DETERMINATION OF STIFFNESS REDUCTION AND DAMAGE ACCUMULATION MONITORING IN COMPOSITE MATERIALS USING ULTRASONIC TECHNIQUES

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SUMMARY: This general purpose of this is the use of ultrasonic technologies to determine and monitor the residual mechanical properties of monolithic composite materials subjected to progressive damage. The study bases on comparison of experimental elastic constants obtained by standard mechanical tests and ultrasonic techniques. A numerical analysis completes this approach. The amplitude treatment of acoustic emission signals, Scanning Electron Microscopy (SEM) observations and C-Scan investigation are used to define damage evolution. The reliability of the methodology has been first validated on undamaged materials of different intrinsic properties. The current results for damaged materials highlight the variation of the intrinsic properties such as induced anisotropy. The elastic constants obtained after damaging by mechanical and ultrasonic techniques are in good agreement. The validation of the methodology on damaged materials could constitute a powerful tool able to define local residual properties, and useful for structures life span monitoring.

KEYWORDS: Residual properties, US measurements, Wave Speeds, C-Scan, Acoustic Emission, Impact, Fatigue, Damage Mechanisms.

INTRODUCTION

Ultrasonic technologies are essentially used to localise and define damages on structures. They allow us a through thickness investigation of materials without changing their intrinsic properties. However, the obtained information concerns mostly the place and the dimensions of detected damages. Knowing and monitoring the local induced residual properties could lead to a better understanding of the material behaviour subjected to a progressive degradation. The speed of ultrasonic waves being propagated in a material depends directly on its rigidity. Experimental ultrasonic speeds can then be used to define elastic constants in materials. The work exposed here gives a methodology to define and monitor, qualitatively and quantitatively, the residual properties of monolithic composite samples subjected to post-impact loading. This methodology was first validated on undamaged composites showing different intrinsic properties: transverse isotropy, orthotropy, anisotropy…

The elastic constants obtained with ultrasonic waves speeds are compared with those obtained by mechanical tests. The changes of intrinsic properties owing to damage accumulation can be related to the residual elastic constants and corroborated with C-Scan analysis. The amplitude treatment of acoustic emission signals and Scanning Electron Microscopy (SEM) observations are used to define the colour code for through thickness visualisation obtained from C-Scan signals treatment.

METHODOLOGY

Elastic waves propagation in solids

An incident plane wave is supposed to create three wave families (or at least two) in the encountered solid. Those are defined according to their propagation and polarisation directions (Fig. 1). The Christoffel's tensor [1], noted [Γ], is correlated to the stiffness tensor, noted [C], and the wave propagation direction, noted $\vec{n}$ (1). The three wave families define the eigenvalues of the Christoffel's tensor (2). A software developed under Visual BASIC® language [2-4] determines all the elastic constants correlated to the experimental wave speeds. The notion of surfaces of slownesses is extended to the rigidities. Thus we define surfaces of rigidities to give the stiffness visualisation for a given plane (Fig. 2).

