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Experimental and Numerical Study on the Behavior of Dyneema® HB26 Composite in Compression

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Abstract: *In the last decades as the need for high economical and technical efficiency items/applications became acute, lightweight, high strength and low-cost materials development and investigation emerged as a logical and promising course of action. With high potential for both military and civil sector, the ultra-high molecular weight polyethylene (UHMWPE) is considered a new class of material. Among this class, the Dyneema® HB26 composite is of most interest for the present study. The present paper focuses on the static and dynamic investigation of the HB26 mechanical behavior experiencing an out of plane compressive load. For experimental purposes, using a 15 mm thickness panel two types of samples (cylindrical and cubic samples) were processed. For compression test Instron Testing Machine and the Split Hopkinson Pressure Bar (SHPB) were used. The experimental tests were then compared against the numerical findings highlighting a good consistency.*

Keywords*: Dyneema® fiber, HB26, mechanical testing, numerical simulation.*

1. Introduction

The development of materials used in ballistic impact protection applications represents the state-of-the-art in the specialized scientific research [1-6].

In the wide industry four types of ultra-high molecular weight polyethylene are commonly used: Certran™ fibers, Dyneema® fibers, Spectra® fibers and Tensylon™ fibers.

The manufacturing process of laminate composite initially includes two main process stages: gel spinning/hot drawing process of the crystalline fibers and resin solution cover of the fibers, respectively. Afterwards the layers are pressed at high temperature which doesn't change the fiber diameter but instead may modify its cross-sectional shape. The manufacturing steps of UHMWPE composites are detailed by Smith and ASTMs [7, 8].

The ultra-high molecular weight polyethylene (UHMWPE) composite is considered to be the newest topics nowadays. UHMWPE high impact resistance and weight reduction compared to other materials makes this particular one a good choice in applications where temperature is not a variable. The scientific literature includes a series of articles regarding the properties and fail mechanisms that makes the UHMWPE a suitable material for penetration and ballistic impact protection applications.

For special applications the UHMWPE fiber are mixed with a polyurethane matrix to form unidirectional plies that are combined in layers that form a 0°/90° cross-ply composite.

Since the impact is a complex phenomenon implying a mechanical behavior induced by multi-axial deformations and stress field, different scientific approaches have been attempted to highlight the material behavior when subjected to simple loads (compression, tension and shear).

On the compression subject of UHMWPE fiber and UHMWPE composites two types of studies have been performed: in-plane compression and out-of-plane compression [9, 11]. Based on these mentioned studies it was concluded that the mechanical response starts with an elastic phase and continues with a softening one, and the cause of failure is the micro buckling on the ply level.

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The UHMWPE single fiber compression tests using an Instron Micro Tester pointed to a value of 2 GPa for elastic modulus and 20 MPa for yield strength. Also, the relation between stress and strain was observed to be non-linear and the strain increase induces a plastic hardening regime that follows the initial elastic regime [12]. Compression test on polyethylene composites for unidirectional and cross-ply [0°/90°] were also investigated [11].

Regarding the tension load static regime, among the first studies are the ones of Capaccio's who stated that Young's modulus increases with the drawn ratio [13, 14].

In terms of strain rate the polyethylene fibers are nearly insensitive for strain rate interval of 0.1 s^{-1} to 1000 s^{-1} [9, 15, 16].

The main challenge associated with UHMWPE testing, as enounced by Russell, B.P. is the grip displacement and the slip between grip and sample [9].

Using standard Instron and tensile Hopkinson bar tests a stiffness value of 5 GPa and a strength value of 500 MPa for static regime and quasi-static strain rate were obtain [17, 18].

Usually, the lack of correlation between fiber and the composite tensile tests results is due to the fact that the soft matrix as a part component of UHMWPE composite makes difficult to induce a tensile tension in a specimen. A solution to this particular shortcoming has been highlighted by Russell, B.P. in form of a dog-bone specimen that will allow inducing axial stress without shear for the fibers in the gripped area. The method was also used by Lässig, T.R. but for a lower failure strain [9, 19].

