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TRANSPORT OF AN ENDLESS BEAM ON A MOVING ROUGH SURFACE

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Summary: The planar deformation of a beam that travels across a given control domain supported by a moving rough plane is analyzed. This model problem is a prototype for several technological processes. Considering a small misalignment between the linear bearings at the boundaries, we formulate a new essentially nonlinear boundary value problem and demonstrate the appearance of multiple segments of sliding with alternating directions when the friction force grows. Supported by a numerical investigation, we find a self-similar limiting solution with infinitely many segments and obtain a closed form expression for the corresponding critical friction force. Its further growth results in the appearance of a zone of stick within the domain, whose length we compute analytically.

ABSTRACT

Various technical solutions such as belt drives or rolling mills feature frictional transport of thin deformable structures. While steady straight motion is usually the desired regime of operation, the real structure may exhibit unwanted vibrations, lateral run-off or deformation with sliding owing to the geometrical imperfections, contact conditions or dynamic instabilities. Practical importance and modelling complexity promote the rapid growth of the body of literature in the field; see review paper [1] as well as author's own works [2-5]. While most studies address transient dynamic processes, sometimes even finding the stationary regime of motion becomes a non-trivial task, see e.g. [6]. In the present contribution, we seek the motion of a beam transported on a moving rough plane, Fig. 1. The main outcomes of the study were recently published in [7].

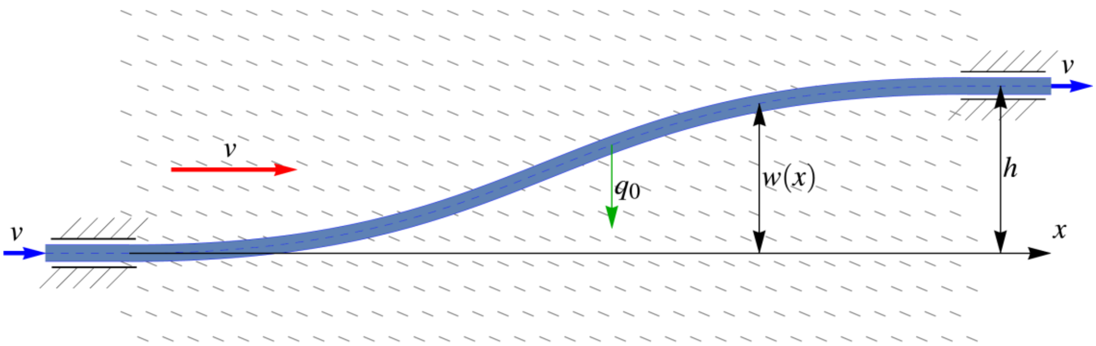

Figure 1 Axially traveling beam transported on a moving surface with sliding

The kinematic boundary conditions impose deformation, which is incompatible with the motion of the plane and thus makes sliding inevitable in at least part of the considered control domain. The current study is restricted to the slow motion of the system, such that the inertia (dynamic effects) can be ignored and a quasistatic solution is sought. We observe the characteristic phenomena within a geometrically linear formulation with small deflections of the beam. It is important that the considered model is far from being a mere mathematical abstraction. It directly describes the motion of a hot metal strip within a rolling mill on a roller table, when the finishing part at the exit has a small transverse or angular misalignment relative to the roughing mill at the entry to the considered domain. The complicated three-dimensional phenomena with partial transverse sliding of a flat belt on a rotating drum of a belt drive are also related to the present analysis, whose results may be used for validating advanced finite element procedures for modelling the frictional transport of slender rods.

The following essentially nonlinear boundary value problem describes the stationary configuration of the beam within the control domain:

$$aw'''' = q, \quad q = \begin{cases} -q_0, & w' > 0 \\ 0, & w' = 0 \\ q_0, & w' < 0 \end{cases}$$

$$w(0) = 0, w'(0) = 0, w(L) = h, w'(L) = 0.$$

Here a is the bending stiffness, $w(x)$ is the deflection, q_0 is the maximal friction force and h is the transverse misalignment of the linear bearings, which the beam follows at the ends $x = 0, L$. The sliding direction depends on the sign of the inclination of the beam axis w'. While axially moving structures with friction have long been considered in the literature, see e.g. the detailed analysis of the belt drive dynamics in [6], the present formulation is new. A problem of the frictional behavior of a beam with temperature induced curvature was treated by the authors of [8].

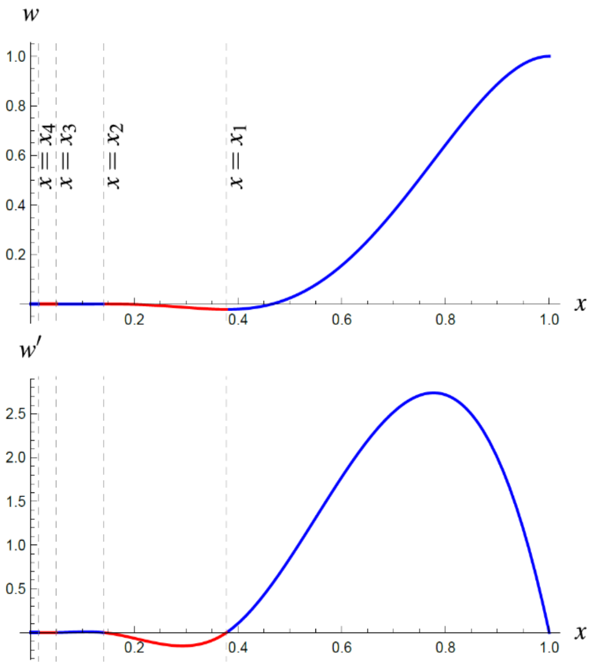

Figure 2 Solution with 5 segments of sliding friction

A detailed study of the above BVP demonstrates the possibility of multiple zones of sliding friction depending on the dimensionless force parameter $f = q_0 L^4/ah$, see the solution with 5 segments with alternating direction of sliding at $f \approx 365.198$ in Fig. 2. At the limiting force level $f = f_\infty \approx 375.659$, the number of sliding zones tends to infinity and the solution becomes *self-similar*: the configuration of an elastic body repeats itself infinitely at any scale, which is a rare case in structural mechanics [8]. A zone of sticking contact with $w' = 0$ appears as the force parameter exceeds the critical level f_∞. An analytic estimation of the size of the zone of sticking contact is available and can be used for practical computations. The analytical results are supported by numerical simulations.

