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Multi-impact mechanical behaviour of short fibre reinforced composites

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ABSTRACT

High velocity transverse impact on reinforced composites is a matter of interest in the automotive, aeronautical and biomedical sectors. Most existing studies have addressed this problem by single isolated impacts; however, this work deals with the distinction between single, sequential and simultaneous impacts on composite structures. This paper proposes an experimental methodology to study the mechanical behaviour of materials under single and multi-impact loadings. The overall objective is to investigate the mechanical response of short carbon fibre reinforced PEEK when is subjected to single and multiple high velocity impacts. Experimental tests are conducted covering impact velocities from 90 m/s to 470 m/s. Energy absorption, damage extension and failure mechanisms are compared to assess additive and cumulative effects in high velocity impact scenarios. Experimental results show that the specific deformation and fracture mechanisms observed during multi-hitting events change with impact velocity. Compared to the behaviour of unreinforced thermoplastics, short fibre reinforced composites present significant limitations at velocities close to the ballistic limit, but multi-hit capability is observed at high impact velocity when the damage is mainly local. As key conclusion, the ballistic limit obtained in single impact test cannot be extrapolated to sequential and simultaneous tests. Multi-impact tests, especially close to the ballistic limit, are necessary to guarantee the structural integrity of composite structures in realistic impact scenarios.

1. Introduction

Thermoplastic polymers have experienced an increasing interest due to their good mechanical properties and possibilities in terms of manufacturing [1–3]. Furthermore, thermoplastics can be reinforced by incorporating long fibres, short fibres and particulate reinforcement, thus improving their mechanical properties [4,5]. Thermoplastic composites are currently employed in different industries for a wide variety of applications. Among these industries, the presence of thermoplastic composites stands out in the automotive, aeronautical and biomedical sectors [6], where metals are being replacing due to their good properties and biocompatibility [7]. In this regard, particular attention has been paid to thermoplastic polymers reinforced with short fibres (SFR thermoplastics) because of their advantages for customized and complex-geometry products, especially useful in biomedical applications [8]. One of the major problems of SFR thermoplastics is that, although an increase in stiffness is achieved with respect to unfilled thermoplastics, the addition of short fibre reinforcement generally results in a reduction of ductility leading to the embrittlement of the composite [9,10]. This can suppose a limitation in applications that are potentially exposed to impact loading, especially common in automotive and aeronautical components, as well as in some human prosthesis [11].

The mechanical response of materials against impact loading has been mainly addressed by single impact testing [6,12–16]. However, in real scenarios, many structures are potentially exposed to multi-impact loading such as in automotive and aeronautical applications due to hailstorms or particle multi-hitting [17–19]. In addition, potential prosthetic devices provide structural support for the body and they must be able to absorb enough energy above its ultimate strength without showing fracture [20]. Therefore, it is essential to study the effect of reduced ductility in order to determine the levels of energy absorption of prostheses, such as cranial implants and hip systems [21], in dynamic conditions with energy levels commonly generated in a fall or accident with multi-point contact.

The importance of studying materials under repeated or simultaneous impacts has been allude by several authors [18,19,22–24], although only few works can be found in the literature. An impact series is considered sequential when the time-hit interval is sufficiently long to avoid synergistic effects from stress waves interaction [17]. These sequential impacts can be understood as the repetition of impact over the same area until failure. On the other hand, an impact series is considered simultaneous when stress and shock wave interaction is

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expected. In this regard, there are only few works that study the mechanical response of materials against more than one projectile impacting sequentially or at the same time and, to the authors' knowledge, these are focussed uniquely on metal materials [18] and long fibre composites [24]. In such works, lower impact energy thresholds have been found to result in failure in comparison with the expected energies from single impact studies. This reduction in critical impact energies arises from combined effects of stress wave interactions and stress concentration due to previous damage or bending. Therefore, the analysis of the mechanical response of materials under sequential and simultaneous impacts is essential to determine their suitability for a specific application potentially exposed to impact loading.

To the authors' knowledge, there is no available work in the literature on the mechanical response of SFR composites under multi-impact loading, scenario where synergetic effects arising from stress wave interactions or stress concentrations due to previous damage and bending are expected, resulting in lower impact energy levels to reach material failure. The main aim of the research presented in this paper is to propose an experimental methodology to study the mechanical behaviour of SFR thermoplastics under single and multi-impact loadings. To this end, we present experiments on plates manufactured with short carbon fibre reinforced polyether-ether-ketone (SCFR PEEK) composites. These experiments cover three potential impact scenarios: single impact, sequential impacts, and simultaneous impacts. The impact energy ranges from 10 J to 184 J, covering an energy range equivalent to usual impact loading observed in industrial applications. The results obtained herein show the need to take into account synergetic effects of stress wave interactions and bending due to multi-hits as well as stress concentrations due to previous damage, and highlight potential limitations of components subjected to impact whose suitability has been only evaluated by single impact testing.

