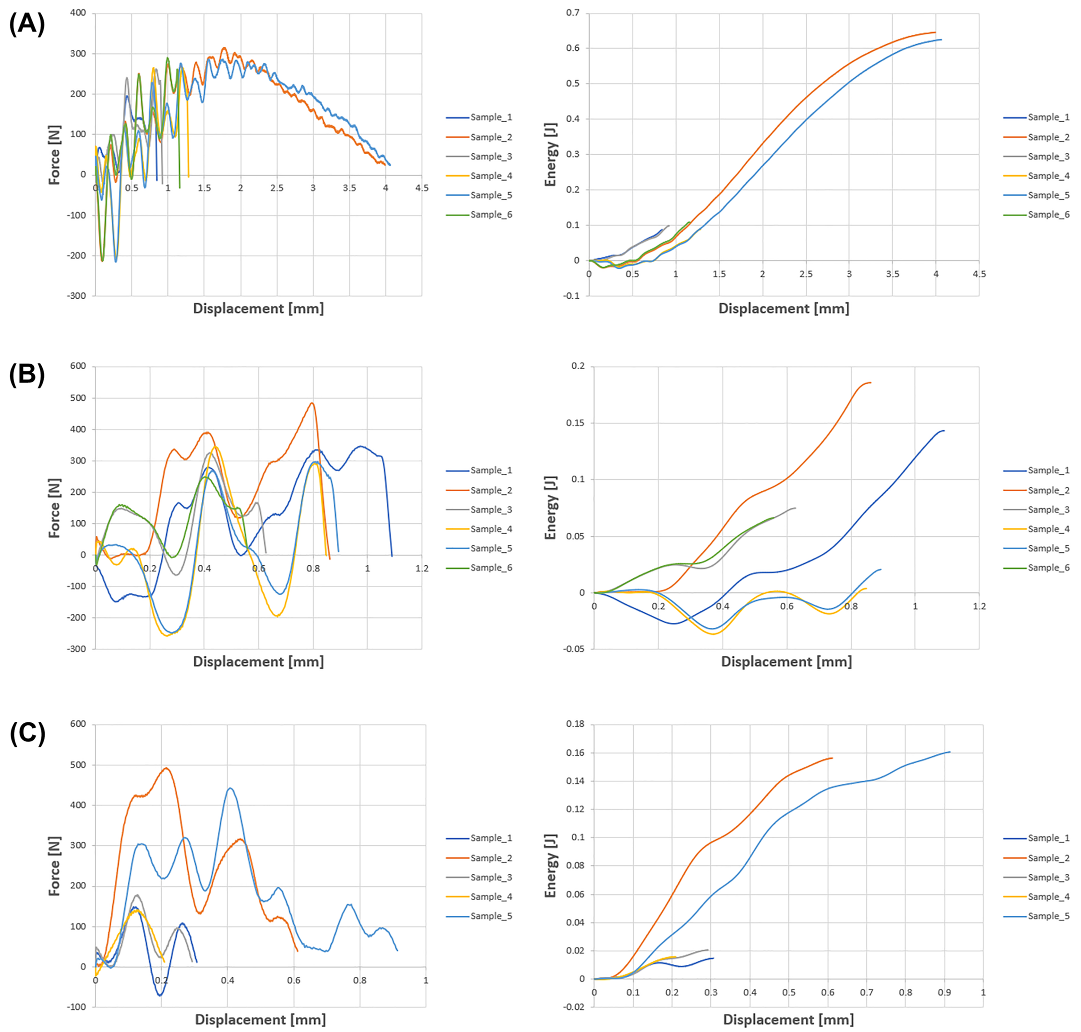

FIGURE 6 Force–displacement and energy–displacement curves—notched specimens: (A) Makrolon 2405; (B) Makrolon 9415; (C) Makrolon 8035

TABLE 1 Impact strength for the tested polycarbonate grades, in both unnotched and notched conditions

Makrolon 2405	Unnotched		Notched	
	Average (kJ/m^2)	SD (%)	Average (kJ/m^2)	SD (%)
	N/A	N/A	6.90	100.97
Makrolon 9415	Unnotched		Notched	
	Average (kJ/m^2)	SD (%)	Average (kJ/m^2)	SD (%)
	131.50	18.41	2.06	85.18
Makrolon 8035	Unnotched		Notched	
	Average (kJ/m^2)	SD (%)	Average (kJ/m^2)	SD (%)
	20.11	10.51	1.54	122.73

3 | NUMERICAL MODELING

The numerical modeling of the experimental measurements has been done with the ANSYS finite element software's explicit module, called LS-DYNA.