For the shear loading only few studies exists. The value of inter-laminar shear that depends on the matrix properties was estimated to be 2 MPa but unfortunately due to the lack of shear deformation uniformity the shear strain is difficult to be evaluated [20].

The literature also points to another test type which is the indentation. Plate structure and beam structure have been subjected to indentation tests in order to understand the deformation and failure during the impact [21].

UHMWPE composites were also investigated for the impact with sharp-tipped punches and blunt projectile. For a single fiber impact, the critical velocity and fiber rupture are dependent on the stress distribution in the impact area [1, 22].

Tests with blunt projectile were used to investigate how the layering influences the ballistic performance: the cross-ply [0°/90°] structure possesses a higher ballistic limit velocity and the quasi-isotropic/helicoidal lay-up allows the minimum back face deflection [23].

Other researchers looking into UHMWPE composite mechanical behavior on different nose shape impact events concluded that the failure is influenced by the indirect tension mechanism, and is also progressive with the number of failed plies that increase with impact increasing velocity [24, 25].

The numerical modeling of UHMWPE composites mechanical behavior when subjected to di- fferent loads was also intensively studied. Models based on the properties of cross-ply composite have been proposed on several papers [26-30]. Matrix properties influence on ballistic performance was also investigated by Hazzard, M.K., [27].

To summarize, the understanding of UHMWPE composites complex mechanical behavior requires the study of its mechanical properties and the mechanism of response for simple axial loads both for static and dynamic regime.

Thus, the proposed paper aims to investigate through experimental tests and numerical simulation the behavior of Dyneema® HB26 as a type of UHMWPE composite, subjected to simple axial load, namely out-of-plane compression both for static and dynamic regime. The experimental investigation and numerical modeling aim to highlight how the energy is absorbed and transferred between layers, the strains and stress evolution in time, deformation of the polyethylene layers, delamination and possibly fibers fracture.

Numerical simulations performed using LS-DYNA® code are used as a complementary tool for determining and understanding the properties that makes Dyneema® HB26 composite fitted for special ballistic applications.

2. Materials and methods

2.1. Material and sample types

The Dyneema® HB26 is a fiber reinforced composite produced by Royal DSM. It is reinforced with yarns of grade SK76 and is used in terminal ballistic applications. The yarns have 780 filaments which are embedded in a matrix of polyurethane. Regarding the mechanical properties of this yarn a value of 3.6 GPa for the strength, 115 GPa elastic modulus and a percent of 3.7 for the failure strain are indicated [31].

Using a 15 mm thickness and 980 kg/m^3 density panel two types of samples were manufactured. The sample types are presented in Figure 1.

The cutting process was a delicate one due to the material low melting temperature point.

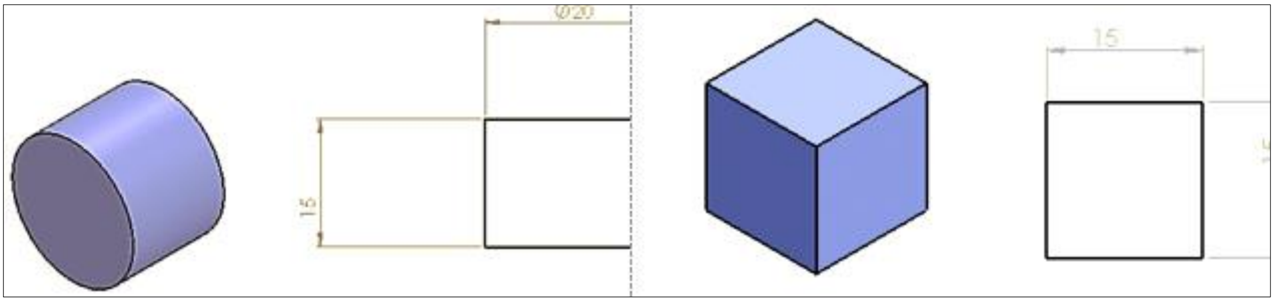


Figure 1. Compression test specimens: a) cylindrical sample; b) cubic sample

2.2. Experimental set-up

The experimental testing procedures were designed to indicate how the material behaves in out-of-plane compression both static and dynamic regime.

