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Analyse Numérique d'un toron de Kevlar KM2 soumis à impact transverse à grand vitesse

Numerical Analysis of Kevlar KM2 Yarn Subjected to Transverse Impact in high speed range

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Abstract

Aramid fibers are widely used in protection systems in the form of woven fabric. These structures present a multiscale nature in which three different levels are classically identified : fiber, yarns, fabric. The fabric level has been widely studied using different approaches which include numerical, analytical, experimental solutions while few attentions have been dedicated to its basic constituents. Here is presented a numerical model for yarn structure. This model relies on an adapted version of the Discrete Element Method in which discrete elements are relatively connected using truss elements. The yarn is modeled at its components level, i.e. fibers, in order to understand the effect of the microstructure on its ballistic properties of the structure. Two different responses have been analyzed in order to validate the model and explore the possible perspectives of these analyses.

Mots Clés : Toron, Impact Transversal, Modélisation Numérique, Méthode des Elements Discrets, Micro-échelle

Keywords : Yarn, Transversal Impact, Numerical Modelling, Discrete Element Method, Microscale

1. Introduction

High performance aramid and polyethylene fibres such as Kevlar and Spectra are widely used for impact protection systems due to their high strength and strength-to-weight ratio. Usually woven in flexible fabrics, they are used as main material in soft body armors or secondary layers in ceramic protections.

Mechanical behaviour of these materials under high velocity impacts has been largely studied and determined using different methods. Classical solutions include analytical [1], semi-empirical [2] and numerical approaches [3].

Within this group, numerical approaches are one of the most promising since they usually relies on less hypotheses compared to the analytical ones and do not require large investments in materials and time as experimental campaigns.

Different numerical models have been proposed for fabrics under high velocity impact [3, 4, 5] while few attention has been dedicated to their basic constituents, i.e. fibres and yarns. Mesoscopic numerical models classically assume yarns as an homogeneous solid due to computational reasons. Usually a linear elastic orthotropic material model is adopted and the elastic moduli are mostly determined by physical assumptions and validated through the available analytical theories [6, 7]. This way of proceeding does not consider other potential important phenomena as fibre-fibre interactions, inter-yarn friction, yarn section rearrangements or fibres three dimensional mechanical behaviour.

In order to determine a proper material model for yarns in highly dynamical applications, a mechanical study which goes further the analytical or experimental limitation is required.

Hereafter, a numerical study of a Kevlar KM2 600 yarn transversely impacted is presented. The single yarn is represented at its components level, i.e. fibres, allowing to take into account fibre-fibre interaction. A revisited version of Discrete Element Method inspired by multifilament models developed by other authors [5] is adopted in order to solve the problem in a friendly computational environment.

Yarn impact response in the long ($0-40\mu s$) and short time period ($0-3\mu s$) have been analyzed and compared to the literature. The first analysis is aimed to understand the structural behaviour of the yarn when it is able to withstand to the tension state induced by the first contact with the projectile. On the other end, the second analysis is more focused on the observation of the first longitudinal wave propagation and the first stresses induced by the impactor within the yarn. These stresses have a primary importance in the resistance of the yarn to high speed impact $\approx 600\text{ m s}^{-1}$. Thanks to this approach all those phenomena which appear during the impact that are not visible using experimental/analytical techniques are carefully described and their effects quantified. Moreover, using numerical sensors, different physical quantities which are not available with classical approaches have been recorded.

2. Test Set up

The impact scenario consists in a single 25.4 mm length Kevlar KM2 600 yarn clamped at the extremities (Fig. 1) and impacted transversely in the centre by a cylindrical projectile. In order to understand the effect of the discrete yarn nature on its high strain-strain rate mechanical behaviour, all the 400 filaments which compose the yarn are individually modelled. Fibres are assumed to be straight and circular with a constant diameter equal to $12\mu m$. A cylindrical projectile with a the mass of 9.91 mg is located in the centre of the yarn with contact condition at the initial time.

For the long period case, a diameter ϕ of 2.2 mm have been assumed for the projectile. The initial speed have been set equal to 120 m s^{-1} in order to validate the model with preexisting results [8].