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SINE VIBRATION QUALIFICATION OF THE EUCLID SPACECRAFT: ANALYSIS AND TESTING

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Summary: The structural-thermal model (STM) of the Euclid spacecraft performed a complete qualification test campaign in the year 2019. The sine vibration test predictions have been performed by using a very detailed structural mathematical model of the spacecraft and by the traditional frequency response analysis of the spacecraft in "hardmounted conditions". In addition, and this is a rather novel aspect for a large scientific spacecraft, the dynamic coupling between the shaker and the test article has been investigated by the so called Virtual Shaker Testing (VST) approach. This approach basically consists of performing the analysis by "merged" mathematical models of the test article, the shaker body, the seismic mass and the vibration control algorithm. This paper reports the main results of both the mentioned computational approaches used for the prediction of the dynamic response of the spacecraft, and it compares the prediction results with the dynamic behavior of the real structure under testing.

ABSTRACT

Euclid is an optical/near-infrared survey mission of the European Space Agency (ESA) to investigate the nature of dark energy, dark matter and gravity by observing the geometry of the Universe and the formation of structures over cosmological timescales.

This paper describes the overall approach for the sine vibration qualification of the Euclid spacecraft. The qualification has been reached by a structural-thermal model (STM). The test campaign has been carried out in October 2019 at the Thales Alenia Space France Test Facilities in Cannes. The sine test had the main objective to demonstrate the capability of the Euclid STM to withstand the "low frequency" flight loads magnified by the applicable qualification factor required by the Launcher Authority. Another important objective of the test was to provide the vibration data to be used for the correlation/validation process of the structural mathematical model.

The vibration test was carried out by installing the spacecraft on the electrodynamic shaker through the Force Measurement Device (FMD) and the Vibration Test Adapter (VTA). A dedicated set of strain gauges has been used to recover the forces at interfaces between the Service Module (SVM) platform and the Payload Module (PLM). Notching criteria, agreed between ESA and Industry, were defined in order not to exceed the spacecraft design loads at the Centre of Gravity (primary notching) and the relevant qualification loads of the equipment (secondary notching). System margins and sub-systems test heritage have also been taken into account to define a coherent test strategy. The sinusoidal test sequence consisted of excitations in lateral and longitudinal axes. Euclid stiffness compliance with the launcher requirements has been confirmed in line with the predicted results.

The sine vibration test predictions have been performed by using a very detailed structural mathematical model of the spacecraft and by the traditional frequency response analysis of the spacecraft in "hard-mounted conditions". In addition, and this is a rather novel aspect for a large scientific spacecraft, the dynamic coupling between the shaker and the test article has been investigated by the so called Virtual Shaker Testing (VST) approach.

Basically a VST approach consists of performing the analysis by “merged” mathematical models of the test article, the shaker body, the seismic mass and the vibration control algorithm. The subsequent coupled dynamic transient simulation, even if more complex than the classical hard-mounted frequency response analysis used for sine test-prediction, is a closer representation of the reality and in principle is expected to be more accurate.
One of the most remarkable potential benefits of the VST analysis is the accurate quantification of the “frequency down-shift” (with respect to the hard-mounted value), typically affecting the first lateral resonance of heavy test-items once mounted on the shaker. The above outcome can play a crucial role if the spacecraft has a marginal design with respect to the stiffness requirement imposed by the Launcher Authority.
Additional advantages of the VST approach are: the possibility to anticipate, prior to the test campaign, the effects on the dynamic responses of the test article induced by test parameters such as the compression factor and the sine sweep rate. The anticipation of possible issues of piloting or of cross-talks, possible overshoots and more in general to anticipate transient phenomena, such as beatings and control instabilities, can also be considered among the potential advantages.
In conclusion this paper reports the main results of the computational approaches used for the prediction of the dynamic response of the spacecraft and compares the prediction results with the dynamic behaviour of the real structure under testing.

Figure 1 Euclid Spacecraft on the shaker at Thales-Alenia Space Test Facilities in Cannes (F)

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Global/local capabilities of MUL2 for the nonlinear analysis of composite structures

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Summary: MUL2 is an in-house finite element (FE) platform whose structural formulation is based on the Carrera Unified Formulation (CUF). This work presents some of the latest capabilities of CUF and MUL2 concerning the structural analysis of complex composite structures. The modelling exploits global/local techniques and the node-dependent-kinematics (NDK) recently proposed within CUF. Assessments consider the evaluation of failure indexes along free edges, the tensile strength of notched specimens, and failure progression. Performances are evaluated in terms of accuracy and computational costs, and perspectives on advanced NDK modelling are drawn.

ABSTRACT

The virtual testing of composite structures necessitates structural models with advanced capabilities and computational efficiency. Examples of advanced capabilities are the detection of out-of-plane stress components and the detection of local effects, for instance, in the proximity of free edges. The computational efficiency is necessary to unleash the use of refined models to the upper levels of the test pyramid. Furthermore, the extension of such models to industrial cases widens the set of requirements, including, for instance, the analysis of structures with tens of layers.

CUF offers many opportunities to handle the modelling challenges listed above by incorporating the selection of structural theories into the set of inputs of the analysis. In other words, while, in commercial codes, a user is forced to use First Order Shear Deformation Theories, via CUF, any-order models are available. The combined use of CUF and 1D or 2D FE results in significant improvements of performance as compared to 3D FE.

Recently, CUF developments have led to the introduction of NDK to enforce a node-wise distribution of structural theory and further improve efficiency. Also, the synergy between NDK and classical global/local approaches makes the interface with commercial codes much less problematic [1, 2, 3].