For compression test an Instron Testing Machine was used. A 1 mm/min velocity was imposed.

The system has incorporated a Dyna-Cell dynamic loads that minimize the inertia effects and a special extensometer was also used. The Bluehill® Universal software combined with the system allows recording and data manipulation. In Figure 2 the experimental set-up for static test is illustrated.

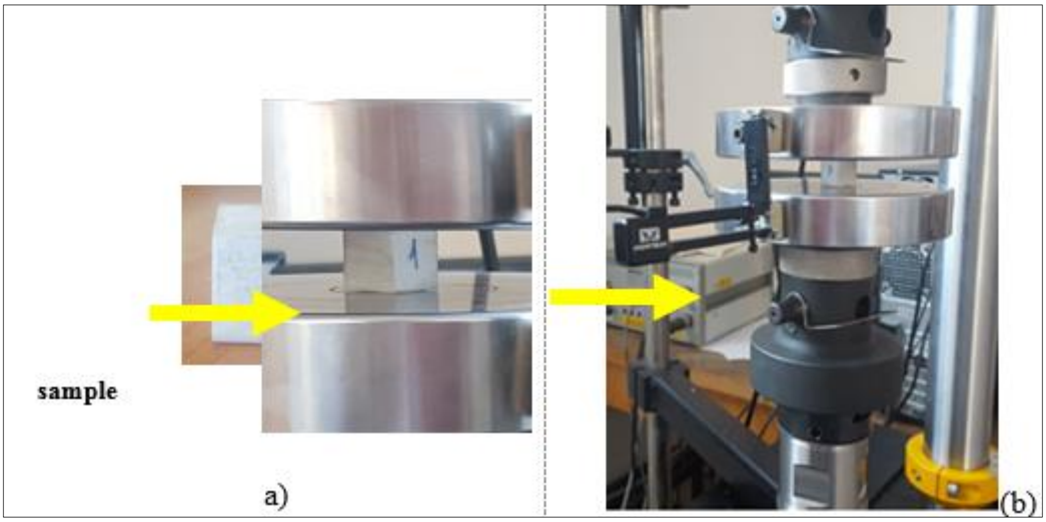


Figure 2. Experimental set-up for experimental tests in static regime:
a) cubic sample; b) Instron compression machine

For dynamic regime experimental tests, a Split Hopkinson Pressure Bar was used. For recording the experimental tests, a PHOTRON high speed camera 1 m away and an acquisition data system, PicoScope®6 were used. In Figure 3 the Split Hopkinson Pressure Bar set-up with an illustration of the general configuration of strain gauges and accelerometer location are presented.

The cylindrical sample behavior will be characterized using the installation bars elastic strains time evolution. A 5 m/s striker impact velocity value was imposed. The strain gauges are placed 800 mm away from sample impact zone.

Figure 3. Experimental set-up for compression tests with Split Hopkinson pressure bar

2.3 Numerical simulations set-up

For moderate deformation values in the static out-of-plane compression tests the specific mechanical behavior of Dyneema® HB26 proved to be non linear even if the deformation is still mainly of elastic nature [10, 11, 27, 32].

Most of the numerical approaches, even the complex ones [10-11] fail to underline this particular behavior. A notable exception is the fabric material model implemented in IMPETUS software [32].