For the short period case, the initial velocity of the projectile has been incremented to 200 m s^{-1} while the projectile diameter has been set to 2 mm. Moreover, projectile speed has been assumed to be constant for this analysis since no appreciable deceleration is expected in the considered time period ($3\mu s$). Due to the nature of the problem, symmetry conditions are applied in both the cases.

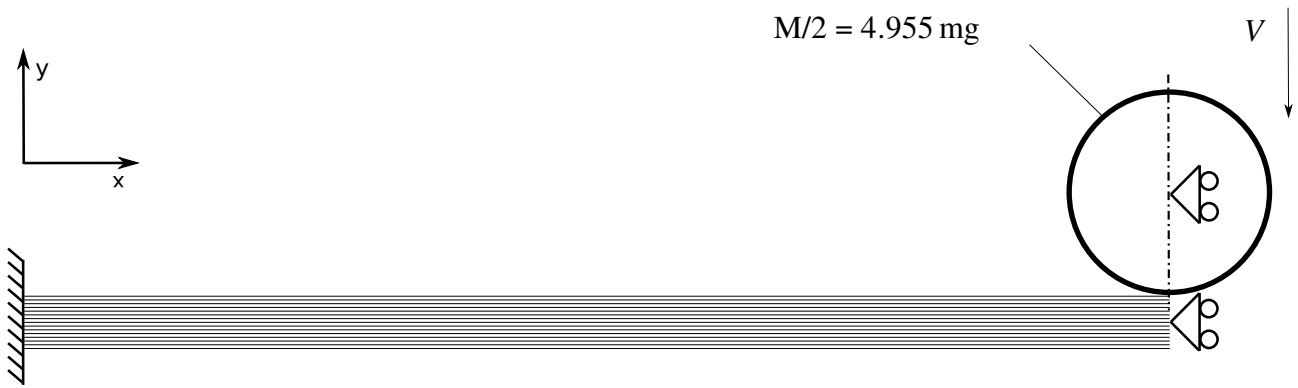


Fig. 1. Transverse impact scenario.

2.1. Material Properties

Kevlar KM2 fibres exhibit a purely elastic strain-rate insensitive behaviour in the longitudinal direction and non-linear elastoplastic behaviour in their transverse direction [9, 10]. Longitudinal Young Modulus E and density ρ have been assumed equal to 84.62 GPa and 1.44 g cm^{-3} respectively [8, 9]. Since truss elements will be adopted within the simulation, transverse behaviour of the fiber will be neglected.

Maximal stress in the longitudinal direction is assumed as failure criterion, with a stress limit σ^{lim} equal to 3.88 GPa. This choice is motivated by the fact that few experimental information are available nowadays for the multiaxial failure of these polymeric fibres.

3. Numerical Model

3.1. Discrete Element Approach

In the present application, a revisited version of the discrete element method inspired by the work of Wang [5] is applied to model yarn fibres. Fibres are modeled as a series of equally spaced DEs relatively linked by truss elements, Fig. 2. These particles carry out the fiber inertial properties and the numerical treatment of contact. Here the fibres will be assumed rigid in the transverse direction, while the longitudinal elastic properties are provided by the truss constitutive behaviour.

Spherical DEs with a constant diameter of $12 \mu\text{m}$ are used to discretize the fibres. Relative distance among joined discrete elements has been set to $12 \mu\text{m}$ in the initial configuration, to provide fibres continuity.

Since all the fibres are equally discretized, the global mass of the yarn has been homogeneously distributed within the particles.