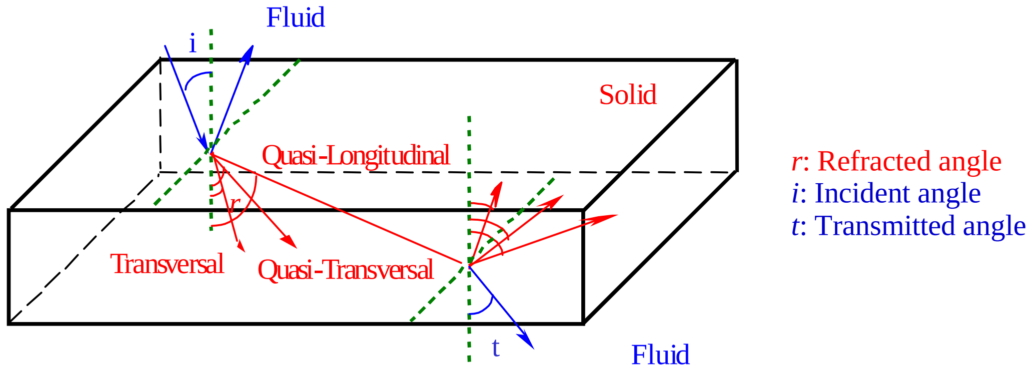

Fig. 1: Ultrasonic waves in a solid induced by an incident plane wave

$$\Gamma_{il} = C_{ijkl} n_j n_k \quad (1)$$

$$\left| \Gamma - I * \rho V^2 \right| = 0 \quad (2)$$

where: ρ, material density, V, wave phase speed and I, unitary matrix

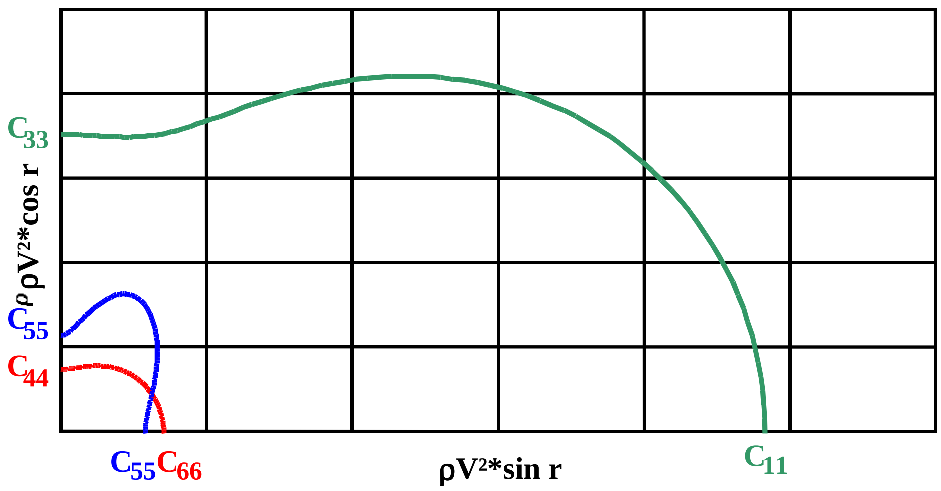

Fig. 2: Schematic surfaces of rigidities in the plane (1,3) for an orthotropic composite

Through thickness visualisation after C-Scan treatment

A second software developed under Matlab ® [2-4] allows to give the damage repartition through specimen thickness. The analysis performed here is based on the handling of ultrasonic C-Scan signals truncated in equal temporal intervals. The colour code uses six different colours. From the higher level of signal saturation to the lower, the tint goes from red to yellow, to green, to cyan, to blue, to magenta, then again to red (Fig. 3).

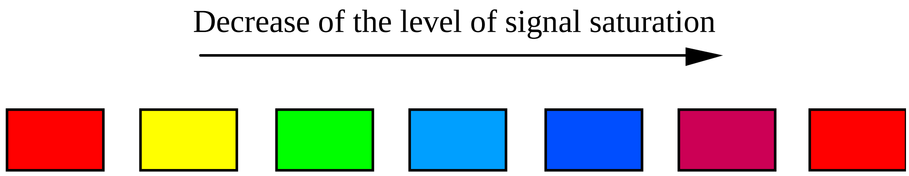

Fig. 3: Colour code

EXPERIMENTAL

Undamaged composites: plates 250 x 50 mm²

A set of different composite materials has been used to validate the correlation between elastic constants obtained by ultrasonic wave speeds and mechanical tests results. Table 1 gives the chosen composites with their intrinsic properties: structural class and density.

Table 1: Undamaged material used for the validation of the methodology

Material	Structural class	Density (kg.l^{-1})
RTM Unifilo® Glass E / Polyester	Isotropic Transverse (1,2)	1.506 ± 0.031
RTM Rovicore ® / Polyester	Isotropic Transverse (1,2)	1.523 ± 0.018
SMC Glass E / Polypropylene	Isotropic Transverse (1,2)	1.772
Pryltex® Glass E / Polypropylene (Extrusion-Compression)	Isotropic Transverse (1,2)	1.424
Unidirectional Glass E / Epoxy	Isotropic Transverse (2,3)	2.080
Unidirectional Glass E / Phenolic, 10% woven	Monoclinic	2.030
$[\pm 45,\text{mat}]_8$ Glass E / Phenolic	Anisotropic (Triclinic)	1.951

The elastic constants obtained from ultrasonic wave speeds are in good agreement with those obtained by standard mechanical tests: torsion, shear, tensile and bending tests. Use of material density obtained experimentally provides a better suitability of the elastic constants. The following examples illustrate the good relationship between ultrasonic wave speeds and material rigidity.