In order to replicate Dyneema® HB26 out-of-plane compression macroscale behavior the test specimen was assimilated to a layered configuration. Thus, two different materials alternatively arranged were considered: a hard one associated to the high-density polyethylene fibers, and a weak one associated to the polyurethane matrix.

For numerical calculus LS-DYNA ® software was used [33].

For static tests a 3D model with implicit solving method option was considered. Due to model symmetry only a quarter of the model was implemented which resulted in 113550 fully integrated type 2 hexahedral elements. Mesh associated with the model is captured in Figure 4.

A CONTACT_AUTOMATIC_SURFACE_TO SURFACE algorithm between layers was considered, also.

To the hard Dyneema® fibers a high yield stress *MAT_PLASTIC_KINEMATIC material model was associated which enabled an exclusively elastic behavior during moderate strain experimental tests.

MAT_PIECEWISE_LINEAR_PLASTICITY model was assigned to the soft matrix. By this way an extremely short elasticity phase followed by a soft plastic flow and a hard-plastic flow afterwards was enabled. The expected macroscale effect, even if the nonlinearity of elastic deformation is lost, is to have an initial low slope for the force/displacement curve followed by a sharper rise, a pattern that may approximates the nonlinear real obtained curve.

Table 1 details the Dyneema® HB26 specimen material parameters.

Table 1. Materials parameters

Density	Young Modulus	Poisson's ratio	Yield stress	Tangent Modulus
***MAT_PLASTIC_KINEMATIC**				
0.98 g/cm^3	4500 MPa	0.47	2890 MPa	2000 MPa
***MAT_PIECEWISE_LINEAR_PLASTICITY**				
0.98 g/cm^3	96500 MPa	0.47	0.1 MPa	0
Effective plastic strain1	Yield stress1			
0	0.1 MPa			
Effective plastic strain2	Yield stress2			
0.06	30 MPa			
Effective plastic strain3	Yield stress3			
0.15	3510 MPa			

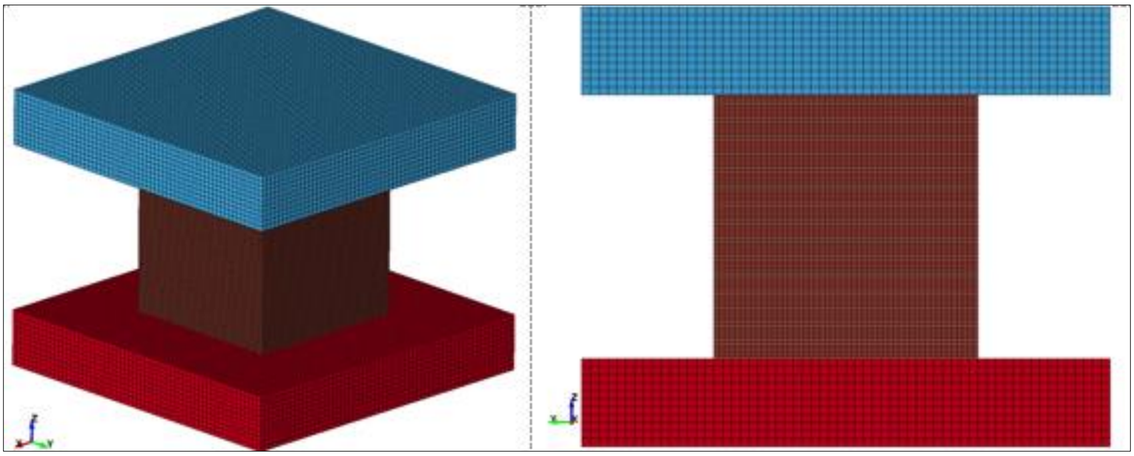


Figure 4. Numerical model for static compression test with a detailed view on the cubic sample

For the numerical modeling of dynamic compression test, a 2D axial symmetric model was generated based on the SPHB system used for tests.

During mesh process a number of 47210 shell elements and 51835 nodes were generated.

An explicit solving method for simulation was used.

