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A numerical study of the seismic response of arched and vaulted structures made of isotropic or composite materials

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A R T I C L E I N F O

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A B S T R A C T

The Generalized Differential Quadrature (GDQ) and Newmark methods are chosen to solve time integration problems such as the dynamics of composite arches and vaults with constant and variable cross-sections, under seismic impulse loading applied at the base. A 2D Equivalent Single Layer (ESL) shell theory is used to analyze the problem numerically, where the governing equations of motion are solved in a strong form without passing through any variational formulation. The total time interval is discretized in time steps, as required by a Newmark approach, and the GDQ method is applied to solve a system of linear ordinary differential equations for each time step. The accuracy of the proposed method in predicting the dynamic response of the arched or vaulted structures is demonstrated by comparing the GDQ-based results for different geometries and external loadings, with the ones obtained with a standard Finite Element Method (FEM).

1. Introduction

The analysis of the dynamics and vibrations of curved beams, arches and vaults, has been very attractive for a long time, due to their great importance in many fields of practical engineering. A complete analytical investigation on the topic is quite complex, because of possible coupling effects between displacements and rotations in the equations of motion, as well as the influence of a non-symmetric geometry, rotary inertia, or shear effects, among others. Some closed-form solutions for the free-in-plane vibrations and dynamics of circular arches with constant and variable cross sections can be found in [1–7].

Different analyses in the literature, however, have increasingly focused on the free vibration and dynamic numerical analysis of circular and/or non-circular in-plane arches, mainly based on finite elements (FE), Rayleigh-Ritz, Galerkin, discrete element methods (DEM). Among the first numerical studies, Petyt and Fleischer [8] proposed three FE models for determining the radial vibrations of a curved beam under different boundary conditions. Ahmed [9] introduced three FE different displacement models by incorporating an element with a varying number of degrees of freedom per node, to investigate the flexural vibrations of some curved clamped-clamped sandwich beams. Laura and Verniere de Irassar [10] applied the Ritz method to determine the natural frequencies of vibration of symmetric circular arches with linearly varying thickness carrying concentrated masses. Huang et al. [11] applied a systematic procedure based on the Laplace transform to study the transient response of circular arches, whereas Huang et al. [12] provided an analytic formulation based on the combined Frobenius and dynamic stiffness methods to study the in-plane vibration of arches with a varying curvature. Some analytical and numerical applications are also addressed in Caliò et al. [13] for a comparative evaluation of the exact frequencies and modal shapes in spatial arched structures. Many other FE models can be found in the literature for the investigation of the dynamic behavior of laminated arches with different geometries and materials (see e.g. [14–28] among others). Another possibility to analyze the dynamics and vibrations of the arched structures, is to apply the numerical DEM, as increasingly adopted in the literature to model masonry structures [29–35]. Such a method typically governs the independent motion of the component blocks caused by rocking, hinging and sliding, thus allowing for fully dynamic analyses with large displacements.

Some critical details and comparative evaluations between different numerical approaches to the topic is beyond the scope of the present work and can be found in the review papers by Chidamparam and Leissa [36] and by Auciello and De Rosa [37] and references therein.

The advent of the Generalized Differential Quadrature (GDQ) analysis, introduced by Shu [38] and recently discussed accurately in a review paper [39], has provided a framework where higher-order polynomials with a general order can be applied to approximate the

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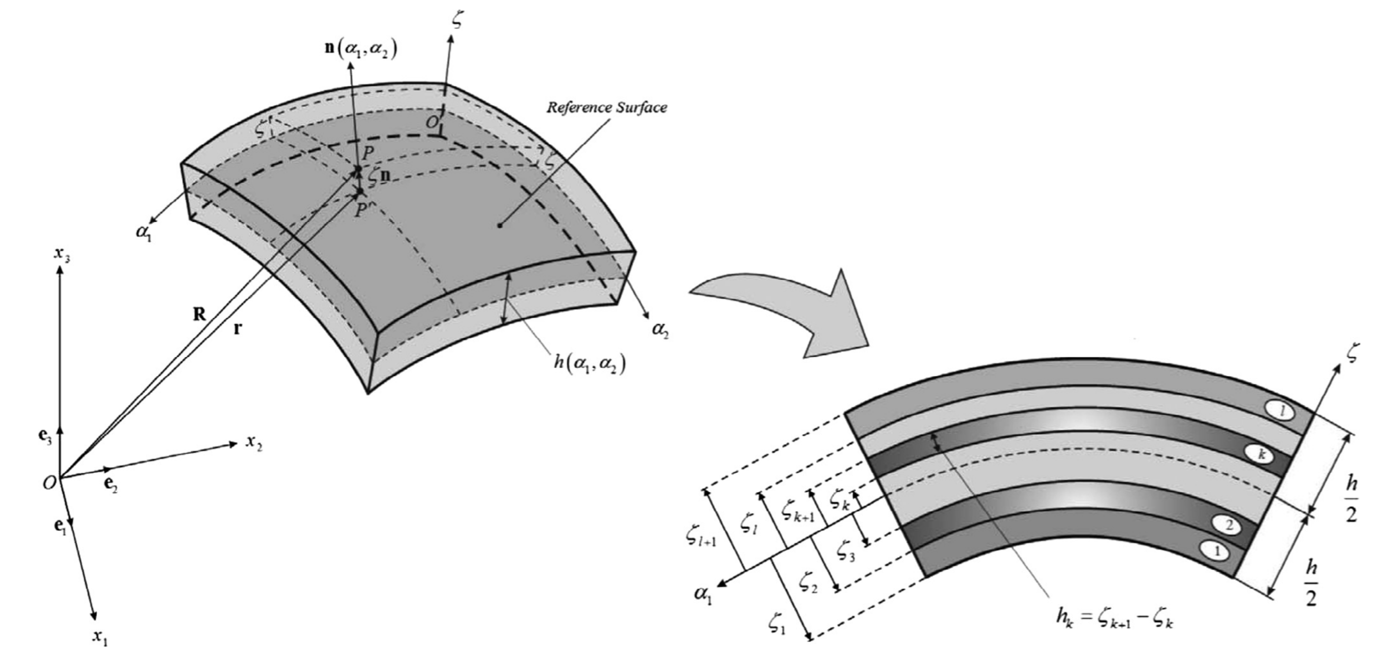

