Tamas Krausz[*], *Cosmin Florin Popa, Sergiu-Valentin Galațanu, Liviu Marșavina*

NUMERICAL AND EXPERIMENTAL STUDY FOR POLYCARBONATE COMPOSITES UNDER STATIC AND DYNAMIC TESTS

NUMERIČKO I EKSPERIMENTALNO ISTRAŽIVANJE POLIKARBONATNIH KOMPOZITA KOD STATIČKIH I DINAMIČKIH ISPITIVANJA

Originalni naučni rad / Original scientific paper
UDK /UDC:
Rad primljen / Paper received: 7.02.2023

Adresa autora / Author's address:
Faculty of Mechanics, Politehnica University of Timisoara, Timișoara, Romania [*]email: tamas.krausz@student.upt.ro

Keywords
- Makrolon®
- Charpy impact strength
- fracture toughness
- finite element analysis

Ključne reči
- Makrolon®
- Šarpi udarna žilavost
- žilavost loma
- analiza konačnim elementima

Abstract

Polycarbonate based thermoplastics are frequently used in several engineering applications as a consequence of their relatively low price to mechanical toughness ratio, making these materials a perfect choice for various products which, during their lifetime, are subjected to different kinds of external loads. This study is meant to investigate the static fracture toughness and Charpy impact strength of three polycarbonate grades: Makrolon 2405 (unreinforced polycarbonate), Makrolon 9415 (reinforced polycarbonate with 10 % glass fibre), and Makrolon 8035 (polycarbonate with 30 % fibre volume fraction). Static fracture toughness measurements of the three polycarbonate grades are performed by conducting three-point bending tests, using pre-cracked specimens on a universal tensile test machine. Based on the mathematical relations, with maximal force obtained during the tests and with geometry factors (a/W), the critical stress intensity factor has been calculated and compared between the unreinforced and reinforced grades.

Charpy impact strength investigations, using standard notched specimens, were conducted on an Instron CEAST 9050 instrumented Charpy impact pendulum system, following the ISO 179-2 standard. During the measurements one could observe that the reinforced material grades suffered brittle failures, whereas ductile/brittle damage has been observed for the unreinforced grade. After the experimental tests, dynamic fracture toughness investigations have been numerically modelled, showing a relatively good correlation of the results.

Izvod

Termoplastični polimeri na bazi polikarbonata se često koriste u nekoliko inženjerskih primena zbog njihovog odnosa relativno niske cene prema žilavosti materijala, što ih čini pogodnim za razne proizvode, koji su tokom radnog veka izloženi različitim vrstama spoljnog opterećenja. Ovo istraživanje ima za cilj određivanje žilavosti loma u statičkim uslovima kao i Šarpi udarna žilavost kod tri klase polikarbonata: Makrolon 2405 (neojačani polikarbonat), Makrolon 9415 (ojačani polikarbonat sa 10 % staklenih vlakana) i Makrolon 8035 (polikarbonat sa 30 % zapreminskog udela vlakana). Određivanje žilavosti loma u statičkim uslovima za ove tri klase polikarbonata je izvedeno ispitivanjima na savijanje u tri tačke, primenom uzoraka sa početnom prslinom, na univerzalnoj mašini za ispitivanje zatezanjem. Na osnovu matematičkih izraza, sa maksimalnom silom dobijenom pri ispitivanju, i geometrijskim faktorima (a/W), izračunava se kritični faktor intenziteta napona i upoređuje kod obe klase, neojačanih i ojačanih polikarbonata.

Šarpi udarna ispitivanja sa standardnim epruvetama su izvedena na Instron CEAST 9050 instrumentiranom sistemu Šarpi udarnog klatna, prema standardu ISO 179-2. Tokom ispitivanja se uočava pojava krtog loma kod klase ojačanih polimera, dok su vidljiva duktilno-krta oštećenja kod klase neojačanih polimera. Posle eksperimentalnih ispitivanja, izvedeno je numeričko modeliranje dinamičke žilavosti loma, koje je pokazalo relativno dobro poklapanje rezultata ispitivanja.

INTRODUCTION

Fracture toughness is generally known to be one of the most important characteristics of a structural material which describes the resistance of a material when enduring a crack, in other words, indicating the material's ability of absorbing strain energy before fracture, /1, 2/.

