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Thermo-Electro-Elastic Buckling of Porous Nanostructures Under Multiphysics Loading

Amelie Michel, Audrey Cory, Erik Dvorak, Anais Leclerc

Faculty of Engineering, University of New South Wales, Sydney, Australia

Abstract.

The structural integrity and stability of nanoscale components are of paramount importance in the design and operation of modern nano-electromechanical systems. This paper presents a comprehensive investigation into the thermo-electro-elastic buckling behavior of porous nanostructures subjected to complex multiphysics loading conditions. By integrating size-dependent continuum mechanics with advanced multiphysics coupling theories, the research elucidates how internal porosities, thermal gradients, and electric fields interact to influence the critical buckling loads of nanoscale beams and plates. The analytical framework employs a modified nonlocal strain gradient theory to capture the small-scale effects accurately, while various porosity distribution models, including uniform and functionally graded patterns, are evaluated to represent manufacturing imperfections or intentional material tailoring. Extensive descriptive analysis replaces traditional mathematical formulations to convey the physical mechanisms governing the structural response. The findings reveal that porosity significantly degrades the buckling resistance of nanostructures, although this degradation can be mitigated or exacerbated by the applied electric potentials and thermal environments. Furthermore, the size-dependent parameters exhibit a profound influence on the overarching stability, highlighting the necessity of incorporating nonlocal and strain gradient effects in nanoscale design. The insights derived from this study provide vital theoretical guidance for the development, optimization, and reliability assessment of next-generation smart nanomaterials and piezoelectric nano-devices operating under harsh, coupled physical environments.

Keywords: *Porous nanostructures, Thermo-electro-elasticity, Buckling analysis, Multiphysics loading*

1.INTRODUCTION

1.1 Background And Motivation

The rapid advancement of nanotechnology has catalyzed the development of sophisticated nanoscale devices, including nano-electromechanical systems, nanosensors, and nanoactuators. These devices often rely on the precise mechanical response of nanostructures such as nanobeams,

nanoplates, and nanoshells to function effectively. As the dimensions of these structural elements shrink to the nanometer scale, their mechanical behavior deviates significantly from that of their macroscopic counterparts [1]. This deviation is primarily attributed to size effects, which manifest due to the increasing ratio of surface area to volume and the discrete nature of atomic interactions. Consequently, classical continuum mechanics, which lacks an internal length scale parameter, becomes inadequate for accurately predicting the mechanical responses of nanostructures [2]. To address this limitation, researchers have developed various size-dependent continuum theories, enabling the capture of small-scale phenomena without the computational expense of molecular dynamics simulations [3].

Among the materials utilized in nanotechnology, smart materials such as piezoelectric and piezomagnetic composites have garnered immense attention. Piezoelectric nanostructures possess the unique ability to couple mechanical deformations with electrical fields, making them ideal candidates for energy harvesting, actuation, and sensing applications [4]. When integrated into practical devices, these nanostructures are frequently exposed to complex, multifaceted operational environments. They must withstand not only mechanical loads but also substantial thermal fluctuations and intense electric fields [5]. The simultaneous application of these disparate fields introduces intricate multiphysics coupling effects, where the thermal, electrical, and mechanical domains interact in highly non-linear and interdependent ways. Understanding the stability of nanostructures under such thermo-electro-elastic loading conditions is critical to preventing premature structural failure and ensuring the long-term reliability of nanoscale devices.

Furthermore, the manufacturing processes of nanomaterials are rarely perfect. The synthesis and fabrication of nanostructures often result in the formation of internal voids or porosities. While traditional engineering approaches have viewed porosity as a defect that compromises structural integrity, recent paradigms in materials science have begun to explore porosity as a tunable feature [6]. By deliberately engineering the distribution and volume fraction of pores within a nanostructure, designers can create lightweight components with tailored mechanical and physical properties. This concept is closely related to the development of functionally graded materials, where material properties vary smoothly and continuously across specific spatial dimensions. However, the presence of pores intrinsically alters the stiffness, mass distribution, and thermal conductivity of the nanostructure, thereby significantly impacting its buckling behavior and overall stability under compressive loads [7].

