A Review on the Mechanical Behavior of Size-Dependent Beams and Plates using the Nonlocal Strain-Gradient Model

Tahereh Doroudgar Jorshari¹ and Mir Abbas Roudbari²,*

¹Faculty of Mechanical Engineering, Islamic Azad University, Takestan, Qazvin, Iran
²School of Engineering, RMIT University, PO Box 71, Bundoora, VIC, 3083, Australia

Article Info:

Keywords: Nonlocal strain-gradient continuum mechanics model, Mechanical loadings, Micro-/nano-beams/-plates.

Timeline:
Received: October 29, 2021
Accepted: November 30, 2021
Published: December 01, 2021

Citation: Jorshari TD, Roudbari MA. A Review on the Mechanical Behavior of Size-Dependent Beams and Plates using the Nonlocal Strain-Gradient Model. J Basic Appl Sci 2021; 17: 184-193

Abstract:

Nowadays, the mechanical characteristics of micro-/nano-structures in the various types of engineering disciplines are considered as remarkable criteria which may restrict the performance of small-scale structures in the reality for a certain application. This paper deals with a comprehensive review pertinent to using the nonlocal strain-gradient continuum mechanics model of size-dependent micro-/nano-beams/-plates. According to the non-classical features of materials, using size-dependent continuum mechanics theories is mandatory to investigate accurately the mechanical characteristics of the micro-/nano-structures. Recently, the number of researches related to the analysis of micro-/nano-structures with various geometry including beams as well as plates is considerable. In this regard, the mechanical behavior of these structures induced by different loadings such as vibration, wave propagation, and buckling behavior associated with the nonlocal strain-gradient continuum mechanics model is presented in this review work. Proposing the most valuable literature pertinent to the nonlocal strain-gradient continuum mechanics theory of micro-/nano-beams/plates is the main objective of this detailed survey.

DOI: https://doi.org/10.29169/1927-5129.2021.17.18

*Corresponding Author
E-mail: mir.abbas.roudbari@rmit.edu.au, m.a.roudbari@gmail.com

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1. INTRODUCTION

Micro-/nano-electromechanical systems (M/NEMS) have been growing in various engineering applications such as mechanical, structural, aerospace, biomedical, as well as electrical, in which their mechanical behavior investigation can be considered as a challenging problem in their modeling. Also, to design various micro-/nano-structures such as micro-/nano-beams as well as micro-/nano-plates, functional knowledge of their physical (mechanical, electrical, thermal, etc.) features is mandatory [1-3]. It is important to mention that after the discovery of novel manufacturing technologies pertinent to size-dependent components, the number of practical applications related to using micro/nano-structures in various disciplines of engineering problems was considerable [4-6]. Furthermore, there are so many examples that can be shown in the design of components of some smart devices or machines including spacecraft, submarines, medical devices, bio/nano-sensors, electrical circuits, and so on. Many approaches can be employed to model the size-dependent structures including molecular dynamics, density functional theory, and tight-binding molecular dynamic [7-9] (peculiar to atomistic simulation schemes), continuum mechanics models, or their combination. Besides, using classical and non-classical continuum mechanical models are easier to model micro-/nano-structures than the atomistic models.

Researchers employed various size-dependent methods such as the nonlocal elasticity of Eringen, the strain gradient theory, the modified couple stress model, the micromorphic theory, as well as the nonlocal-stress gradient (as a hybrid model) procedure [10-20] to introduce the differences between classical and non-classical models. Many researchers studied the mechanical behavior of micro-/nano-structures based on the non-classical continuum mechanics models induced by different types of loadings including vibration [21-32], wave propagation [33-43], and buckling phenomenon [44-54] associated with linear and nonlinear approaches related to the kinematic relations. According to their hypothesis as well as obtained results, various methods such as analytical, semi-analytical, as well as numerical schemes were proposed to investigate the static/dynamic characteristics of their models.