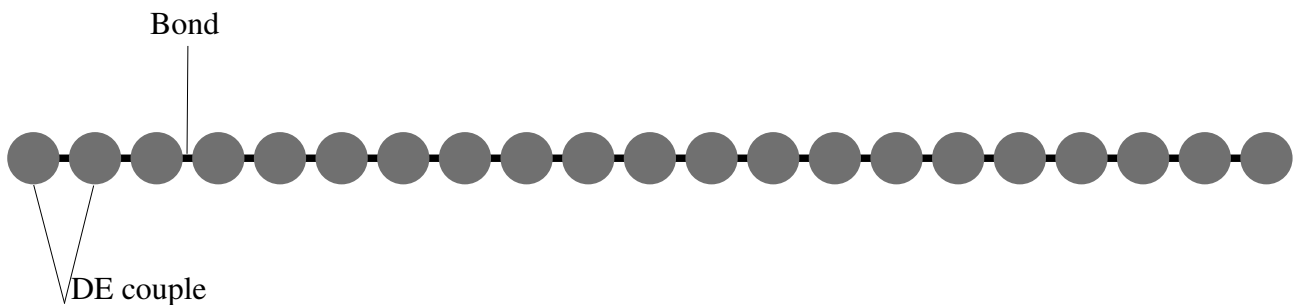


Fig. 2. Fibre model using DEs

3.2. Bond Constitutive Behavior

All bonds of the system are modelled as linear trusses, Fig. 3. Bond force f^b applied by a truss to its relative particles is equal to :

$$f^b(t) = k(l(t) - l_0) \quad (\text{Eq. 1})$$

$$\text{with } k = \frac{EA_0}{l_0}, \quad (\text{Eq. 2})$$

where E is the Young Modulus of the material in the fibres longitudinal direction, A_0 is the initial area of the fibre section, l_0 is the initial length of the bond and l is the current length of the bond.

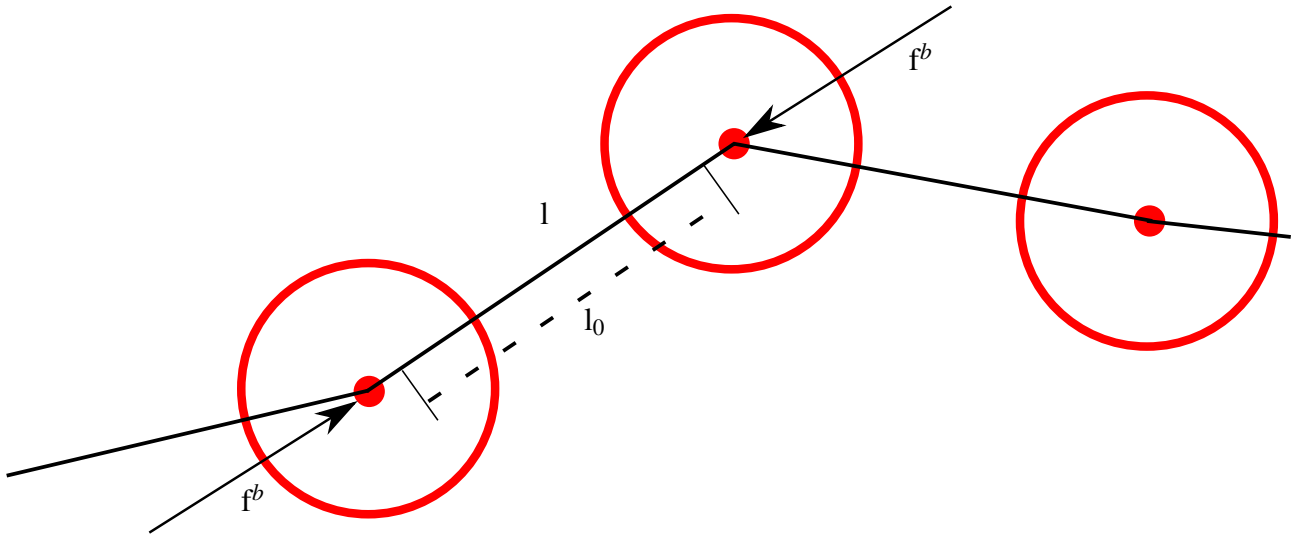


Fig. 3. Bond Forces

This force is directed along the truss axis and it is respectively attractive for $l(t) > l_0$ and repulsive for $l(t) < l_0$.

When a bond reaches the failure stress it is deleted by the simulation.