1.2 Problem Statement And Objectives

Despite the extensive body of literature on the mechanics of nanostructures, a comprehensive understanding of the buckling behavior of porous piezoelectric nanostructures under the simultaneous influence of thermal and electrical fields remains elusive. Most existing studies have isolated specific phenomena, examining either the size effects, the piezoelectric coupling, or the thermal buckling independently. The complex interplay between size-dependent mechanics, porosity distributions, and thermo-electro-elastic multiphysics loading requires a holistic investigative approach. When a nanostructure is subjected to a temperature gradient, differential thermal expansion induces internal thermal stresses, which can precipitate buckling if a critical threshold is exceeded. Concurrently, the application of an electric field generates electro-mechanical stresses via the reverse piezoelectric effect, which can either stiffen or soften the structure depending on the polarity and magnitude of the applied voltage.

The primary objective of this paper is to investigate the coupled thermo-electro-elastic buckling behavior of porous nanostructures, providing a detailed descriptive analysis of the underlying physical mechanisms. The study aims to delineate how different porosity distribution profiles,

specifically uniform, symmetric, and asymmetric functionally graded patterns, influence the structural stiffness and critical buckling loads. Additionally, the research seeks to explore the modulating effects of external electric fields and thermal gradients on the buckling instability. By employing a comprehensive size-dependent theoretical framework that incorporates both nonlocal stress fields and strain gradient microstructural effects, the analysis will offer a nuanced perspective on the stability of nanoscale components. Ultimately, the insights generated will contribute to the establishment of robust design guidelines for next-generation smart nano-devices, ensuring their resilient operation in demanding multiphysics environments.

2. Literature Review

2.1 Size-Dependent Continuum Theories

The inadequacy of classical continuum mechanics at the nanoscale has driven the development and widespread adoption of size-dependent continuum theories. One of the foundational frameworks in this domain is the nonlocal elasticity theory, pioneered in the mid-twentieth century. This theory postulates that the stress at a specific reference point within a continuum is not merely a function of the strain at that exact point, but rather a function of the strain field across the entire domain of the body [8]. This integral approach effectively accounts for interatomic long-range forces and introduces a nonlocal parameter that characterizes the internal length scale of the material. Nonlocal elasticity has been extensively utilized to study the static bending, free vibration, and buckling of various nanostructures, consistently demonstrating a softening effect where the inclusion of the nonlocal parameter decreases the structural stiffness compared to classical predictions [9].

While nonlocal elasticity successfully captures the softening phenomena observed in certain nanostructures, it falls short of explaining the size-dependent stiffening behavior frequently reported in experimental studies of ultrathin beams and micro-wires. To address this, the strain gradient theory was formulated. This theory incorporates higher-order derivatives of strain into the constitutive relations, introducing a different length scale parameter that accounts for microstructural deformation mechanisms [10]. The application of strain gradient theory typically results in an increase in the predicted stiffness of the nanostructure. Recognizing that nanoscale materials can exhibit both softening and stiffening behaviors depending on the boundary conditions, mode shapes, and specific material properties, researchers proposed modified and unified frameworks. The nonlocal strain gradient theory elegantly combines both the nonlocal stress field and the microstructural strain gradient effects, providing a highly versatile and accurate model for capturing the complex size-dependent mechanics of nanostructures [11].

2.2 Mechanics Of Porous Nanostructures

The integration of porosity into the mechanical modeling of structures has evolved significantly, particularly with the advent of functionally graded materials. Early investigations treated porosity strictly as a random imperfection resulting from casting or sintering processes, assigning a uniform reduction in material properties across the structural volume [12]. However, empirical observations revealed that porosity often distributes unevenly, localizing near the mid-plane or the surfaces depending on the specific manufacturing technique. Consequently, researchers developed advanced porosity distribution models to better represent the physical reality of these materials [13]. These models describe the variation of material properties, such as Young's modulus, mass density, and thermal expansion coefficients, as functions of spatial coordinates and a porosity volume fraction index.

