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Experimental and Numerical Investigation of Long Fibre Thermoplastic Composite Subjected to Impact

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ABSTRACT

The present study concerns with the experimental and analytical investigation of long fibre thermoplastic composite beam subjected to impact loading. Nylon 6 beam specimens are used in this report. The specimens were subjected to a low velocity impact, drop weight test rig and a number of empirical relations and observations were obtained which relate the deformation of a specimen to the impact energy, percentage glass reinforcement (20%, 40%, 50%) and temperature (23°C). Three different glass fiber reinforcements have been tested and compared with the additional finite element results. A three-dimensional (3D) finite element analysis (ABAQUS/Explicit) has been employed to determine the deformation and failure of Nylon 6. A good agreement between finite element results and experimental findings was found.

Keywords : Low Velocity Impact, Nylon 6, Thermoplastic, Finite Element Analysis

I. INTRODUCTION

Thermoplastic polymers are widely used in many engineering fields, while the properties and characteristics of such type of materials have been approached by many researchers [1-4]. For instance, the excellent mould filling properties during reaction injection moulding process (RIM), make Nylon 6 (PA6) an important matrix for composite systems for use in the automotive and related industries [5]. The polyamide (PA) family consists of different grades depending upon the way they were polymerized. The polymerization conditions, which affect the degree of crystallinity, the spherulite size and molecular weight can affect the mechanical properties of Nylon 6 [6] where, for example, a change from brittle to ductile fracture in Nylon 6 is caused by the increase in the molecular weight and spherulite diameter (which is affected by raising the polymerization temperature). Moreover, such materials have also limitations, especially its response to localized impact loading.

In literature, there are several studies that have been performed in order to investigate the impact properties of thermoplastic materials [7-16] but only few studies examined the fracture toughness, as well as, the fibre content and length effects [17,18]. From these studies, the results show, that the addition of fibers up to 35% weight of a polyamide matrix led to an improvement of fracture toughness with a minor advantage for long fibers. Fibers such as carbon and glass fibers, could increased the properties. The tensile and shear strengths of the above systems were satisfactory predicted using the law of mixtures and fracture surfaces of these systems were mainly characterized by very small fibre pull-out lengths [19]. However, low velocity impacts induce damage to the composite in the form of matrix cracking, delamination, debonding and fiber breakage. Usually, the tested specimens were plates were almost rigids while the materials depend from the product. Plates can be manufactured from different materials, such as of poly(ethylene terephthalate) [**8, 12**], polypropylene [**10, 14, 15**], polyethylene [**16, 20, 21, 22**] and PEEK [**9, 23**] fiber reinforcement. It should be noted, that the stiffening effect is depending on the aspect ratio and surface treatment on the fibres [**19, 24**].

For simulating low-velocity impact events, the most common test setup is to use a free-fall drop-weight impact test rig [**25–32**], also proposed by an ASTM standard [**33**]. For high velocity impact, gas-gun impact test setups are commonly used [**34–36**]. The impact resistance depends, on the properties of the structure, such as, material, thickness, and the properties of the impactor [**37, 38, 39**]. It should be noted that, despite increased use of polyamides, few studies on the impact behavior is found [**40-44**].

The purpose of this present work is to investigate experimentally the impact behavior of glass reinforced Nylon 6 for different amounts of glass reinforcement (20%, 40% and 50% b.w.) at room temperature (23°C). The impact tests were carried out on a plate specimen cut from the above systems and using an instrumented impact machine. A finite element code ABAQUS/Explicit was also used to predict the low velocity impact behavior of glass fibre-reinforced polyamide. Numerical and experimental results, of the composite plate subjected to low-velocity impact, are in a good agreement.

II. METHODS AND MATERIAL

Specimen Configuration and Material

The testing configuration was based on the ASTM standards D7136, for multidirectional polymer matrix composite laminated plates subjected to a drop-weight impact event. The experimental impact test was carried out in instrumented drop-weight impact rig machine (Instron CEAST 9340), while the specimen dimensions are shown in **fig. 1**.