2. Materials and methods

2.1. Baseline material

PEEK stands out among thermoplastic polymers used as composites matrix due to its good properties such as thermal stability, chemical resistance, low flammability and excellent mechanical properties [25,10]. In this regard, semi-crystalline polymers show a complex mechanical behaviour that presents a strong non-linearity, large deformations, plastic flow and dependencies on strain rate, temperature, and stress state [3]. In addition and for dynamic processes, thermal softening also influences the deformation process of thermoplastic polymers [2], as observed in other ductile materials [26]. Moreover, fibre reinforced semi-crystalline composites are used in applications that require excellent impact performance due to the incorporation of short fibres into a thermoplastic matrix permits to improve the stiffness and strength [27]. Despite the good mechanical properties of SFR polymers, the fibres distribution along these composites often presents dispersion and disorientation, not providing the advantages of unidirectional long fibre composites [10]. However, SFR thermoplastics offer excellent advantages in their manufacturing process, which allows different possibilities such as extrusion or injection moulding [28]. Extrusion and injection moulding processes lead to a preferred orientation along the mould filling direction [29]. Among the different materials used for the fibre reinforcement, carbon fibres are the most commonly employed in load-bearing components [30]. In this regard, carbon fibre reinforcement is one of the most widely used for PEEK based composites due to its strong interfacial interaction with PEEK matrix [31].

In this work, we chose PEEK reinforced with PAN short carbon fibres 30% in weight, denominated CF30 PEEK, as baseline material. Several plates were manufactured by injection moulding technology and were purchased measuring 130x130x3 mm^3. The diameter and length of the fibres were 7 μm and 200 μm respectively. This reinforcement leads to an increase of the tensile elastic modulus up to more than seven times the value of unfilled PEEK and doubles the failure strength value [16]. Previous experimental results show a preferred fibre orientation mainly aligned in the injection flow direction, IFD, resulting in anisotropy with higher stiffness in the IFD [10,16]. In addition, an enhanced behaviour has been reported under compressive loading with respect to tensile loading. The main mechanical properties of this material are shown in Table 1. Regarding the fracture in SFR composites subjected to impact loading, this occurs as the result of a variety of complex damage mechanisms such as fibre cracking, fibre debonding and pull-out, plastic localisation and ductile fracture due to void growth and coalescence in the matrix [29].

Table 1
Material properties of SCFR PEEK [16].

	SCFR PEEK composite (CF30)	
	Transversal	Longitudinal
Density (kg/m^3)	1400	
Tensile elastic modulus (GPa)	12.6	24
Compressive elastic modulus (GPa)	15	44
Poisson's rate	0.38	0.385
Yield stress (MPa)	130	180
Tensile strength (MPa)	148	214
Compressive strength (MPa)	174	239
Elongation at break (%)	1.9	2.0

2.2. Experimental method

In this paper, a series of single, sequential and simultaneous impacts were conducted on SCFR PEEK plates with a fibre weight fraction of 30%. These tests were performed using rigid spherical steel projectiles with a mass of $m_p = 1.71$ g and a diameter of $\varnothing_p = 7.5$ mm. The setup used for the tests is shown in Fig. 1. The active area of all plates was reduced to 100 × 100 mm^2 in order to impose boundary conditions that avoid sliding and ensure a correct clamping of the specimen, Fig. 2.

The measurement of the impact and residual velocities was carried out with two high-speed video cameras (Photron Ultima APX-RS) that were placed in both sides of the target plate during all the tests. In addition, two 1200 W HMI lamps were used to adequate the lighting. The cameras were configured to obtain 70,000 frames per second (fps) for simultaneous impact tests and 100,000 for single and sequential impact tests and, with the aim of better understanding the ultimate deformation state after impact, a reference grid composed by 1 × 1 cm^2 squares was drawn in each plate.

2.2.1. Single tests

Single impact tests provide information about the deformation and failure mechanisms that govern the perforation process. These consist

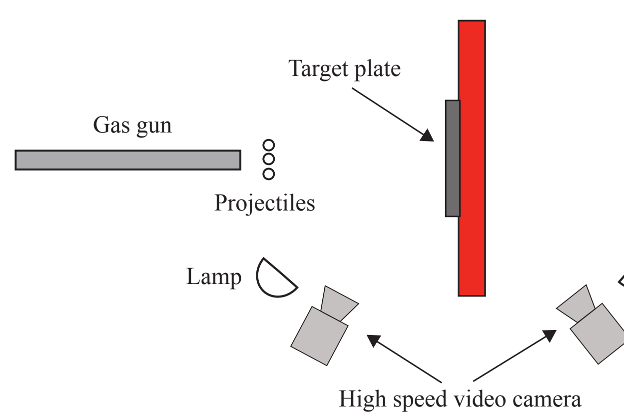

Fig. 1. Experimental device.