Assessing the fracture toughness values in the selection process of a material in various design applications is critical in avoiding different kinds of mechanical failures, /3, 4/. Structural materials with higher fracture toughness values have better resistance to crack propagation.

Fracture toughness values can be determined by specific experimental measurements of which the most commonly utilized methods are the Charpy impact and the three-point bending crack displacement tests. Both tests are conducted on standardized specimens with preset V-shaped or U-shaped notches prior to applying particular loadings /5-7/.

Polycarbonates are well known for their superior resistance to impact, capacity that qualified them as the material of choice in a wide variety of commercial and engineering applications, /8-10/. Nevertheless, due to highly increasing demands, mainly in the automotive industry, where more and more applications are subjected to severe safety regulations, glass fibre reinforced material grades are selected over the base polycarbonate.

The objective of this study is to evaluate three commercially available polycarbonate materials for static fracture toughness and Charpy impact strength characteristics in order to determine if the advantages driven by fibre reinforcements, such as strength and stiffness increase, can also be found in fracture toughness properties of these optimised material grades.

In addition, with data obtained from experimental measurements, numerical simulations have been set up and calibrated, as part of a material model setup process for LS-Dyna specific explicit analysis of the studied polycarbonate grades.

EXPERIMENTAL INVESTIGATIONS

Preparation of test specimens

Specimens used for both static fracture toughness and Charpy impact strength investigations have been derived from standard dog-bone tensile test samples, obtained directly in dumbbell shape by injection moulding process, with specific dimensions according to type 1B test specimens mentioned in ISO 527-2 tensile testing standard, /11/.

In order to achieve the required rectangular shapes, the ends of the abovementioned specimens have been sawed. After this machining process cracks are generated in all specimens, but by applying a different procedure for both static and dynamic test pieces.

In case of static fracture toughness measurements, the cracks for the test specimens to be used were manufactured according to ASTM D5045 standard /12/. As the document states for the single-edge-notch bending (SENB) specimens, the ratio between the length of the preset crack and the specimen width should be in the range 0.45-0.55. Following the descriptions, sharp notches are sawed in samples, and further, a natural crack has been generated by tapping on a razor blade placed in the machined notch (Fig. 1a).

a)

b)

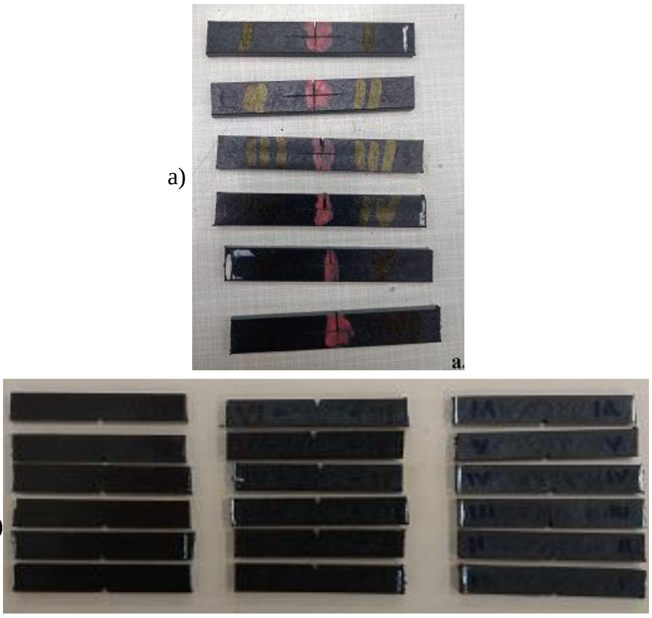

Figure 1. Test specimens prepared for (a) static; and (b) dynamic fracture toughness investigations.

For impact measurements, on the other hand, the test standard to be followed for the preparation of cracks was ISO 179-1, /13/. According to this document, type A notches are machined on specimens, with a 45±1° notch angle and a radius at the apex of 0.25±0.05 mm (Fig. 1b).

The finally obtained impact test specimens had a deviation in length of 20 mm to those described by test standard, due to the fact that these were cut out from specific tensile specimens, rather than out of injected plates. This deviation, however, did not have a negative impact on the measurements, as shown by a previous study of Krausz et al. /14/.

Test setup

Static fracture toughness measurements were conducted on a universal, electro-mechanical, Zwick-Roell Z005 testing machine, equipped with a 5 kN load cell.

