STUDY OF LOW VELOCITY IMPACT DEFECTS IN ORGANIC INTERLOCK WOVEN COMPOSITE

A. Elias[a,b*], M. Kaminski[a], F. Laurin[a], L. Gornet[b]

[a]*Onera, the French aerospace lab, Department of Composite Materials and Structures, BP72 - 29 avenue de la Division Leclerc*
FR-92322 Châtillon cedex
[b]*GeM UMR CNRS 6183, Ecole Centrale de Nantes, 1 rue de la Noë FR-44321 Nantes*
**adrien.elias@onera.fr*

Keywords: Impact, Woven Interlock, Damage, Simulation

Abstract

Woven interlock composites are now used to design aircraft structures in order to improve their impact resistance. This work aims to study and predict low velocity / low energy impact defects in interlock woven composites. Impact tests at different energies were performed and analyzed using microscopic observations in order to understand damage mechanisms occurring in these materials. Finite element simulations were performed using the continuum damage model ODM developed at Onera for woven composites under static loadings. Simulations and experiments tend to show that experimental mechanisms are well described by the model. The predictions are in good agreement with experimental results even if improvements can be made to take into account specific impact mechanisms.

1. Introduction

In the aeronautical field, composite materials are used to design structures that could be submitted to low velocity impact events such as drop tools or runway debris. Because of the poor impact resistance of unidirectional laminate composites, woven interlock composites are planned to be used in structures exposed to impact. The impact resistance of unidirectional laminate composites has been widely studied for many years. Experimental studies have shown that a low velocity impact causes matrix cracking, fibers fracture and delamination between plies [1]. Due to delamination, an important loss of the residual strength under compressive loading is observed for such materials. The strength of laminate structures under compressive loading is mainly studied through an experimental point of view which requires a lot of tests. It can also be predicted by using a simplified representation of impact damage (hole, single delamination…), but still, a lot of experimental data is needed in order to calibrate the models. A more predictable solution consists in an accurate estimation of the impact damages with simulations and then the use of the results to simulate the post-impact compressive loading with the same model. Very few authors [2-3] succeeded in proceeding this way. This is mainly because of numeric difficulties to take into account delamination into impact simulations. In woven interlock composites, some yarns link the layers together in order to prevent large delaminations. There are few studies on impact damage resistance of recent interlock composites. The influence of the reinforcement architecture on impact and post-impact behavior has been studied in [4-6]. It has been pointed out that CAI (Compression After Impact) strength is improved by using three dimensional woven composite instead of unidirectional or 2D laminate. The damage mechanisms are very different from those encountered in laminate. Indeed, large delaminations are no more induced and thus CAI test may not be the only loading that has to be studied [5]. Some recent experimental studies [5-7] show that low velocity impacts on woven interlock composite create decohesion between layers, matrix cracking and few fibers bundle fracture. Only few impact modeling studies [7] can be found in the literature but the agreement with experimental data remains limited because of the complexity of the damage mechanisms. This study aims to predict low velocity / low energy impact damage in polymer matrix interlock woven composites. Firstly, impact tests have been performed and analyzed in order to assess the different damage mechanisms involved. Some impacted coupons have been cut and the cracks have been observed using a microscope. Then, the Onera Damage Model (ODM) developed for interlock composites structures under static loading defined at the macroscopic scale, has been used in finite element simulations for impact solicitations.

2. Impact test results

2.1. Experimental device

Impact tests have been performed on woven interlock composites with polymer matrix using a drop weight tower as illustrated on Figure 1. Coupons are hold by two square jaws with a circular free zone. Jaws have been chosen to obtain boundary conditions which are readily reproducible in finite element simulations. The impactor is hemispheric, made of steel, and its mass is set to 15 kg. Different energy levels (from 60J to 210J) have been achieved by changing the velocity set by the height of the drop weight. Each test has been repeated two or three times to estimate the scattering.