In order to understand better the material behavior and to ensure the material model's reliability, the material cards used for the correlations were based on the findings of the quasi-static investigations done previously,[10] as part of a comprehensive study conducted for the proposed polycarbonate grades. The corresponding experimental plan for the impact characterization is briefly summarized in Figure 7.

With the obtained curves, multilinear isotropic hardening models have been set up and defined for the finite element models of the tested specimens (Figure 8). In addition to the isotropic data, plastic strain failure criteria have been defined for each material, based on literature values, for modeling the post damage response of the materials by element erosion, as similarly described by Hufenbach et al.[11]

The boundary conditions were identically set up for each individual material. The striker of the hammer was modeled according to the dimensions provided by Instron: angle of 30°, radius at tip of 2.06 mm, and considered as a rigid, steel body. Similarly, the supports of the test rig were also modeled as rigid parts with fully constrained nodes and

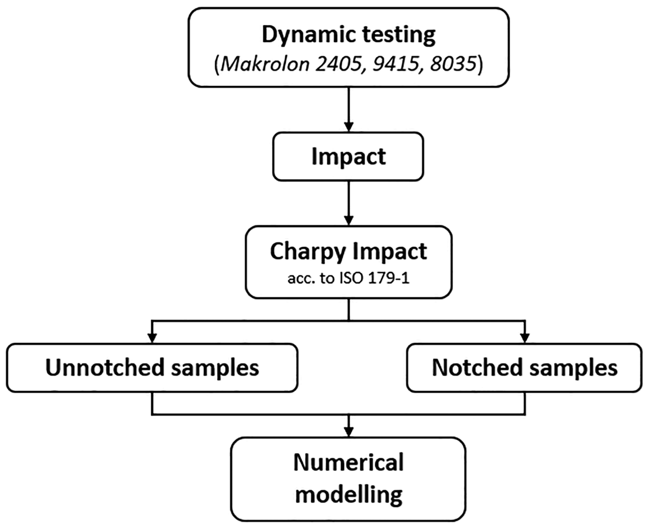

FIGURE 7 Overview of the experimental plan

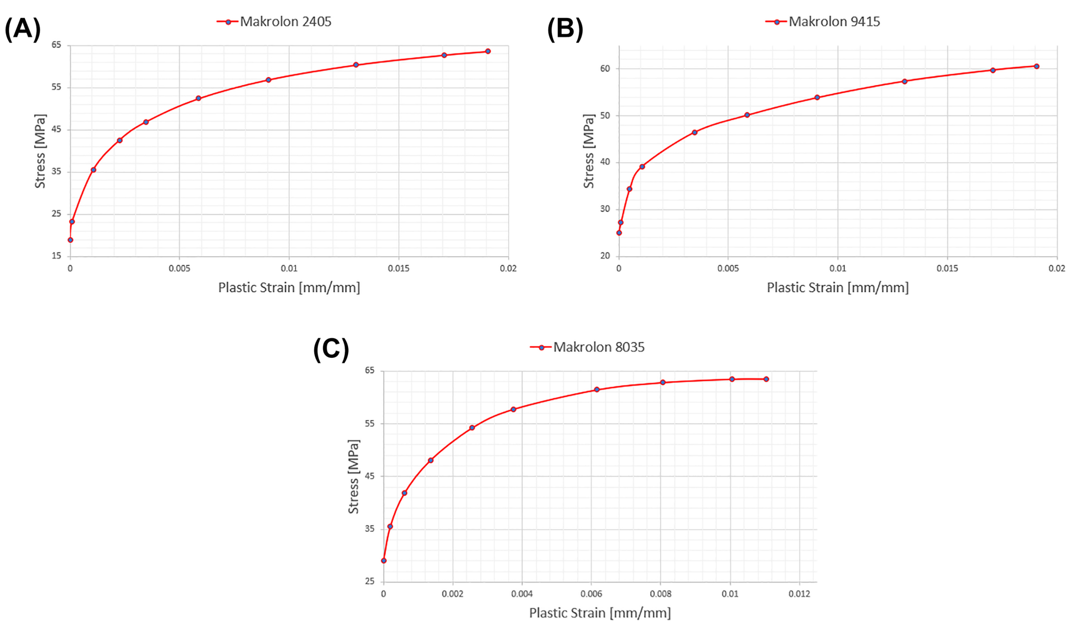

FIGURE 8 True stress–plastic strain representing the multilinear isotropic hardening model for (A) Makrolon 2405; (B) Makrolon 9415; (C) Makrolon 8035