Recently, researchers decided to utilize nonlocal strain-gradient models of small-scale effects such as the nonlocal-stress gradient method. This method has the advantages of both the nonlocal and strain gradient models together. Some scientists proposed that employing the nonlocal elasticity and the strain gradient models can change the stiffness behavior of the micro/nano-structures drastically, in particular in some specific small-scale parameters. Therefore, using the nonlocal strain-gradient model size-dependent model gives a more realistic model at micro/nano-scale. In this regard, there are many advantages, drawbacks, and key applications pertinent to using the nonlocal-stress gradient size-dependent methods [55-60]. For example, this hybrid model contains both nonlocal and material length scale parameters and predict the stiffness-hardening influences using the length scale parameter [61-62]. Also, a nonlocal strain-gradient model is more accurate for modeling and analysis of micro/nano-structures using both stiffness reduction and enhancement influences [61-62]. Of course, for certain boundary conditions, the results are not accurate and correct. Moreover, some key applications of this theory are wave dispersion analysis of FGM, biological tissues, energy harvesting, M/NEMS cantilever actuators [24, 61-62].

There are several interesting papers in the literature pertinent to the review of micro/nano-structures [63-67]. It is significant to mention that the investigation of the important outcomes pertinent to the influences of the nonlocal-stress gradient size-dependent methods on various micro/nano-structures is the main motivation of this study as well as the major difference between the current review and published papers.

2. NONLOCAL STRAIN-GRADIENT CONTINUUM MECHANICS THEORY

Several procedures can be used in modelling small-scale structures such as molecular dynamics, density functional theory, as well as tight-binding MD [9,68], which are proposed as atomistic simulation models and continuum mechanics. Moreover, as it was mentioned, there are many size-dependent effects including strain gradient method, couple stress theory, and micromorphic model. Using the mentioned size-dependent effects can be relevant to the application of micro-/nano-structures in various engineering disciplines. Indeed, based on the softening or hardening behavior of material and proposed boundary conditions used in various small-scale structures such as Euler-Bernoulli, Rayleigh, Timoshenko, higher-order beam theories as well as plate models, nonlocal Eringen, couple stress, strain-gradient, and micromorphic theories can be employed.
Based on the above-mentioned, using a suitable size-dependent model is significant to scrutinize the mechanical characteristics of micro-/nano-structures at micro-/nano-sized scales. The nonlocal strain-gradient method has been utilized to investigate the nonlocal and strain gradient models, simultaneously. Using the higher-order theory by Lim et al. [69], the internal energy density potential \( U_{ss}(\varepsilon_{ij}, \varepsilon'_{ij}, \varepsilon_{a}) \) within the domain \( V \) can be given as follows:

\[
U_{ss}(\varepsilon_{ij}, \varepsilon'_{ij}, \varepsilon_{a}) = \frac{1}{2} \varepsilon_{ij} C_{ijkl} \int_{V} \alpha_{l}(x-x'), \varepsilon_{a} \varepsilon'_{l} dV \\
+ \frac{l^{2}}{2} \varepsilon_{ij} C_{ijkl} \int_{V} \alpha_{l}(x-x'), \varepsilon_{a} \varepsilon'_{l} dV,
\]

where \( \varepsilon_{a}, \varepsilon_{a}, C_{ijkl}, l \) are the small-scale parameters, elastic modulus tensor, and material length scale parameter, respectively. Moreover, \( \alpha_{l}(x-x'), \varepsilon_{a} \) and \( \alpha_{l}(x-x'), \varepsilon_{a} \) are the nonlocal attenuation kernel functions and is the volume of the model. Furthermore, \( \varepsilon_{ij} \) and \( \varepsilon'_{ij} \) are the Cartesian terms of the strain tensors. The total stress tensor will be proposed as follows:

\[
\tau_{ss} = \sigma_{ss} - \frac{d \sigma_{ss}}{dx},
\]

where \( \sigma_{ss} \) and \( \sigma_{ss} \) are the classical and higher-order stresses, respectively. Based on Lim’s theory, the final constitutive equation of the nonlocal strain-gradient model can be proposed as [69-79]:

\[
\left(1-(ea)^{2} \nabla^{2}\right) \varepsilon_{ss} = E \left(1-(l)^{2} \nabla^{2}\right) \varepsilon_{ss}.
\]

in which \( E \), \( \tau_{ss} \), \( \varepsilon_{ss} \) are the elasticity modulus, the stress, and strain counterparts, respectively.