As the chosen test samples are of the SENB specimen type, flexural or three-point bending tests were carried out with the specimen simply supported on its two ends, at an equal distance from the pre-set crack, oriented to the ground, and from the pusher, placed on the opposite side of the specimen from its notch. Measurements were done at an ambient temperature of 23 °C and with a strain rate of 2 min/mm.

Charpy impact testing of the selected polycarbonate grades was conducted on Instron CEAST 9050 instrumented test equipment, consisting of a 229.7 mm impact pendulum, with a 1.18 kg hammer integrated at the striker end, having a potential energy of 5 J and an impact speed of 2.9 m/s. The force signal measurements were transferred to the data acquisition system. Specimens were tested in edgewise manner, in other words, supported on the entire width, with the impact load applied similarly to three-point bending measurements.

Results

In order to achieve the fracture toughness characteristics of all three material types, for both static and dynamic loading scenarios, six-six notched specimens have been tested out of each material grade.

Interesting findings could be made in case of three-point bending static measurements, where the unreinforced base material has shown brittle fracture behaviour. Contrarily, the fibre reinforced grades did not undergo a full fracture by the end of the test. The test pieces subjected to bending load have plastically deformed, but the pre-generated crack did not propagate throughout the entire cross section of the specimen. Figure 2 shows the microscopic images of the notch area for some of the tested specimens.

From the images one can observe the propagation direction of the crack and the glowing glass fibre ends, reflecting the light emitted by the microscope. A possible explanation for these observations is related to the extrinsic mechanisms detected in case of fibre or lamella reinforced composites /15/. These filler materials may act as a bridge which holds fracture surfaces together after the crack propagated into the matrix. Force-deflection curves of the tested grades show a relatively good repeatability of measurements, without significant scattering between individual data, Fig. 3.

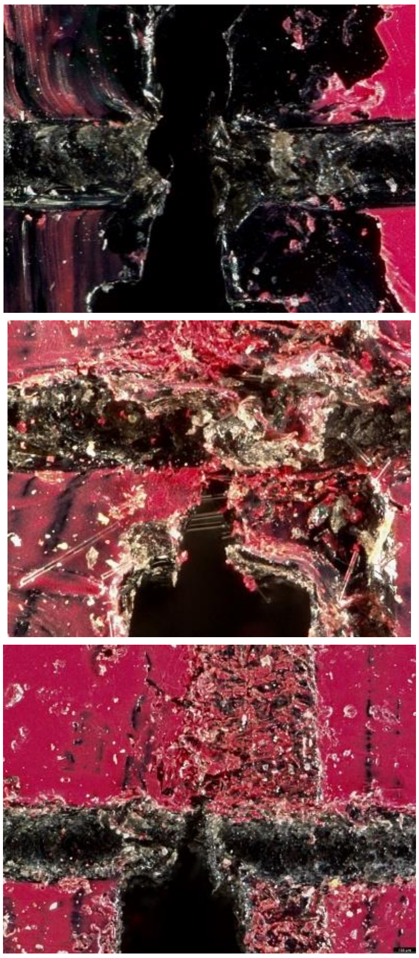

Figure 2. Microscopic images of test specimens subjected to three-point bending static loads.

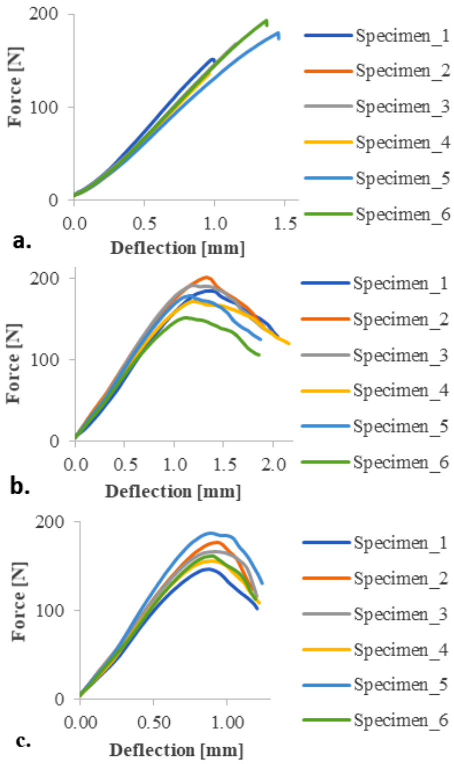

Figure 3. Force-deflection curves of the three polycarbonate grades: a) MK2405; b) MK9415; and c) MK8035.