structural steel as assigned material. As for the impact load, a velocity type initial condition has been selected, with an input speed of 3.8 m/s, as stated by the equipment's specifications, assigned to the striker.

The discretization has been done using solid 8-node hexahedral elements (Hex8) for the specimen, in combination with solid tetrahedral and prismatic elements (Tet4 and Wed6) for the striker and support, with an imposed mesh size of 1 mm for all the components (Figure 9). Therefore, the result has been a meshed 3-D model with a total number of 32,730 elements and 15,096 nodes.

As for the modeling of any type of physical testing, in the case of the Charpy impact test, too, the first step is making a comparison of the experimentally and numerically obtained loading curves.[12]

The force–time diagram plotting the results both from the physical testing and from the simulation, for the unnotched Makrolon 2405 specimen, is presented in Figure 10.

As it can be observed from Figure 10A, the matching between the two curves is quite good in the elastic region, up to the maximum force, but high discrepancy will be seen after the apex point, due to the nature of the selected plasticity model. On the other hand, the deformed shape specimen resulting from the finite element method (FEM) simulation (Figure 10B) resembles very well with the specimens after the impact shown in Figure 3A.

In the case of Makrolon 9415, one can again observe a good matching of the experimental and numerically obtained curves (Figure 11A). The maximum force detected in the simulation has a value almost equal to the force determined during the measurements, and the elastic deformations are following the same slopes. In addition, although the simulation exhibits some differences in the plastic deformation region, the coverage of the two data is much better than in the case of Makrolon 2405. Also, the imposed failure criteria described quite correctly the material's fracture triggered by the impact load (Figure 11B).

As opposed to the first two materials, for Makrolon 8035, the comparison between the two plots did not lead to very good matches. In terms of force amplitude, the differences are quite big, although a similarity for the shape of the curves in the elastic region is observed (Figure 12A). From deformation and breakage perspective, the element erosion criteria predicted the fracturing of the test sample due to the impact load (Figure 12B). One possible explanation to the

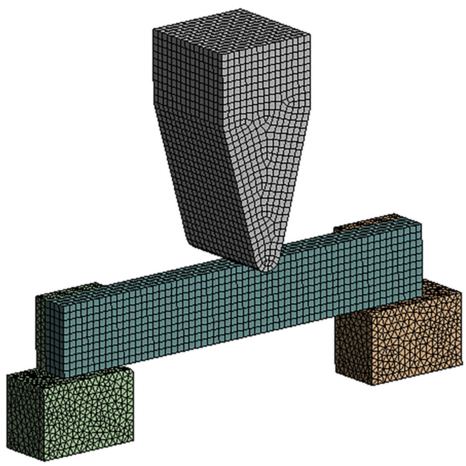

FIGURE 9 Finite element model used for the simulations—solid mesh with hexahedral elements

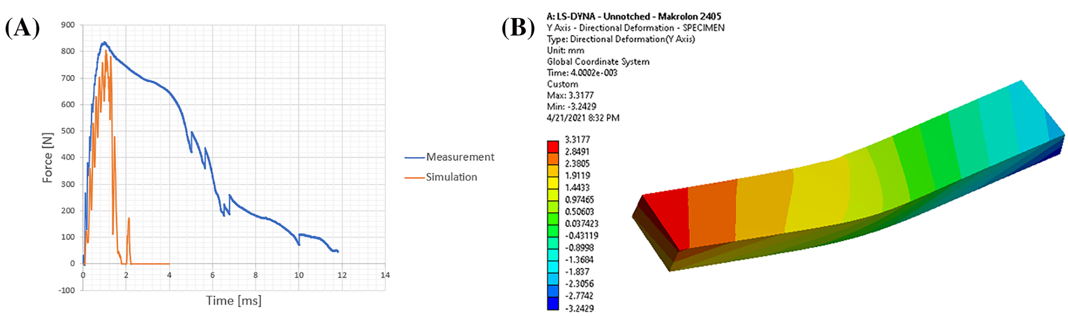

FIGURE 10 Unnotched Makrolon 2405 specimen: (A) force–time plot; (B) deformation result from simulation