For the contact between parts CONTACT_2D _AUTOMATIC_NODE_TO SURFACE card was filled in. For the Dyneema® HB26 sample the same approach and parameters as in the previous 3D simulations were adopted.

SHPB mesh sample with a detailed view on the specimen is depicted in Figure 5.

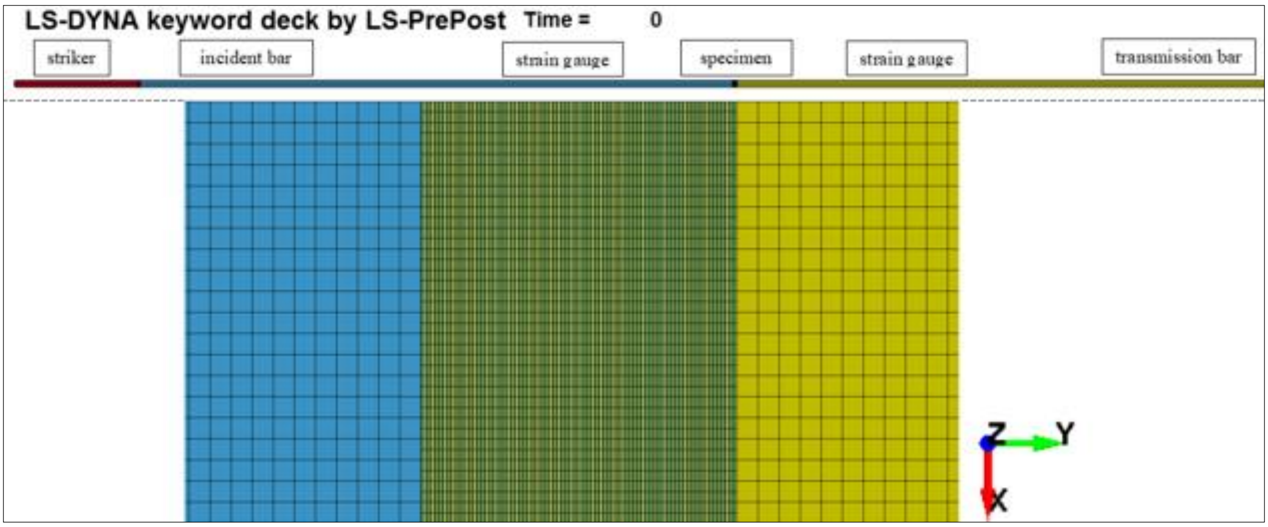


Figure 5. Numerical model of SHPB configuration test with a detailed view on the cilindrical sample

3. Results and discussions

The material samples static/dynamic regime mechanical testing is intended to be used for determining the associated constitutive models and to better understand the response of Dyneema® HB26 composite when subjected to out-of-plane compression load. Therefore, an analysis of both the acquisition system data and post-test patterns failure specimen investigation were performed.

During the cubic sample static regime compression tests the inner layers exhibits a slipping behavior (Figure 6).

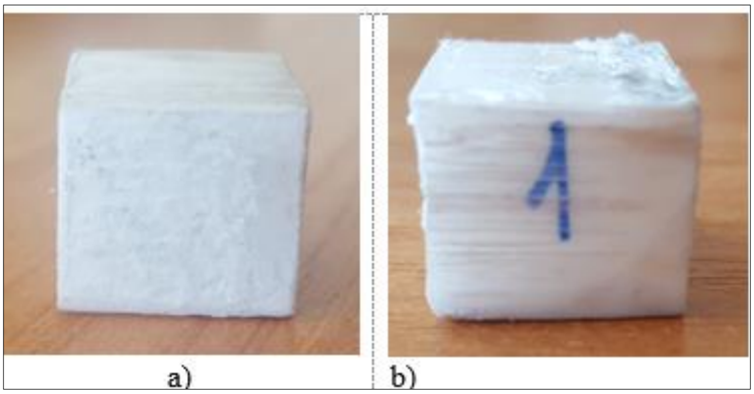


Figure 6. Cubic specimen for experimental compression test:
a) before test; b) post-test

The experimental force vs. displacement curves profile for static out-of-plane compression tests and numerical simulation are plotted in Figure 7. As Figure 7 points out the virtual Dyneema® HB26 sample bi-linear formulation accurate reproduce the experimental macroscale recorded response.

