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Numerical investigations on a yarn structure at the microscale towards scale transition

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ABSTRACT

Since the beginning of the last decade, few examples of multifilament models for dry fabrics have been presented in literature. This work deals with the simulation of a single yarn subjected to transverse impact. Inspired by the models previously developed by other authors, a revisited form of Discrete Element Method has been adopted to perform microscopic analyses in a more efficient computational environment. Transverse impact analysis onto a single KEVLAR KM2 yarn has been performed using this approach. Truss elements have been adopted to discretize yarn filaments instead of heavy computational 3D finite elements. A good agreement with literature results has been achieved with an important reduction of computational resource. In the end, a proposed scale transition is discussed.

1. Introduction

Dry fabrics comprised of high performance materials as Kevlar, Spectra, Zylon and Twaron have been largely adopted in protection systems due to their high penetration resistance and high strength to weight ratio. Some of applications include protecting clothing and containment systems for jet engines.

The outstanding performances of these materials in impact applications are directly related to a large number of parameters which includes fibres mechanical behaviour, weaving type and fibres reciprocal interaction. The energy absorbed by a fabric during an impact could be attributed to a large number of phenomena as fabric acceleration, fabric deformation, friction dissipation by yarn-to-yarn or fiber-to-fibre interactions. All these aspects cannot be individually evaluated using experimental approaches, which are restricted to the evaluation of macroscopic phenomena as penetration or projectile residual speed.

Since their first applications, numerical simulations turned to be a powerful tool to understand and to evaluate mechanical behaviour of dry fabrics under ballistic impact.

Some models assumed the fabric as an homogeneous medium [1–4] while others were based on a mesoscale representation of the structure [5–10].

In the first case, the computational efficiency is preferred to the model accuracy. The discrete nature of the fabric here is not addressed and capturing phenomena as yarn pull-out, individual yarn breakage or inter-yarn friction dissipation becomes difficult or impossible.

In the second case, fabric architecture is explicitly modelled. Representing the yarn individually, it is possible to have a more realistic description of the failure mechanisms near the impact zone and evaluate the effect of yarns interaction.

More recently fibre-level modelling has been adopted for an entire fabric or a part of it [11–14]. Since their high computational requirement, these last models are only justified when microscopic effects, as fibre–fibre interaction or yarn section rearrangement, would be tracked.

The original approach, denoted Digital Element Method, was developed by Wang et al. to simulate weaving processes [15–17]. This method was successively improved by different authors [18,19] and finally extended to impact applications [11,14]. In this specific approach, yarns are modelled as a group of “Digital Fibres”. The term “Digital” refers to the fibres section which is larger than reality.

Each “Digital Fibre” was discretized as a sequence of pin-joined trusses while their transversal behaviour was included in the contact model. Usually, a coarse discretization (few dozen of Digital Fibres) was adopted for each yarn.

This method shows considerable improvements in results and phenomena description compared to the mesoscale models, however it relies on some hypotheses that still have to be verified:

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- an elastic equivalence between Digital Fibres and real fibres was established only in longitudinal direction and no information was provided concerning their transverse mechanical behavior as well as the mechanical contact law among fibres. However, it has been demonstrated that inter-fibres contact plays an important role during an impact [12];
- optimum number of Digital Fibers was obtained by a convergence study on the ballistic performance of the whole fabric. This equivalence could fall if the mechanical response of a single yarn is analysed, as the yarns resultant mechanical behaviour is influenced by their reciprocal interaction within the fabrics.

More recently Nilakantan and Sockalingam [13,20,21] approached the filament-level modelling in a more radical way. In these works, a single yarn submitted to transverse impact is analysed. Each fiber of the yarn was considered and modelled using 3D Finite Elements, in order to describe accurately their transverse behaviour. Contact, friction and material anisotropy were considered too. The role of different parameters as fibres transversal stiffness, shear modulus and friction on yarn ballistic performance was exploited. The high computational time, given by the large number of degrees of freedom involved in the simulation, is one of the major drawback of this method. In this work, the same test performed by Nilakantan is reproduced using a revisited version of the Discrete Element Method (DEM) [22]. As in Digital Element Method, each fibre is discretized as a pin-joined sequence of truss elements. However, three main points differentiate it from the works by Wang:

- contact is evaluated using a particle-based approach;
- the multifilament analysis concerns a single yarn instead of a fabric;
- all the 400 fibres are explicitly modeled.