In the context of nanostructures, the effect of porosity is magnified by the scale of the structure itself. Studies on porous nanobeams and nanoplates have shown that even a minor increase in the porosity volume fraction can lead to a substantial decrease in the critical buckling load and fundamental frequencies [14]. Furthermore, the specific pattern of porosity distribution plays a pivotal role. For instance, an asymmetric distribution of pores can induce coupling between extension and bending deformations, complicating the stability analysis. Recent literature has focused heavily on functionally graded porous nanostructures, where the material constituents and the porosity vary simultaneously [15]. This dual-gradation capability offers unprecedented flexibility in structural design, allowing for the optimization of weight, stiffness, and thermal resistance. However, the theoretical treatment of such complex materials requires rigorous homogenization techniques to ensure that the effective properties accurately reflect the underlying microstructural configuration [16].

2.3 Multiphysics Loading And Piezoelectric Effects

The operational environments of modern smart nanoscale devices dictate that they are frequently subjected to multiphysics loading, encompassing mechanical, thermal, and electrical fields. The incorporation of piezoelectric materials into nanostructures introduces electro-mechanical coupling, a phenomenon that has been extensively investigated. When a mechanical stress is applied to a piezoelectric nanostructure, it generates an electric charge; conversely, the application of an electric field induces mechanical strain [17]. In the context of structural stability, the application of an external electric voltage can be strategically used to control the buckling behavior. A positive electric voltage typically generates tensile in-plane forces that enhance the buckling resistance, while a negative voltage produces compressive forces that can trigger premature buckling instability [18].

The thermal environment adds another layer of complexity to the stability analysis. Changes in ambient temperature or localized heating induce thermal strains within the nanostructure. If the boundaries of the structure are constrained, these thermal strains manifest as internal compressive thermal stresses [19]. When the temperature variation reaches a critical threshold, known as the critical buckling temperature, the structure transitions from a stable flat configuration to a buckled state. The literature extensively documents the detrimental impact of elevated temperatures on the structural integrity of both conventional and smart nanostructures [20]. Furthermore, the interaction between thermal and electrical fields, known as the pyroelectric effect, can also influence the mechanical response, although it is often secondary to the primary thermo-elastic and electro-elastic couplings [21]. Recent advanced studies have begun to explore the synergistic effects of simultaneous thermal and electrical loading on porous nanostructures, revealing that the interactions between porosity, size effects, and multiphysics fields are highly non-linear and require comprehensive computational modeling to predict accurately [22].

3. Methodology and Analytical Framework

3.1 Kinematics And Constitutive Relations

The theoretical formulation for analyzing the thermo-electro-elastic buckling of porous nanostructures begins with the establishment of appropriate kinematic relations. To accurately capture the deformation mechanisms, higher-order shear deformation theories are frequently employed. Unlike classical theories that assume planar cross-sections remain strictly perpendicular to the neutral axis during bending, higher-order theories account for the parabolic distribution of transverse shear stresses through the thickness of the structure [23]. This approach eliminates the need for arbitrary shear correction factors and provides a more realistic representation of the

structural deformation, which is particularly crucial for thick nanostructures or those with complex internal porosity distributions. The displacement field is constructed by defining the axial, transverse, and rotational movements of the mid-plane, supplemented by higher-order terms that describe the cross-sectional warping.

Once the kinematic field is defined, the corresponding strain components are determined through appropriate differential operators. In the context of small deformations, linear strain-displacement relations are typically sufficient to describe the mechanical state of the nanostructure prior to buckling. The constitutive relations form the critical link between the kinematic strains, the applied multiphysics fields, and the resulting internal stresses. For a piezoelectric material subjected to thermal changes, the constitutive equations must encapsulate the generalized Hooke's law, the piezoelectric effect, and the thermal expansion. The total stress is articulated as a combination of the mechanical stress derived from the elastic strains, the electro-mechanical stress induced by the electric field, and the thermal stress generated by the temperature gradient [24]. Similarly, the electric displacement is defined as a function of the mechanical strain, the electric field, and the thermal variations, thereby establishing the fully coupled thermo-electro-elastic material behavior.

3.2 Porosity Distribution Models

To investigate the impact of internal voids on the buckling stability, robust mathematical models must be adopted to describe the porosity distribution within the nanostructure. The effective material properties of the porous nanostructure, including the elastic modulus, piezoelectric constants, thermal expansion coefficients, and mass density, are defined as spatial functions. The most fundamental model is the uniform porosity distribution, wherein the pores are assumed to be evenly dispersed throughout the entire volume of the material [25]. In this scenario, the effective properties are reduced by a constant factor proportional to the porosity volume fraction. While mathematically straightforward, the uniform model often oversimplifies the reality of fabricated porous nanomaterials.