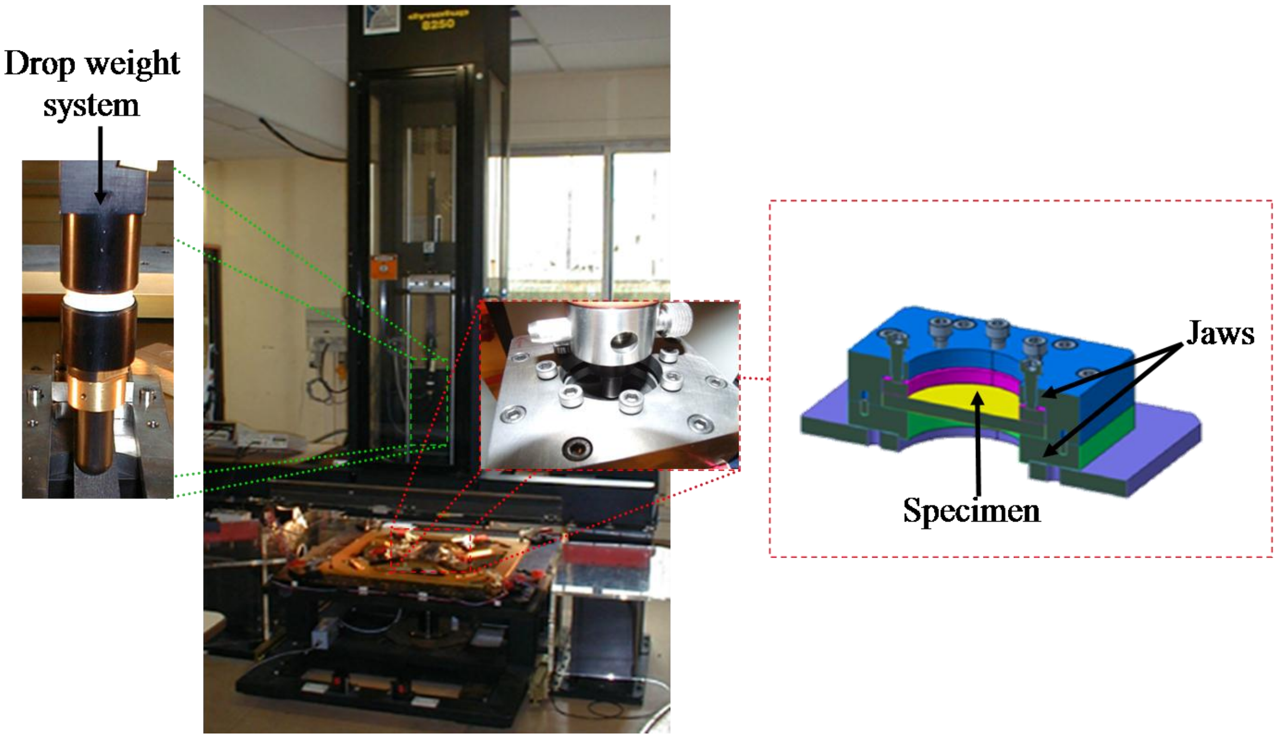

Figure 1. Drop tower for impact tests and jaws with a circular free zone developed at Onera.

2.2. Indentation depth

Residual indentation depth has been measured after impact using two cameras associated with a digital stereo-correlation image system. For some plates, the measurement has been done at different times to characterize the evolution of the indentation depth. Figure 3 presents the evolution of the residual indentation depth with the incident energy level and with the time for the highest incident energy level tested. Relaxation is observed since indentation depth decreases of 8% the first 48h hours after impact. It means that residual indentation can be partially attributed to the viscosity of the matrix. Some authors attribute the indentation depth to debris in cracks [8], and model it using a plastic behavior without taking into account the viscous aspect of the polymer matrix.