The ROVICORE® / Polyester composite is used for structures in toll boxes and produced by Stratime Cappello System. This material is obtained by RTM process. The ROVICORE® 300/B5/300 (860 g/m²) is a stack composed by a mat of glass E (300 g/m²), a non-woven synthetic polypropylene core (250 g/m²) and a mat of glass E (300 g/m²). Table 2 gives the comparison of the obtained and modelled results. Fig. 4 shows the good repeatability of the surfaces of rigidities for three samples. Fig. 5 gives the experimental and computed surfaces of rigidities.

Table 2: Elastic constants comparison for a Rovicore® / Polyester composite

Constants (GPa)	Ultrasounds	Mechanical	Numerical
E_1	7.42 ± 0.11	7.25 ± 0.74	7.42
E_3	7.20 ± 0.10		4.82
G_{12}	2.79 ± 0.05	2.94 ± 0.11	2.71
G_{13}	2.72 ± 0.06		1.41
ν_{12}	0.326 ± 0.011	0.330 ± 0.018	0.338
ν_{13}	0.313 ± 0.004		0.385

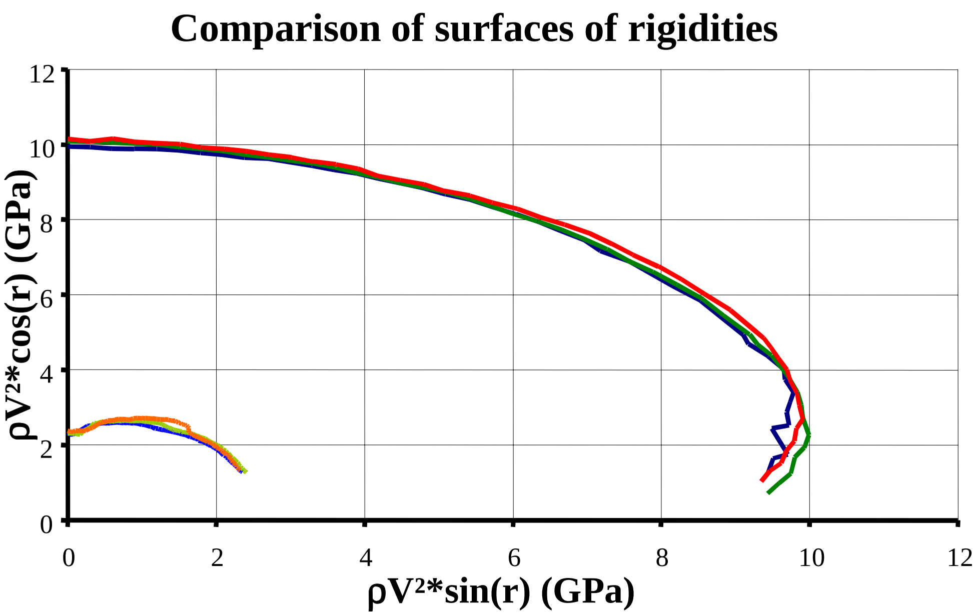

Fig. 4: Comparison of surfaces of rigidities for three Rovicore® / Polyester samples