The characteristic curves highlight the conclusions drawn from the first analysis of the test samples, more exactly that base 2405 grade has demonstrated brittle fracture behaviour, whereas in case of the 9415 and 8035 reinforced grades, the curves clearly state that materials undergo ductile deformation before the machine reaches imposed displacement limits.

From geometrical parameters of the tested specimens and with measured maximal forces, the fracture toughness values are calculated following the equation:

$$K_c = \frac{F_{max}}{\sqrt{W}B} f(a/W) , \tag{1}$$

where: F_{max} is critical load (N); √W is the square root of specimen width ($mm^{0.5}$); B is specimen thickness (mm); and $f(a/W)$ is the geometry factor (-).

The obtained fracture toughness values are presented in comparison among the three polycarbonate types in Fig. 4.

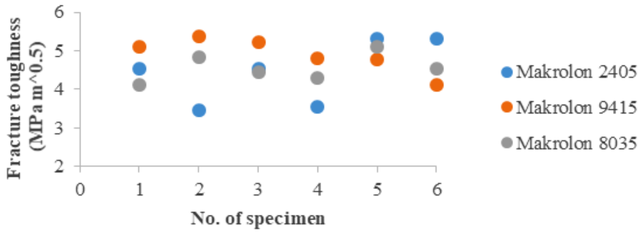

Figure 4. Fracture toughness values obtained for the tested polycarbonate types.

In the case of dynamic fracture tests all samples from all three material types exhibited brittle fracture behaviour, triggered by the hammer impact load. Fracture surfaces of all tested samples, in case of each specific grade, had shown the same crack initiation and propagation tendency. Images of broken test specimens are shown in Fig. 5.

Figure 5. Broken probes from the dynamic fracture toughness test.

In order to better evaluate and compare the dynamic fracture behaviour of selected grades with the help of instrumented Charpy impact machine, force vs. deflection and energy vs. deflection curves are plotted and shown in Fig. 6.

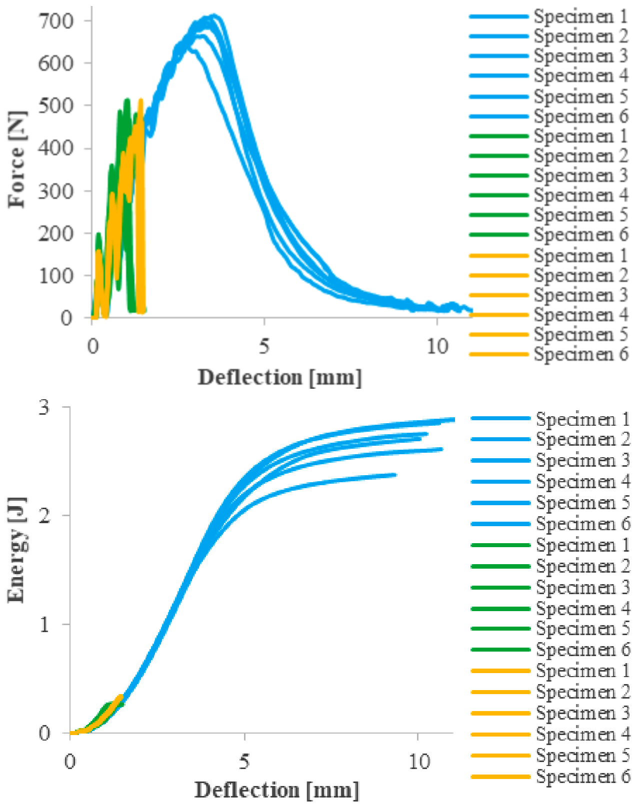

Figure 6. Force-deflection and energy-deflection curves obtained after impact measurements.

The high impact absorbing capacity of base polycarbonate (Makrolon 2405) in comparison to the reinforced materials can already be extracted from force vs. deflection values. However, if analysing the energy vs. deflection curves, one can observe that the energy absorbed by the unreinforced grade is 10× higher than energies absorbed by strengthened grades. Impact tests have been repeated for additional test samples, but the same tendency has been detected, thus minimizing the chance of erroneous measurements.