3.3. Contact Model

A penalty model is used to compute the contact force among discrete elements. When two particles get in contact, a repulsive force f^c dependent on δ is applied, Fig. 4. The value of the contact is evaluated as follow :

$$f^c(t) = -k\delta(t), \quad (\text{Eq. 3})$$

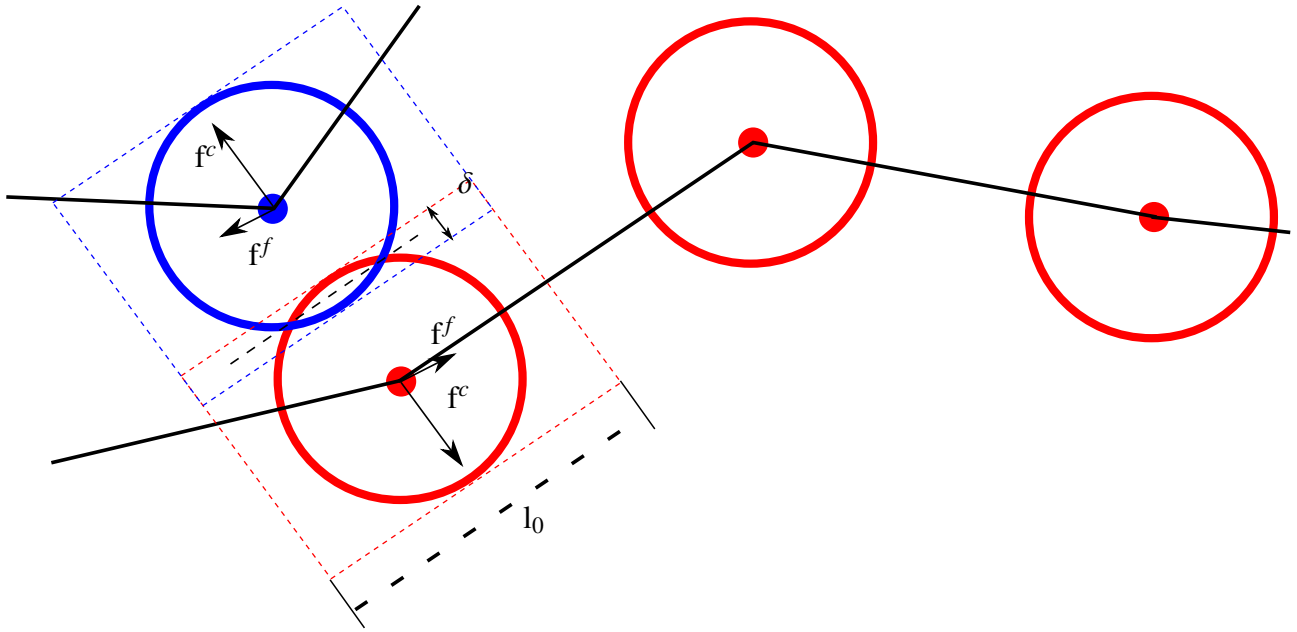


Fig. 4. Contact Forces

The value of the indentation stiffness k as been assumed equal to 500 kN m^{-1} . This value resulted as the optimum compromise between simulation stability and avoided interpenetration [?]. The force f^c is always repulsive and directed as the normal to the contact plane. It is important to underline that contact has not been activated between bonded elements before bonding failure.

A Coulombian model has been adopted for friction forces f^f :

$$f^f(t) = \mu_f f^c(t), \quad (\text{Eq. 4})$$

where μ_f is the kinetic friction coefficient. Friction coefficients have been differentiated for fibre-fibre contact and fibre-projectile contact with a respective value of 0.20 and 0.18 [8].

3.4. Integration Scheme

An explicit integration scheme inspired by the Verlet Velocity algorithm [11] is used to perform the analysis. Total force which act on each Discrete Element is firstly evaluated summing the previously mentioned contribution from all the domain, then kinematic variables are computed.

4. Long Period Analysis results

Fig. 5 reports the yarn deformation at 0 μs (a), 10 μs (b), 25 μs (c) and 40 μs (d).