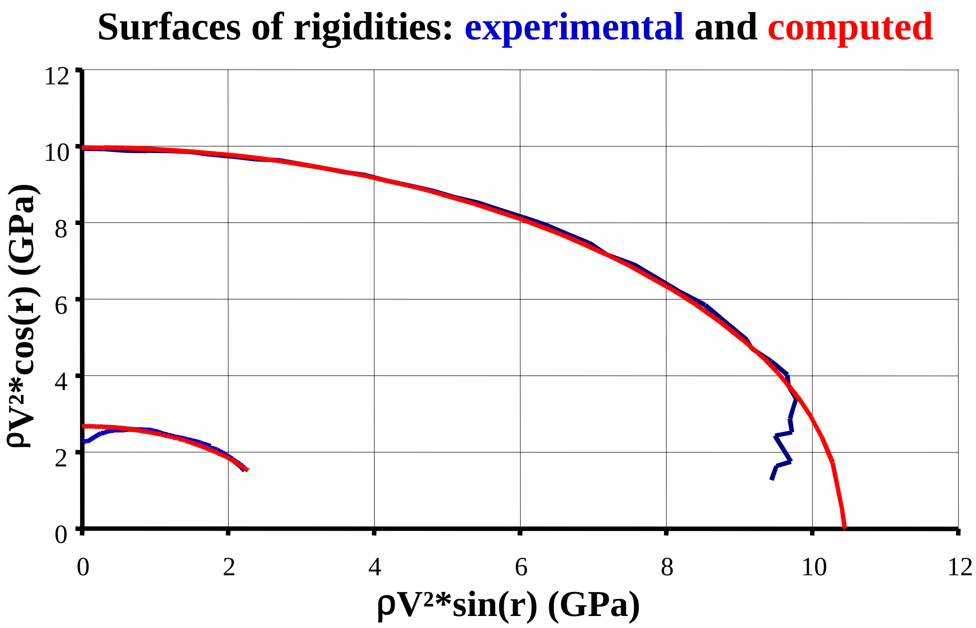

Fig. 5: Comparison of experimental and computed surfaces of rigidities for a Rovicore® / Polyester composite

The Glass E / Phenolic unidirectional composite transversally woven with Glass E (10%) is used for railway structures. Table 3 shows the elastic components obtained with ultrasounds and standard tests. The composite is transversally woven enough to induce coupling terms in the rigidity tensor. Thus the material structure is not isotropic transverse in the plane (2,3). Fig. 6 gives the experimental and computed surfaces of rigidities.

Table 3: Elastic constants comparison for a Glass E / Phenolic unidirectional composite transversally woven with Glass E (10%)

Constants (GPa)	Ultrasounds	Mechanical
E_x	38.12	37.6 ± 1.7
E_y	16.55	14.4 ± 1.6
E_z	13.87	
G_{xy}	5.99	5.2 ± 0.9
G_{xz}	5.88	
G_{yz}	3.73	
ν_{xy}	0.203	0.233 ± 0.012
ν_{xz}	0.189	
ν_{yz}	0.452	

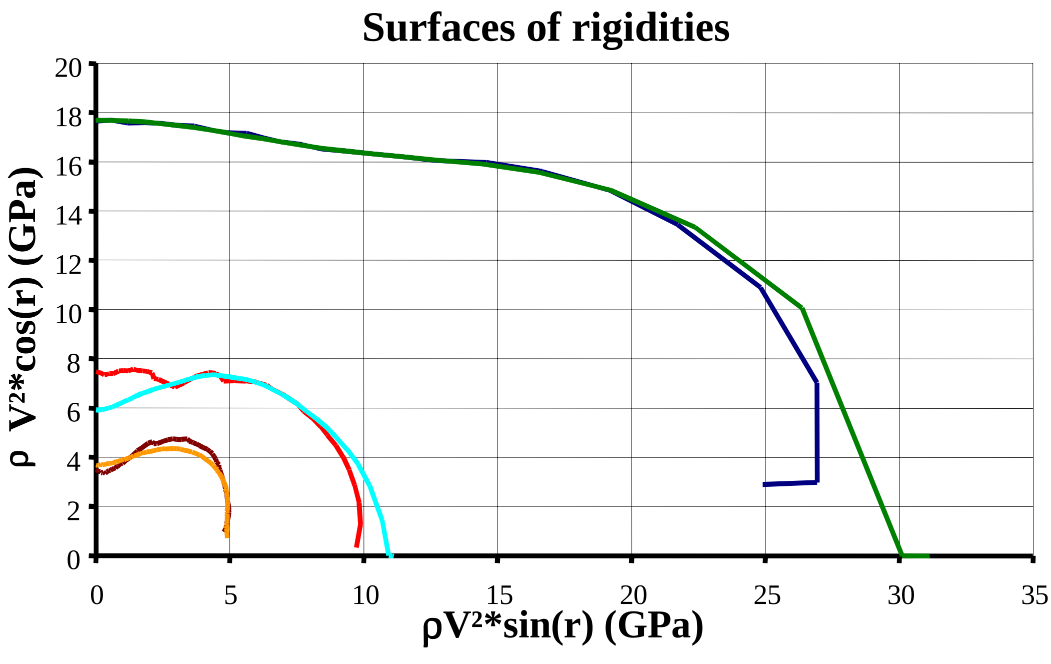

Fig. 6: Comparison of experimental and computed surfaces of rigidities for a Glass E / Phenolic unidirectional composite transversally woven with Glass E (10%)