The dimensions for each specimen were 100x20x4 (mm), simply supported over a clamp assembly which had a nominal span of 50mm. The assembly was secured onto the base of the impact machine so that the specimen could be placed directly under the path of a striker mass, or tup, which was able to slide between two rigid steel bars. The tup was released (demagnetized an electromagnet) and allowed to fall freely (maximum drop height of 1.1m) and strike the mid span of the specimen with mass equal to 1kg. In this study the drop height varied between 0.50 and 0.80 meter, enabling a maximum impact speed of 3.92m/sec.

Nylon 6 (PA6) with amount of glass reinforcement, has a high degree of toughness, good resistance to creep, excellent abrasion, low coefficient friction and processing material. The mechanical properties of the materials are given in Table 1.

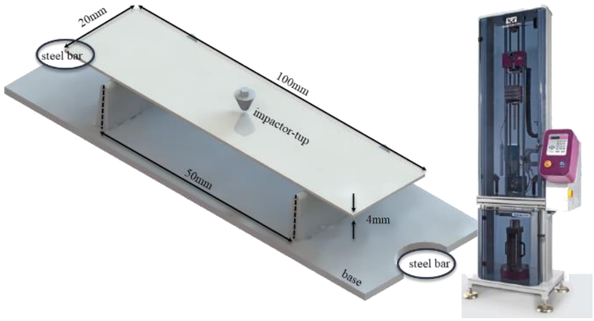


Figure 1: Typical test specimen configuration and specimen detail

PA6	20% GF	40% GF	50% GF
Specific gravity	1.27	1.45	1.60
Tensile Strength (MPa)	128	230	221
Tensile Modulus (MPa)	8276	11724	15172
Tensile Elongation (%)	2-3	2-3	2-3
Flexural Strength	203	328	362

(MPa)			
Flexural Modulus (MPa)	7586	9655	11724
Unnotched Izod Impact (J/m)	1175	1602	1816

Table 1. Materials properties of Nylon 6 with different amounts of glass reinforcements (injection molding)

Method and Experimental Results

Figure 2 shows the force-time response of low velocity. In the classical drop weight case, the velocity can be determined, by calculating the distance travelled by the impactor between two photo-sensors (emitter and detector) [**45**], or by incorporating an optical laser measurement system where the distance is measured according to the principle of triangulation [**33, 46**]. The energy levels are identified from visualizations of force-time history. The energy level varied between 5.30J and 7.67J which corresponds to a drop height of 0.58-0.78m. In the case of the monolithic specimens, the response was almost elastic and did not show any physical damage at the lower energy level. However, significant damage was observed for the higher impact energy, visible as a load drop in the force-time response.

Fig. 3 present experimental load time curves of nylon 6 specimens with different amounts of glass reinforcements. In the case of the specimens of 20% GF, a 50% increase of the peak load can be observed when increasing the amount of glass reinforcement from 20% to 50%, while the difference between 40% and 50% is less than 0.7%. It is very well known that the mechanics of the impact geometry can be quite complicated, owing to a great sensitivity to geometrical parameters. One of the main factors influencing the impact strength is the ability to develop an internal force multiplied by the deformation of the part as a result of impact. The influence of altering the amount of glass reinforcement is often considered a convenient means to maximizing the peak loads (**fig.2-3**).

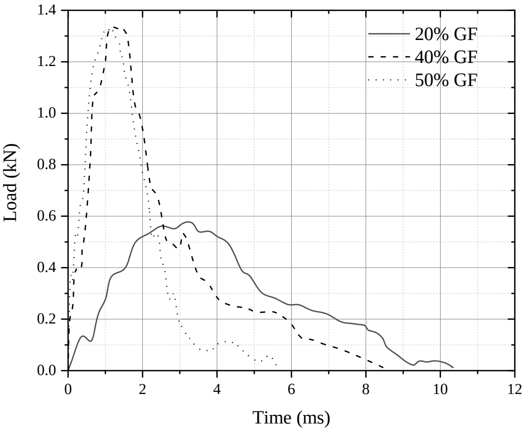


Figure 2 : Load time curves of specimens for three different amounts of glass reinforcements

