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Thermal buckling and natural vibration of the beam with an axial stick–slip–stop boundary

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ABSTRACT

As a first attempt to study the dynamics of a heated structure with complicated boundaries, this paper deals with the thermal buckling and the natural vibration of a simply supported slender beam, which is subject to a uniformly distributed heating and has a frictional sliding end within a clearance. This sliding end is initially at a stick status under the friction force, but may be slightly slipping due to the thermal expansion of the beam until the sliding end contacts a stop, i.e., the bound of the clearance. The material properties of the beam are temperature-independent for low temperature, but temperature-dependent for high temperature. For each case, the analytic solutions for the critical buckling temperature and the natural frequencies of the heated beam are derived first. Then, discussions are made to reveal the effects of beam parameters, such as the ratio of beam length to beam thickness, the ratio of clearance to beam length and the temperature-dependent material properties, on the critical buckling temperature and the fundamental natural frequency of the heated beam. The study shows that both friction force and clearance have significant influences on the critical buckling temperature and the fundamental natural frequency of the beam. When the friction force is not very large, the clearance can greatly increase the critical buckling temperature. These conclusions enable one to properly design the stick–slip–stop boundary so as to improve the mechanical performance of the beam in thermal environments.

1. Introduction

The structure of a hypersonic flight vehicle or a reusable space transportation system works at a hypersonic speed such that the aerodynamic heating gives rise to a significant and inevitable influence on the structure. For such a structure, the surrounding environment may reach a local temperature from 1200 °C to 1800 °C. If the structure is restrained on the boundaries, the thermal stress induced by the restrained thermal expansion of the structure may become dangerous. When the thermal stress is large enough, the thermal buckling may occur and result in the failure of structure. In addition, the higher temperature may degrade the material properties to withstand loads. For example, Young's modulus can be significantly reduced

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when the temperature is high. Hence, the temperature rise has great influences on the mechanical behaviors of the structure, such as thermal buckling and thermal vibration [1].

The research on thermal mechanics of structures, especially beams, has had a long history and witnessed new achievements over the past decades. Some recent studies in this field have focused on the thermal structures made of either advanced composite materials or functionally graded materials, the properties of which are usually temperature-dependent. For example, Ganesan and his co-workers studied the thermal buckling and vibration of a sandwich beam having a viscoelastic core with temperature-dependent complex shear modulus, and a sandwich beam made of a functionally graded material with temperature-dependent properties, respectively, via the finite element method [2,3]. Wattanasakulpong et al. used an improved theory of the third-order shear deformation and Ritz method to study the thermal buckling and vibration of beams of a functionally graded material with temperature-dependent properties [4]. Vosoughi et al. analyzed the thermal buckling and post-buckling of laminated composite beams with temperature-dependent properties based on the beam theory of the first-order shear deformation by applying differential quadrature method [5]. Fu et al. studied the thermal buckling, nonlinear vibration and dynamic stability for the beams of a functionally graded piezoelectric material with temperature-dependent properties by using the model of Euler–Bernoulli beam [6]. Kiani and Eslami studied the critical buckling temperature of beams made of a functionally graded material with temperature-dependent properties via the model of Euler–Bernoulli beam [7].

Some other recent studies in this filed have dealt with complicated environments surrounding the structure of concern, such as beams. For example, Li and Batra analyzed both thermal buckling and post-buckling of homogeneous and isotropic Euler–Bernoulli beams on a nonlinear elastic foundation and with pinned–pinned and fixed–fixed boundaries by using the shooting method [8]. Song and Li studied both thermal buckling and post-buckling of a pinned–fixed beam supported on an elastic foundation via the geometrically nonlinear theory of Euler–Bernoulli beam and the shooting method [9]. Pradhan and Murmu presented the thermal vibration analysis for a beam of functionally graded material and a sandwich beam of functionally graded material resting on the variable Wrinkler foundation by using the modified differential quadrature method [10]. Pi et al. studied the thermo-elastic lateral-torsional buckling of a fixed slender beam in the linear gradient temperature field [11].

In the abovementioned studies, the boundary conditions of a beam are either free, simply supported or clamped, and the two ends of the beam are axially immovable. In practice, however, at least one end of the beam is often allowed to move axially so as to reduce the axial thermal stress. A simple mechanical assembly for this purpose is to allow one end of the beam to axially slide within a small range, named as the clearance in this study. The sliding end of the beam is subject to a pair of adjustable normal force and friction force such that the sliding process includes an initial stick, a thermal slip and a final stop when the axial thermal stress increases. That is, the beam has an axial stick–slip–stop boundary. Even though some studies have shown the effects of boundaries on the thermal mechanical behaviors of a beam [12–14], no study has dealt with the thermal mechanics of a beam with an axial stick–slip–stop boundary so far.

As a first attempt to study the complicated dynamics of the beam with such a boundary, this paper deals with the thermal buckling and natural vibration of a simply supported Euler–Bernoulli beam with an axial stick–slip–stop boundary. The objective of the study is to derive some useful formulas, which can not only reveal the influences of both friction and clearance in the axial stick–slip–stop boundary on the thermal buckling and natural vibration of the beam, but also give the start for further approximate analysis of nonlinear thermal vibration of the beam.

2. Description of problem

The study focuses on a simply supported Euler–Bernoulli beam of rectangular cross-section, which is made of a linear elastic, isotropic and homogenous material. As shown in Fig. 1, the beam has the length l, width b and thickness h in x, y and z directions, respectively.

As assumed in many previous studies, the beam is subject to a uniformly distributed heating such that the temperature distribution in the beam is also uniform. Let T denote the temperature in the beam and θ denote the temperature rise as follows:

$$\theta = T - T_{\mathrm{ref}} \tag{1}$$

where T_{ref} is the reference temperature at which the beam is free of thermal stress.

Previous studies showed that the material parameters, such as the coefficient of thermal expansion and the elastic modulus, keep constant if the temperature is not high. Otherwise, the coefficient α of thermal expansion linearly varies with

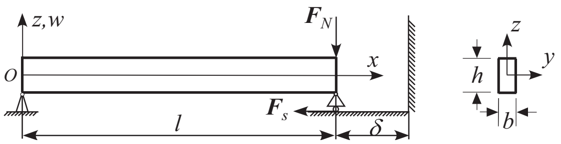

Fig. 1. Schematic of the simply supported beam with a stick–slip–stop boundary.