Damaged composites: plates 250 x 50 mm²

Study on the RTM Unifilo® Glass E / Polyester material

A study carried out on a Glass/Polyester composite impacted at 15 J highlights the presence of a cone through the thickness. Fig. 7 gives the schematic visualisation of damage in material thickness. According to impact energy, a cylindrical zone (tube) of lower damage crosses whole or part of this cone. A halation could be also detected. Amplitude treatment of acoustic emission signals and the SEM observations enable us to correlate the saturation levels of the C-Scan cartographies with detected damage mechanisms. The damage evolution was investigated through fatigue tests performed at 31 % of the failure static stress (5Hz and 20000 cycles). After cyclic loading, the tube size decreases. The cone becomes more opaque and the halation wider. This widening can be explained by the matrix micro-cracks growth. The more intense red pitting and the tube size reduction could be related to the contribution of pseudo-delamination in material progressive degradation. The rigidities obtained by ultrasounds were compared with those predicted by a numerical model [5] and the elastic properties determined experimentally. These results were in a good agreement. As shown in Table 4, the elastic constants show a significant decrease certainly due to matrix cracking and pseudo-delamination accumulation.

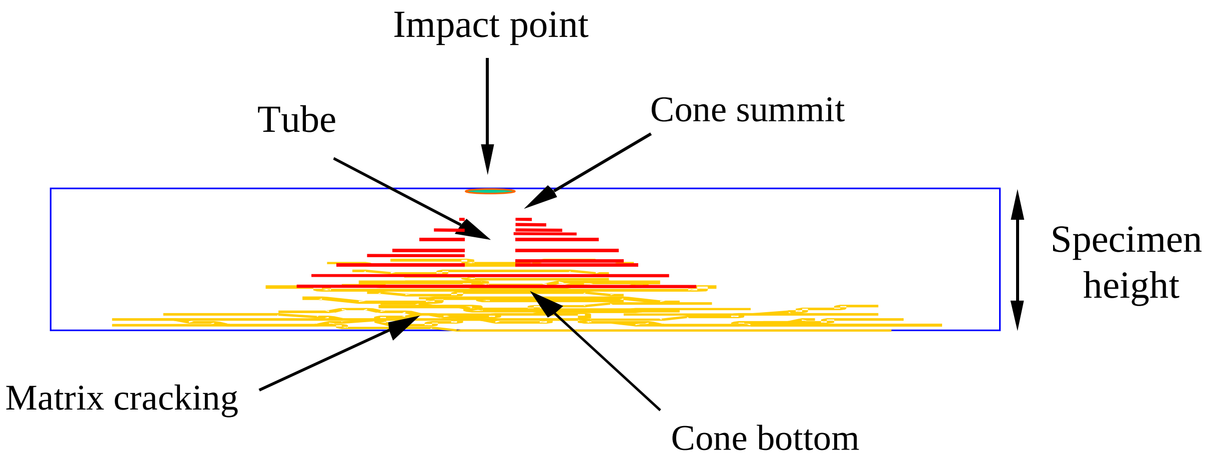

Fig. 7: Schematic visualization of damage in material thickness

Table 4: Elastic constants decrease for a RTM Unifilo® Glass E / Polyester in an its undamaged state, impacted at 15 J and fatigued during 20000 cycles at 31% of the tensile failure after an impact at 15J

Constants (GPa)	Undamaged state	Impact at 15J	Impact at 15J and fatigue 20000 cycles
E_x	9.78	9.11	8.60
E_y	9.78	9.11	7.70
E_z	8.16	7.78	7.31
G_{xy}	3.51	3.37	3.06
G_{xz}	2.63	2.46	2.46
G_{yz}	2.63	2.46	2.39
ν_{xy}	0.390	0.352	0.340
ν_{xz}	0.321	0.333	0.232
ν_{yz}	0.268	0.284	0.373