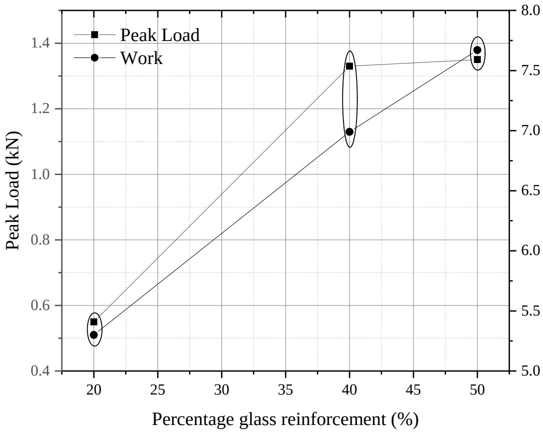


Figure 3 : Useful comparisons among the three different amounts of glass reinforcements for the peak load and work (experimental results)

Additionally, for the case of PA6 with 40% and 50% GF, the absorbed energy is much greater than the additional results for the peak load. In other words, the ability of the thermoplastic polymers to absorb energy elastically depends on several parameters, such as, (a) the mechanical properties of the matrix and fibers; (b) the interfacial strength; and (c) the velocity of impact and the size of the component (**fig. 3**).

III.FINITE ELEMENT ANALYSIS

Finite element simulations were carried out by using Abaqus/Explicit [**47**]. An eight-noded brick element

(C3D8R) with reduced integration has been used to model the plate. The integration point of the C3D8R element is in the middle of the element. Thus, small elements are required to capture a stress concentration at the boundary of a structure. This type of element is not useful without hourglass control. The plate was meshed with 290043 linear hexahedral elements, while the impactor meshed with 2561 linear quadrilateral elements (R3D4). Moreover, the free plate impacted at its center by a cylindrical impactor with hemi-spherical nose is considered (Fig. 1). The accuracy of the impacted model depends on geometrical properties, the element type, the contact method. For instance, mesh density is a critical issue which closely relates to the accuracy of the finite element model, as it determines its complexity level. The impactor model was assumed not to be deformable.

Finite Element Results

The finite element analysis predicted that the impact stresses are symmetric about the center of the overlap and reach a maximum at the bottom of the overlap, except from the case of PA6 20GF (fig. 4, FEA). This underlines that the amount of glass reinforcement is critical regarding plates strength and stability as a structure.

It is obviously, that plates with less amount of glass reinforcement present a different behavior than those with higher amount, standing higher principal stresses-strains, especially in microscopic level (elastic, plastic, fig. 4). It should be noted, that representative volume elements for long fiber thermoplastic that consider the microstructure in a cross section over the entire thickness lead to a large computational effort.

On the other hand, it should be mentioned that the effective volume fraction on geometry differs from the additional theoretical one (table 2). Volume fraction effect influence a) density and hardness; b) flexural strength; c) the inter-laminar shear strength as well as the impact strength.

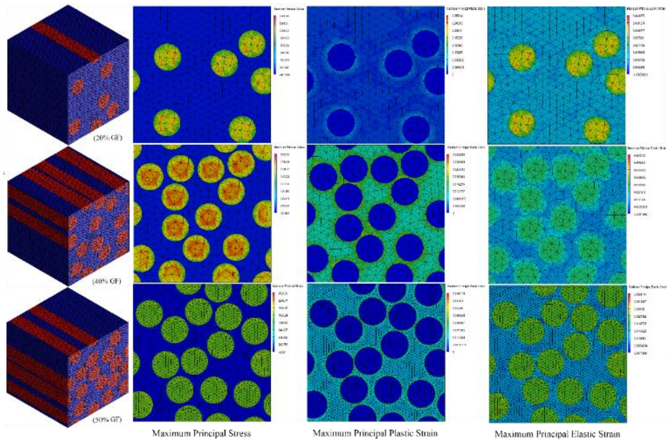


Figure 4 : Representative volume elements for PA6 with 20%, 40% and 50% GF, respectively.

Theoretical Volume fraction	Phase	Effective Volume Fraction (on mesh)	Effective Volume Fraction (on geometry)
20%	Fiber	18.85%	18.85%
20%	Matrix	81.15%	81.15%
40%	Fiber	40.84%	40.84%
40%	Matrix	59.16%	59.16%
50%	Fiber	50.26%	50.26%
50%	Matrix	49.74%	49.74%

Table 2 : Theoretical and effective Volume fraction on mesh and geometry.