### 2.1. Static Bending and Buckling

In recent years, the investigation of linear and nonlinear bending, as well as buckling of micro/nano-structures based on the nonlocal strain-gradient method was carried out by some researchers. Many studies proposed analytical approaches to scrutinize their linear bending behavior. Lu et al. [76] studied the investigation of a nonlocal strain-gradient theory related to the micro-/nano-beams with consideration of the importance of higher-order terms using Euler–Bernoulli as well as Timoshenko beam models. Based on Hamilton’s principle and the relevant boundary conditions, the relations were obtained. The effects of the nonlocal strain-gradient theory on the bending characteristics of the sandwich porous nanoplate using piezomagnetic face sheets as well as the first-order shear deformation model were proposed by Arefi et al. [77]. They used the power-law function to scrutinize changing the porosity along with the direction of thickness encapsulated by the Pasternak medium. Allam and Radwan [81] investigated the nonlocal strain-gradient model of bending as well as buckling of the FG curved micro-/nano-beam on an elastic foundation with viscoelastic effects and different boundary conditions. They employed the two power-law models to show any changes in material features associated with viscoelastic FG curved micro-/nano-beam. Xu et al. [82] proposed the bending and buckling characteristics of the micro-/nano-beams using the nonlocal strain-gradient elastic model. They proved that using the higher-order boundary conditions leads to having no significant effect on the bending deflection of the micro-/nano-beam.

Barretta et al. [83] examined the boundary conditions effects on nonlocal strain-gradient micro-/nano-beams. They indicated equivalence between a differential model as well as the nonlocal strain-gradient integral scheme using the proposed constitutive boundary conditions. Gao et al. [84] investigated nonlinear static bending characteristics of an FG porous micro-/nano-beams using physical fields and the nonlocal strain-gradient theory. They obtained the nonlinear relations using Hamilton’s method. Beddia et al. [85] proposed a new hyperbolic in conjunction with two-unknown micro-/nano-beam related to buckling and bending characteristics with consideration of the nonlocal strain-gradient theory. They utilized Navier’s solution for the governing equations to solve them analytically based on the S-S boundary condition. Besides, several authors employed discretization methods to investigate the buckling as well as post-buckling characteristics of the micro-/nano-structures. Farajpour et al. [86] proposed the nonlocal strain-gradient theory for buckling behavior of an orthotropic micro-/nano-plate induced by the thermal environment. Based on the DQM procedure the equations were examined and solved. Bending/buckling/vibration characteristics of axially FG micro-/nano-beams with consideration of the nonlocal strain-gradient as well as Euler–Bernoulli beam theories were proposed by Li et al. [87]. According to the through-length grading model of the FG material, the mechanical behavior was investigated. Also, the buckling load, deflection, and frequency values were controlled with appropriate amounts of the power-law index.
Moreover, numerical procedures were employed by researchers to scrutinize the nonlinear behavior of buckling, as well as post-buckling of micro-/nano-structures. Post-buckling, as well as bending behavior of nano-beams using nonlocal strain-gradient model based on the nonlinear influences, were carried out by Zhong et al. [88]. They scrutinized the multi-scale method of the Euler Bernoulli nano-beam based on the long deflection model. Li and Hu [89] studied the post-buckling features of FG nano-beams using nonlocal stress/strain gradient models with consideration of the nonlinear geometric associated with von Kármán theory. They used the physical neutral surface for removing the proposed coupling between bending/stretching associated with geometric nonlinearity related to the FG micro-/nano-structure. Mao and Zhang [90] investigated the buckling and post-buckling characteristics of FG graphene reinforced piezoelectric micro-/nano-plate using axial forces and the electric potential. They utilized the Halpin-Tsai parallel method to obtain the effective Young’s modulus pertinent to each layer. They indicated that graphene platelet has an interesting influence on the buckling and post-buckling strength associated with the FG piezoelectric micro-/nano-plate.

