

Preface

This book endeavors to present a unified treatment of the foundational elements of nonlinear structural mechanics and dynamics, the modern modeling and computational aspects, and the prominent nonlinear structural phenomena, unfolded by careful experiments and computations.

Scientific and technological advances in the field of material and manufacturing processes and the development of formidable computational power allow structures and mechanical systems to be designed closer and closer to the limit of their structural capacity. Structures are consequently very slender and flexible, and thus they respond nonlinearly to typical disturbances. The nonlinearities become an essential aspect of the structural behaviors under both static and dynamic excitation.

In spite of the emerging need for a multidisciplinary approach to the design of structural systems, *nonlinear dynamics* and *nonlinear structural mechanics* are becoming somewhat independent fields. Theories and methods have reached a high level of maturity in both cases. However, a sophisticated use of the tools and theories that enable the investigation of nonlinear dynamic phenomena in systems and structures does not justify the lack of nonlinear physics in the structural models which, if not properly addressed, can only poorly, or misleadingly, describe the mechanical performance of the systems.

The separation between these fields has been reflected to date in the lack of textbooks and monographs that encompass, within the same comprehensive framework, all leading aspects of nonlinear structural mechanics and dynamics which range from the formulation and modeling to computational strategies and interpretation of nonlinear phenomena [23, 332, 339, 450]. Among these books, I consider *Nonlinear Oscillations* [332], a masterpiece of nonlinear dynamics and *Nonlinear Problems of Elasticity* [23], a masterpiece of nonlinear mechanics. Moreover, the few existing books with this flavor are often hardly accessible to graduate students and engineers because of the high level of mathematical structure. The motivation for this book is to create a common framework “nonlinear mechanics-nonlinear dynamics” which can be easily accessible to graduate students, researchers, and engineers.

The proposed unified approach enables high-fidelity investigations of the dynamic response of nonlinear systems and structures in traditional engineering

fields such as civil, aerospace, mechanical, ocean engineering, as well as in emerging fields such as bioengineering and nano/microengineering. In the latter, the nonlinearities can play an even more significant role.

The theoretical and computational tools that allow the formulation, solution, and interpretation of nonlinear structural behaviors are presented in a systematic fashion, so as to gradually attain an increasing level of complexity, under the prevailing assumptions on the geometry of deformation, the constitutive aspects, and the loading scenarios. Specific problems—such as, to name but a few, the nonlinear response of suspension bridges or arch bridges, the nonlinear response of long strings and cables such as those used in tethered satellite systems, the flutter and post-flutter response of aircraft wings, the nonlinear elastic deformation of prestressed laminated composite plates—are extensively discussed in terms of their formulation and solution.

The book is largely based on the lecture notes for the course *Nonlinear Analysis of Structures* that I teach at Sapienza University of Rome in the Civil and Aerospace Engineering Master programs. A broad discussion was initiated a few years ago regarding the need to offer such a class to graduate students due to major changes that were and are still occurring in design practices and philosophy, changes that clearly require innovative approaches to investigate advanced structures. The key considerations can be summarized as follows.

In recent years, theoretical and computational advances in the formulation and solution of problems of nonlinear structural mechanics have led to significant enhancements in the design codes. Up to recent times, the design of civil and industrial structures has been mostly based on linear theories, and consequently several generations of engineers have only been trained in linear structural theories. One of the key properties of linear theories is the principle of superposition by which any problem can be broken down into a set of simpler/elementary problems whose solutions are available or can be easily found. Thus the solution to the original problem is expressed as a superposition of the solutions of the elementary problems.

This scientific context has invariably influenced the intuitive aspects of the structural and mechanical design. In the last decades, theoretical breakthroughs, higher deployable computational power, and the great experience gained from the analysis of major structural failures have allowed nonlinear analyses to officially enter the design practices through new design codes. The codes have completely transitioned from the so-called method of admissible stresses (largely based on linear theory), to those based on limit states, which are framed within the context of limit analysis.

More recently, design codes, such as the performance-based American codes or the *Eurocodes* in Europe, have opened the possibility of performing step-by-step analyses up to the failure states of a structure, thus conferring remarkable importance to the role of nonlinear analyses and of the underlying nonlinear models. The seeds of this process were, for example, sown in the last decades in the specific area of earthquake engineering. For example, in the *Vision 2000* report by the Structural Engineers Association of California [417], it was stated: *Performance-based engineering methodology encompasses the full range of*

engineering activities necessary to create structures with predictable seismic performance within established levels of risk.