Charpy impact strength values have also been calculated based on recorded data (Fig. 7).

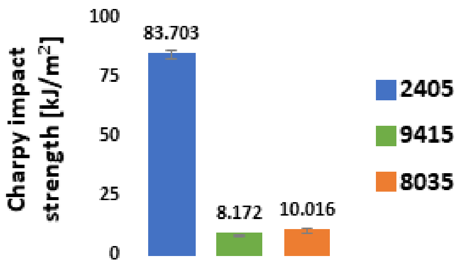

Figure 7. Charpy impact strength values based on recorded data.

Although there are not too many studies in the literature focusing on the impact behaviour of notched polycarbonate materials, Allen et al. /8/ mention almost identical impact strength values for unreinforced grade as those obtained in these dynamic investigations. As per the quasi-static fracture toughness tests, the repeatability of impact measurements has been relatively good.

NUMERICAL MODELLING

As the paper objective already states, the presented investigations are part of a comprehensive material characterization and validation study, with final end applications in numerical simulations of automotive specific products.

In order to calibrate an explicit material model for Charpy impact strength investigations of the studied polycarbonate grades, finite element analyses have been set up using the commercial explicit simulation solver LS-DYNA, from the ANSYS© products family. The simulation model consists of the entire test specimen, the hammer striker and two supports, modelling the anvils of the test rig. The striker has been considered as a rigid steel component, having its geometry modelled according to specifications given by Instron, and meshed with solid hexahedral elements. The two supports are also considered as rigids, but for sake of simplicity are meshed with shell quad elements.

As per the numerical specimen model, it was meshed similarly to the hammer, with solid hexahedral elements and with local mesh refinements in the notch area, but with flexible deformation considerations (Fig. 8).

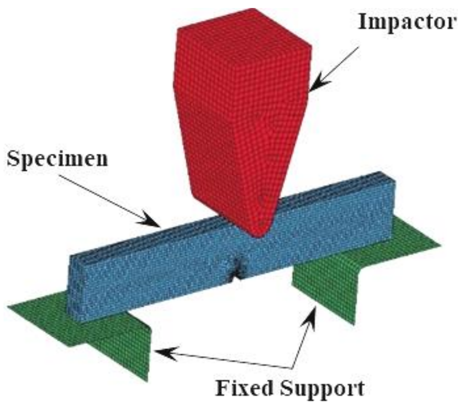

Figure 8. Specimen model together with the modelled hammer and fixed supports.

In order to replicate the impact conditions, a velocity type initial condition is applied to the hammer in the direction of the strike, having an input velocity of 2.9 m/s. In terms of material model used for the specimen, a *MAT_089 (*MAT_PLASTICITY_POLYMER) LS-DYNA specific polymer material card was selected that also permits the definition of arbitrary strain rate dependencies. The card was based on previously determined stress-strain curves at various strain rates by Krausz et al. /16/.

To numerically reproduce the damage observed during experimental testing, *MAT_ADD_DAMAGE_DIEM parameters have also been defined, based on failure strain rate dependency. The over imposed velocity-time graphs, obtained from impact tests and from explicit simulations, for Makrolon 2405 and Makrolon 8035 materials are shown in Fig. 9.

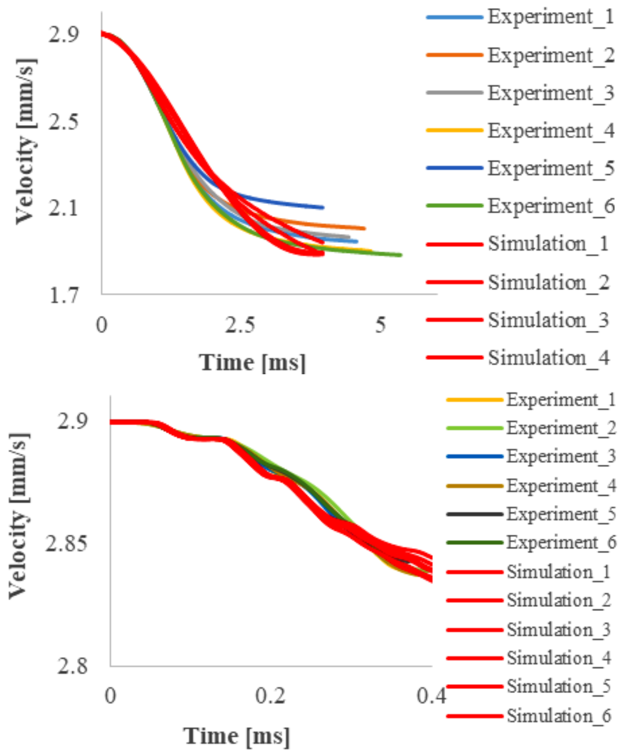

Figure 9. Velocity vs. time plots of impact tests and explicit simulations for Makrolon 2405 and Makrolon 8035.