2.2. Vibration and Wave Propagation

The following researches indicate the proposed works related to the linear and nonlinear free/forced vibration as well as wave propagation of the micro-/nano-structures.

Roudbari and Ansari [80] analyzed the physical characteristics of SWBNNT as a bio-/nano-sensor due to sensing attached micro-/nanoscale objects. Based on the various boundary conditions including SS-SS, C-C, and C-F, the vibrational characteristics of the model were examined. They used Rayleigh and Timoshenko beam models in their study. Furthermore, the nonlocal strain-gradient method was employed to show the size-dependent influences. Also, numerical methods were employed to investigate the mechanical properties of size-dependent structures. Figure 1a-c show the influences of the dimensionless amounts of the mass weight of attached nanoparticles on the relative frequency shift values. It was obvious that relative frequency shift values increase with an increase in the amounts of mass weight of attached nanoparticles, which was correct for nonlocal strain-gradient RBT and TBT. Moreover, the results of nonlocal strain-gradient TBT track the outputs of nonlocal strain-gradient RBT for all magnitudes of mass weight of the attached nanoparticle. Also, the discrepancy between the obtained relative frequency shift values for nonlocal strain-gradient RBT and TBT was observable in higher values of the mass weight of the attached nanoparticle. Furthermore, the C-C boundary condition had higher values than other case studies.

They also obtained the predicted first four dimensionless flexural frequencies of zigzag (7,0) form SWBNNT as a bio-/nano-mass sensor which is provided in Table 1. Their obtained results were pertinent to S-S, bridged and cantilever types of boundary conditions and also nonlocal strain-gradient RBT and TBT models. It was clear that the C-F boundary condition case study had lower values of dimensionless flexural frequencies than other types of boundary conditions.

Figure 1: (a-c). The influences of the dimensionless amounts of the mass weight of attached nanoparticles on the relative frequency shift values.
Nonlinear vibration behavior of bi-directional FG micro-/nano-beams with consideration of the nonlocal stress as well as micro-structural strain gradient effects was examined by Sahmani and Safaei [91]. They utilized GDQM as well as Galerkin procedures and also pseudo-arc-length continuation schemes to solve the proposed relations of motions. They studied the nonlocal strain-gradient of 2D FGM against different magnitudes with the nonlinear dynamic response of the axial material characteristics. Ghayesh et al. [92] investigated the coupled dynamics pertinent to nanofluid-conveying micro/nanotubes. Using the Beskok–Karniadakis model, the size-dependent influences of the nanofluid were proposed. Likewise, they used Coriolis acceleration effects based on the influences of the centrifugal acceleration. At a specific speed of nanofluid, the coupled bifurcation variation of the nanofluid-conveying micro/nanotubes was examined. Roodgar Saffari et al. [24] worked on the vibration behavior of fluid conveying SWCNT surrounded by a visco-Pasternak substrate with nonlinearity effects using the nonlocal strain-gradient model. They indicated that the size-dependent parameters have considerable effects on the dynamic behavior of the proposed model. The effect of variation of eigenvalue by velocity for different values of Winkler and damping parameters were illustrated in Figure 2. The real part (damping ratio) curve did not change at lower values of fluid speed but divergence at higher values of fluid speed. Also, by increasing damping parameters, total damping of the system increased, the imaginary part and the critical values of speed decreased. Also, the real part increased and divergence at lower values of fluid speed.

