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A mechanical particle model for analyzing rapid deformations and fracture in 3D fiber materials with ability to handle length effects

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ABSTRACT

A mechanical model for analyses of rapid deformation and fracture in three-dimensional fiber materials is derived. Large deformations and fractures are handled in a computationally efficient and robust way. The model is truly dynamic and computational time and memory demand scales linearly to the number of structural components, which make the model well suited for parallel computing. The specific advantages, compared to traditional continuous grid-based methods, are summarized as: (1) Nucleated cracks have no idealized continuous surfaces. (2) Specific macroscopic crack growth or path criteria are not needed. (3) The model explicitly considers failure processes at fiber scale and the influence on structural integrity is seamlessly considered. (4) No time consuming adaptive re-meshing is needed.

The model is applied to simulate and analyze crack growth in random fiber networks with varying density of fibers. The results obtained in fracture zone analyses show that for sufficiently sparse networks, it is not possible to make predictions based on continuous material assumptions on a macroscopic scale. The limit lies near the connectivity $l_c/L = 0.1$, where l_c/L is the ratio between the average fiber segment length and the total fiber length. At ratios $l_c/L < 0.1$ the network become denser and at the limit $l_c/L \to 0$, a continuous continuum is approached on the macroscopic level.

1. Introduction

The aim of this work is to derive a numerical three-dimensional material model to explore the dynamics of rapidly loaded and fracturing fiber-based materials. There are many natural materials based on networks of fibers such as wood, bone, silk, tissue and organic plants. Examples of engineered fiber materials are fabrics, composites, textiles and paper. The traditional attempts to model network materials as continuous materials have not been completely successful, cf. Kulachenko et al. (2005), Wellmar et al. (1997) and Heyden et al. (2000). An assumption of macroscopic continuum has been shown to be a too rough estimation, cf. Silling and Bobaru (2005), Isaksson and Hägglund (2009a,b) and Isaksson and Dumont (2014), because certain heterogeneities linked to the microstructure cannot be captured within the traditional continuum mechanics framework. Advanced material modeling approaches are required to complement traditional methods.

The mechanical behavior of network materials has been the subject of many studies. Primarily static deformations have been analyzed, cf. Åslund and Isaksson (2011), Niskanen and Alava (1994) and Åström et al. (1994). Recently the focus of the mechanical analyses has been shifted toward fracture, cf. Hägglund and Isaksson (2008), Isaksson and Hägglund (2007), Åström and Niskanen (2007), Azecedo and Lemos (2006), Fahrenthold and Horban (2001), Shivarama and Fahrenthold (2004) and Johnson et al. (2011), and is often based on finite element models, or in the form of gradient enhanced of non-local fracture methods, cf. Hägglund and Isaksson (2006) and Isaksson and Hägglund (2007), but still under quasi-static conditions. However, in some situations the loading of the material is too rapid to be captured by quasi-static models as complex dynamic phenomena prevails. One example, picked from the paper making industry, is in the "open draw section" where strain rates of 2–3% per millisecond are present. Another example is in high velocity ballistic impact. In later years a new group of computational models have emerged which are suited for dynamic problems, called "hybrid particle element models" developed to deal with e.g. high velocity impact, cf. Fahrenthold and Horban (2001), Shivarama and Fahrenthold (2004) and Johnson et al. (2011). When modeling impact, much of the simulation time is consumed by the search for mechanical

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contact. If this is handled in a more efficient manner there is room for great improvement in computational speed.

The model derived here is a three dimensional representation of the mechanical behavior, and works for any type of network material, be it thick or thin, sparse or dense. It is well suited for several types of analyses, including; resonance, flexibility and various types of fracture behavior. Contacts are dealt with without the cumbersome search for contact, which greatly improves the computational speed and allow for analysis of very large systems and long sequence of events. The focus is on dynamical analyses, but it is also possible to do quasi-static analyses which could be of interest for large systems since the memory demand scales linearly to the number of structural components. Special attention is given to dynamic fracture of thin network materials. A special class of problems picked from the real world, paper-web break under uniaxial load, is tackled to exemplify how the model might be utilized. The fringing shown in Fig. 1 are typical results from a quasi-static response to uniaxial load. A crack then nucleates from a present flaw and as the crack rapidly grows, new fringes arise whilst the existing fringes remain. The last image in the sequence shows the complete fracture, i.e.when the material is unloaded and the fringes have disappeared.