In case of unreinforced polycarbonate the obtained velocity from explicit simulations has a slightly less steep drop than in physical measurements. The deviation between simulated and experimental data is more emphasized in the time range of 1 to 3 milliseconds. After this 3 ms time interval the numerical results will start to converge and follow the same tendency as the measured data.

As opposed to the previous observation, in case of the Makrolon 8035, the simulation shows a more conservative behaviour. Repetitive peaks and valleys are detected in both raw data and numerical results, but this time with a slightly more significant velocity drop in the explicit model than in physical measurements. A possible explanation to the resulting differences might be the isotropic, homogeneous material modelling of polycarbonate grades, or the damage parameters defined, for which additional material measurements would have been necessary.

CONCLUSIONS

The aim of the investigations was to evaluate the dynamic Charpy impact strength and static fracture toughness of three different polycarbonate grades, from the same Makrolon family.

For both mechanical tests a relatively good repeatability of the measured values could be observed, without significant scattering of determined force-deflection and energy-deflection results.

Despite obtaining almost identical dynamic responses, in the case of all individual materials, when plotted against each other, massive differences close to an order of magnitude could be observed between the energy absorbed before fracture by the base material and by fibre reinforced grades.

In case of quasi-static tests, the aforementioned high discrepancy in terms of energies and fracture toughness between the three materials could not be observed.

One common aspect of both loading conditions could still be found, although specific material responses. In both test cases, the Charpy impact strength and fracture toughness values follow a linearity related to the fibre volume fraction. The highest values are obtained for pure polycarbonate grade, whereas the lowest energy, and subsequent fracture toughness and Charpy impact strength values are observed for the 30 % glass fibre reinforced material. From this, one can draw the conclusion that in the case of applications having to withstand severe impact or shock loads, the less the added fibre reinforcement, the better the obtained dynamic response.

Numerical simulations conducted for calibrating an explicit dynamics material model led to a really good replication of Charpy impact measurements. The overlaid velocity-time plots show that the numerical model is slightly underestimating the velocity decrease of the actual samples, but only in the case of Makrolon 2405. This behaviour is expected to be mainly influenced by the damage parameters defined in the material card, which could be improved by optimisation studies.

ACKNOWLEDGEMENTS

This paper was financially supported by the Project ‘Network of excellence in applied research and innovation for doctoral and postdoctoral programs’ / InoHubDoc, project co-funded by the European Social Fund financing agreement no. POCU/993/6/13/153437 and by European Union’s Horizon 2020 research and innovation programme (H2020-WIDESPREAD-2018, SIRAMM) under grant agreement no. 857124.

REFERENCES

1. Vasiliev, V.V., Morozov, E.V., Chapter 3: Mechanics of a Unidirectional Ply, In: Advanced Mechanics of Composite Materials, 2nd Ed., Elsevier Ltd., 2007, pp.57-132. doi: 10.1016/B978-008045372-9/50003-8
2. Mouritz, A., Fracture Toughness Properties of Aerospace Materials, In: Introduction to Aerospace Materials, Woodhead Publ. Ltd., 2012, pp.454-468. doi: 10.1533/9780857095152.1
3. Friedrich K. (Ed.), Application of Fracture Mechanics to Composite Materials, Compos. Mater. Series, Vol.6, Elsevier B.V., 1989. ISBN: 978-0-444-87286-9, ISSN: 0927-0108, 1989.
4. Marsavina, L., Linul, E., Voiconi, T., Sadowski, T. (2013), *A comparison between dynamic and static fracture toughness of polyurethane foams*, Polym. Test. 32(4): 673-680. doi: 10.1016 /j.polymertesting.2013.03.013
5. Hufenbach, W., Ibraim, F.M., Langkamp, A., et al. (2008), *Charpy impact tests on composite structures - An experimental and numerical investigation*, Compos. Sci. Technol. 68(12): 2391-2400. doi: 10.1016/j.compscitech.2007.10.008
6. Hirose H., Kobayashi T., Kohmo Y. (1984), *Charpy impact and dart drop impact*, Polym. Test. 4(1): 31-44. doi: 10.1016/0142-9418(84)90031-X
7. Server, W.L, *Instrumented Charpy test review and application to structural integrity*, In: D. François, A. Pineau (Eds.), From Charpy to Present Impact Testing, Europ. Struct. Integr. Soc. Book Ser. Vol.30, Elsevier, 2002, pp.205-212. doi: 10.1016/S1 566-1369(02)80022-X