Fig. 1. Geometry of a generally-shaped doubly-curved shell and lamination scheme.

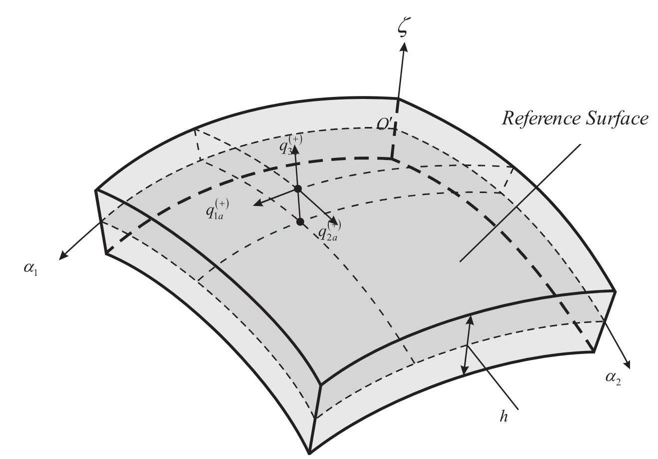

Fig. 2. Representation of the external forces applied at the upper surface of a generally-shaped doubly-curved shell.

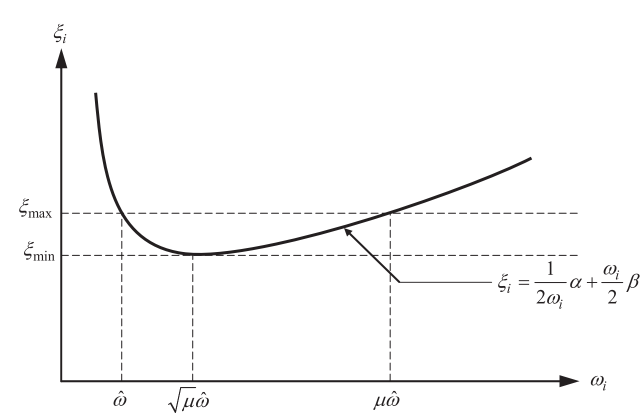

Fig. 3. Damping ratio ξ_i for the ith mode as a function of the circular frequency ω_i.

numerical solution in a strong form. The potential advantages of GDQ over conventional FE approaches for the modeling of free vibrations and dynamics of undamaged and damaged arches with different shapes has been widely verified in the literature [40–52].

The first thorough application of the GDQ to arched problems can be found in [40], where the GDQ approach is combined with the δ-technique to compute the fundamental frequencies of inextensible non-uniform cross-section rings. Following this pioneering work, Kang et al. [41,42] extended the same procedure to investigate the dynamics of both extensible and inextensible circular arches with a uniform cross-section, whereas Liu and Wu [43] generalized the problem to circular arches with varying cross-sections and different boundary conditions. Moreover, Kang et al. [44] investigated the influence of the shear deformation on the natural vibrations, while Karami and Malekzadeh [45] later removed the hypothesis of inextensibility of the central axis, including the rotary inertia in their differential quadrature formulation. De Rosa and Franciosi [46] applied the GDQ method to solve the sixth-order differential equation of motion that governs the free in-plane vibration of circular arches, where the higher-order derivatives at the boundary points were considered as additional independent variables. Many other works in literature have successfully studied the free vibrations of arch- and shell-structures with different shapes and innovative materials by means of the GDQ approach (see e.g. [47–64] among others), whereas an increasing attention has been devoted, in the scientific community, to solve transient problems by means of higher-order methods [65–72]. In the last case, it is well known as the computational efficiency and reliability of numerical solvers are strictly related to the selected integration scheme, and they represent two necessary prerequisites for a good quality solution in dynamics. In such a context, Tomasiello [65] applied successfully the GDQ-based approach to study the non-linear dynamics of some continuous beam systems, considering the effect of internal resonances and other phenomena usually neglected in the reduction to a single-degree-of-freedom oscillator. Civalek [66] studied the dynamics of thin isotropic plates by applying a discrete singular convolution approach and a harmonic differential quadrature method to discretize the spatial and temporal domain, respectively.