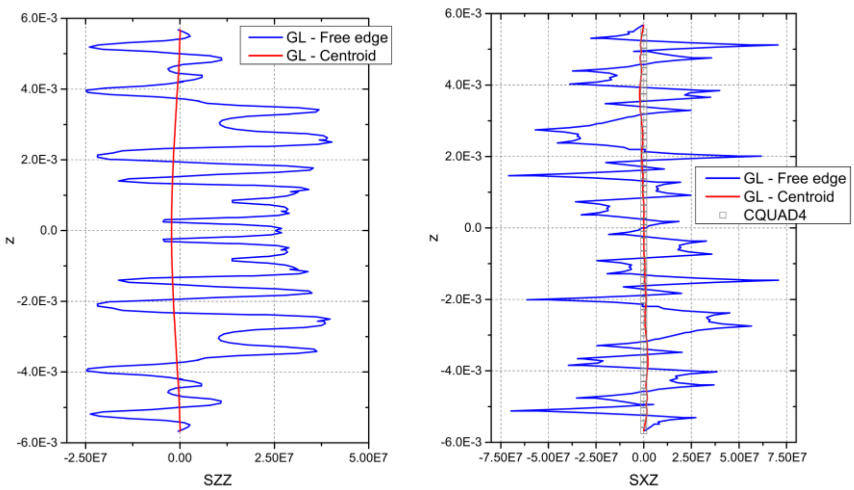

Figure 1 Free-edge peeling and transverse shear stress distributions along the thickness of a 64-layer laminate [2]

Figure 1 shows a numerical example concerning the out-of-plane stress distributions at different points of a laminate with tens of layers. Such distributions do not require post-processing techniques, e.g., numerical integrations, as they stem from the use of the constitutive equations.
The use of CUF can significantly extend the range of applicability of numerical models to problems with high modelling and computational complexity. Examples are the multifield modelling of manufacturing, the nonlinear progressive failure analysis, and the virtual testing of complex structures.

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VIBRATION CONTROL OF THIN PANELS WITH PIEZOELECTRIC PATCHES CONNECTED TO TUNEABLE RL-SHUNTS

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Summary: This paper presents a modular vibration control unit formed by a piezoelectric patch connected to a self-tuning RL-shunt, which can be bonded in batches on thin structures to reduce the resonant response of target low-order flexural modes generated by stationary stochastic excitations. The resistive and inductive components of the shunt are tuned online with an extremum seeking gradient search algorithm in such a way as to maximise the time-averaged electric power absorbed by the shunt itself.

ABSTRACT

Figure 1 shows the test rig used for this study, which is composed by a thin flat rectangular panel made of steel. Five thin square MFC piezoelectric patches are bonded on one side of the panel with the terminals connected via *ad hoc* interface circuits to a multi-channel dSPACE digital board, which has been used for the online implementation of the five self-tuning RL-shunts [1]. The panel is fixed to a rigid frame and is excited by a transverse point force exerted by a shaker via a stinger with a force cell.

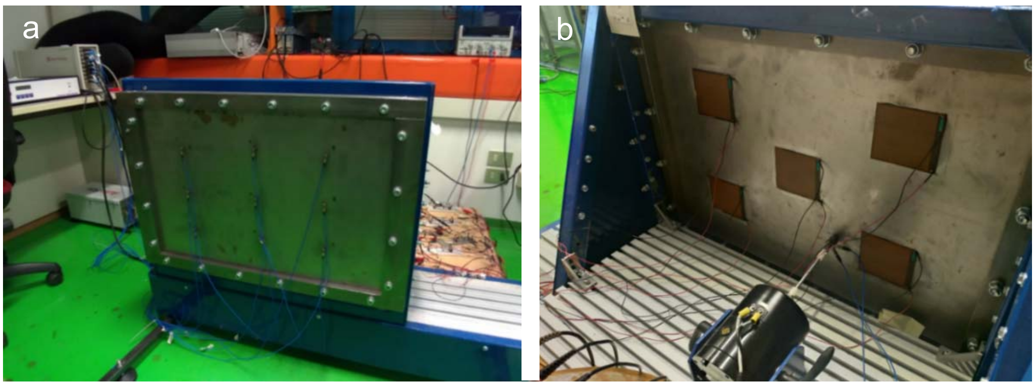

Figure 1: Thin panel model structure (a), which is equipped with five shunted piezoelectric patches (b).

Figure 2 shows the measured maps of the reference cost function, $\overline{K}_r(R_{sj}, L_{sj})$ (left hand side plots), and tuning cost function, $\overline{P}_r(R_{sj}, L_{sj})$ (right hand side plots), when the shunt connected to the centre patch is set to control the resonant response of the fourth mode (i.e. $r = 1$). For both modes, the map of $\overline{K}_r$ is characterised by a non-convex inverse bell-shape with a single minimum whereas the map of $\overline{P}_r$ has a mirror non-convex bell-shape with a single maximum. The positions of the minimum of $\overline{K}_r$ and the maximum of $\overline{P}_r$ closely overlap in the maps. Therefore, it can be concluded that, considering the resonant response of well-separated low-order flexural modes of the structure, the minimum of the time-averaged total flexural kinetic energy of the plate and the maximum of the time-averaged electric power absorbed by the shunt are characterised by the same optimal shunt resistance and inductance [2]. Hence, to minimise the time-averaged and spatially-averaged flexural response of the structure, the resistance and inductance of the shunt should be tuned to maximise the time-average electric power absorbed by the shunt itself.