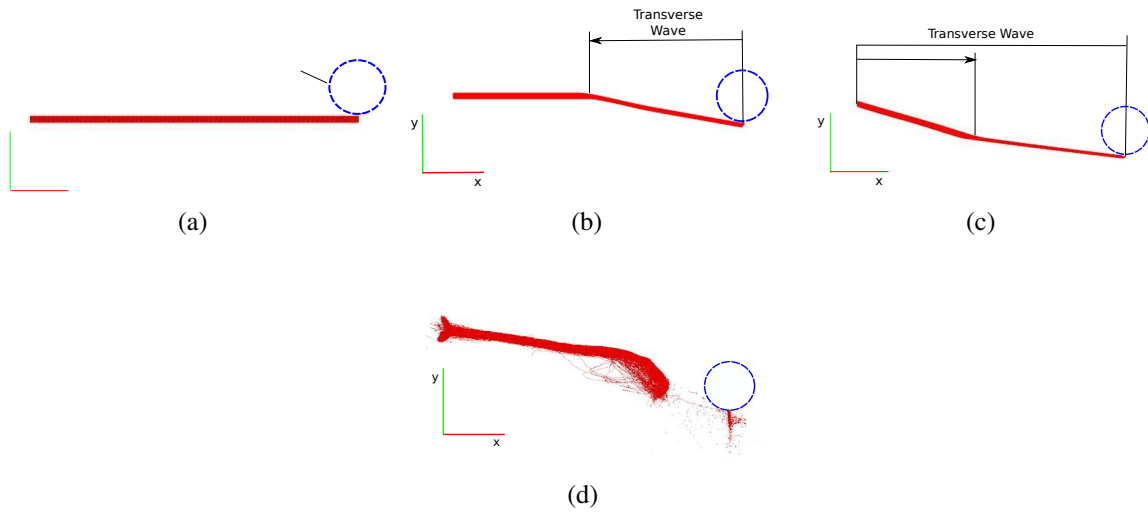


Fig. 5. Impacted Yarn

Transverse and spreading waves are both observed. The first one moves leftwards to the clamped edge in the period between 0 μs and 20 μs , it is reflected and then then moves rightwards to the impact point, 20 μs -30 μs . Finally when it reaches the impact point the yarn fails. The second wave is related to the yarn section rearrangement. When the yarn gets in contact with the projectile, the different fibres spread under the charge and the yarn section changes into a new configuration. This rearrangement of the section travels in the form of a wave in the same direction of the transverse one, Fig.6

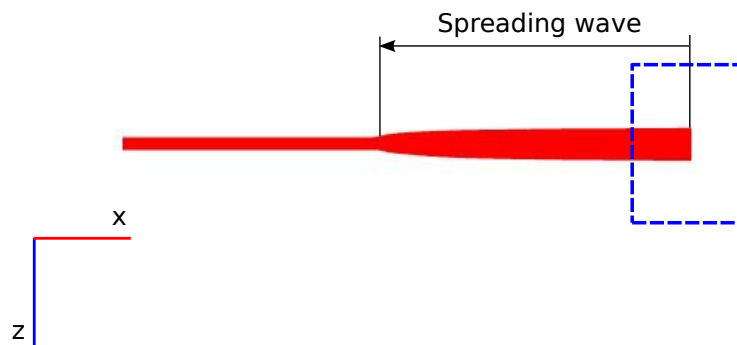


Fig. 6. Spreading wave propagation (10 μs)

Fig. 7 reports the history of the projectile velocity compared to the results obtained in [8] with the same impact configuration. The curves are in very good agreement up to the failure. The relative difference on the residual velocity between the two models is around 6 m s^{-1} , which is closed to 5% compared to the initial speed of 120 m s^{-1} .

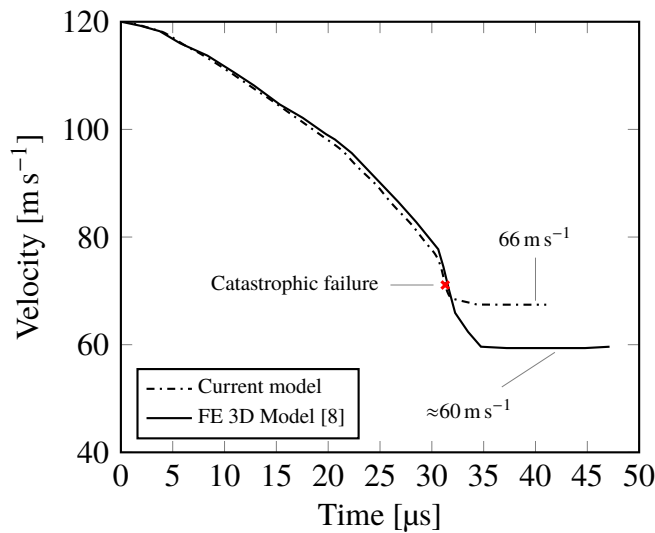


Fig. 7. Projectile velocity comparison for a transverse impact at 120 m s^{-1} .