The importance of nonlinear constitutive behaviors does not relate to traditional materials alone—steel, aluminum or reinforced concrete—but also to broad classes of innovative materials such as shape-memory alloys, high-damping rubbers or fiber-reinforced materials and, more recently, nanostructured materials. Moreover, the formidable strength exhibited by the newly engineered materials, associated with their higher flexibility, and the more pronounced slenderness of modern lightweight structures require stability analyses, often including dynamic stability analyses arising from nonconservative fluid–structure interactions or from gyroscopic forces such as the Coriolis forces in rotating structures.

One of the open problems in structural engineering is that of constructing in a reliable and efficient fashion the nonlinear equilibrium paths when varying one or more control parameters associated with the loading conditions and/or design parameters. This issue leads in turn to at least two sets of problems; on the one hand, the need for refined nonlinear structural models, both in their geometric and constitutive aspects; on the other hand, the need for refined computational techniques to path-follow the response when the structures are exposed to various loading scenarios. At the same time, there is a parallel need for highly efficient computational architectures that allow sensitivity analyses with respect to control parameters, including uncertainties, and to make these analyses reasonable and affordable.

I would not give full justice to the current state of affairs in nonlinear structural mechanics if I did not mention the overwhelming wealth of physical phenomena in nonlinear structural mechanics and dynamics that have yet to be unfolded, interpreted, and framed within paradigmatic conceptual frameworks. Suitable nonlinear structural models become important, not only for mere calculations and strength justification but also for the comprehension of the basic physical mechanisms underlying certain structural behaviors in the nonlinear regime. All these efforts are directed toward the long-term objective of gradually facilitating the emergence of a nonlinear design culture forging the engineering practice so as to aim at the design of super-performing structures by leveraging the nonlinear behavior of materials and structural components and systems incorporating integrated multifunctionality.

Let us consider, as an illustrative example, an elastic beam, straight or curved. The beam load-carrying mechanisms are well known within the linear regime; at the same time, the effects of the boundary conditions on the elasto-static or elasto-dynamic response can be grasped with relative ease. This is no longer true in the nonlinear regime, where the role of the internal kinematic constraints which depends on the slenderness and the role of the constitutive laws or that of the boundary conditions are not well clarified and are certainly less intuitive, except in limited and simplified contexts. These considerations become more stringent when increasingly complex structures are assembled through coupling different elastic elements, such as in suspension or arch bridges, in aircraft wings or fuselages, and are enhanced by passive or active control and structural health monitoring systems.

Although it is true that the finest structural modeling is based on nonlinear continuum mechanics, it is also true that the calculation of the response within three-dimensional theory [23, 295] is computationally prohibitive in many cases,

especially in those cases where the requirement for performance is high, and there are significant fluid–structure or soil–structure interaction issues. Likewise, the polar continuum nonlinear theories, especially those for beams, plates, and shells, developed from the pioneering work of the Cosserat brothers [121], through seminal contributions by nonlinear elasticists such as Truesdell [437], Antman [20, 23], and Simo [404], to cite but a few, are sufficiently complex on both mathematical and computational grounds. Therefore, there is also a need for simplified versions of these fine theories, while maintaining an acceptable predictive capability from an engineering point of view, so as to make the analyses computationally affordable and controllable. With these ideas in the background, I have conceived the organization of this book into eleven chapters with the titles listed below.

- Chapter 1: Concepts, methods, and paradigms
- Chapter 2: Stability and bifurcation of structures
- Chapter 3: The elastic cable: from formulation to computation
- Chapter 4: Nonlinear mechanics of three-dimensional solids
- Chapter 5: The nonlinear theory of compact beams in space
- Chapter 6: Elastic instabilities of slender structures
- Chapter 7: The nonlinear theory of curved beams and flexurally stiff cables
- Chapter 8: The nonlinear theory of plates
- Chapter 9: The nonlinear theory of cable-supported structures
- Chapter 10: The nonlinear theory of arch-supported structures
- Chapter 11: Discretization methods

In Chap. 1, introductory concepts such as those of geometric and material nonlinearities are presented through simple yet illuminating examples. Most of the basic concepts, such as the geometric stiffness, the role of nonlinear constitutive laws, the linearization about a natural or a generic prestressed configuration, are elucidated. It is clearly pointed out that real structural problems seldom exhibit a nonlinearity of one type uncoupled from the nonlinearity of the other type. A rigorous presentation of the concepts and theories at the foundation of nonlinear structural analyses should encompass both nonlinearities at the same time.

However, some problems of formidable technical interest—such as the onset of the limit state due to loss of elastic stability and the initial postcritical regime—are prominently governed, under suitable conditions, by geometric nonlinearities while the material behavior is well described by linear elasticity. With this in mind, geometric nonlinearities, which can be grasped more easily, are first discussed in this chapter. Chapter 1 also illustrates the principal path-following methods of nonlinear mechanics and dynamics [126, 335] to help understand the computational algorithms by which the equilibrium paths in the nonlinear regime can be constructed. At the same time, these schemes are applied to a rich collection of simple yet paradigmatic structures to unfold important properties of the responses in the nonlinear static and dynamic regime.