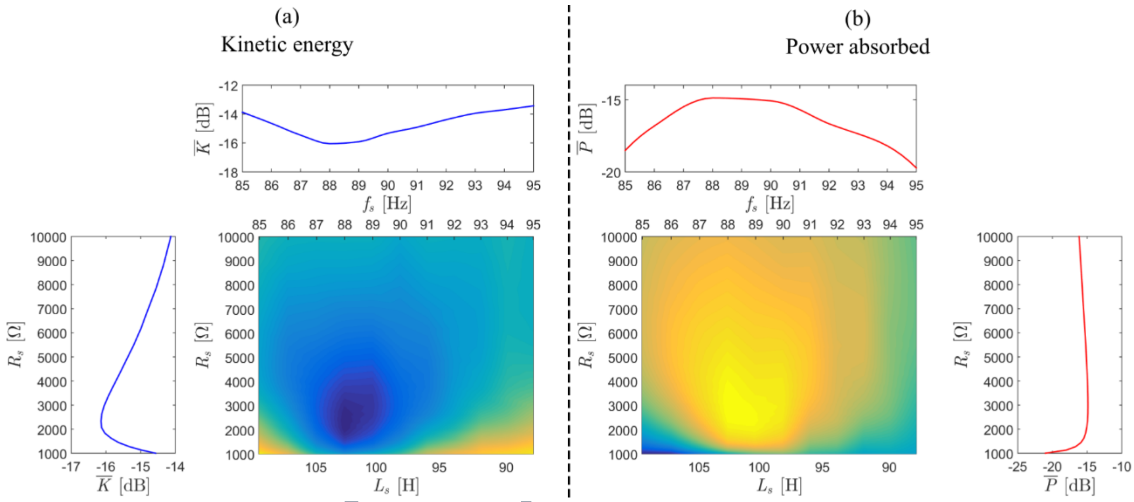

Figure 2: Plate mode 4. Measured maps of $\overline{K}(R_s, L_s)$ (a) and $\overline{P}(R_s, L_s)$ (b), with slices cut at L_{opt} (lateral plots) and R_{opt} (top plots).

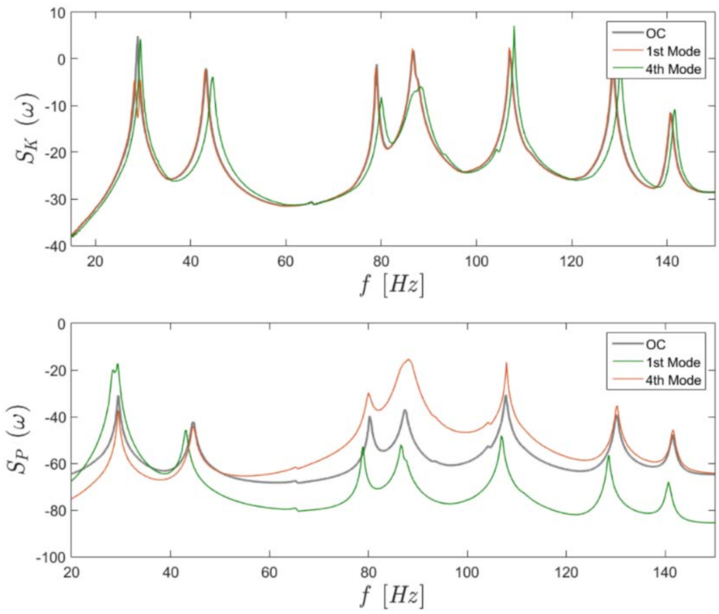

Figure 3: Measured spectra of (a) $S_K(\omega)$ and (b) $S_P(\omega)$ when the piezoelectric patches are in short circuit (grey lines) or connected to the shunts set to maximise the power absorbtion from the resonant response of the first (red line) and fourth (green line) modes.

The spectra in Figure 3 show that, when the 5 patches are connected to the shunts tuned to maximise the time-averaged electric power absorbed from the resonant response either of the first or fourth flexural mode of the structure, the two resonance peaks of the total flexural kinetic energy PSD are levelled down by about 12 dB and 10 dB. In parallel, the amplitudes and the widths of the two resonance peaks in the spectra of the absorbed electric power PSD are considerably raised.

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MIXED FINITE ELEMENTS FOR MULTILAYERED SMART PLATES NONLOCAL ANALYSIS

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Summary: A mixed finite element formulation for the Eringen's nonlocal analysis of smart, magneto-electro-elastic, multilayered plates is presented. Finite elements for different refined higher order plate layerwise theories are systematically developed. They ensure interface continuity and allow associating different values of the nonlocal parameter to the laminate layers. Standard 9-node and 16-node isoparametric, quadrilateral finite elements have been implemented and tested, showing the characteristics and limitations of the proposed approach.

ABSTRACT

Small scale effects are observed in many engineering structural applications. Classical continuum theories do not account for small-scale effects; thus, modified continuum-based theories have been introduced to overcome this limitation. Among the approaches proposed in the literature, the Eringen's nonlocal elasticity model [1] has been recognized as very promising. It assumes that the stress at a point is a function of strains at all points in the continuum; in this way, the small-scale effects are introduced through the constitutive equations, which involve a scale parameter depending on the material microstructure. In the present work, a mixed finite element formulation for the analysis of multilayered magneto-electro-elastic plates with layers exhibiting Eringen's nonlocal behavior is presented. To implement general high order plate theories, according to the Carrera Unified Formulation [2], the problem primary variables are expressed at layer level (layerwise approach) as through-the-thickness expansions of suitable selected functions. The set of governing equations for the laminate layers is deduced via the Reissner Mixed Variational Theorem, assuming the generalized displacements and out-of-plane stresses as primary variables [3]. The weak form of these governing equations is deduced and employed to formulate the corresponding finite elements by approximating the variables expansion coefficients by the finite element scheme. In the formulation, the through-the-thickness expansion order is retained as a free parameter, so that finite elements for different refined higher order plate theories are systematically developed by assembling the layers contributions associated with the variable expansion terms. These contributions are called fundamental nuclei and their definition results formally unique irrespective of the considered expansion order. The obtained finite elements inherently ensure stresses and displacements continuity at the layer interfaces and they allow associating different values of the nonlocal parameter to the laminate layers. Standard 9-node and 16-node isoparametric, quadrilateral finite elements have been implemented to verify the viability of the proposed formulation for static and free vibration problems. The obtained results agree with literature solutions and highlight characteristics and limitations of the approach.