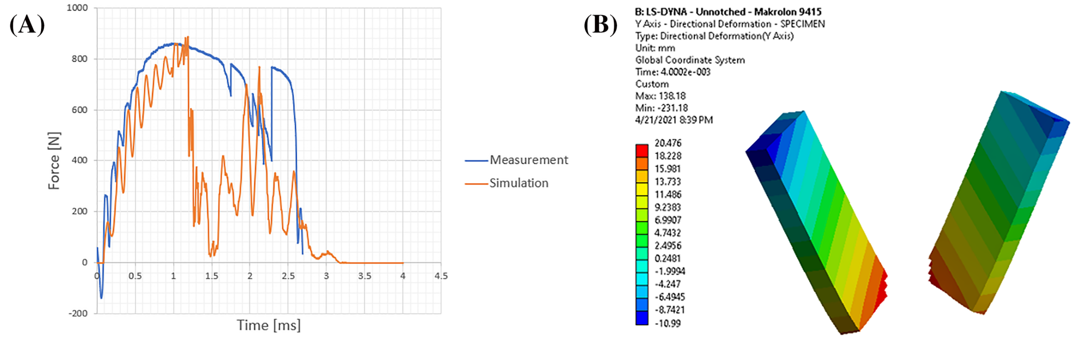

FIGURE 11 Unnotched Makrolon 9415 specimen: (A) force–time plot; (B) deformation result from simulation

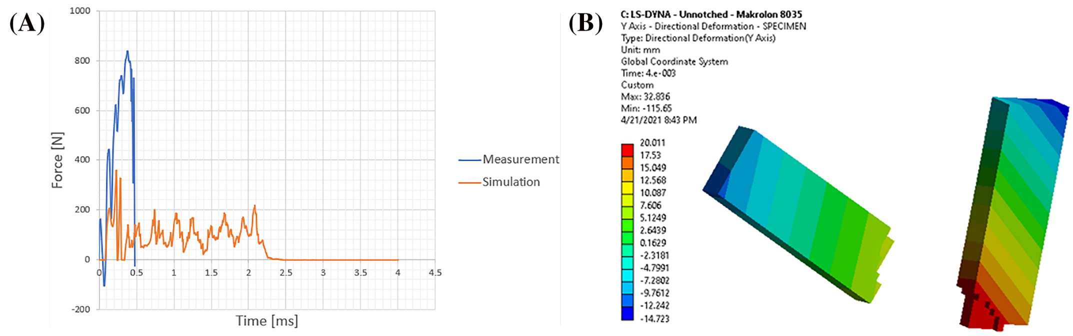

FIGURE 12 Unnotched Makrolon 8035 specimen: (A) force–time plot; (B) deformation result from simulation

differences observed concerns the used material model: the isotropic hardening model in case of a 30% fiber volume ratio material does not reflect correctly the material's impact behavior.

Because of the high scattering of the measurements done for the notched samples, the numerical modeling for the current study was only focusing on the unnotched specimens. Experimental testing will be reperformed for the notched test specimens, with a smaller impact hammer—having a potential energy of 5 J, instead of 25 J, and with an increased attention on the geometrical aspects of the notch during the milling process.

4 | CONCLUSIONS

The objective of the investigations has been to study the impact behavior and the corresponding numerical modeling for three polycarbonate materials from the commercial Makrolon family. With the force and displacement measurements done by using an instrumented Charpy impact test machine, numerical models have been built up and correlated, as well the impact strength of the materials has been calculated and compared to values given in literature.

For the numerical modeling, a good match has been observed in case of the unnotched Makrolon 2405 and 9415 materials, regarding maximum force and slope of the curves in the elastic region. On the other hand, for Makrolon 8035, the proposed isotropic plasticity model did not meet the expectations, mainly due to the inhomogeneity of the 30% glass fiber reinforced material. A better plasticity model, capable of accounting an increased amount of damage caused by the stiffness drops in the material of the specimen, needs to be investigated for further studies.

