Global/local and coupled high order FEM-Peridynamics models for fracture analysis of isotropic and composite structures

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Abstract: *In industrial practice, design and maintenance phases mainly rely on similitudes and past experience to characterize the current integrity state and to take into account its effect on performance. However, this approach can easily lead to unjustified heavy structures or not ideal inspection procedures and intervals. This thesis aims to provide high-fidelity numerical models that can be integrated with data from experience to support design and maintenance procedures. The framework relies on higher-order structural theories based on the well-established Carrera Unified Formulation (CUF). CUF is a generalized hierarchical formulation that generates a class of refined structural theories through variable kinematic description. CUF-based models can provide accurate 3D-like stress fields at a reduced computational cost, e.g., approximately one to two orders of magnitude of degrees of freedom less than standard 3D brick elements.*
CUF-based finite element models are combined with a Hashin-based orthotropic damage model for dealing with damage in fibre-reinforced composite materials. This method belongs to the family of computational models based on the so-called Continuum Damage Mechanics (CDM). Hence, cracks are smeared out within the volume of the finite element, degrading the stiffness of the involved material points. The proposed method's main novelty lies in its capability to consider a full three-dimensional stress state to describe the damage propagation. Furthermore, this approach can also view three independent failure modes: fibre, matrix and interlaminar.
In order to deal with progressive failure analysis, CUF-based Finite Element Models (FEM) are also coupled with Peridynamics (PD). PD is a non-local formulation capable of coping with discontinuities, such as cracks. The PD theory does not suffer from the inapplicability of the classical continuum mechanics theory when cracks or interfaces happen due to the integro-differential nature of the governing equations. Thus, PD presents a unique capability of analyzing damage and progressive failure of materials and structures by directly predicting the displacements, crack nucleation and propagation with arbitrary paths without any special numerical techniques or criteria. Two methods are here presented to couple high order 1D and 2D CUF-based finite elements with 3D PD sub-regions. The first one is based on the adoption of Lagrange multipliers at the interface surface between PD and FEM domains. Furthermore, a second method, based on the continuity of the displacement field at the interface, is also proposed.
Furthermore, a global-local approach has been extended to deal with the refined local analysis of larger regions. It consists of a two-step procedure. In particular, the first step makes use of finite element modelling based on classical 2D plate elements by using commercial FE software, whereas a refined layer-wise model based on CUF is employed to extract the 3D stress and strain fields in some critical regions that may have arbitrary dimensions. This approach allows for dealing with large local areas, increasing the static solution's accuracy and possibly embedding this technique in more complex procedures, such as the least-weight design of large heterogeneous complex assemblies and stiffness optimization. This approach has then been combined with the previously mentioned coupled FEM-PD

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models for dealing with progressive failure analysis in specific regions of large structures, for example, in regions where a crack is more likely to develop or has been detected in previous inspections.
Finally, CUF-based finite element models have also been employed as a data generator for the training of data-driven deep learning approaches, to create a complete mapping of damages in aeronautical structures, even considering those occurring in localized components. A vibration-based method is first introduced. An Artificial Neural Network (ANN) is employed to solve the inverse problem: given some specific features, the ANN should be able to predict both the location and intensity of damages in the investigated structure. For this method, some vibrational characteristics (e.g. natural frequencies and Modal Assurance Criterion (MAC) scalars) are considered. The second proposed technique uses displacement and strain field images to perform a complete mapping of damages in composite laminates through a Convolutional Neural Network (CNN).
A selection of numerical results obtained by adopting the formulations and techniques proposed in this thesis are employed to demonstrate the framework capabilities, both in terms of efficiency and efficacy.

Keywords: Finite Element Method; Carrera Unified Formulation; Higher-order beam/plate models; Isotropic material; Composite material; Peridynamics; Global/local; Progressive failure analysis; Damage detection; Coupling methods.