Chapter 2 presents an overview of stability and bifurcation theory discussing the methods aimed at determining the critical conditions or limit states regarding the elastic static and dynamic stability, as well as the postcritical structural responses beyond the limit state [59]. This is done in the context of one- and multi-degree-of-

freedom paradigmatic structures. Eulerian and non-Eulerian (e.g., the snap-through phenomenon occurring in shallow arches and more general shallow structures) losses of stability are illustrated at length. The flutter problem of lifting airfoils (wings, bridges, suspended structures) occurring at a Hopf bifurcation is treated comprehensively.

In Chap. 3, the derivation of the nonlinear problem of elastic cables, treated as a one-dimensional continuum [206, 207, 250], is explained. The cable problem combines a striking simplicity of its nonlinear formulation with an eminently complex structural behavior. The cable problem is employed as a powerful illustrative problem which allows to introduce the chief steps of a full nonlinear formulation of the governing equations, as well as the leading steps of a consequent nonlinear structural analysis through computational approaches that enable the parameterized unfolding of the structural response to loads of varying magnitude. Two applications feature the study of the galloping instability of iced cables subject to steady winds and the full nonlinear formulation of the tethered satellite system employed in space applications. The cable problem also provides the motivation for studying nonlinear structural distributed-parameter systems such as beams, arches, and rings within the more general context of the three-dimensional theory.

Three-dimensional theory of solids, in its geometrical, balance, and constitutive aspects, is the subject of Chap. 4. This chapter may, however, be deferred to a later more comprehensive reading without making the rest of the material hard to understand.

Chapter 5 presents the geometrically exact formulation of beams [23] undergoing planar [246] and spatial motions. Most of the aspects of the dynamical formulation are illustrated paying attention to both the classical form of the equations of motion and the weak form that is the basis of all discretization strategies. The linearization as well as the perturbed versions of these theories or *ad hoc* approximate theories are discussed. Fundamental nonlinear behaviors of beams undergoing planar motions are unfolded both theoretically and experimentally.

Chapter 6 treats the static and dynamic loss of stability of slender beams. In particular, the Eulerian buckling problem is discussed for closed-section (uniform and nonuniform) beams subject to conservative unstabilizing loads. The loss of stability of the straight equilibrium configuration of slender thin-walled, open-section beams into twisted/bent buckled configurations is addressed both in general terms and through examples. Dynamic instabilities called parametric resonances are studied both theoretically and experimentally in slender beams subject to parametric excitations such as pulsating end thrusts causing large-amplitude oscillations. The perturbation method used to unfold this dynamic instability is generalized to arbitrary one-dimensional distributed-parameter conservative systems with linear damping. The chapter presents a fully nonlinear model of wings subject to steady airflows causing the Hopf bifurcation called flutter.

Chapter 7 presents the general theory of curved beams (arches) and rings. Within this general framework, the case of planar motions is discussed in terms of the fundamental nonlinear behaviors of curved elements which depend on the shallow or nonshallow character of the curved configurations. The special problem of deeply

buckled beams is discussed in the more general context of prestressed beams. The chapter closes with the discussion of the theory of cables which also offer flexural resistance to external loads.

The formulation of geometrically exact theories of thin elastic plates is presented in Chap. 8. Both elastic isotropic single-layer and multilayer composite laminated plates are treated. Extensive experimental results for thin isotropic metallic plates and carbon/epoxy multilayer plates are shown thus confirming the high fidelity of the presented nonlinear theories in the nonlinear range.

The focus of Chaps. 9 and 10 is on nonlinear one-dimensional theories of bridges with major interest in suspension and arch bridges which have a formidable role in structural engineering. Specific loading scenarios are addressed, such as the aeroelastic forces induced by winds. In particular, the problem of aerodynamic stability is discussed with emphasis on the calculations of aeroelastic limit states such as the torsional divergence or the coupled flexural–torsional flutter condition.

The major semi-analytical spatial discretization methods, including the method of weighted residuals (such as the Faedo–Galerkin method) and some versions of variational methods [78, 126, 216, 488], are described in Chap. 11. In particular, the link between the weak form of the equations of motion or the Principle of Virtual Power and the considered discretization approaches is highlighted.

Throughout the book a significant number of examples and problems are illustrated to make the theory and methods more accessible also in terms of their finest details.

Corrections or comments sent to walter.lacarbonara@uniroma1.it are most welcome. Corrections will be placed in due course on my web page: <http://w3.disg.uniroma1.it/lacarbonara>.

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