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Large deformations induced in planar pantographic sheets by loads applied on fibers: Experimental validation of a discrete Lagrangian model

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ABSTRACT

In [1] a novel metamaterial has been designed and studied, whose performances include an enhanced toughness in extension: one of the problems to be solved in the further development of the concept involves the study of its deformation induced by loads concentrated on fibers (fiber pull-out test). A continuum model seems particularly unfit for the description of this kind of phenomena. As a consequence, in order to design a campaign of experimental tests we resorted to numerical simulations based on a novel Lagrangian, finite dimensional model for pantographic sheets. The developed code has the robustness features necessary to supply reliable predictions also in presence of very large deformations and, indeed, produces very accurate predictions. The agreement between the presented three-elastic-parameters discrete Lagrangian model and the numerous experimental measurements performed is very accurate. Therefore we are confident that, once we will have improved the model to include damage onset, it will be possible to describe also the rupture and final failure of planar pantographic sheets.

1. Introduction

To become mature for technological applications a new concept needs to be tested from a theoretical and experimental point of view. It is crucial in this process, which leads from the initial scientific elaboration to the final technological application, is the systematic theoretical, numerical and experimental study of all properties of the novel artifact, which one wants to transform into an engineering solution. Recently, (see for instance [1,2]) it has been proposed the design of a novel orthotropic metamaterial to which some exotic performances are requested: (i) it must have a large compliance toward large deformations, still remaining in the largest possible elastic domain; (ii) the ratio of its toughness to weight must be as low as possible; (iii) the ultimate toughness before failure in extension has to be extremely high.

Actually the class of proposed metamaterials, which have been named pantographic sheet or lattices, was conceived at the end of precisely directed mathematical investigations (which lasted several decades see *e.g.* [3–13]) whose aim was to prove the effective existence of materials which could be modeled as second gradient materials. Therefore the efforts were directed to prove the possibility to realize (or *synthesize*, as it is usual to say in some scientific milieux) a material whose continuum model, at a suitable large length-scale, was outside the allowable scope of first gradient (*i.e.* the so-called Cauchy) standard continuum mechanics, see [14]. Only recently these abstract investigations were proven to have a physical verification, as some results obtained using mathematical methods like, for instance, Gamma-convergence as in [15–18] or

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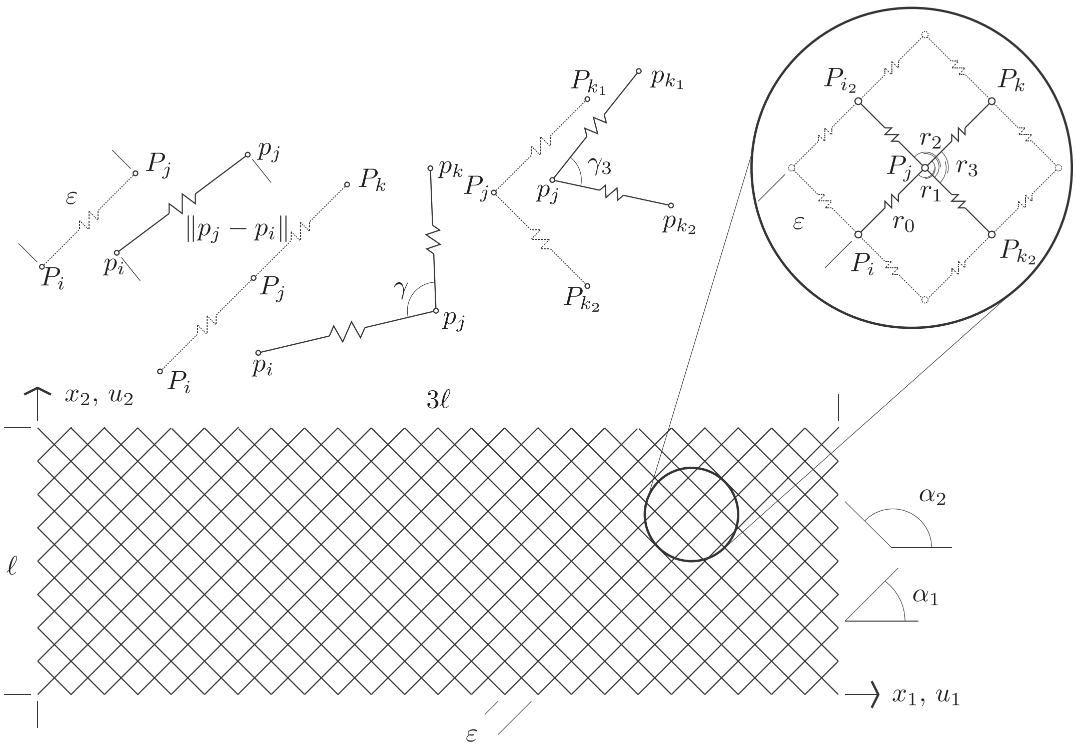