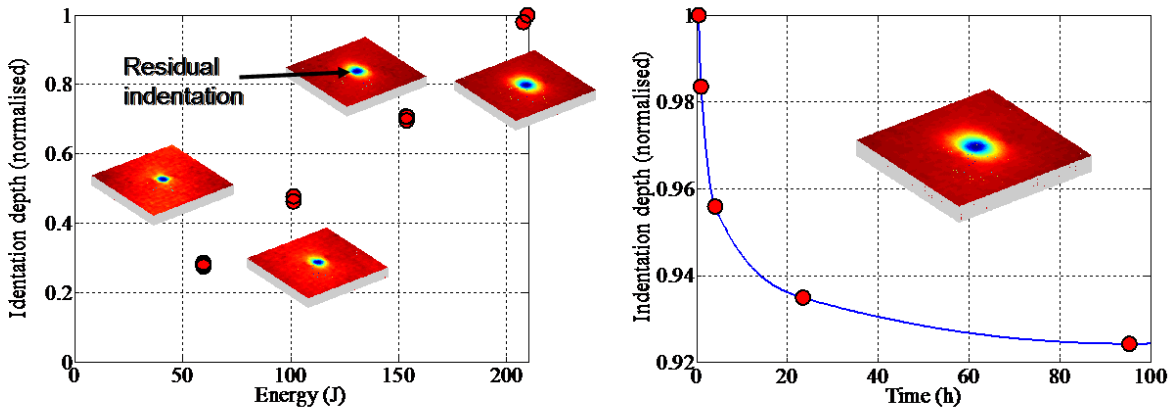

Figure 3. Evolution of the residual indentation depth with energy and with time for a 210J impact.

2.3. Damages due to impact loading

In order to observe in details the damage mechanisms occurring during impact tests, some plates have been cut through the damage zone in different directions (0°, 45°, 90°). Microscopic observations have been made on polished faces. They have been completed with the analysis of micro-tomographies on others specimens to have an estimation of the three dimensional localization of the damages within the material. Microscopic observations done on cut faces through the damage zone (Figure 4) show that damages are mainly decohesion between yarns and matrix cracking. The decohesions can be quite long but are not continuous and follow the architecture of the material and matrix cracking is observed mostly between the yarns. The damage zone is approximately conical through the thickness. Damages patterns are complex within these materials and so, elastic finite element simulations have been done to explain the damages repartition according to the local stresses (Figure 5). The back face of the plate is subjected to a local in-plane tensile loading due to the global bending of the plate. It creates straight matrix cracks in this zone. Through the thickness, the plate is subjected to inter-laminar shear stresses, especially at mid thickness. The inter-laminar shear stresses create matrix cracks which are inclined and present a round shape. They also create decohesion between yarns since the decohesion repartition seems to follow the shear stresses one. Finally, no or few damages are observed under the contact zone between the plate and the impactor. This could be explained by the high level of hydrostatic pressure located directly under the impactor. Indeed, the hydrostatic pressure may reinforce the apparent strength of the material and prevent the creation of cracks as already observed for laminate composites [9].

