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Leonardo Leonetti, Domenico Magisano, Francesco Liguori, Giovanni Garcea

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An isogeometric formulation of the Koiter's theory for buckling and initial post-buckling analysis of composite shells

Leonardo Leonetti[a,*], Domenico Magisano[a], Francesco Liguori[a], Giovanni Garcea[a]

[a] *Dipartimento di Ingegneria Informatica, Modellistica, Elettronica e Sistemistica Università della Calabria 87036 Rende (Cosenza), Italy*

Abstract

Numerical formulations of the Koiter theory allow the efficient prediction, through a reduced model, of the behavior of shell structures when failure is dominated by buckling. In this work, we propose an isogeometric version of the method based on a solid-shell model. A NURBS interpolation is employed on the middle surface of the shell to accurately describe the geometry and the high continuity typical of the displacement field in buckling problems and to directly link the CAD model to the structural one. A linear interpolation is then adopted through the thickness together with a modified generalized constitutive matrix, which allows us to easily eliminate thickness locking and model multi-layered composites. Reduced integration schemes, which take into account the continuity of the shape functions, are used to avoid interpolation locking and make the integration faster. A Mixed Integration Point strategy makes it possible to transform the displacement model into a mixed (stress-displacement) one, required by the Koiter method to obtain accurate predictions, without introducing stress interpolation functions. The result is an efficient numerical tool for buckling and initial post-buckling analysis of composite shells, characterized by a low number of DOFs and integration points and by a simple and quick construction of the reduced model.

Keywords: Geometric nonlinearities, isogeometric analysis, composite shells, reduced integration, MIP

1. Introduction

Composite shells are nowadays employed as primary structural elements in a very wide range of applications. Their success is mainly due to the high strength/weight ratio that is crucial for lightweight structures. The failure of such elements often occurs because of buckling phenomena which make them sensitive to material, geometrical and load imperfections [1, 2]. Thousands of equilibrium path evaluations can be required in order to detect the worst imperfection case in terms of failure load. Once discretization techniques are applied to the continuum problem, the arc-length nonlinear analysis is the standard approach for reconstructing the equilibrium path of such structures. This analysis consists in solving step-by-step a system of nonlinear equations where the unknowns are the discrete degrees of freedom (DOFs) and the load factor. Although this method easily provides the desired information for assigned data, it is too time consuming [3] and inappropriate for an imperfection sensitivity analysis with current CPUs when fine meshes are needed. Furthermore, the stacking sequence has proven to strongly affect the buckling and post-buckling response of the shells [4–6] and the design of an optimal layup can significantly increase the load-carrying capability [7]. Consequently, the need for an optimization process leads to a further computational burden and requires more efficient tools of analysis and design.

For these reasons, a great amount of research has focused on developing reduced order models (ROMs) based on the finite element (FE) implementation [8–20] of the Koiter theory of elastic stability [21]. This

*Corresponding author

Email addresses: leonardo.leonetti@unical.it (Leonardo Leonetti), domenico.magisano@unical.it (Domenico Magisano), francesco.liguori@unical.it (Francesco Liguori), giovanni.garcea@unical.it (Giovanni Garcea)