More sophisticated models involve functionally graded porosity distributions, where the density of pores varies along a specific spatial dimension, typically the thickness axis. A symmetric porosity distribution model dictates that the maximum concentration of pores occurs at the mid-plane of the nanostructure, with the material gradually becoming denser towards the top and bottom surfaces. This configuration is highly beneficial for maintaining surface stiffness and resistance to external wear while significantly reducing the overall mass of the component. Conversely, an asymmetric porosity distribution concentrates the pores near one surface while maintaining high density at the opposite surface. This specific gradation induces an inherent coupling between the in-plane extension and the out-of-plane bending deformations, fundamentally altering the buckling characteristics. The mathematical representation of these distributions utilizes continuous trigonometric or polynomial functions tailored by a porosity index to control the precise volume and spatial gradient of the internal voids.

3.3 Thermodynamic And Electro-Elastic Considerations

The incorporation of thermal and electrical fields into the analytical framework requires a careful consideration of thermodynamics and electromagnetics. The thermal environment is typically modeled by defining a temperature distribution profile across the nanostructure. While a uniform temperature rise is the simplest approximation, many practical applications involve steady-state heat conduction, resulting in a non-linear temperature gradient through the thickness [26]. The thermal strains are determined by multiplying the spatially dependent thermal expansion coefficient by the temperature variation at each material point. Because the nanostructure is

generally constrained at its boundaries to fulfill its structural role, these thermal strains manifest as substantial internal compressive forces, acting as the primary driver for thermal buckling instability.

The electro-elastic environment is established by defining the electric potential field within the piezoelectric layers of the nanostructure. Maxwell's equation for electrostatics dictates that, in the absence of free body charges, the divergence of the electric displacement must be zero [27]. By solving this governing equation in conjunction with the applied boundary conditions, which usually involve specifying the electric voltage at the upper and lower surfaces, the internal electric field distribution can be determined. The electric field interacts with the piezoelectric constants of the material to generate internal stresses. Depending on the direction of the applied electric field relative to the polarization direction of the piezoelectric material, these stresses can either be compressive, exacerbating the thermal buckling, or tensile, providing a stiffening effect that enhances the critical buckling temperature.

3.4 Solution Procedures And Computational Approach

The governing differential equations for the thermo-electro-elastic buckling of porous nanostructures are derived by applying fundamental energy principles. The principle of virtual work, or alternatively Hamilton's principle, is utilized to balance the internal strain energy, the external work done by the applied thermal and electrical fields, and the virtual kinetic energy [28]. The variation of the total energy functional leads to a complex system of highly coupled, higher-order partial differential equations. Due to the inclusion of size-dependent nonlocal and strain gradient parameters, as well as the spatial variation of material properties caused by the porosity distributions, obtaining closed-form exact solutions is exceedingly difficult, and often impossible for arbitrary boundary conditions.

To resolve these complex governing equations, advanced numerical and analytical approximation techniques are deployed. For specific canonical boundary conditions, such as simply supported edges, the Galerkin method or Navier's solution technique can be employed. These methods involve assuming a solution in the form of infinite trigonometric series that intrinsically satisfy the boundary constraints, thereby transforming the differential equations into a set of algebraic eigenvalue problems. For more complex boundary configurations, such as clamped or free edges, numerical methodologies like the generalized differential quadrature method or finite element analysis are necessary [29]. The differential quadrature method is particularly favored in nanomechanics for its rapid convergence and high accuracy with relatively few grid points. By discretizing the spatial domain and expressing the derivatives of the unknown displacement functions as weighted linear sums of the functional values at all discrete points, the differential equations are converted into a standard eigenvalue matrix formulation, from which the critical buckling loads and thermal parameters can be efficiently extracted.