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Experimental study of additively manufactured cylindrical Negative Stiffness Structures for shock absorber applications

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Summary: Negative Stiffness Structures (NSS) are particularly suitable for shock absorber applications. In this work the design, production and testing of three special-shaped NSS are presented. The influence of dimensional parameters and materials on structures' performances has been investigated producing, for each concept, five different samples in two different materials, namely PEBA (PolyEther Block Amide) and TPU (Thermoplastic PolyUrethane), and performing quasi-static compression tests.

ABSTRACT

Negative stiffness structures (NSS), as a branch of multi-stable mechanical metamaterials, exhibit multiple stable configurations. Their characteristics, such as bi-stability, snap-through and negative stiffness, make them particularly suitable for shock absorber applications. The majority of NSS is designed in a cuboidal shape and only recently few studies focused on cylindrical negative stiffness structures [1].

During this study, three types of special-shaped NSS have been designed, produced and tested.
To determine the influence of dimension parameters and materials on the functionality of these flexible structures, for each one of three concepts, five different versions in two different materials and techniques have been realized.

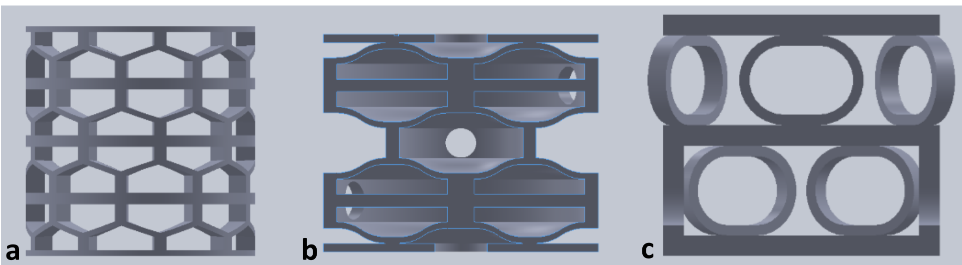

Figure 1: a) Cylindrical NS structure, b) NS honeycomb convolution structure, c) Elliptic unit cell structure.

The specimens were fabricated in PEBA and TPU using, respectively, Selective Laser Sintering (SLS) and MultiJet Printing (MJP) technologies; the design freedom of Additive Manufacturing (AM), allows the production of complex structures and the possibility of functional integration like shock absorber functionality.

Albite in different ways, in all the three structures unit cells are present pre-shaped curved beams to ensure snap-through and bi-stable mechanisms and are expected to exhibit exceptional energy dissipation properties.

The first concept (fig. 1a), based on the results presented by Xiaojun Tan et al. [1], investigates the effect of asymmetrical unit cells.
In the second one (fig. 1b), a cylindrical structure has been obtained convolving a well-known NS honeycomb structure [2]. The major design challenge for this structure is to overcome the manufacturing constraints. In order to face this challenge, discontinuities in both the internal and external shape have been included to allow the residual powder removal in the post-processing production phase.
The third and last structure (fig. 1c), has been designed with a circular repetition of elliptic unit cells to achieve a circular cross-section.

To investigate the mechanical and NS properties of these structures and their deformation mechanisms, quasi-static compression tests have been performed according to ASTM D695 – 15 regulation.
The results analyzed through force-displacement curves, highlighted the energy recovery of the specimens during deformation and the influence of dimension parameters on the response to the applied loads.
During the tests, it was also evident how the usage of different dimensions and materials can lead, for the same structure, to a symmetric or asymmetric buckling mode in the collapse of the layers and to prevent the structure to return to its original shape once the load has been removed.

Moreover, to evaluate the combined effect of all the dimensional and manufacturing variables on the structures, the experimental results have been processed through a Design of Experiment (DOE) methodology.

At last, the experimental results of the structures showing a NS behaviour have been exploited to develop and validate a FEM numerical model which will allow the optimization of NSS with different geometries and materials. The numerical analyses have been performed in Ansys. The buckling phenomenon is solved by a transient structural analysis with quasi-static behaviour and the hyperelasticity of the material is described by the Neo-Hookean model [1].

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ANALYSIS OF BEAM STRUCTURES BY COMBINED 3D PERIDYNAMICS AND REFINED 1D FINITE ELEMENTS

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Summary: Previous literature has demonstrated that the Carrera Unified Formulation (CUF) can be used to generate higher-order finite elements with unprecedented accuracy. As a matter of fact, either 1D CUF elements can provide accurate 3D internal stress states within simple to complex structures and still preserve a high computational efficiency. The objective of this work is to present the latest developments in the coupling of refined 1D CUF-based finite elements with 3D peridynamics grids. The effectiveness of the proposed models is tested with both static and fracture analysis.

ABSTRACT

The peridynamic theory is a continuum version of molecular dynamics [1]. Essentially, it assumes that a solid body is composed by material particles and each pair of those interacts if their distance is less than a prescribed material horizon of radius δ. The physical interaction between the particles at $\boldsymbol{x}$ and $\boldsymbol{x}'$ is called a *bond*, which extends over a finite distance. Bonded particle $\boldsymbol{x}$ exerts a force $\boldsymbol{T}(\boldsymbol{\eta},\boldsymbol{\xi})$ on particle $\boldsymbol{x}'$, where $\boldsymbol{\eta}$ and $\boldsymbol{\xi}$ are the relative displacement and initial distance vectors of the two particles. Evidently, peridynamics is a non-local theory and recently has attracted the attention of the scientific community for being successfully applied to solid mechanics and crack propagation problems. Nevertheless, this method can be computationally prohibitive for many applications, because the resulting matrices are sparse (not generally banded) and large. In this context, researchers have been extensively working in coupling models, in which peridynamics coexists with classical finite element (FE) approximations [2].

In the present work, the first step has been the coupling of 3D bond-based peridynamics (PD) is with refined 1D finite elements based on the Carrera Unified Formulation (CUF) [3]. In essence, by expressing the 3D displacement field as a generic expansion of the 1D generalized unknowns, CUF allows to generate low to high order finite elements in a general and unified manner. The theory approximation, i.e. the accuracy of the model, is a free parameter in CUF, which has been demonstrated to provide efficient (tunable) models able to describe accurately the 3D strain/stress states of structures with simple to complex geometry and for any material anisotropy.