For the notched specimens, however, statistical and finite element analyses were not possible to conduct because of the high scattering of the measured data. Impact testing for these samples is planned to be repeated for a more thorough characterization, with a higher number of specimens and more rigorous control on notch quality during mechanical processing.

The study of the notch sensitivity—as considered one of the main issues associated with polycarbonates[13]—and comparison of the chosen polycarbonate grades, concerning the Charpy impact properties, are rather an untapped potential in the mechanical characterization and material selection process of these polymeric materials—similar to the fracture behavior[14] and impact characterization of glass and carbon fiber reinforced composites[15]—which together with the other investigations from the proposed experimental plan is expected to gain high popularity in engineering departments.

ACKNOWLEDGMENTS
We would like to thank our colleagues from the Strength of Materials Laboratory for the assistance provided regarding the preparation of the test samples. In addition, we would also like to show our gratitude to the SIRAMM project for offering the necessary environment to conduct the presented studies.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon request.

ORCID
Tamas Krausz https://orcid.org/0000-0001-6033-7930
Sergiu Valentin Galatanu https://orcid.org/0000-0002-7629-8662
Liviu Marsavina https://orcid.org/0000-0002-5924-0821

REFERENCES
1. Hirose H, Kobayashi T, Kohno Y. Charpy impact and dart drop impact. *Polymer Testing*. 1984;4:31-44.
2. Saba N, Jawaid M, Sultan M. An overview of mechanical and physical testing of composite materials. In: *Mechanical and Physical Testing of Biocomposites Fibre-Reinforced Composites and Hybrid Composites*. Woodhead Publishing Series in Composites Science and Engineering; 2019:1-12.
3. Chandrasekaran C. Testing of rubber lining. In: *Anticorosive Rubber Lining*. Plastics Design Library; 2017:165-172.
4. Tanks J, Sharp S, Harris D. Charpy impact testing to assess the quality and durability of unidirectional CFRP rods. *Polymer Testing*. 2016;51:63-68.
5. Server W. Instrumented Charpy test review and application to structural integrity. *European Structural Integrity Society*. 2002;30:205-212.
6. Lucon E. Estimating dynamic ultimate tensile strength from instrumented Charpy data. *Materials and Design*. 2016;97:437-443.
7. Server W. General yielding of Charpy V-Notch and precracked Charpy specimens. *Journal of Engineering Materials and Technology*. 1978;100:183-188.
8. ISO 179-1. *Plastics—Determination of Charpy Impact Properties—Part 1: Non-Instrumented Impact Test*. Seconded; 2010.
9. ISO 527-2. *Plastics—Determination of Tensile PropertiesvPart 2: Test Conditions for Moulding and Extrusion Plastics*. Seconded; 2012.
10. Krausz T, Serban D, Negru R, Radu A, Marsavina L. The effect of strain rate and temperature on the mechanical properties of polycarbonate composites. *Materials Today: Proceedings*. 2021;45(5):4211-4215.
11. Hufenbach W, Ibraim FM, Langkamp A, Böhm R, Hornig A. Charpy impact tests on composite structures—an experimental and numerical investigation. *Composites Science and Technology*. 2008;68:2391-2400.
12. Pineau A. Practical application of local approach methods. *Comprehensive Structural Integrity*. 2003;177-225.
13. Ahmed A, Asija N, Chauhan H, Kartikeya BN. Study of polycarbonate based nano-composites at high strain rate impact. *Procedia Structural Integrity*. 2019;14:507-513.
14. Soutis C. Fibre reinforced composites in aircraft construction. *Progress in Aerospace Sciences*. 2005;41:143-151.
15. Yang B, Lu L, Liu X, Xie Y, Li J, Tang Y. Uniaxial tensile and impact investigation of carbon-fabric/polycarbonate composites with different weave tow widths. *Materials and Design*. 2017;131:470-480.

How to cite this article: Krausz T, Ailinei I-I, Galatanu SV, Marsavina L. Charpy impact properties and numerical modeling of polycarbonate composites. *Mat Design Process Comm*. 2021;3:e260. https://doi.org/10.1002/mdp2.260