Among the three amounts of glass reinforcement, the PA6 20% GF, presents the lower improvement of the impact strength between experimental and finite element result (fig. 5). During the finite element analysis, the friction coefficient between tup and plate is set to 0.3. It should not be neglected, because the impact loads could be reduced significant [**48**]. Moreover, there is a little difference among the three cases between load ant time. The results are in a good agreement (fig. 6a-c).

On the other hand, a little difference was noted between the 40% and 50% fiber volume composite. As it can be seen from figure 2, a steep increase in load followed by a less steep tail off. That means, the plates can absorb large quantities of energy, as the plate undergoes, after reaching the maximum load. Moreover, the displacement at the center of the plate according to the time is presented in figure 7.

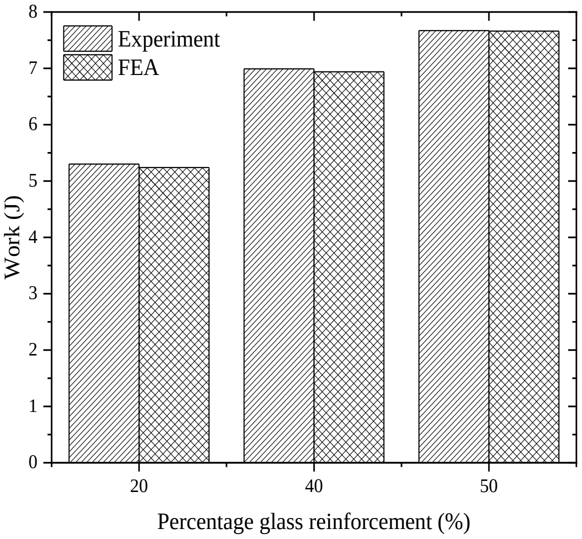
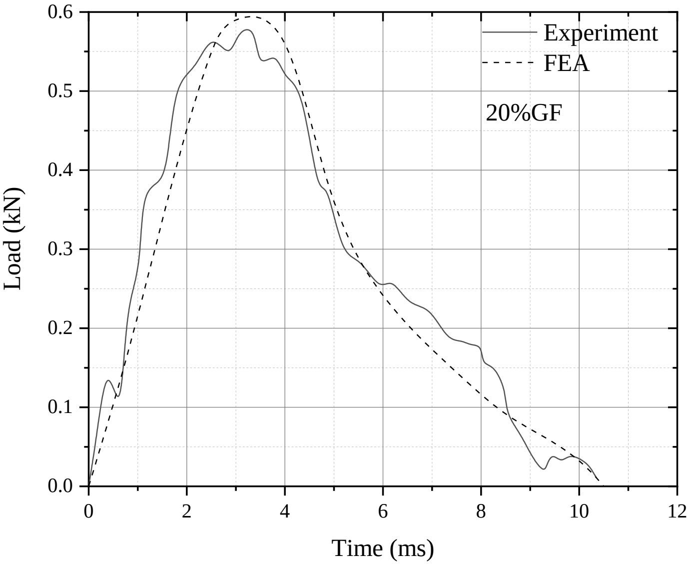
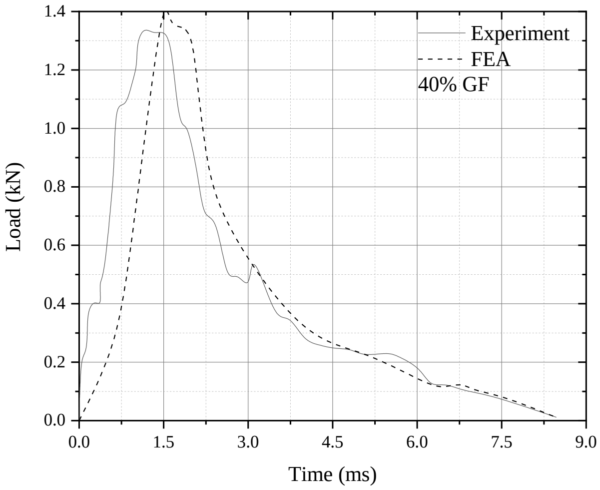