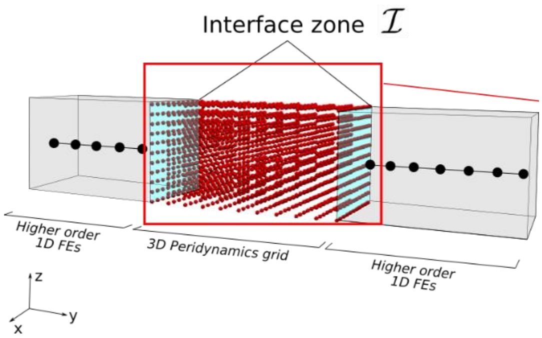

Figure 1 Coupling 3D peridynamics with refined 1D CUF finite elements

Figure 1 shows a solid beam in a Cartesian reference system. A portion of the solid body is modelled by 3D peridynamics, whereas the rest of the domain is discretized by high order 1D elements. Given an interface (contact) zone, denoted by $\mathscr{I}$ in the figure, between the peridynamic domain and the 1D FEs, Lagrange multipliers are used in this work to satisfy the congruence conditions on $\mathscr{I}$ and eliminate the singularity of the global stiffness array. Pagani and Carrera [4] showed that the coupled models have low computational costs and have demonstrated to be effective for a wide range of structures.

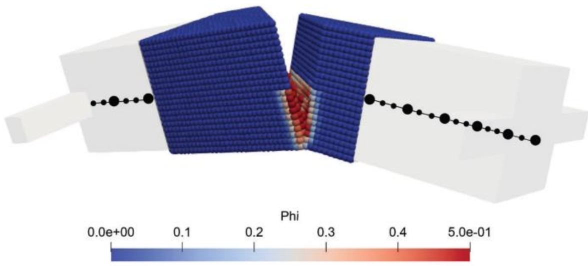

Figure 2 Damage distribution in a beam under torsion load by 1D CUF – 3D PD coupling [5].

Thus, this coupling method has been applied for quasi-static fracture analysis, providing good results for both the failure load of a structure and the shape of the crack pattern, as shown in Figure 2 [5]. Then, the method has been extended to the state-based peridynamics formulation [6], which allows the removal of any constraint on the Poisson ratio's value. Moreover, the method proposed by Galvanetto et al. in [2] has been implemented for the coupling of 3D state-based PD and refined 1D finite elements based on CUF. This method considers that peridynamics bonds act only on peridynamics nodes, while finite elements apply forces only on FE nodes, and it has proven to be very effective for a large number of case study. These aspects may bring to further and more in-depth studies on fracture analysis by coupled PD-FE models for problems of practical interest.

Acknowledgements
The authors would like to acknowledge the DEVISU project which was supported by the Ministero dell'Istruzione, dell'Università e della Ricerca research funding programme PRIN 2017.

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FAST ANALYSIS OF POSTBUCKLED CURVILINEARLY STIFFENED PANELS

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Summary: The work covers the development of a fast approach for the nonlinear analysis of variable stiffness composite panels with curvilinear stringers. The postbuckling response is investigated for loading conditions of compression and shear. The method is developed based on First Order Shear Deformation (FSDT) theory and beam modeling for the stringers. The solution is sought in the context of the Ritz approximation. The so obtained tool is a powerful mean for addressing the potential of innovative configurations designed to operate in the postbuckling regime and offering a high degree of design tailoring due to non-uniform stiffness properties.

1 INTRODUCTION

The seek for efficient structures is a constant challenge in the aerospace field. Growing interest has been recently devoted to variable stiffness (VS) laminates, offering the potential to achieve weight saving due to improved design flexibility. Similarly, improved efficiency could be obtained by relaxing topological constraints on classical stringer-stiffened configurations and by allowing the stiffener path to run along curvilinear directions. The combination of skins with variable stiffness properties and curvilinear stiffeners is then a promising chance to further improve the design tailoring of classical aerospace constructions. Recent works are found focusing on the linear buckling and vibration response of these new structures [1-4]. Investigations addressing the nonlinear response are scarce, although crucial for further understanding their potential as load bearing components. The present work stems from previous investigations focusing on the linear case [3,4] and aims at extending the field of application of the formulation to the nonlinear postbuckling regime.

2 FORMULATION

A semi-analytical formulation is developed in the framework of a displacement-based approach. The plate kinematics relies upon First Order Shear Deformation Theory (FDST), which turns to be particularly suited for handling the compatibility requirements between the skin and stringers. Geometric nonlinearities, both for the plate and the curvilinear stringers, are accounted for in the context of von Kármán-like approximations.
The problem is formulated by referring to the Principle of Virtual Work, where the unknown fields are approximated using global Ritz functions, in the framework of a total Lagrangian approach. The set of resulting nonlinear algebraic equations are solved in the context of an incremental-iterative approach based on the Newton-Raphson scheme. Special care is given to the implementation of the formulation to guarantee reduced time for analysis.

3 RESULTS

Exemplary results are presented for the postbuckling response of a VS panel with five curvilinear stringers [1]. The plate is loaded in pure compression through an imposed axial displacement at the two longitudinal sides. The load is applied up to a total shortening Δu corresponding to five times the linearized buckling condition Δu_{cr}. Hence, the investigation is extended up to the moderately deep postbuckling field. An imperfection is introduced with shape corresponding to the first buckling mode and amplitude equal to 10% of the skin thickness. The contours of the out-of-plane deflection and the membrane resultant N_{xx} are reported in Figure 1, where the comparison against Nastran finite element results is illustrated.