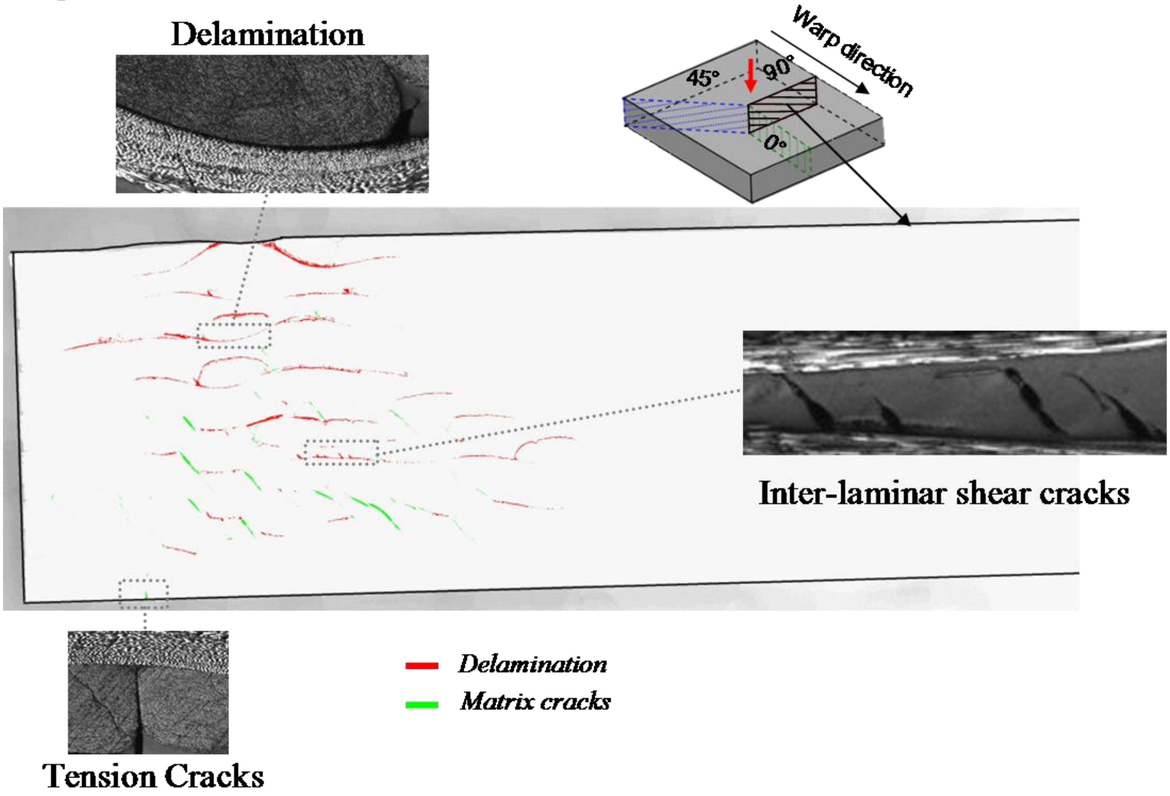

Figure 4. Microscopic observation of damages for a 100J impact test.

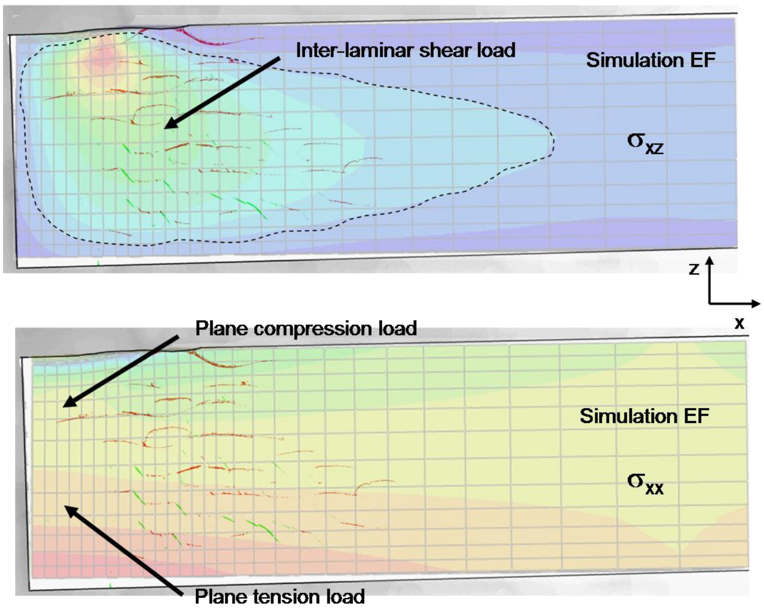

Figure 5. Understanding of the damage pattern observed on a 100J impact test through the elastic finite element analysis.

2.4. Influence of the loading rate on the damage mechanisms

In order to study the influence of the loading rate on the damage pattern, a quasi-static indentation test has been performed. The maximal load applied in the indentation test was set equal to the maximal load achieved in the 80J impact test. The damage mechanisms and their reparation seem to be similar for an impact test or an indentation test (Figure 6). The main difference lies in the residual indentation which is three times deeper for the quasi-static solicitation than for the impact solicitation. This is due to a longer time of contact between the plate and the impactor.

