Nonlocal buckling of orthotropic nanosheets with a central crack

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ABSTRACT

In this study, a comprehensive study of the non-local buckling of orthotropic nanosheets with a central crack under uniaxial and biaxial loads has been conducted. Given the increasing advances in nanotechnology and the widespread applications of nanosheets in various industries such as electronics, medicine, and engineering structures, a detailed analysis of the mechanical behavior of these nanostructures is essential. Damages such as cracks that occur during the production process of nanosheets can have significant negative effects on the performance of these materials. In this regard, non-local non-classical theories have been used as a new approach to analyze the behavior of nanosheets. This research involves the development of governing equations based on first-order shear deformation theory and the use of the extended finite element method to analyze cracked nanosheets. The main variables studied in this study are: crack length to sheet width ratio, small-scale parameter that refers to the effects of nanostructures on buckling behavior, nanosheet thickness, and different support conditions. The results obtained show that the small-scale parameter significantly reduces the critical buckling capacity of nanosheets. In particular, for nanosheets with an aspect ratio of 0.6, the non-local effect can increase up to 1.18 times that of the case without a crack. Furthermore, as the lateral dimensions of the nanosheets increase, the effect of the non-local factor gradually decreases. By providing comprehensive analysis results, this research provides a solid foundation for the design and optimization of orthotropic nanosheets under various loadings and helps to clarify the buckling behavior of these nanostructures. In addition, these results can lead to the development of new production methods and optimal applications of nanosheets in industries.

KEYWORDS

Orthotropic nanosheets, central crack, compressive buckling, nonlocal theory, extended finite element method.

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1. Introduction

Nanotechnology, as one of the most revolutionary branches of science and engineering, has opened new horizons in the development of advanced materials and devices. Nanoplates, due to their unique properties, have attracted increasing attention in emerging industries such as battery production [1], chemical and biological sensors [2], solar cells [3], and field emission devices [4]. Considering these widespread and critical applications, a precise understanding of the mechanical behavior of nanostructures, particularly under stresses and structural defects, is essential to ensure reliability and optimize their design.

Buckling, as an elastic instability phenomenon under compressive load, is one of the most critical limit states in the design of mechanical structures. At the nanoscale, phenomena such as the size effect parameters significantly differentiate the mechanical behavior of these materials from that of macro-scale materials. Previous research on the buckling and vibration of nanoplates, especially graphene nanoplates, highlights the importance of studying these phenomena. Studies such as those of Farajpour et al. [5–6], Aksencer and Aydogdu [7], Malekzadeh et al. [8–9], and Memarzadeh and Abdolvahab [10] have investigated issues such as the buckling of graphene nanoplates using classical and non-classical theories, the influence of boundary conditions, and the effect of small-scale parameters.

In many practical applications, nanomaterials exhibit defects such as cracks, which can significantly affect their load-bearing capacity and stability. Analyzing the behavior of cracked nanoplates, especially while accounting for nonlocal effects, which are key characteristics of nanoscale material behavior, represents an important challenge in materials engineering and mechanics. To date, incorporating both small-scale effects and crack presence in orthotropic nanosheets requires more advanced approaches. Employing nonlocal elasticity theory, which extends the stress–strain relationship to neighboring points, is essential for accurately modeling small-scale effects in nanosheets.

This study provides a comprehensive investigation of the nonlocal buckling of orthotropic nanoplates containing a central crack. Within the framework of nonlocal elasticity theory and the first-order shear deformation theory (FSDT), the governing equations of these structures are derived. Subsequently, numerical analysis is carried out using the extended finite element method (XFEM). The focus on orthotropic nanoplates, due to their wider applications compared with isotropic materials in certain industries, along with an examination of the influence of geometric parameters, loading mechanisms, and material properties on buckling behavior, places this research among the leading studies in the field.

2. Methodology

2.1. Theoretical Foundations

To model orthotropic nanoplates while accounting for small-scale effects, the framework of nonlocal elasticity theory is employed. To describe the deformation behavior of nanosheets, the first-order shear deformation theory (FSDT) is used. The governing equations for the buckling of orthotropic nanoplates are derived using the principle of minimum energy along with the application of nonlocal elasticity theory and FSDT. These equations are formulated as an eigenvalue problem, whose solution determines the critical buckling load.