8. Allen, G., Morley, D.C.W., Williams, T. (1973), *The impact strength of polycarbonate*, J Mater. Sci. 8: 1449-1452. doi: 10.1007/BF00551669
9. Shah, Q.H. (2009), *Impact resistance of a rectangular polycarbonate armor plate subjected to single and multiple impacts*, Int. J Impact Eng. 36(9): 1128-1135. doi: 10.1016/j.ijimpeng.2008.12.005
10. Rosenberg, Z., Kositski, R. (2017), *Deep indentation and terminal ballistics of polycarbonate*, Int. J Impact Eng. 103: 225-230. doi: 10.1016/j.ijimpeng.2017.01.018
11. ISO 527-2:2012 Plastics. Determination of tensile properties. Part 2: Test conditions for moulding and extrusion plastics, Second Ed., 2012.
12. ASTM D5045-99 Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials, last updated 2017. doi: 10.1520/D5045-99
13. ISO 179-1:2023 Plastics. Determination of Charpy impact properties. Part 1: Non-instrumented impact test, Third Ed., 2023.
14. Krausz, T., Ailinei I.-I., Galatanu S.V., Marsavina, L. (2021), *Charpy impact properties and numerical modeling of polycarbonate composites*, Mat. Design Process. Comm. 3(4). doi: 10.1002/mdp2.260
15. Piggott M.R. (1970), *Theoretical estimation of fracture toughness of fibrous composites*, J Mater. Sci. 5: 669-675. doi: 10.1007/BF00549751
16. Krausz, T., Serban, D.A., Negru, R.M., et al. (2021), *The effect of strain rate and temperature on the mechanical properties of polycarbonate composites*, Materials Today: Proc. 45(1): 4211-4215. doi: 10.1016/j.matpr.2020.12.121

ESIS ACTIVITIES

CALENDAR OF CONFERENCES, TC MEETINGS, and WORKSHOPS

January 17-20, 2024	ESIS TC16 Meeting	Turin, Italy	
February 1-2, 2024	PCF2024, Portuguese Conference on Fracture 2024	Polytechnic of Setúbal, Portugal	https://www.pcfracture.pt/
March 24-27, 2024	ESIS TC4, 9th International Conference on Fracture of Polymers, Composites and Adhesives	Les Diablerets, Switzerland	Flyer link
April 17, 2024	TAGSI–FESI Symposium 2024 Future Challenges for Structural Integrity of High Integrity Components	Manchester, UK	https://www.fesi.org.uk/events/tagsi-fesi-symposium-2024/
June 11-13, 2024	VAL5, 5th Int. Conf. on Material and Component Performance under Variable Amplitude Loading	Dresden, Germany	Flyer link
June 19-21, 2024	Fatigue 2024, 9th Engineering Integrity Society Int. Conf. on Durability & Fatigue	Cambridge, UK	http://fatigue2024.com/
July 7-10, 2024	ICEFA X, 10th Int. Conf. on Engineering Failure Analysis	Athens, Greece	elsevier.com/events/conferences/international-conference-on-engineering-failure-analysis
July 15-17, 2024	ICMM8, 8th Int. Conf. on Material Modelling	London, UK	https://www.lboro.ac.uk/research/icmm8/
August 26-30, 2024	ECF24, 24th European Conf. on Fracture, and Summer School	Zagreb, Croatia	www.ecf24.eu
September 10-12, 2024	ESIS TC3, CP 2024, The 8th Int. Conference on Crack Paths	Rimini, Italy	https://www.crackpaths.org/