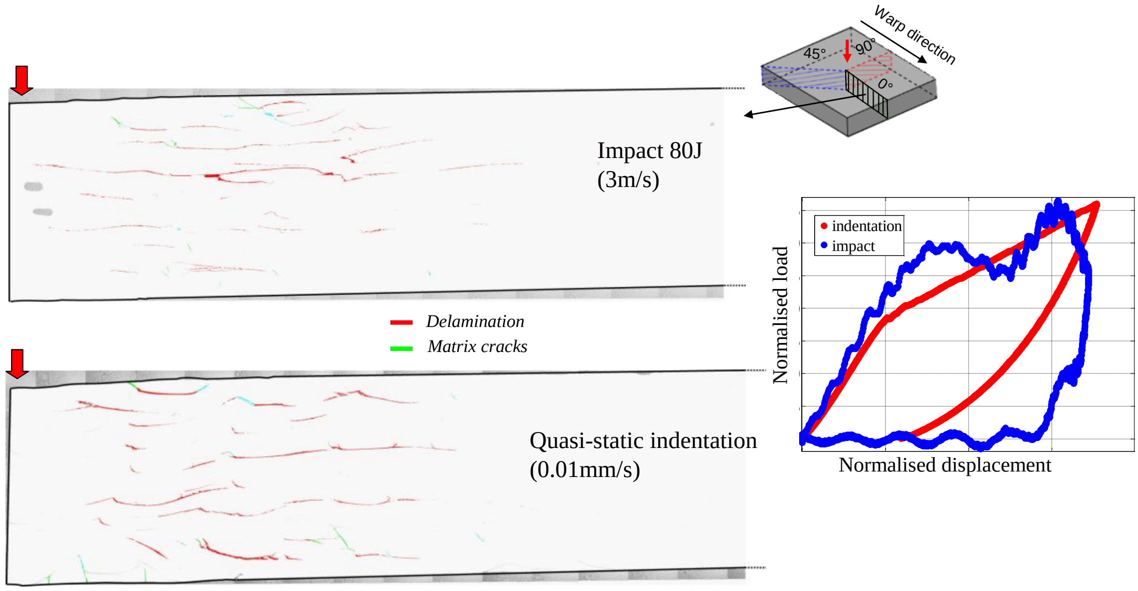

Figure 6. Comparison of impact damage and quasi-static indentation damage (at similar maximal force)

3. Modeling

3.1. Onera Damage Model for polymer matrix composites (ODM_PMC)

A damage model, defined at the macroscopic scale, has been developed at Onera for several years to describe the behavior of woven composites with polymer matrix [10]. Until now, the model has been validated for in-plane static solicitations and has been extended to fatigue loadings [11]. This model is thermodynamically admissible. It takes into account the viscosity of the matrix through a non linear viscous model which permits to describe the loading rate influence and creep tests. The influence of damage on the viscosity is also taken into account. Moreover, in woven composites with polymer matrix, damage is oriented by the microstructure since fiber and matrix have very different mechanical properties. This is the reason why damage variables are defined in the main axes of the material (warp, weft, and through-the-thickness). There are three classes of damage variables in the model. The first class concerns the damage variables representative of in-plane matrix cracking which have a small nonlinear effect on the material behavior. The second class is the damage variable representative of decohesion which has a strong nonlinear effect. The last class of damage variables represents the yarns failures and these variables also have a strong effect on the material behavior. The damage values increase and affect the rigidity of the material through effect tensors. During compression, damage effects are progressively deactivated to take into account the closure of cracks. The unilateral aspect of damage is thus taken into account. The behavior law of the model is written equation 1.

$$\underline{\sigma} = \underline{\underline{C}}^{eff} : (\underline{\varepsilon} - \underline{\varepsilon}^{ve}) - \underline{\underline{C}}^{0} : (\underline{\varepsilon}^{s} + \underline{\varepsilon}^{r}) \qquad (1)$$

where $\underline{\underline{C}}^{eff}$ is the total damaged rigidity tensor (taking into account matrix and yarns damages) and $\underline{\underline{C}}^{0}$ is the initial elastic rigidity, $\underline{\varepsilon}^{ve}$ is the viscous strain tensor, $\underline{\varepsilon}^{r}$ is the residual strain tensor at null stress (due to matrix damage), $\underline{\varepsilon}^{s}$ is the stocked strain tensor which permits to guarantee the continuity of the material behavior even for complex loadings. More details concerning ODM_PMC can be found in [12].

3.2. Impact tests simulations

Finite element simulations have been performed with the implicit code Abaqus standard. Only the circular free zone of the plate is considered and according to symmetries, only one quarter of the system is represented. The impactor is modeled using an isotropic elastic behavior law. Orthotropic elastic modelings of the plate have shown the necessity to take into account the damage mechanisms in the simulations (figure 7). Thus, ODM_PMC has been used to model the behavior of the plate. The in-plane parameters of the model have already been identified on static tests (tension, creep …) but the through-the-thickness properties are still difficult to identify on simple static tests. Moreover, parametric studies have shown that the through-the-thickness damage, representative of decohesion, is the main dissipating energy mode in the model. The through-the-thickness damage properties of ODM_PMC have been identified on the 150J impact test so that both the load/time response and the damage patterns are in good agreement with experimental data and the microscopic observations (Figure 7). Then, the identified model has been used to predict the damage patterns and the dissipated energies of others impact tests (Figure 8). The predictions are in good agreement with experimental responses. However, ODM_PMC does not take into account the reinforcement of the material under hydrostatic pressure and thus damages are predicted by the model under the contact zone while none are observed experimentally. The consideration of the hydrostatic pressure effect in the model is in progress. Moreover, a residual indentation is predicted with the model due to the viscosity but the depths are lower than the experimental ones. A visco-plasticity model may be needed. That point is currently under investigation.

