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MWCNT/epoxy strip-like sensors for buckling detection in beam-like structures

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ABSTRACT

Buckling of slender structures constitutes a hazardous failure mechanism that can yield partial or total collapses. Nonetheless, given that buckling failure is characterized by a highly non-linear and sudden loss of stability, most off-the-shelf monitoring systems fail to detect buckling and very few research works in the literature can be found in this regard. Recent advances in the field of Nanotechnology have fostered the development of innovative composite materials with multifunctional properties, offering vast possibilities in the field of Structural Health Monitoring. Along these lines, the present work proposes a novel concept of smart beams for buckling detection applications. This consists of the deployment of carbon nanotube-reinforced epoxy strip-like sensors on the upper and bottom faces of a beam-like structure. Carbon nanotube-reinforced composites exhibit strain self-sensing capabilities, that is to say, these composites provide measurable variations in their electrical properties under the action of mechanical strains. In this way, the proposed sensing strips not only act as mechanical reinforcements, but also confer self-diagnostic properties to the system. The failure detection principle of the proposed smart beams consists of the assessment of the bending-induced variations of the normal strains during buckling. To do so, the electrical resistance of the sensing strips is continuously monitored through a two-probe resistivity measurement scheme. The present research furnishes detailed numerical parametric analyses to investigate the effectiveness of the proposed smart beams to detect buckling under uniaxially compression, as well as to evaluate the influence of design parameters such as filler volume fraction, boundary conditions and electrodes layouts. The macroscopic behaviour of the smart beams is simulated by a micromechanics-based piezoresistivity model and a multiphysics finite element code. The numerical results demonstrate that the buckling failure can be tracked through sudden disturbances in the electrical output of the smart strips.

1. Introduction

Structural Health Monitoring (SHM) has become a consolidated discipline in many areas of Engineering and constitutes today a common practice in manifold industrial activities. This encompasses the application of Non-Destructive Testing (NDT) and damage detection in order to evaluate the soundness of infrastructures and conduct timely condition-based maintenance that allows expanding their life span [1]. In particular, most research efforts have focused on detecting damages through variations of the stiffness properties of structural members. Such variations often stem from aging degradation processes, corrosion, fatigue, cracking or accidental events [2]. Nevertheless, the number of studies on the application of SHM techniques to detect the loss of structural stability, that is buckling failure, are sorely lacking. Instability phenomena are highly determined by geometric and material non-linearities which limit the effectiveness of most off-the-shelf sensing solutions. The recent development of multifunctional composite materials, often termed smart materials, offers an innovative solution in the assessment of the integrity of structures. Particularly attractive are the self-sensing materials which fulfil a structural function and, at the same time, provide self-diagnostic capabilities apt for condition-based maintenance [3,4]. While promising, the application of these novel materials is still at a very early stage and, indeed, their application for buckling detection is yet to be explored.

Even though instability is a fundamental strength limit state in design codes, few research works in the literature have reported about the application of monitoring systems for buckling detection. Among them, one approach is the Vibration Correlation Technique (VCT) which tracks the change in natural frequencies identified from acceleration records in order to estimate the buckling loads [5]. Both theoretical and experimental results have demonstrated that the natural frequencies of isolated structural members decrease for increasing compression loads

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and, in particular, the fundamental frequency decreases to zero when the load reaches the critical buckling load [6]. Therefore, buckling failure can be identified by continuous monitoring of the natural frequencies. Although these approaches have been shown effective for the buckling detection of isolated structural members like beams [7] or panels [8], their application to full-scale structures is limited, since the local buckling of a member is often hardly noticeable in the global natural frequencies. Qu et al. [9] proposed a two-step detection method to diagnose buckling damages in transmission towers. The first step consists of a wavelet packet energy curvature of the acceleration response of the structure to locate potential regions of buckling. Subsequently, the second step specifies the position of the buckled members through differences of modal strain energy change rates and confidence intervals. Overall, vibration-based buckling detection approaches are only applicable to cases where linearity remains valid, which is not the case in most buckling failures. A second group of approaches exploits the variations in the normal strains of structural members induced by the appearance of bending efforts at buckling [10]. A promising solution for buckling detection is the use of distributed strain fibre optic sensors [11]. Ravet et al. [12] reported the application of a Brillouin sensor system to identify buckling in a steel pipe and a column specimen under laboratory conditions. Similarly, Feng et al. [13] proposed the use of Brillouin fibre optic sensors for lateral buckling detection in subsea pipelines. Fibre Bragg Grating sensors (FBG) were used by Ryu et al. [14] to monitor the buckling behaviour of a composite wing box. Embedded into the structural components of the structure, these sensors provide distributed stress and strain measurements that permits detecting bending-induced strains derived from buckling. Other innovative solutions include the use of piezoelectric transducers [15], Frequency Selective Surfaces (FSS) [16], or Digital Image Correlation (DIC) measurements [17].

Novel multifunctional materials, such as smart concretes or self-sensing polymer composites, offer an innovative monitoring alternative with a vast spectrum of applications for SHM [18]. Commonly, these smart composites are enriched with carbon-based inclusions, such as carbon black, carbon nanofibers, Carbon NanoTubes (CNTs) or graphene nanoplatelets [19–21]. When added in small concentrations and adequately dispersed, such fillers have been reported to confer remarkable mechanical improvements to cement-based and polymer materials, as well as multifunctional properties including enhanced electrical conductivity and self-sensing capacities [22,23]. Self-sensing capabilities manifest as measurable variations in the electrical properties of the composites when subjected to mechanical deformations, that is to say, a piezoresistive behaviour.