Results of the simulation are then compared to those presented by Nilakantan [13], in order to validate the proposed approach. In the final part a multiscale approach based on the Digital Element Formulation is presented. A comparison between the proposed real scale model and its equivalent "Digital Fibres" model is finally discussed.

2. Yarn transverse impact test

2.1. Test set up

The model consists in a 25.4 mm length Kevlar KM2 600 single yarn clamped at the extremities (Fig. 1) and impacted transversally in the centre by a cylindrical projectile. As in [13], all the 400 filaments which compose the yarn are modelled. Fibres are assumed to be straight and circular with an constant diameter equal to 12 μm. A cylindrical projectile with a mass M of 9.91 mg is located in the centre of the yarn with contact condition at the initial time. Its specific dimensions are a height h of 2 mm and a diameter ϕ of 2.2 mm. The impact velocity V is set to 120 m s^{-1}. Due to the nature of the problem, symmetry conditions are applied. Just half of the yarn is simulated and the original mass of the projectile is divided by two. Moreover, the displacement along the initial yarn axis is imposed to be zero for the yarn centre and for the projectile.

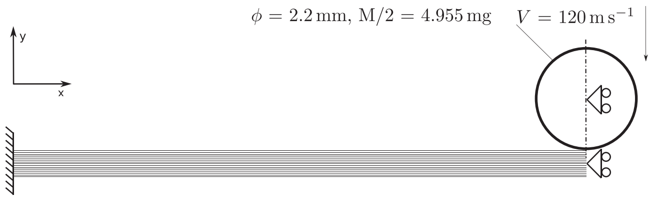

Fig. 1. Transverse impact set up.

The current work differs from the referenced initial configuration in two details:

- The initial section is supposed to be circular (Fig. 2) with a yarn packing density lower than the hexagonal configuration adopted by Nilakantan. Final results should not be significantly influenced by this difference since a natural redistribution of the fibres is expected under the impact loading;
- Symmetry conditions are introduced, in order to reduce computational time.

2.2. Material properties

Kevlar KM2 is notoriously a transversal isotropic material [23,24]. Since truss elements are used, only longitudinal stiffness here will be considered. Longitudinal Young Modulus E and density ρ are taken equal to 84.62 GPa and 1.44 g cm^{-3} respectively [13,23].

Maximal stress is assumed as failure criterion, with a stress limit σ^{lim} equal to 3.88 GPa. It is worth to notice that the reference author explicitly assumes that failure is only related to the longitudinal stress, since few experimental information are available for the multiaxial failure of these polymeric fibres.

3. Numerical model

3.1. Discrete Element Approach

It has been demonstrated that fabric ballistic performances are strongly influenced by parameters involved in contact mechanisms [25–27,12], then it should be carefully treated in these numerical models. In order to deal efficiently with contact mechanic, a revisited version of the Discrete Element Method (DEM) inspired by the models developed by Wang [11] hereafter is proposed. Discrete Element Method was firstly developed for simulation of granular media by Cundall [28,29]. This method consists in using physical particles, usually rigid, named Discrete Elements (DEs) to discretize a granular system.

More recently, the efficiency of different DEM contact search algorithms have led to an extension of this numerical method to continuous media. Examples of these applications were presented

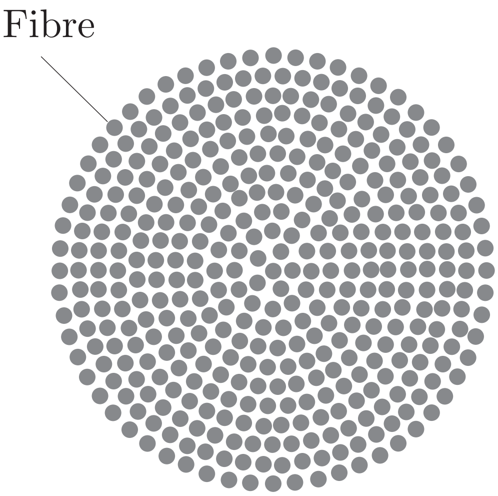

Fig. 2. Initial yarn section layout.

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