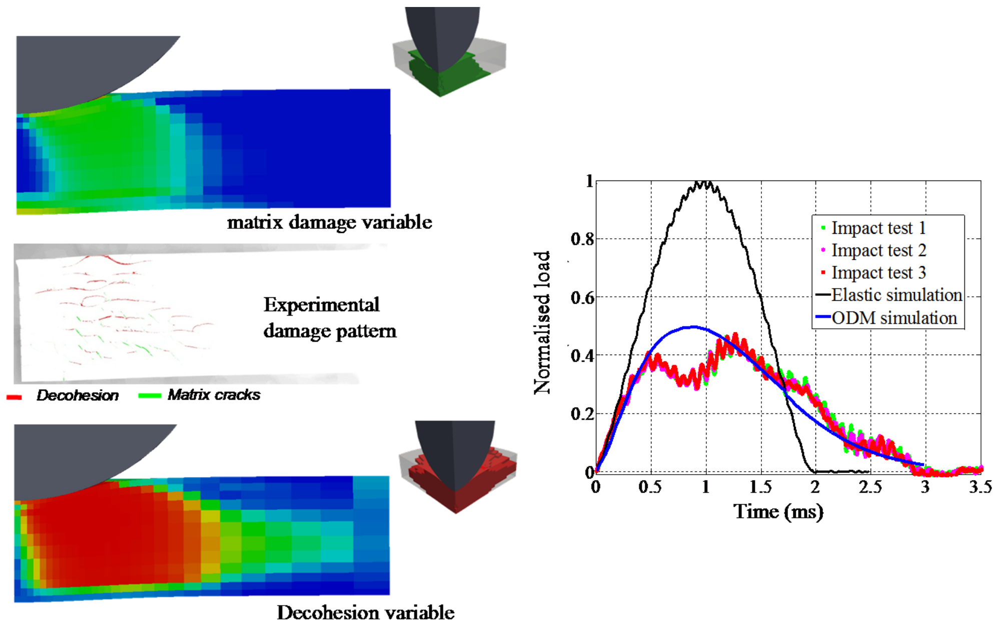

Figure 7. Identification of through-the-thickness damage properties on damage pattern and load/time response of the 150J impact test.

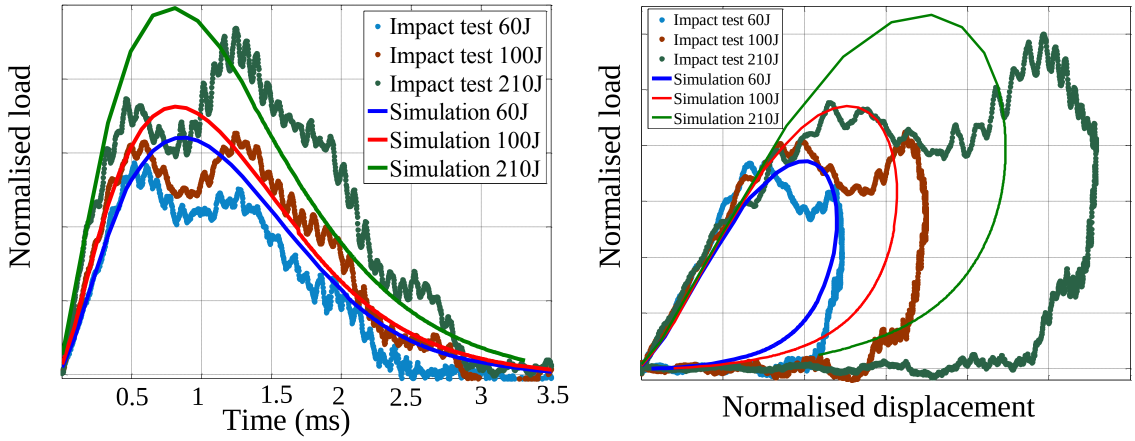

Figure 8. Predictions of load/time and load/displacement response for 60J, 100J and 210J impacts.