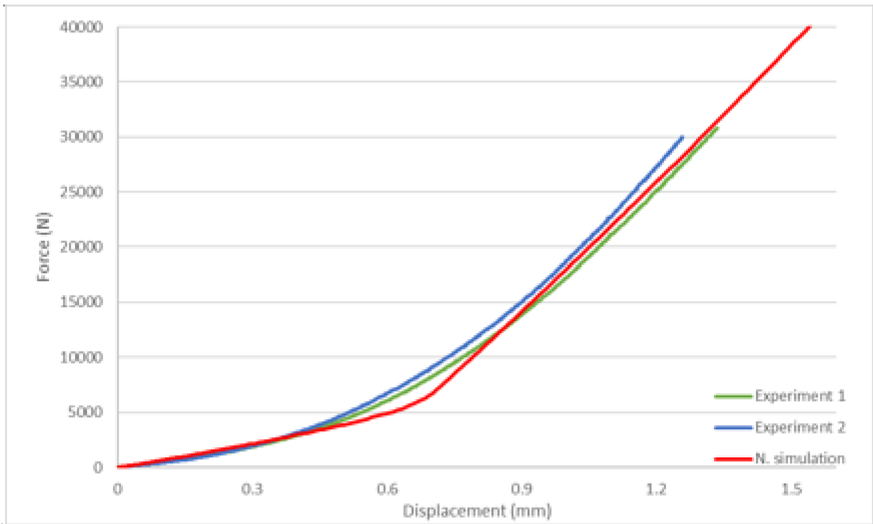


Figure 7. Force vs. displacement curves evolution for through thickness compression for experimental and numerical tests (1 mm/min)

As in static regime tests, the dynamic out-of-plane compression tests were followed by an extensive data analysis which combined the strain gauges signal analysis with post-test patterns deformation investigation.

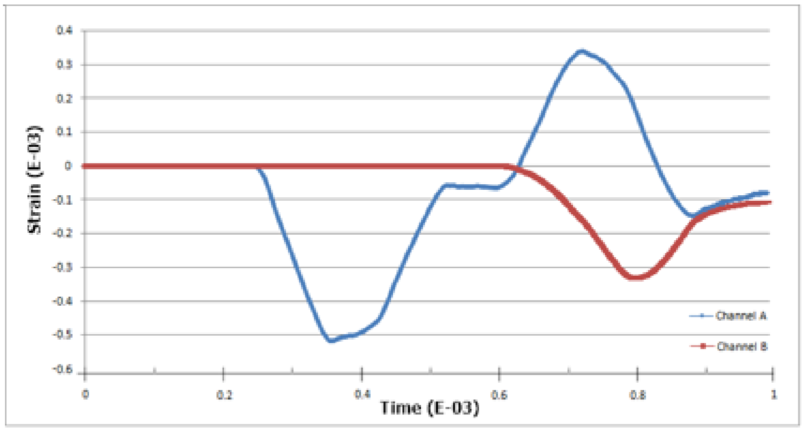


Figure 8. Experimental strain waves evolution on the Split Hopkinson Presure Bars:Channel A-incident bar, Channel B-transmission bar

The recorded and numerical computed strains are plotted in Figure 8 and Figure 9, respectively. A good correlation between them is observed.

