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Stress-driven modeling of nonlocal thermoelastic behavior of nanobeams

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ABSTRACT

A consistent stress-driven nonlocal integral model for nonisothermal structural analysis of elastic nano- and microbeams is proposed. Most nonlocal models of literature are strain-driven and it was shown that such approaches can lead toward a number of difficulties. Following recent contributions within the isothermal setting, the developed model abandons the classical strain-driven methodology in favour of the modern stress-driven elasticity theory by G. Romano and R. Barretta. This effectively circumvents issues associated with strain-driven formulations. The new thermoelastic nonlocal integral model is proven to be equivalent to an adequate set of differential equations, accompanied by higher-order constitutive boundary conditions, when the special Helmholtz averaging kernel is adopted in the convolution. The example section provides several applications, thus enabling insight into performance of the formulation. Exact nonlocal solutions are established, detecting also new benchmarks for thermoelastic numerical analyses.

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1. Introduction

Research breakthroughs in nanotechnology over recent years have caused an increased interest in the mechanical behaviour of structures at nanoscale as well. Most commonly, sensors that measure forces or displacements are analysed. However, the mechanics of such structures fails outside usual macroscale mechanical principles. Origins of such behaviour are manifold. The structures at the nanoscale have discrete nature manifested in the form of atoms and interactions between atoms so that continuum mechanics can have limited success in describing discrete nanostructures. Furthermore, forces that are completely irrelevant at the macroscale, van der Waals forces for example, can dominate the nanoscale behaviour. As a consequence, size effects start to appear. The research community has been very active lately trying to capture this behaviour by accounting for the nonlocal nature of the phenomenon. Although such a claim can be made for the problems involving isothermal deformation processes, when the nonisothermal problems are concerned the results are not so numerous. For a short review of the existing nonisothermal models, see Canadija, Barretta, and Marotti de Sciarra (2016b) for statical and Zenkour, Abouelregal, Alnefaie, Abu-Hamdeh, and Aifantisb (2014) for dynamical problems.

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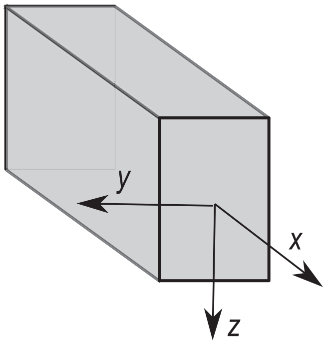

Fig. 1. Coordinate system of a Bernoulli–Euler nanobeam.

The existing methods are almost exclusively based on gradient methods and are applied to a variety of different problems, see Barretta, Canadija, and Marotti de Sciarra (2015), Sedighi (2014a), Simsek and Yurtcu (2013), Papargyri-Beskou, Tsepoura, Polyzos, and Beskos (2003), Romanoff, Reddy, and Jelovica (2016) and Sedighi (2014b) for a start. As a cornerstone of most approaches, the assumption that the strain gradient also contributes to the stress state in a point is utilized (Marotti de Sciarra & Barretta, 2014). To tune-up theoretical models to experimentally observed behaviour, the existence of the so-called nonlocal (small-size) constitutive parameter is postulated. However, the literature survey in Barretta, Brčić, Čanadija, Luciano, and Marotti de Sciarra (2017) shows surprisingly low number of results on determination of the nonlocal parameter obtained either by means of an experimental or a theoretical procedure. The latter paper also shows that nonlocal behaviour of the nanostructures do exists even in the case of harmonic interatomic potential and may be attributed to the discrete nature of the structure. Moreover, it demonstrates that the gradient methods have difficulties matching simulated bending of carbon nanotubes.

A gradient method, widely adopted to describe size-dependent phenomena in nanostructures, is based on Eringen differential model (EDM) associated with the strain-driven nonlocal integral theory conceived in Eringen (1983). As shown more than a decade ago (Peddieson, Buchanan, & McNitt, 2003), although nanosensors are usually designed as a cantilever nanobeam with a tip force and nonlocal effects are readily experimentally observed, EDM is not adequate to assess size effects. Elastic responses associated with EDM are technically unacceptable, as discussed in Challamel and Wang (2008), Challamel, Reddy, and Wang (2016), Fernández-Sáez, Zaera, Loya, and Reddy (2016), Eptaimeros, Koutsoumaris, and Tsamasphyros (2016) and Koutsoumaris, Eptaimeros, and Tsamasphyros (2016). Strain-driven nonlocal integral theory, introduced and successfully adopted by Eringen to study (in unbounded domains) screw dislocations and surface waves, is inapplicable to Structural Mechanics (Romano & Barretta, 2016).

This conclusion is due to the fact that the elastostatic problem of a continuous structure defined on a bounded domain, formulated by the strain-driven nonlocal integral model, admits no solution for all static schemes of engineering interest. Nonlocal (strain-driven) stress fields in bounded structural domains are indeed not included in the affine manifold of equilibrated stresses fields, as recognized in literature (Barati, 2017; Fathi & Ghassemi, 2017; Fernández-Sáez & Zaera, 2017; Karami, Shahsavari, Janghorban, & Li, 2018; Morassi, Fernández-Sáez, Zaera, & Loya, 2017; Sourki & Hosseini, 2017; Vila, Fernández-Sáez, & Zaera, 2017; Xu, Zheng, & Wang, 2017; Zhang, 2017; Zhu & Li, 2017; Zhu, Wang, & Dai, 2017) on the basis of the original contribution in Romano, Barretta, Diaco, and Marotti de Sciarra (2017). All difficulties can be overcome by resorting to the innovative stress-driven nonlocal integral theory recently proposed by Romano and Barretta (2017a). According to the stress-driven approach, the nonlocal elastic strain field is the convolution between the stress field and a suitable averaging kernel. Properties and merits of the stress-driven strategy in comparison with strain-driven formulations can be found in Romano and Barretta (2017b) and Romano, Barretta, and Diaco (2017). Transverse free vibrations of Bernoulli-Euler nanobeams are investigated in Apuzzo, Barretta, Luciano, Marotti de Sciarra, and Penna (2017) by stress-driven integral approach.

The research at hand aims to provide a well-posed nonlocal integral formulation of nanobeam mechanics in nonisothermal regime. It is assumed that the nanobeam can be described by Bernoulli-Euler kinematics. This kind of model has not been previously addressed in literature. The method presents an extension of the contributions presented in Romano and Barretta (2017a) and therefore can be categorized as a stress-driven model.

2. Kinematics of nonisothermal Bernoulli–Euler Beams

This section will introduce the notation and provide well-known governing equations that will serve as a starting point for the nonlocal integral formulation introduced in Section 4. In the subsequent analysis, a straight nanobeam made of the material with the coefficient of thermal expansion α is considered. The nanobeam's cross-section Ω is assumed to lay in the $y-z$ plane while the longitudinal axis is denoted with x, Fig. 1. The longitudinal axis x is assumed to pass through centroids of the cross-section. Due to the Bernoulli-Euler assumption, only normal stresses directed along x axis exist and

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