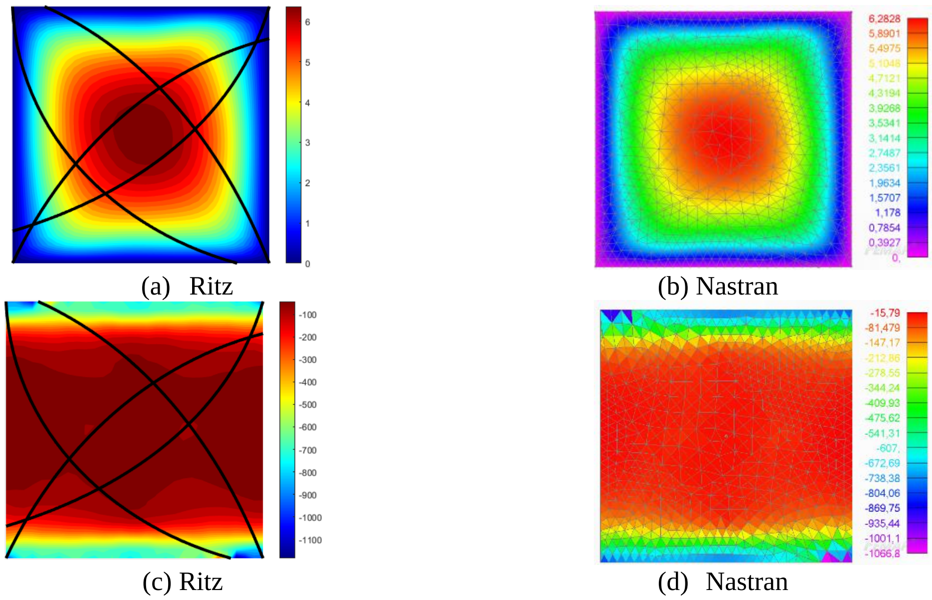

Figure 1: Postbuckling response of curvinearly stiffened VAT plate at $\Delta u=5\Delta u_{cr}$:
(a), (b) out-of-plane deflection, (c), (d) membrane force N_{xx}.

As seen, close agreement is observed both in terms of deflected shapes as well as membrane forces. The proposed method allows the analysis to be run in few seconds, and no time for the modeling is needed. Both these features are essential for properly assessing the nonlinear behaviour of structures characterized by a relatively complex configuration, such as the ones investigated here.

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EXACT COMPUTATION OF THE CUBE-SPHERE INTERSECTION VOLUME TO IMPROVE PERIDYNAMIC NUMERICAL INTEGRATION

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Summary: An innovative method is developed to exactly compute the cube-sphere intersection volume for any value of the sphere radius, length of the cube edges and position of the cube with respect to the sphere. The results obtained with this method are used to achieve an improved accuracy and convergence behavior of the numerical integration in peridynamic models.

ABSTRACT

Peridynamics is a non-local continuum theory capable of simulating crack initiation, propagation, interaction and bifurcation without any *ad hoc* criteria [1]. Any material point in the body interacts with every other point within a radius δ. The sphere containing all those points is named "neighborhood". The neighborhoods of the points near the boundary of the body are not complete, but this problem can be solved by using the method presented in [2,3]. The most common discretization in Peridynamics is the meshfree method with a regular grid, in which the body is subdivided into cubic cells with a uniform grid spacing h. However, in order to improve the accuracy of the numerical integration, the contribution of each cell in a neighborhood should be weighted as the fraction of the cell volume lying within the neighborhood itself [4]. Therefore, the exact evaluation of the cube-sphere intersection volume is of paramount importance in Peridynamics. We proposed an innovative method to compute the intersection volume for any value of δ/h ratio and for different positions of the cell within the neighborhood [5]. Several numerical examples adopting the new method have been carried out to show the improvements in accuracy and convergence behavior of the numerical results with respect to previously proposed approximated algorithms.

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MULTIPLE LOCAL RESONATORS PERIODIC DESIGN FOR INTERIOR NOISE CONTROL

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ABSTRACT

Nowadays, an aircraft project cannot neglect noise consideration for interior and exterior noise. Furthermore, exterior acoustic disturbance is crucial in terms of noise pollution and regulations, while interior annoyances due to acoustic sources should be avoided (or at least minimized), in order to upgrade travel conditions and comfort for passengers. The frame of an aircraft is generally made by thin structures of aluminum or composite materials, which are surely perfect materials for their main function but inadequate for acoustic insulation purposes.
Hence, acoustic solutions must be introduced, but they should guarantee great performances without requiring excessive weight and/or space increase. Acoustic metamaterials are designed to take into account these boundaries, by assembling complex cells with a proper arrangement, shape or geometry aimed at reducing sound disturbance [1–2]. This approach, even through the use of conventional materials, allows to produce systems which exhibit extraordinary properties, such as negative refraction, sub-wavelength imaging, cloaking, one-way transmittance. Meta-material can be designed through basic acoustic objects like Helmholtz Resonators [3], porous materials [4], quarter-wavelength tubes [5] and Dynamic Vibrating Absorbers (DVA) [6].
The main advantage of acoustic metamaterial is the design flexibility: indeed, each sub-system can be useful for a specific purpose (and of course less effective for others). For instance, acoustics resonators like Helmholtz Resonators and Dynamic Vibrating Absorbers have great performance when they are applied for the suppression of tonal sources; acoustic resonators are characterized by tunable resonance frequencies that can completely delete the source sound disturb. In contrast, a porous layer can suppress high-frequency noise; however, it works as a damper either, hence its coupling with an acoustic resonator will affect the correct behavior of the resonator in correspondence of its resonance frequency.
Furthermore, a considerable number of applications are related to absorb the sound energy, while others are principally deployed when the sound wave should be not transmitted (transmission loss applications). For instance, a transmission loss application can be the one in Figure 1: a double-plate system made by coupling a structural panel with a panel employed for sound suppression (acoustic panel).
The acoustic panel is divided in multiple sub-structures, which are tuned through appropriate boundary conditions (BCs). Each sub-structure is helpful to arise the transmission loss of the whole model at a