Three main strands of integration of self-sensing composites into large-scale structures for SHM can be found in the literature, namely structures completely made of smart materials [24], embedded sensors [25], and self-sensing skins [26]. Although the development of fully smart structures provides a comprehensive monitoring of their integrity, the high costs of the fillers and complex current fabrication processes related to their dispersion hinder the extensive implementation of these solutions [27]. Alternatively, the application of smart composites in the shape of embedded small-dimensions sensors forming dense sensing networks offers a more cost-efficient solution. Naeem et al. [28] analysed the stress and crack sensing capabilities of cement-based composites doped with Multi Walled CNT (MWCNT) under flexural loadings. Those authors manufactured prismatic embeddable sensors with different geometries, including smart sensors of $50 \times 50 \times 50\,\mathrm{mm}^3$, $160 \times 40 \times 40\,\mathrm{mm}^3$ and $1500 \times 15 \times 15\,\mathrm{mm}^3$. When embedded into steel-reinforced mortar beams, their results reported steep increases in the electrical resistance of the sensors indicating the appearance of flexural cracks in the host structure. More recently, Downey et al. [29] proposed a novel piezoresistive clay brick for crack detection applications in masonry structures. While promising, the implementation of embedded sensors is limited to new-construction structures, being difficult their deployment into pre-existing structures. As an intermediate solution, the development of smart piezoresistive skins offers a cost-efficient alternative for the health monitoring of pre-existing structures. In virtue of their piezoresistive properties, it is possible to relate the monitored strain state to the presence of damages in the host structure. In this line, it is worth noting the works by Kang et al. [30] who developed 10 wt% MWCNT-reinforced Poly(methyl methacrylate) (PMMA) strain sensors. Under laboratory conditions, the authors bonded MWCNT/PMMA sensors with dimensions $50 \times 4 \times 0.08\,\mathrm{mm}^3$ to an aluminium cantilever using a spray-on technique. Their results demonstrated the ability of the sensing strips for damage localization of prescribed damages. Although great efforts have been done from experimentation, there is no a generalized theoretical approach allowing a proper understanding of the output of the sensors, as well as assisting their design and optimization.

The modelling of the behaviour of CNT-based composites for SHM applications is in essence a multiscale-multiphysics problem. Considering that piezoresistance defines a one-way coupled electrical–mechanical property, it is possible to conduct the homogenization of the mechanical and electrical properties of CNT-based composites in two consecutive steps. Firstly, the mechanical properties of CNT-based composites have been reported to be determined by the load transfer mechanisms from matrix to fillers at the nano-scale. Such interactions are defined by weakly non-bonded van der Waals (vdW) interatomic potentials [31]. Hence, the mechanical homogenization of CNT-based composites is formulated in a bottom-up multi-scale framework where the atomic interactions must be scaled up to the macro-scale. In this regard, the most common approaches in the literature include [32]: Molecular Dynamics (MD) simulations, atomistic-based continuum modelling, and mean-field homogenization with interfacial effects. Molecular dynamics simulations permit the study of the atomic structure of CNTs and their interaction with the matrix material [33]. Since realistic systems with a representative number of atoms demand exorbitant computational costs, MD simulations are generally well-suited to investigate local effects in reduced populations of atoms. Atomistic-based continuum techniques assume certain relations between the interatomic potentials and the stiffness of continuum structures such as truss rods or link elements. In this way, it is possible to describe the atomistic structure of the composite through a continuum framework such as Finite Element (FE) modelling with moderate computational costs [34]. Finally, mean-field homogenization approaches with interfacial effects offer a simplified alternative by considering the load transfer mechanisms as certain mechanical conditions at matrix/CNT interfaces [35–37].

The second step of the homogenization of the constitutive properties of CNT-based composites concerns the electrical conductivity and piezoresistivity. The electrical conductivity of these composites has been widely depicted through a percolative-type behaviour [38,39]. This achieves to explain the sudden increases in the overall electrical conductivity of CNT-based composites when the filler concentration reaches a critical value, termed percolation threshold [40,41]. A noteworthy contribution was made by Feng and Jiang [42] who proposed a Mori-Tanaka micromechanics model in the framework of percolation theory for CNT/polymer composites. That model distinguished two conductive mechanisms, namely the electron hopping (quantum tunnelling effect) and conductive networking mechanisms. The electron hopping mechanism, which defines the transfer of electrons between proximate nanotubes across an isolating gap, was modelled by conductive coatings surrounding the tubes. On the other hand, the conductive networking mechanism, which alludes to the appearance of microscopic conductive paths of interconnected nanotubes, was simulated by changes in the fillers' aspect ratios. Those authors demonstrated that the conductive networking mechanism represents the onset of the percolation process and, above the percolation threshold, both mechanisms govern the overall conductivity of composites. Concerning the piezoresistivity of CNT-based composites, the number of works is considerably lower. Most studies agree to ascribe their self-diagnostic