2.2. Extended Finite Element Method (XFEM)

The extended finite element method (XFEM) is a powerful numerical technique for modeling discontinuities such as cracks in material structures. In XFEM, the solution space is divided into standard finite elements; however, for modeling cracks, additional degrees of freedom are introduced at nodes around the crack. These additional degrees of freedom are defined through enrichment functions, which capture the discontinuous nature of the problem. Since the present research examines the buckling load of an orthotropic nanosheet in the presence of a center crack defect under a compressive load, as shown in Fig. 1.

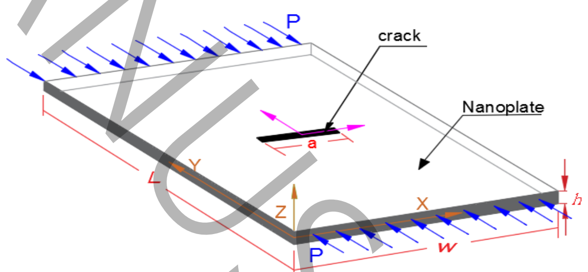

Fig. 1. Schematic of an orthotropic nanosheet in the presence of a center crack defect under a uniform uniaxial compressive load. In this figure, L, W, and h are the length, width, and thickness of the orthotropic nanosheets, respectively, and a denotes the crack length.

For crack modeling, a combination of standard finite element shape functions and specific enrichment functions is employed to accurately represent the displacement field near the crack tip and crack edges. These enrichment functions usually include a Heaviside function to model displacement discontinuity along the crack line, and singular functions to represent the asymptotic behavior of stress and displacement fields at the crack tip.

3. Results and Discussion

In this study, eight-node plate elements are used to model cracked nanoplates. The buckling coefficient is typically defined as the ratio of the critical buckling load of the cracked structure to that of the equivalent pristine structure. This coefficient indicates the effect of crack presence and/or small-scale effects on the reduction of buckling capacity. To validate the accuracy of the XFEM-based results, numerical outputs are compared with existing analytical and numerical findings from credible publications. The key variables studied in this research (see Fig. 1) include the crack length-to-width ratio, the small-scale parameter reflecting nanostructural effects on buckling behavior, nanoplate thickness, and different boundary conditions.

In addition, according to Fig. 2, the crack existence in the nanosheet and its length increase intensify the nonlocal effect. e.g., in the case of $\mu=1.5nm^2$, the nonlocal effect causes a 22% and 26% reduction in the buckling load for a/W=0 and 0.6, respectively. It means that a crack with a ratio of 0.6 increases the non-local effect by about 1.18 times compared to the case without a crack.

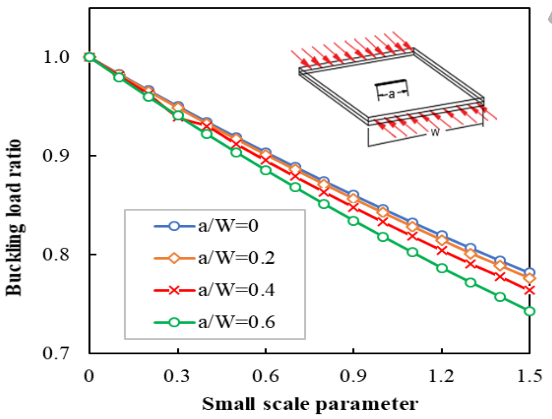

Figure (2) Investigation of the effect of the small scale parameter (μ) and the component (a/W) on the buckling load capacity of cracked square orthotropic nanosheets under uniaxial loading.

4. Conclusion

The key findings of this research indicate that:

1. Small-scale effect: The nonlocal parameter significantly reduces the critical buckling capacity of orthotropic nanoplates, with this effect becoming more pronounced at higher intensities.
2. Crack influence: The presence of a crack, especially at higher relative lengths, amplifies the small-scale effect, leading to further reductions in the critical buckling load of orthotropic nanoplates.
3. Geometric dimensions: The lateral dimensions of the nanoplate play a significant role in the intensity of the small-scale effect; as the dimensions increase, the effect diminishes and the results converge toward classical elasticity theory.
4. Boundary conditions: Boundary constraints also influence the intensity of the nonlocal effect; more restrictive boundary conditions (such as clamped edges) enhance the small-scale effect.

his study provides a solid foundation for a deeper understanding of the buckling behavior of cracked orthotropic nanoplates and for optimizing their design in engineering applications. Understanding the impacts of parameters such as small-scale effects, crack geometry and position, and boundary conditions enables engineers and designers to create nanoscale structures with higher reliability and efficiency. Furthermore, the results of this research can contribute to the development of new methods for producing materials with tailored mechanical properties and for the optimized application of nanoplates in advanced industries.

5. References

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