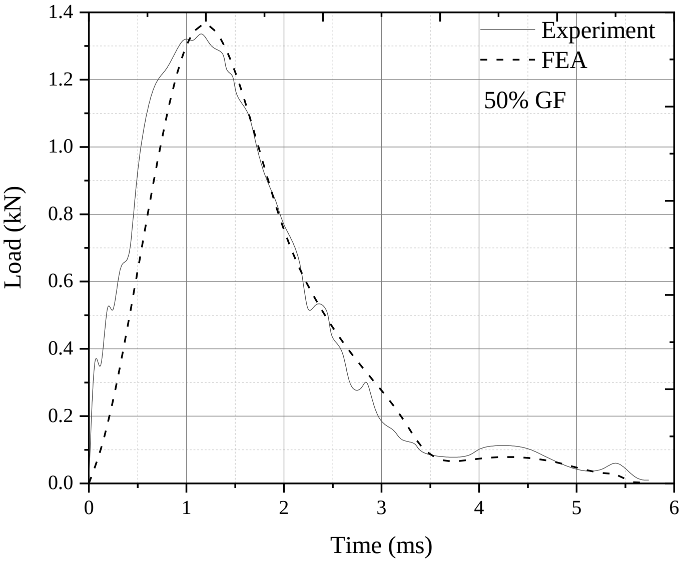
Figure 5: Useful comparison between finite element results and experimental results for kinetic energy (work, J).



(a)



(b)



(c)

Figure 6 : Finite element results vs. experimental results for load vs. time.

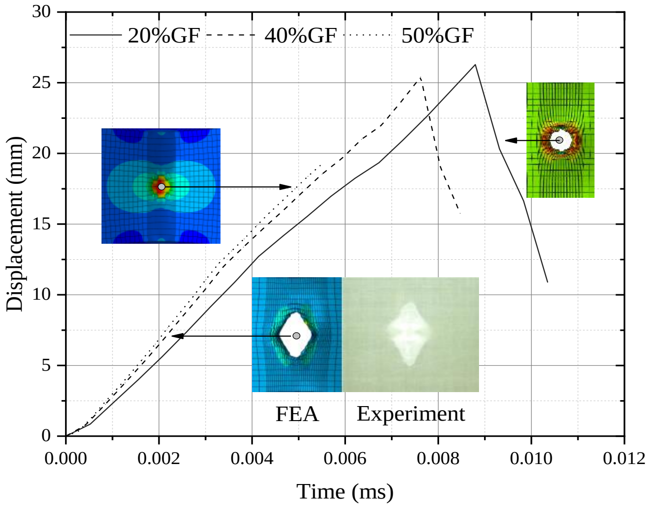


Figure 7 : Center plate displacement for PA6 with 20%, 40% and 50% GF, respectively.

By increasing the amount of fibers, there is a great reduction of the center plate displacement between 20% and 50%, of 37%, while the difference between 40% and 50% is almost 32%. Such deflection keeps decreasing until the peak force appears. Furthermore, the increase of the glass fiber volume fractions introduced in polyamide causes an increase in the values of the maximal impact forces and a greatly decrease in impact time. In other words, the case of 50%, can absorb more energy due to dissipation in the form of fiber breakage and matrix cracking. It is well known, the use of long fibers, as well as, the use of fibers with small diameters, decreases the number tips which act as a stress concentrator. It should be noted, that long fibers suffered from localised rupture, that means, the damaged area is quite small (fig. 7).

IV.CONCLUSION

Impact behaviours at low velocity of glass fibre-reinforced polyamide are investigated for different glass fibre volume fractions (20%, 40% and 50%, respectively). According to the impact test-analysis, the following conclusions can be made:

- First of all, no oscillating components have been found, as well as, there is no transfer of energy from the impactor to the rig.
- The low-velocity impact test reveals different damage events using the load-time response.
- The elastic-plastic model was implemented in ABAQUS/EXPLICIT for studying the behavior of the plates under low velocity impact.
- The results have shown that the impact force increase with increasing fibre volume fractions.
- Plates with 50% GF, absorbs more energy, while
- Long fibers with small diameter, decreases the number tips which act as a stress concentrator.

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