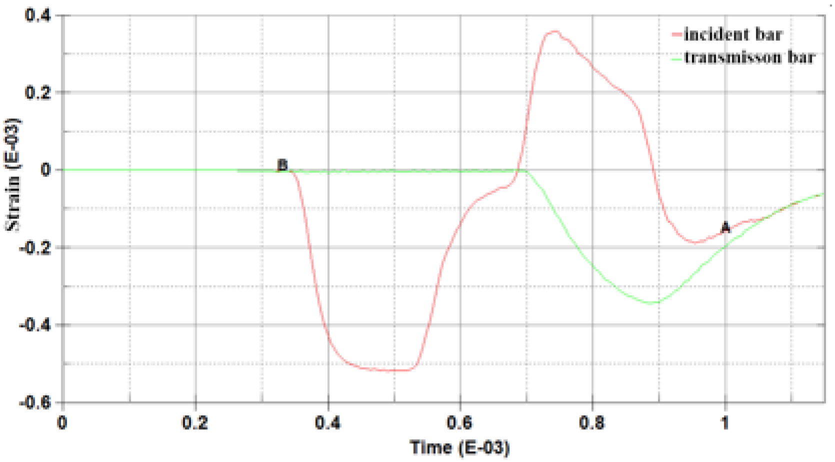
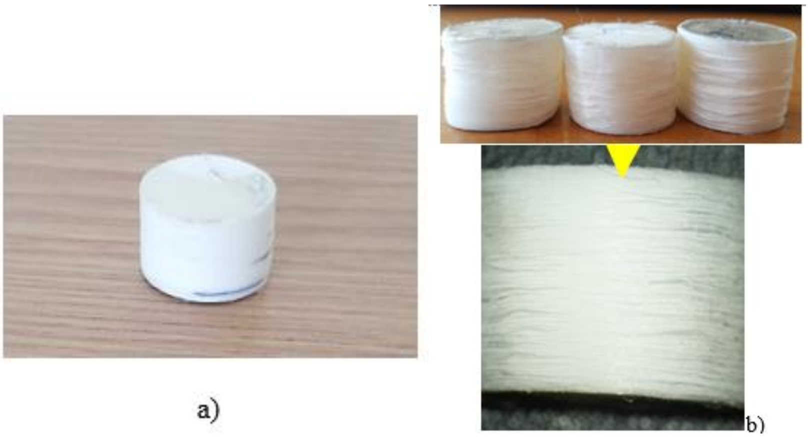


Figure 9. Numerical strain waves evolution on the Split Hopkinson Presure Bars

The sample aspect after dynamic out-of-plane compression test is presented in Figure 10. The fibers slipping behavior for inner layers is also observed for experimental samples.



a) b)

Figure 10. Specimens/sample zoom before and after experimental dynamic compression at 5m/s: a) before test; b) after test

4. Conclusions

The paper intends to investigate aspects regarding the deformation and failure mechanism under static and dynamic out-of-plane compression of Dyneema® HB26 composite in order to understand its high impact resistance.

For Dyneema® HB26 testing, experimental tests were performed in accordance with the experimental approaches highlighted by scientific literature. Moderate strain out-of-plane compression tests were performed both for static and dynamic regime using Instron testing machine and Split Hopkinson Pressure Bar.

In order to extent the constitutive model validity for other test types further experimental tests are in place.

Based on experimental and numerical findings, within the paper a simplified constitutive material model for Dyneema® HB26 able to account for its mechanical behavior under static and dynamic out-of-plane compression is proposed. The proposed constitutive model proves good correlation with Dyneema® HB26 mechanical behavior under compression loading.

Successive layers formulation with alternative properties reproduces the specific macroscale response of the composite material Dyneema® HB26 when subjected to static and dynamic out-of-plane compression. An obvious conclusion is related to the potential of the proposed MAT_PIECEWISE_LINEAR_PLASTICITY model. By using more than two intervals with constant tangent modulus in the plastic deformation domain the simulation results may achieve a high fidelity comparing to the experimental ones in the loading phase.

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