A complete energetic analysis has also been performed, Fig. []. Unfortunately the reference [8] only reports the internal energy for this impact scenario, however a qualitative comparison of the energetic trends could be done with other cases presented in the same work.

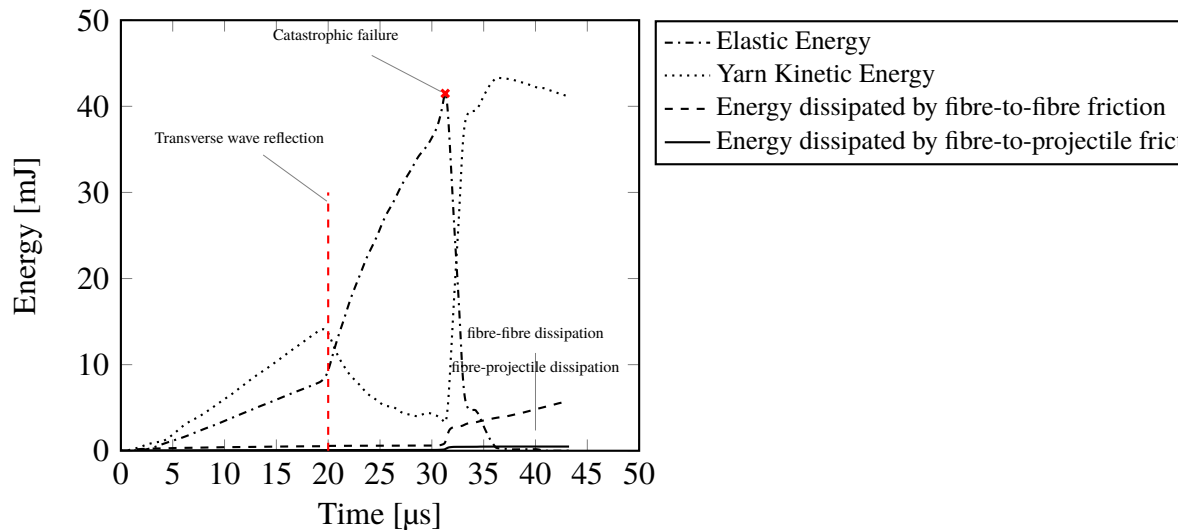


Fig. 8. Energy Balance for a transverse impact at 120 m s^{-1} .

Yarn kinetic and elastic energy grow linearly before the first transverse wave reflection. When transverse wave is reflected, a drastic conversion of kinetic energy into elastic energy is observed. Finally, when catastrophic fail occurs, elastic energy within the yarn is fully converted in yarn kinetic energy. As it can be seen on Fig. 8, friction dissipation doesn't play an important role in energy absorption during the impact. It only appears when the system starts to fail. According to the model, internal friction plays a primary role in friction dissipation, however its effects are mostly related to the dissipation of the yarn kinetic energy in the post failure phase.

5. Short period Analysis results

The aim of this second analysis is to analyze the propagation of the stress wave directly induced by the impact, also called longitudinal wave, and the deformation of the yarn near the impact zone during the first phase of the contact. These two informations are extremely important since they are directly related to the ballistic limit of the yarn.

