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Local and nonlocal continuum modeling of inelastic periodic networks applied to stretching-dominated trusses

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Abstract

We present a nonlocal continuum model and its numerical implementation to describe the macroscale response of periodic discrete networks via second-order homogenization. The scale-bridging technique is applied to the specific example of stretching-dominated elastic and inelastic periodic truss networks. Experiments on small-scale truss structures have highlighted the importance of nodal connections on the effective stiffness and strength. Therefore, we describe the mechanics of trusses by accounting for the stretching of truss members and the deformation of nodes. For the representative 2D examples of lattices having square and triangular architectures and for example bar and nodal constitutive laws, we show that a simple continuum model based on affinely deforming a representative unit cell is sufficient to reproduce the nonlinear elastic behavior of discrete trusses. By contrast, localization that arises, e.g., from inelastic deformation requires a refined model. This is where the presented nonlocal continuum model is capable of accurately capturing details of localized deformation. We illustrate the performance of the model by comparing the results of example finite element simulations using the continuum constitutive model to discrete lattice calculations with elastic-plastic bars. Optimal performance is achieved when the representative unit cell of the continuum model agrees with the actual size of the discrete truss unit cell, which accounts for size effects even in regimes where a separation of scales between finite element size and unit cell size does not strictly apply.

Keywords: nonlocal model, elasticity, plasticity, homogenization, truss

1. Introduction

Over the past decade, the advent of micro- and nanoscale additive manufacturing techniques has revived the interest in accurately predicting the mechanics of truss structures across scales. Trusses have served as building blocks for hierarchical and periodic (meta-)materials with interesting effective properties resulting form the collective response of structural members across multiple scales. Examples include microtrusses (Schaedler et al., 2011a; Torrents et al., 2012) and nanotrusses (Meza et al., 2014), which can be tailored, e.g., for optimal stiffness and strength (Deshpande et al., 2001a; Meza et al., 2015), nonlinear stress-strain behavior (Fleck, 2001; Fan et al., 2009), fracture toughness (Romijn and Fleck, 2007; Fleck et al., 2010b), energy absorption (Wadley et al., 2008; Kumar, 2011), or acoustic wave propagation (Ruzzene and Scarpa, 2005; Gonella and Ruzzene, 2008; Krödel et al., 2014). Especially in the nonlinear elastic regime, the observed wide mechanical hysteresis (associated with plasticity or buckling of structural members) furnishes truss networks with high energy absorption and accommodates large reversible deformation at the nanoscale (Schaedler et al., 2011b; Meza et al., 2014). The mechanical performance of such architected materials is a function of the deformation mechanism, the relative density, and the constituent material properties, see, e.g., Fleck et al. (2010a); Hutchinson and Fleck (2006); Symons and Fleck (2008); Fleck and Qiu (2007); Jacobsen et al. (2007); Zheng et al. (2014); Valdevit et al. (2013) for recent studies.

The new opportunities to create such versatile materials systems also call for advanced modeling techniques, in particular since the number of individual truss members in micro- and nanotrusses can increase dramatically compared

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