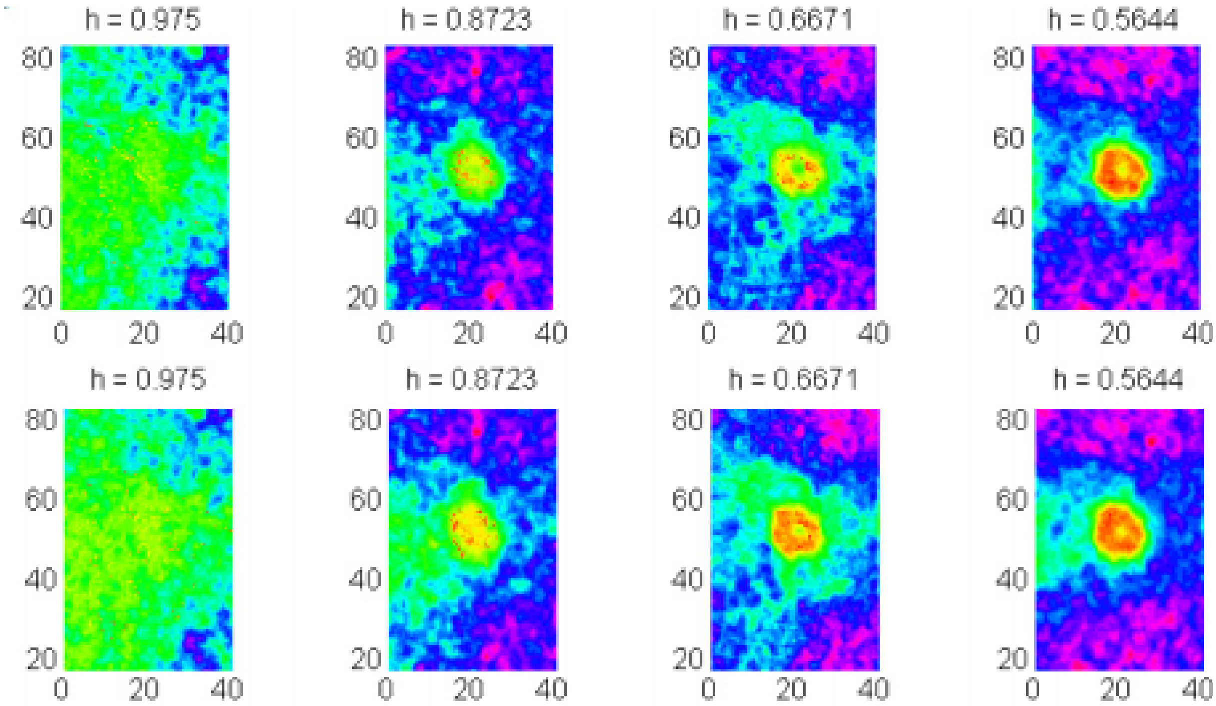

Fig. 8: Damage variation after post-impact fatigue. Above: Unifilo® Glass E / Polyester impacted at 15J. At the bottom: Unifilo® Glass E / Polyester impacted at 15J and fatigue during 20000 cycles at 31% of the tensile failure.

After fatigue loading the tensor of rigidity can't be obtained with isotropic transverse (1,2) computation. The post-impact fatigue has changed the structural class of the sample. In the current case the computation gives good results for the monoclinic class. These highlights an induced anisotropy in the material due to coupling terms appeared during post-impact fatigue.

Fig. 8 gives examples of the damage variation in the thickness from impact to post-impact fatigue. We can see a widening of the green zone and a more intense yellow pitting for the height h = 0.975 mm. This stands true for the three other proposed heights. This can be attributed to larger matrix cracking and cracks propagation. The red pitting is also higher in the damage cone. This seems to grew in a less circular way. The tube becomes more yellow and decreases in size. Locally the matrix cracking and the pseudo-delamination become higher due to cyclic loading.

Study on the RTM Rovicore® / Polyester material

A current study on a RTM Rovicore® / Polyester material is performed to highlight the effect of impactor diameter and impact energy level on the induced damaged structural class. Are rejected samples showing perforation and ply rupture to provide the monitoring of damage evolution through cyclic loading. Are also rejected samples with permanent bending strong enough to perturb C-Scan analysis.

With a big diameter (50 mm) impactor and impact energy level less than 10 J, the specimen seems remaining isotropic transverse (1,2). There is no damage cone but a scattered red pitting near the impact zone. A higher condense yellow-red pitting nears the non-impacted sample face certainly due to the permanent bending after impact. The lack of damage cone can be explained by the large diameter of the impactor and the impact energy level: there is no indentation.

The small diameter (12.5 mm) impactor induces serious changes in samples. For a specimen impacted at 3.5 J the computation gives good results for the Tetragonal 2 structural class: axe 1 equals axe 2. For higher impacts the samples seems to have a monoclinic structural class. This is validated by C-Scan observations. Longitudinal or Transverse stripes of red saturation appear in the thickness. They are especially transverse when the impact energy level increases. The edge effect is reached. If it exists, the damage cone shows preferential directions.