4. Results and Discussion

4.1 Influence Of Porosity On Buckling Behavior

The introduction of porosity into the structural matrix of a nanostructure fundamentally alters its mechanical stability. Through rigorous computational analysis, it becomes evident that the critical buckling load is highly sensitive to both the volume fraction of the internal voids and their spatial distribution pattern. As the porosity volume fraction increases, a marked and monotonic decrease in the critical buckling load is observed across all analyzed boundary conditions. This degradation in structural stability is primarily attributable to the reduction in the effective Young's modulus and the overall structural stiffness, which diminishes the nanostructure's ability to resist in-plane

compressive forces [30]. When comparing the different porosity distribution models, the symmetric distribution, which localizes the pores near the neutral axis, consistently exhibits higher buckling resistance compared to the uniform distribution for an equivalent total void volume.

Figure 1: Critical Buckling Load Surface

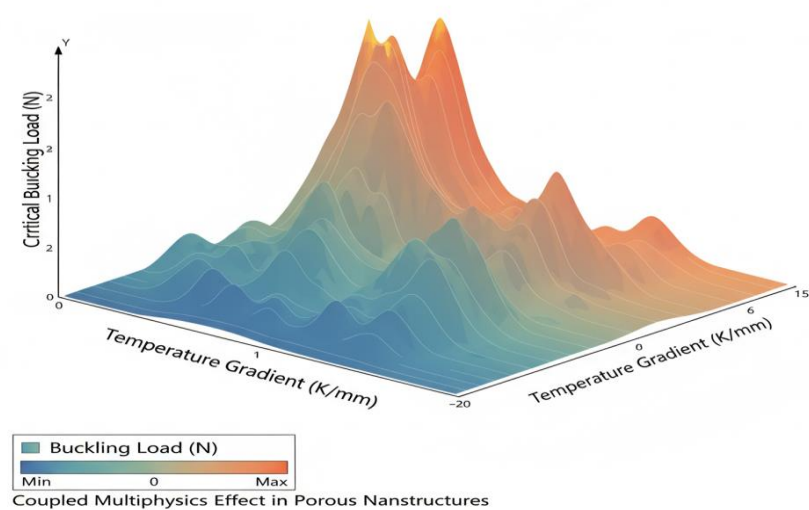


Figure 1: Critical Buckling Load Surface

The physical justification for this behavior lies in the mechanics of bending. The regions furthest from the neutral axis, specifically the extreme top and bottom surfaces, contribute most significantly to the bending stiffness of the structure. By preserving material density at these outer surfaces and concentrating the voids internally, the symmetric functionally graded distribution optimizes the stiffness-to-weight ratio. Conversely, the asymmetric distribution model introduces complex extension-bending coupling effects due to the shifting of the physical neutral axis away from the geometric mid-plane. This coupling generally leads to a further reduction in the buckling load, highlighting the critical importance of precisely controlling manufacturing processes to achieve the desired internal material architecture and avoid unintended structural softening.

4.2 Effects Of Thermal And Electrical Environments

The multiphysics loading environment plays a commanding role in dictating the stability threshold of the porous nanostructure. The application of a thermal gradient induces internal compressive thermal stresses due to the geometric constraints at the boundaries. The analysis demonstrates a distinct inverse relationship between the magnitude of the applied temperature change and the mechanical buckling resistance. As the environmental temperature rises, the pre-existing internal thermal compressive stresses consume a portion of the structure's load-bearing capacity, thereby reducing the amount of additional mechanical load required to initiate buckling. If the temperature rise is sufficiently high, purely thermal buckling can occur without any external mechanical compressive force.

Table 1: Critical Buckling Loads Under Various Multiphysics Conditions

Porosity Fraction	Volume	Electric (Negative)	Voltage	Electric (Positive)	Voltage	Thermal Applied	Gradient
Low Porosity		Reduced Stability		Enhanced Stability		Rapid Buckling Onset	

Moderate Porosity	Severe Instability	Moderate Stability	Extremely Rapid Buckling
High Porosity	Critical Failure Risk	Marginal Stability	Immediate Structural Failure

The integration of piezoelectric layers provides a mechanism to actively modulate this thermally induced instability. The application of an external electric voltage generates electro-elastic forces that can either counteract or compound the thermal stresses. An applied positive electric voltage generates internal tensile forces via the reverse piezoelectric effect. These tensile forces effectively stiffen the nanostructure, thereby increasing the critical mechanical buckling load and elevating the critical buckling temperature. This phenomenon offers a promising avenue for actively controlling and delaying the onset of structural instability in high-temperature environments. Conversely, a negative electric voltage generates additional compressive forces, which synergize with the thermal stresses to drastically lower the buckling threshold, potentially leading to premature and catastrophic structural failure. The precise balance between the applied electric field and the thermal gradient is therefore a critical design consideration for multiphysics nano-devices.