2. Theory

2.1. Random fiber network

The materials that are in focus in this study are those consisting of fibers, initially randomly oriented in a thin structure and on the macroscopic scale considered being in-plane isotropic. Any matrix material is ignored. This is a good approximation for e.g. paper, non-woven felts and polyester textiles. Any shape of the fibers cross-section can be applied, but the fibers are here idealized to have square cross-sections with side length h. The model allows for forces and movement in three dimensions. To assure that the fibers are evenly distributed over the whole network domain A_n some precautions are added when generating the networks. As shown in Fig. 2, fiber segments reaching outside the domain's boundary are moved one side-length in a specified direction and are so located inside the network domain.

A random network is characterized by its connectivity $l_c/L = \pi A_n/[2NL^2]$, where L is the fiber length, l_c the average distance between two adjacent bonds along a fiber and N is the total number of fibers in the domain A_n. There is an upper limit of the connectivity, called the percolation limit, $l_c/L \approx 0.27$, meaning that with a length ratio l_c/L above this limit the network is not connected. In the limit $l_c/L \to 0$, a continuum is approached on the macroscopic scale.

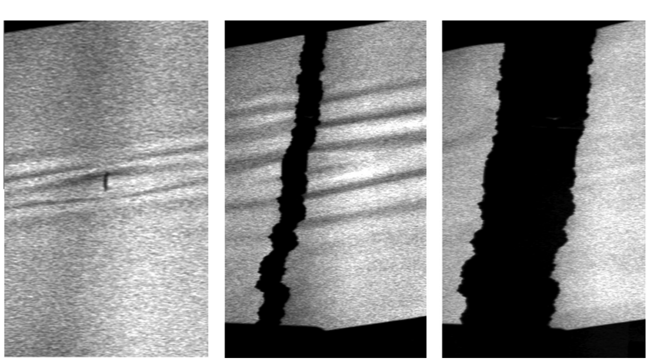

Fig. 1. Crack growth in a paper-web under uniaxial tension.

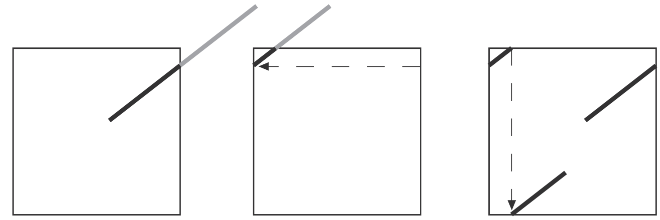

Fig. 2. Illustration of fiber modification to ensure that fiber and bond densities are similar over the network and have a periodic arrangement. The fiber is cut at the boundaries and the deserted part is moved one side-length and placed within the domain. This procedure is repeated until all fiber parts are located within the domain.

2.2. Particle representation

The end of each fiber segment is represented by a particle, with six degrees of freedom, three translational and three rotational, illustrated in Fig. 3. Let the deformation tensor ${}^l u_i$ be the change in orientation for particle l with original position r^0 and present position r such that ${}^l u_i = r_i - r_i^0$ (Fig. 3).

The particles are subjected to forces and move according to Newton's mechanics. Moreover, the particles have inertia and mass according to the fiber segments they represent. With reference to Fig. 4, particle k holds the mass and moment of inertia for the left segment part; particle l holds the mass and moment of inertia for the middle segment, while particle m holds the mass and moment of inertia for the right segment.

2.3. Fiber-to-fiber bonds

In the network generation process, each fiber is initially represented by two particles, one in each end. Wherever two fibers intersect, they form a bond and a new particle is added to each of the crossing fibers at that point. A bond, illustrated in Fig. 5, is a massless linear elastic spring having translational and torsional stiffness and vanishing thickness. The materials that are in focus have rigid bonds, compared to the rigidity of the fibers, therefore the spring in the bond is very stiff compared to the fibers in the network. For another material the bond may be computed in another fashion, such as freely rotating or to include slip–stick events, but this is left for future studies. The stiff connection results in small deformations of the bonds even when the bonds are translated and rotated in space. The governing equation for a bond is:

$$
{}^lF^b_i = -\frac{\partial \Pi^b}{\partial\, {}^l u_i}, \quad \Pi^b = \left[\frac{k^b_{ij}}{2}\, {}^l u_j ({}^l u_i - {}^m u_i)\right] \tag{1}
$$

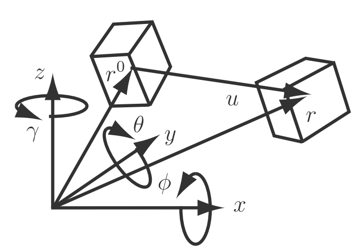

Fig. 3. A particle with six degrees of freedom is moved from position r^0 to position r in a fixed global Cartesian coordinate system.