2D phase-field ductile fracture modeling in orthotropic paperboard materials

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Driven by growing online shopping habits and demand for recyclable packages, the global carton packaging market is rapidly expanding. In the case of food packaging, to match the more and more restrictive regulations on recyclability and waste reduction, carton packaging manufacturers have to use thinner and lighter weight grades of carton board, reducing at the same time the use of polymeric or aluminum coatings, without compromising safety and quality of the packaging. The combination of growing competition and more severe regulations is forcing the packaging companies to search for new designs and innovative solutions, where the structural behavior of the paperboard material plays a key role, since it provides the mechanical strength to the final product.

The present work is devoted to the phase-field simulation of crack propagation in paperboard. Paperboard is a strongly orthotropic material: Machine Direction (MD) and Cross-machine Direction (MD) are the in-plane directions, whereas ZD denotes the thickness direction. MD and CD mechanical properties are in general up to two orders of magnitude higher than in ZD. While large strains and damages are associated to out-of-plane deformations, in-plane fractures are usually associated to small strains. As an initial step towards the modeling of crack propagation in paperboard under arbitrary loading conditions, the present work is restricted to small-strain, in-plane crack propagation.

Very accurate orthotropic elastoplastic models for paperboard are available in the literature (see, e.g., [1, 2]). However, a reliable model for the description of coupled ductile elastoplastic and brittle damage mechanisms in paperboard is still missing. The objective of the present contribution is therefore to propose a phase-field model of in-plane (MD-CD) crack evolution in paperboard.

A variational, finite-step formulation for elastoplastic solids, based on a backward-Euler return mapping scheme, is taken as starting point for a variational formulation of ductile fracture. The energy functional is enriched with a phase-field damage-like variable and with its gradient, following the phase-field approach to brittle fracture. An AT1 model is used, guaranteeing in this way the presence of a purely elastoplastic regime in the material response. An effective stress description, with plasticity developing only in the continuous (undamaged) part of the material, is adopted. The damage activation criterion is modified by the addition of a non-variational term to account for the plasticity-driven nature of crack evolution and for the orthotropic behavior of paperboard. The purpose of this function, depending on a scalar measure of accumulated plastic strains, is to modulate the competition between plastic and fracture dissipation mechanisms in the crack nucleation phase and their interaction in the subsequent crack propagation. Unlike in standard approaches to orthotropic phase-field formulation, the orthotropic nature of the material is accounted for without considering an additional damage variable or introducing a structural tensor in the gradient damage term. Rather, the scalar measure of plastic evolution in the modulation function is chosen to depend in a different way on the plastic strains developed in the different material orthotropy directions.

The proposed model is validated against experimental results and its predictability is assessed. While only the application to paperboard has been studied, the model is general and the same approach could be considered for the modeling of other orthotropic elastoplastic materials.

References

[1] E. Borgqvist, M. Wallin, M. Ristinmaa, J. Tryding, An anisotropic in-plane and out-of-plane elasto-plastic continuum model for paperboard, Compos. Struct. , 126, 184-195.

[2] Y., Li, S. E., Stapleton, S., Reese, J. W., Simon, Anisotropic elastic-plastic deformation of paper: Out-of-plane model, Int. J. Solids and Struct. (2018), 130–131, 172–182.