4. Conclusions

Analyses of impact tests on woven interlock composites have been performed in order to improve the understanding of damage mechanisms in these recent materials. Analyses have shown that the main modes of damage are decohesion between layers and matrix cracking. Elastic finite element simulations have helped to understand that the conical shape of the damage pattern is due to local tensile loadings at the back face of the plate and to the inter-laminar shear stresses through the thickness. The ODM_PMC has been used to simulate impact on interlock composites. Despite the fact that ODM_PMC has been only validated for in-plane loading, it seems that impact damage mechanisms are well described by the model. Moreover the predictions of impact damage and impact responses performed with the model are in a quite good agreement with the experiments. Nevertheless some improvements have still to be made. The next step consists in predicting the static residual strength after impact of interlock composites. The impact damage repartition obtained by simulation can be used as an input for static loading simulations using the same ODM_PMC model.

Acknowledgements

The collaboration with Snecma and Messier-Bugatti-Dowty is gratefully acknowledged. This work was supported under the PRC Composites, French research project funded by DGAC, involving SAFRAN Group, ONERA and CNRS.

References

[1] G.A.O. Davies and R. Olsson. Impact on composite structures. *The Aeronautical Journal*, vol. 108: pp 541-563, 2004.

[2] E.V. Gonzáles, P. Maimí, P.P. Camanho, A. Turon, J.A. Mayugo. Simulation of drop-weight impact and compression after impact tests on composite laminates. *Composite Structures*, vol. 94: pp 3364-3378, 2012.

[3] S. Rivallant, C. Bouvet, N. Hongkarnjanakul. Failure analysis of CFRP laminates subjected to compression after impact: FE simulation using discrete interface elements. *Composites: Part A*, vol 55: pp 83-93, 2013.

[4] G. Bibo, P. Hogg. Review: the role of reinforcement architecture on impact damage mechanisms and post-impact compression behaviour. *Journal of Materials Science,* vol. 31: pp 1115-1137, 1996.

[5] F. Chen, J. Hodgkinson. Impact behaviour of composites with different fibre architecture. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 2009.

[6] C. Chiu, M. Lai, C. Wu. Compression failure mechanisms of 3-d angle interlock woven composites subjected to low-energy impact. *Polymers & Polymer Composites*, vol 12: pp 309-320, 2004.

[7] S. Heimbs, B. Van Den Broucke, Y. Duplessis Kergomard, F. Dau, B. Malherbe. Rubber Impact on 3D Textile Composites. *Applied composite materials*, vol 19: pp 275-295, 2012.

[8] C. Bouvet, S. Rivaillant, J.J. Barrau. Low velocity impact modeling in composite laminates capturing permanent indentation. *Composites Science and Technology,* vol. 72, pp 1977-1988, 2012.

[9] N. Carrere, F. Laurin, J.F. Maire. Micromechanical based hybrid mesoscopic 3D approach for non-linear progressive failure analysis of composite structures – Part B: Comparison with experimental data, *Journal of Composite Materials,* vol. 47: pp 733-741, 2013.

[10] C. Rakotoarisoa, F. Laurin, M. Hirsekorn, J.F. Maire, S. Otin, J. Henry, Z. Aboura. Prévision de la durée de vie en fatigue des composites à matrice organique tissés interlock. *Comptes-rendus des 17èmes Journées Nationales sur les Composites*, Poitiers, 2011.

[11] C. Rakotoarisoa, F. Laurin, M. Hirsekorn, J.F. Maire, L. Olivier. Development of a fatigue model for 3D woven polymer matrix composites based on a damage model. *Proceedings of the 15th European Conference on Composite Materials*, Venice, 2012.

[12] A. Hurmane, F.X. Irisarri, F. Laurin, S. Leclercq, M. Benzeggagh. Strength analysis of woven interlock composites subjected to compressive loading experiments and simulations. *Proceedings of the 16th European Conference on Composite Materials*, Seville, 2014.