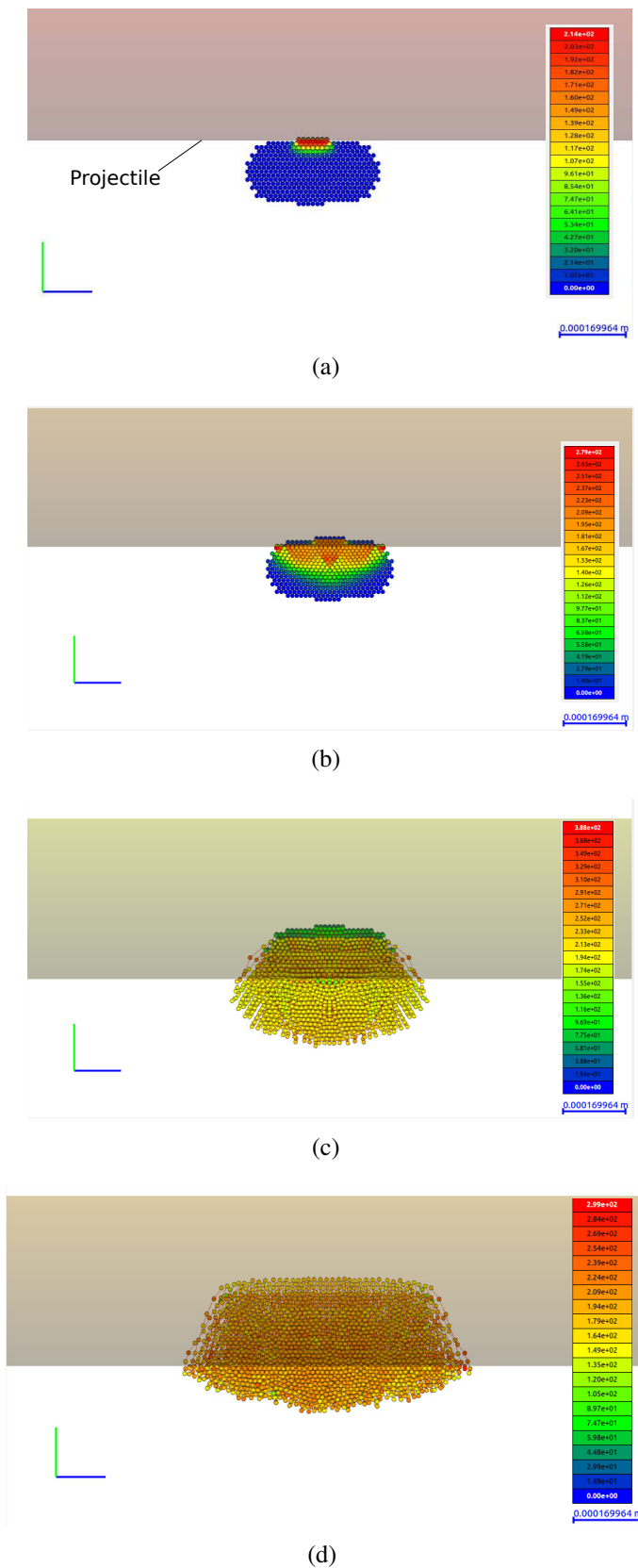


Fig. 9. Discrete elements velocity at the yarn centre [m/s] at 0.1 μ s(a), 0.2 μ s(b), 0.8 μ s(c), 2 μ s(d)

Fig. 9 reports the evolution of the section from the beginning up to 2 μ s . A compressive wave which propagates through the yarn section is clearly observed. When this wave reach the free boundaries of the section, particles "bounce off" from the yarn bottom and the section is rearranged. This phase is the initialization of the spreading wave previously observed in long time scale simulation. Oppositely

to the classical continuum representation of the yarn, here the section is strongly deformed. Notably, a particle velocity close to 400 m s^{-1} is reached in some points. This value is higher than 100% compared to the classical analytical solution [6] and find some theoretical basis in the work of Walker et al. [12] Longitudinal wave propagation can be even tracked, Fig. 10. Even in this case, the longitudinal wave appears not to be homogeneous as in classical 1D solutions but it presents a three-dimensional nature with some zones more stressed than others. Since yarn failure is intimately related to the stress concentration within the yarn, some localized stressed zone could represent the reasons for which ballistic limit is usually overestimated by the classical analytical approaches.