4.3 Impact Of Size-Dependent Parameters

The macroscopic stability of the nanostructure is profoundly influenced by the micro- and nano-scale phenomena captured by the size-dependent theoretical framework. The analysis isolates the individual and combined effects of the nonlocal stress parameter and the strain gradient microstructural parameter. The nonlocal parameter, which accounts for the interatomic long-range attraction forces, consistently exhibits a softening effect on the structural stiffness. An increase in the nonlocal parameter corresponds to an increase in the influence of the surrounding strain field on a localized reference point, effectively making the material appear more compliant. Consequently, as the nonlocal parameter increases, the critical buckling load significantly decreases. This size-dependent softening is particularly pronounced in higher buckling modes and structures with smaller characteristic lengths.

In stark contrast, the strain gradient parameter, which encapsulates the effects of microstructural deformation mechanisms and surface energies, imparts a stiffening effect on the nanostructure. An increase in the strain gradient length scale parameter leads to a corresponding increase in the critical buckling load. The simultaneous inclusion of both parameters in the modified nonlocal strain gradient theory reveals a complex competitive dynamic. The ultimate stability of the porous nanostructure depends on the specific ratio between the nonlocal softening and the strain gradient stiffening effects. If the nonlocal parameter dominates, the structure is more susceptible to buckling; if the strain gradient parameter is more prominent, the structure demonstrates enhanced stability. This delicate balance underscores the absolute necessity of utilizing advanced, unified size-dependent theories rather than classical continuum mechanics, which would entirely miss these critical scale-driven phenomena and yield dangerously inaccurate predictions for nanoscale engineering design.

5. Conclusion

5.1 Summary Of Findings

This paper has presented a thorough and rigorous investigation into the thermo-electro-elastic buckling behavior of porous nanostructures operating under complex multiphysics loading environments. By integrating a sophisticated nonlocal strain gradient theory with advanced functional grading models for internal porosities, the research has elucidated the intricate

dependencies between nanoscale material architecture, size effects, and environmental loads. The comprehensive descriptive analysis demonstrates that the presence of internal voids universally compromises the buckling resistance of the nanostructures, although strategically employing symmetric porosity distributions can mitigate this degradation by preserving critical surface stiffness.

Crucially, the study highlights the profound impact of multiphysics coupling on structural stability. Elevated thermal environments induce severe internal compressive stresses that drive the structure toward thermal buckling. However, the incorporation of piezoelectric materials allows for active intervention; the application of a positive electric voltage generates beneficial tensile electro-elastic forces that can successfully counteract thermal degradation and enhance the overall buckling threshold. Furthermore, the analysis confirms that classical continuum mechanics is inadequate for such applications, as the competitive interaction between nonlocal softening and strain gradient stiffening fundamentally dictates the true mechanical response at the nanoscale.

5.2 Future Research Directions

The insights derived from this extensive analysis establish a robust theoretical foundation for the design and optimization of advanced smart nano-devices, yet they also illuminate several critical pathways for future research. Subsequent investigations should aim to transition from linear static buckling analysis to complex non-linear dynamic stability assessments. Exploring the post-buckling behavior and the large-amplitude dynamic responses of porous nanostructures under harmonically varying thermo-electric fields will provide a more comprehensive understanding of their performance limits in real-world applications.

Additionally, the integration of multi-directional porosity distributions, representing highly complex 3D-printed nanoscale architectures, presents an exciting frontier. The theoretical framework could also be expanded to incorporate the effects of surface elasticity, surface residual stresses, and fluid-structure interactions, which become increasingly dominant as the structural dimensions reach the lower bounds of the nanoscale. Ultimately, the continuous refinement of these predictive multiphysics models, validated by emerging experimental nano-characterization techniques, will be instrumental in driving the next generation of highly resilient, efficient, and intelligent nano-electromechanical systems.

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