The medium diameter (25 mm) impactor creates anisotropy if the impact energy level is higher enough. The following figures (Fig. 9 – 10) illustrate the induced anisotropy in a sample impacted at 9.32 J. The crater can be detected near the impacted face. It is not symmetrical. The yellow-red saturation appears like sparse marks on the left zones near the impacted surface. In the bottom we can see larger yellow-red saturation showing preferential directions of extend. Totally in the bottom a total red saturation mark indicates there is a local total degradation of the material. In fact the impact induced a local extend of pseudo-delamination and fibers pull out clearly visible on the back of the specimen.

The elastic constants obtained for those samples are still to be compared to experimental results. SEM observations and amplitude treatment of acoustic emission signals would validate or not the corresponding colour code established for the study on the Unifilo® Glass E / Polyester material obtained by RTM process.

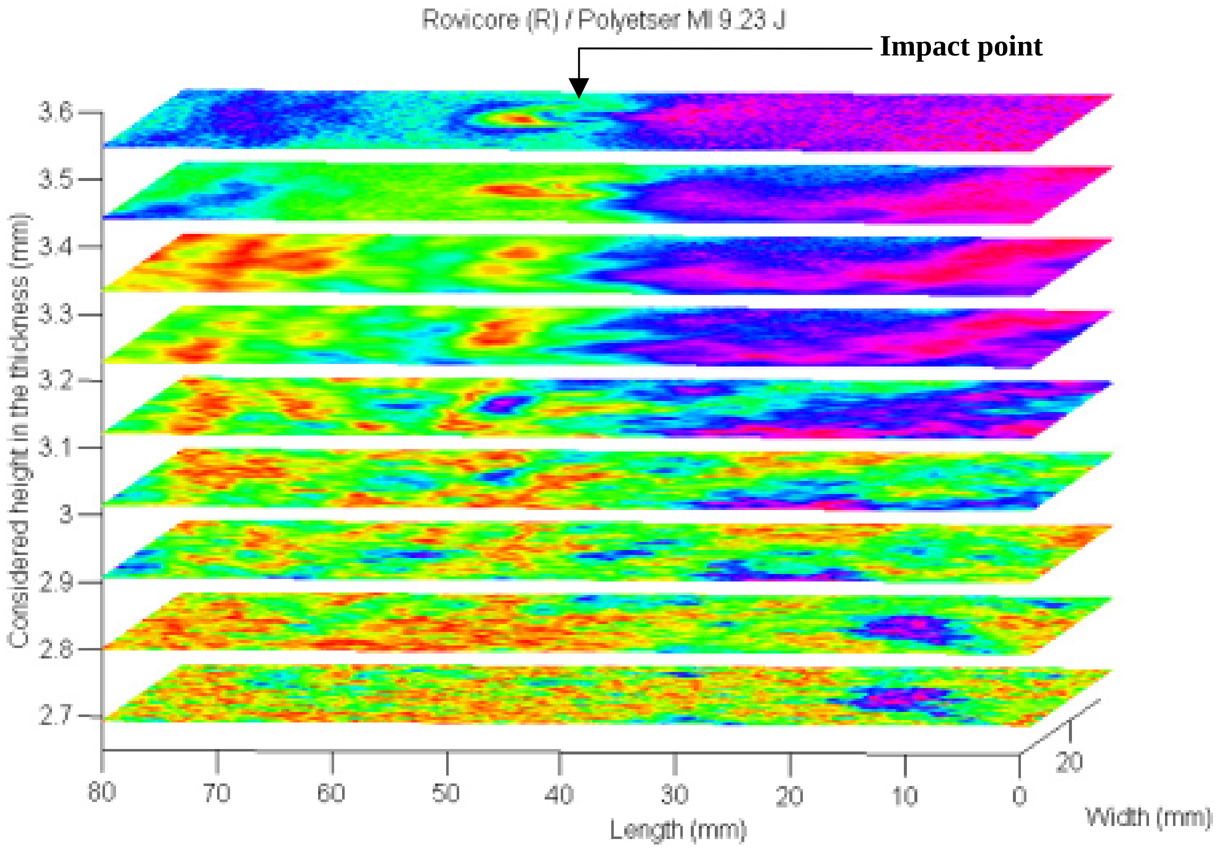

Fig. 9: Rovicore® / Polyester impacted at 9.32 J: visualisation near the impacted surface.