Barati et al. [61] worked on the forced vibration characteristics of the heterogeneous porous FG micro-/nano-plates using the nonlocal stress-strain gradient theory. He examined the effects of the stiffness-softening/hardening behavior to scrutinize the mechanical features of the proposed model. Roudbari and Doroudgar Jorshari [93] analyzed the control behavior of SWCNT acted upon by a moving nanoparticle using the nonlocal strain-gradient as well as the Rayleigh beam theories with consideration of thermal and magnetic influences. They proved that the PZT patches as bio/nano-sensors can be connected to a charge amplifier for actuating the SWCNT which can be shown in Figure 3.

Wu et al. [94] proposed forced vibration behavior of FG graphene platelet-reinforced nanocomposite micro-/nano-beams based on the nonlocal strain-gradient
theory as well as the refined hyperbolic shear deformation beam procedure. The material features of laminated FG graphene platelet-reinforced nanocomposite micro-/nano-beams were obtained using the Halpin–Tsai method. Mahmoudpour [95] reported the nonlinear resonant behavior of a thick multi-layered nano-plate using the nonlocal strain-gradient model and the first-order shear deformation plate theory. The interactional vdW forces between the proposed adjacent layers of the nano-plate were considered. Vahidi-Moghaddam et al. [96] examined the nonlinear characteristics of forced vibration of the micro-/nano-beam using the nonlocal strain-gradient theory and the Euler-Bernoulli beam model for C-C boundary conditions. A reduced motion equation based on the central harmonic load as well as the Galerkin procedure was proposed.

Several works related to the analytical methods for the elastic wave propagation of the micro-/nano-structures have been carried out. Wave propagation behavior of the visco-elastic SWCNT using the nonlocal strain-gradient model was reported by Tang et al. [97]. They indicated that the blocking diameter value was related to the damping ratio, Winkler modulus, and the nonlocal strain-gradient scale parameters. The wave propagation characteristics of micro-/nano-beams for the Timoshenko beam model with consideration of the nonlocal strain-gradient theory were analyzed by Norouzzadeh et al. [98]. They showed that the classical beam model underestimates and overestimates the wave frequency values for without as well as with consideration of the nonlocal parameter, respectively.

On the other hand, discretization procedures were employed to show the mechanical characteristics of the elastic wave propagation responses with nonlinear effects of the micro-/nano-structures. Ebrahimi et al. [62] examined wave propagation of the FG nano-plates with consideration of the inhomogeneous effects and the nonlinear thermal influences based on the nonlocal strain-gradient model. Nonlinear modelling of the flexural wave propagation using the nonlocal strain-gradient scheme related to the Euler-Bernoulli and Timoshenko beam models was investigated by Huang et al. [99]. Also, Huang and Wei [100] worked on the flexural wave propagation modelling of the infinite micro-/nano-plate with consideration of the homogeneous effects and fractional nonlocal strain-gradient model. They employed the spatial and

Figure 2: Effect of variation of eigenvalue by velocity for different value of Winkler and damping parameter.

Figure 3: The PZT patches as sensors connected to charge amplifiers to actuate the SWCNT induced by a moving nanoparticle.
temporal fractional differential to indicate the spatial nonlocal and the history-dependent characteristics pertinent to the thermoelastic features of the micro-/nano-structures.

3. CONCLUSION

A comprehensive survey of the nonlocal strain-gradient continuum mechanics model pertinent to the micro-/nano-beams and -plates were examined. The proposed parts of this review are based on the nonlocal strain-gradient theory to show the size-dependent influences with consideration of different external loading including bending, buckling, vibration, and wave propagation. The recently published papers pertinent to using small-scale methods for micro-and nano-structures are considerable; thus, the current review is aimed to work on the proposed small-scale method employed in various beams and plates with different geometrical and physical parameters. Hope the present review help researchers to address the advantages, limitations, and deficiencies of using this procedure in the modelling of small-scale structures.

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