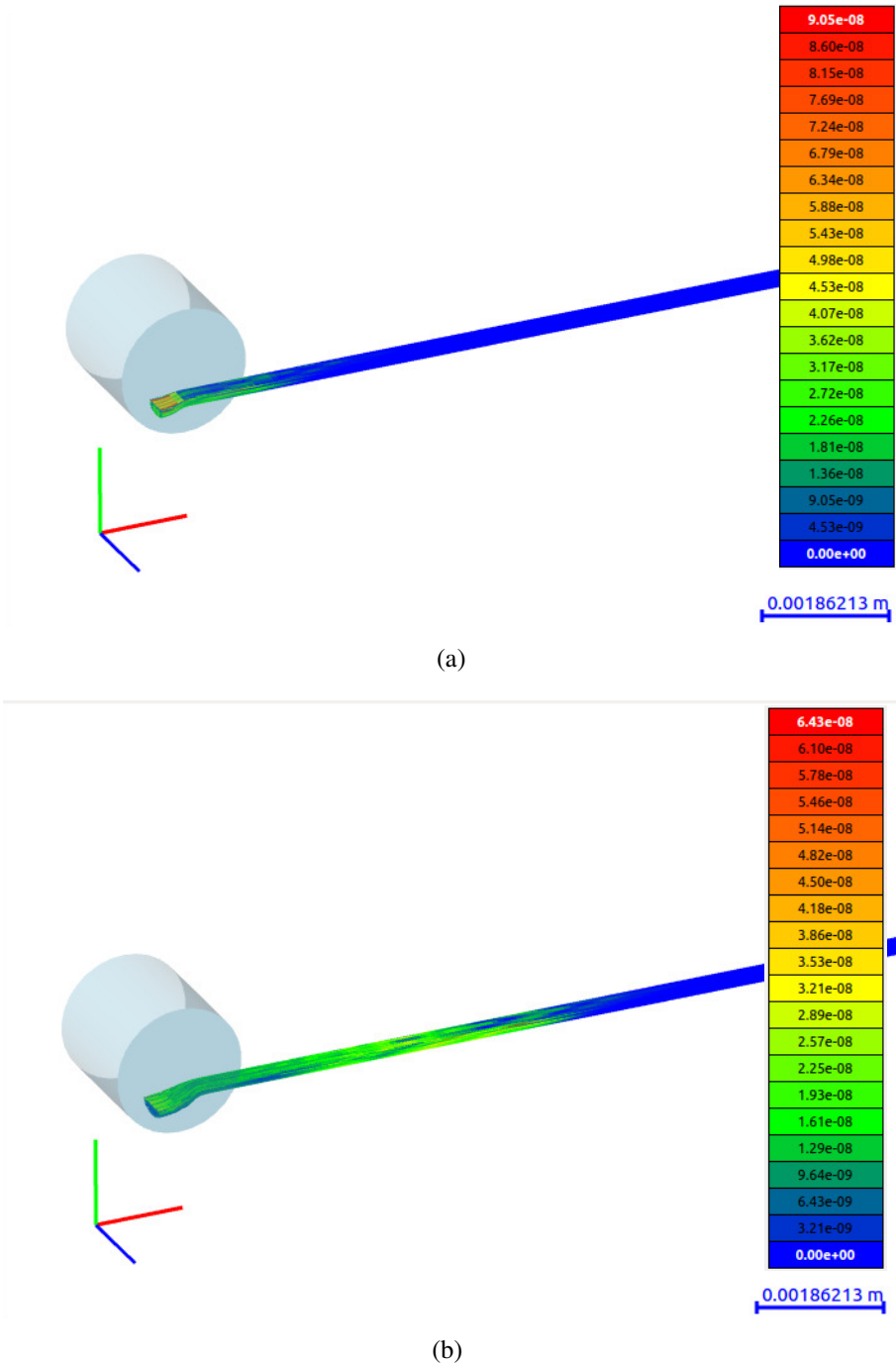


Fig. 10. Internal energy of the yarn [J] at $0.6 \mu\text{s}$ (a), $1.2 \mu\text{s}$ (b)

6. Conclusion

Real scale microscopic analyses of a single yarn of Kevlar KM2 600 impacted transversely have been performed. Long period analysis has been used to validate the proposed model with preexistent literature results. All the main phenomena typical of this time scale, as transverse and spreading wave propagation, have been observed. Moreover, projectile speed history has been found to be very similar to that obtained using a full 3D finite element model, especially before failure initialization.

An energetic analysis has been conducted in order to track the different contribution of energy absorption. Kinetic and internal energy results to be the main responsible of projectile deceleration.

Short term analysis shows the propagation of compressive wave within the yarn section. This compressive wave brings to a rearrangement of the cross section which results in high deformations. Longitudinal wave propagation has been even observed. This wave results not to be homogeneous as in classical analytical theory but presents a 3D configuration with higher stressed zones. Both stresses as section rearrangements seems to be regulated by fiber-fiber interaction and fiber-fiber contact stiffness. The implementation of a physical based contact law is a perspective of this work. In this way, quantitative observations on the short period response of an impacted yarn could be performed.

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