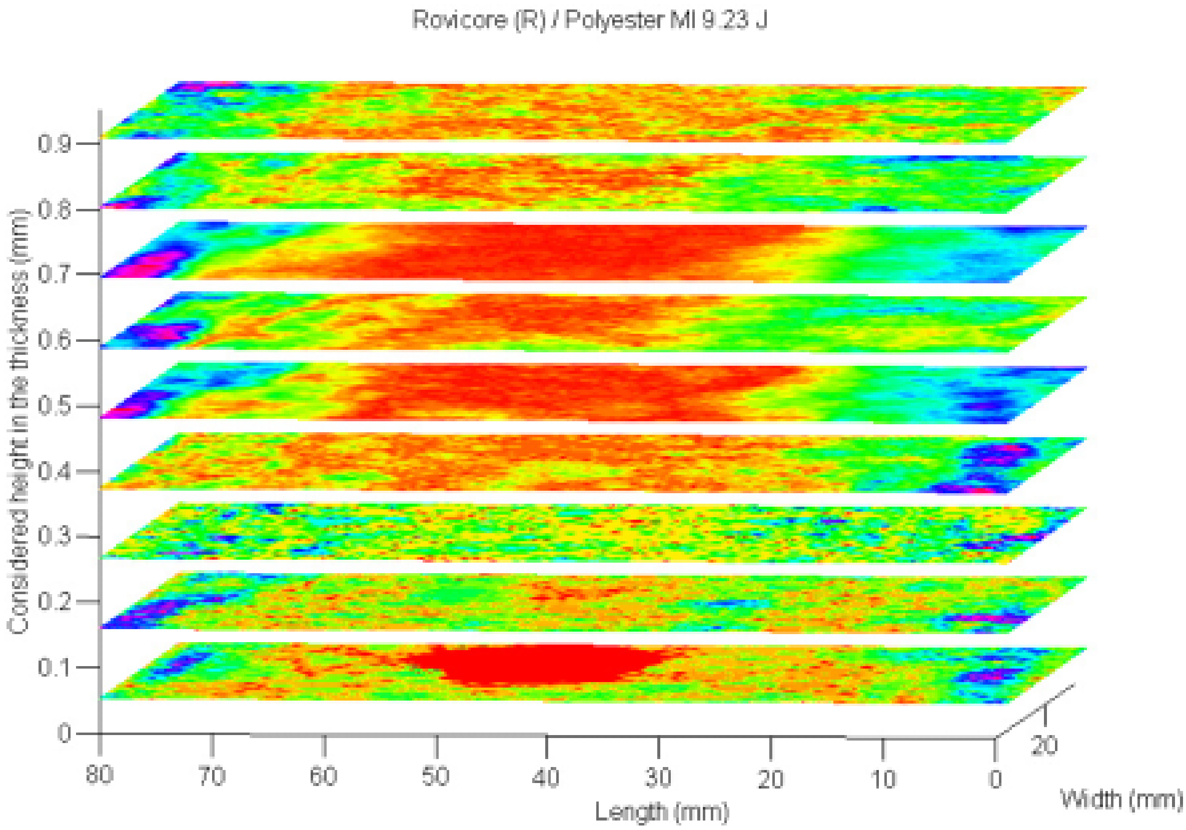

Fig. 10: Rovicore® / Polyester impacted at 9.32 J: visualisation near the non-impacted face.

CONCLUSION

The main current result shows the existing correlations between mechanical tests and ultrasonic measurements to obtain elastic constants. The methodology validated on undamaged material is now extended to damaged material. Use of ultrasonic wave speeds can give good information on intrinsic properties changes. The computation highlights their reliability to account for induced anisotropy. Through thickness C-San analysis gives a good tool to validate and visualise these internal structural changes.

The principal objective of this work was to show the capability of a totally non-destructive method to describe the residual behaviour of a monolithic damaged material. It has to be demonstrated the reliability of the methodology to describe and monitor any kind of damage and damage evolution. The first step is the validation for damages of different structural class inducing changes in intrinsic properties of different materials. If so, the methodology would be able to describe damage and material properties changes after cycling loading. The last step would be to extend this approach to sandwich structures.

The final objective of the study is to propose to structures designers a helpful tool able to define and monitor local residual properties to perform structures parametric analysis. With this in mind, a life span criterion can be defined and used in terms of damage tolerance.

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