Fig. 1. Hencky-type pantographic structure.

more standard convergence methods as in [19] allowed for the design of real mechanical systems, which after some experimental investigations proved to have the expected properties, see *e.g.* [20–23].

The construction of the searched for micro-structures was made possible by the advent of more advanced 3D printing technologies. In particular, in [1] the actual feasibility and applicability of the concept leading to pantographic sheets seems to have been reasonably substantiated. One of the main problems which needs to be solved in the further development of the considered concept involves the study of the deformation of pantographic sheets induced by loads concentrated on fibers: this is what is called in the theory of composite fiber reinforcements the *fiber pull-out test*. The aware reader will immediately agree that a continuum model seems particularly unfit for describing this kind of phenomena, although it is known (see [24,25]) that second and higher gradient models are perfectly able to encompass boundary conditions including concentrated forces and imposed displacements at single points.

Therefore, in order to design a campaign of experimental tests, it has been considered more effective to resort to numerical simulations based on a novel Lagrangian, finite dimensional model for pantographic sheets [26]. In fact, the developed code has shown to have the robustness features which are necessary to supply, in a reasonable amount of time, reliable predictions also in presence of very large deformations and, indeed, it produces very accurate estimates of the reaction forces exerted by the applied hard devices. The agreement between the presented three-parameter discrete Lagrangian model (the reader will remark that we are avoiding proliferation of material parameters) and the numerous experimental

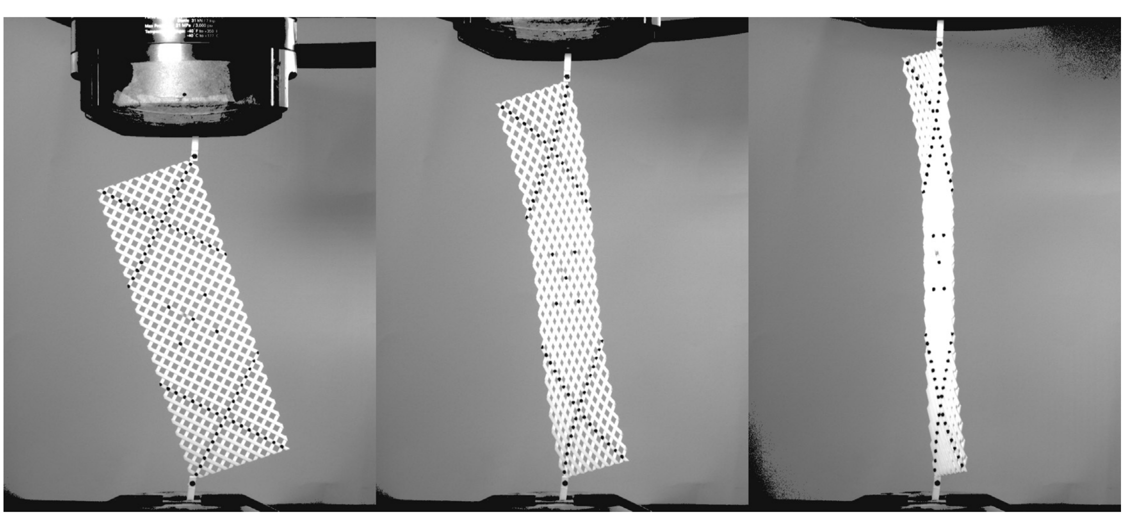

Fig. 2. T_1 test: initial (left), intermediate (middle) and final (right) configuration.