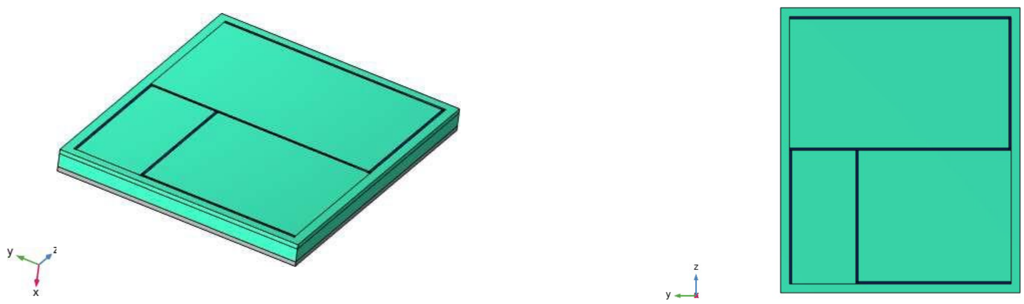

Figure 1: Double plate configuration; thick lines represent free edges, while thinner ones are the (clamped) junctions between the resonating sub-panels and the external frame.

specific tunable frequency. In contrast, a model like this is not useful for absorption objectives. Another acoustic metamaterial design can be otherwise successful for sound absorption but not the best option for transmission loss applications. An example is herein presented (Figure 2), made by three labyrinthine resonators (LRs), where each LR has a tunable resonance frequency similar but not equal to the others, in order to increase the bandwidth of influence and ensure good absorption properties in a specific range of frequency instead of being productive just in a narrow bandgap.

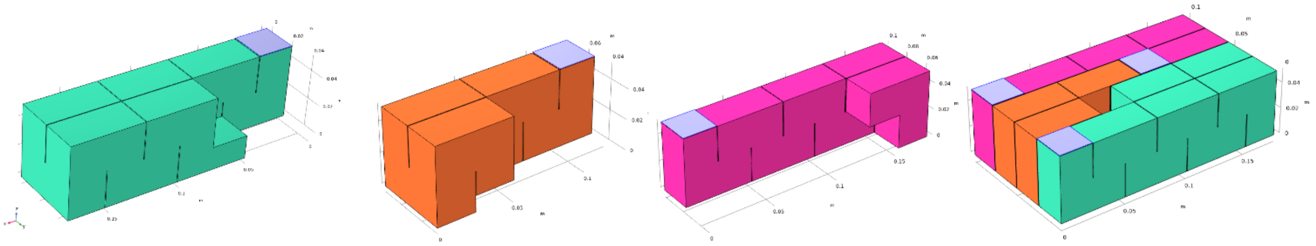

Figure 2: Labyrinthine acoustic metamaterial, made by 3 LRs.

In this work, different acoustic metamaterial solutions are numerically studied and compared, in order to highlight benefits and drawbacks of each objects in terms of sound absorption and transmission loss.

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NOISE ATTENUATION IN COMPOSITE LAMINATED STRUCTURES USING SGUF AND DMS

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Summary: In this paper we conduct multiobjective optimization of composite laminated panels with viscoelastic layers for noise attenuation and weight reduction. The Sublaminate Generalized Unified Formulation (SGUF) [1] is used along with the Direct MultiSearch (DMS) algorithm [2] to obtain the nondominated optimal solutions.

ABSTRACT

The generalized introduction of lightweight composites in the automotive and aerospace industries, while leading to significant weight reductions and associated fuel savings, pose a serious problem of low acoustic performance of these lightweight composites when subjected to mechanical or acoustic excitations. Passive damping technologies are nowadays frequently used to control sound and vibration levels using viscoelastic materials, as these are an efficient way of reducing structural vibrations and providing noise attenuation.

The open literature regarding the subject of vibration and sound radiation from passive or active composite and sandwich structures is quite scarce. Regarding the vibration control using passive technologies, previous works have been presented for mechanical vibration suppression and sound level attenuation and, more recently, the vibroacoustic problem has been addressed in double-wall sandwich panels [3,4].

This paper addresses the issue of noise reduction in laminated composite plates with viscoelestic layers. A Ritz implementation of SGUF is used to obtain the frequency response of the composite panels. The sound transmission characteristics of the panels are evaluated by computing their radiated sound power, using the Rayleigh integral method. The optimal layout of the laminate stacking sequence is obtained, where the design variables are the number of layers in the laminate, the type of material in each layer and the thickness and orientation of each ply. Minimization of both weight and noise radiation are sought with structural constraints (stresses and/or displacements). The optimization is conducted with the DMS optimization algorithm, which does not employ derivatives and does not aggregate any of the problem objective functions. Trade-off Pareto optimal fronts and the respective optimal laminate configurations are obtained, and the results will be presented, analyzed and discussed.

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TOPOLOGY OPTIMIZATION OF A TWO-DIMENSIONAL STRUCTURE USING PERIDYNAMICS

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Summary: The present work presents an engineering approach to topology optimization of a two-dimensional structure using peridynamics. The use of peridynamics enables the non-local form of the differential equations and allows the natural crack nucleation without any special treatment.

ABSTRACT

Structural optimization constitutes one of the most important topics in engineering in the last 30 years. Usually, the objective function evaluations are done with the use of the Finite Element Method (FEM). Its widespread use and ease of implementation allied to its numerical efficiency makes it an attractive tool to this end. However, it is not free of limitations, such as the existence of stress singularities on crack tips, or its difficulty dealing with crack propagation.

Peridynamic theory of solid mechanics is a recent theory introduced by Silling [1] in 2000 and extended by Silling et al. [2] in 2007. Peridynamics allows the natural nucleation and propagation of cracks without an additional special treatment and is free of stress singularities. Furthermore, due to its formulation, the theory is nonlocal, which allows the simulation of materials at multi scale due to a horizon parameter that enables interactions between non neighbor material points. Recently, Vieira and Araújo [3] extended the peridynamics framework for piezoelectric media.

In this work an engineering approach to topology optimization of a two-dimensional structures is conducted, using peridynamics. The formulations are presented for different objectives, and different examples, with and without cracks, are discussed and analyzed.

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AFS-ACTIVE FLUTTER SUPPRESSION PROJECT: ACTIVITIES OVERVIEW AND FINAL RESULTS

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Summary: AFS – Active Flutter Suppression is a research project leaded by University of Washington (Seattle), sponsored by FAA and participated as subcontractor by the Department of Aerospace Science and Technology (DAER) of Politecnico di Milano, started in 2017 and close to the end, scheduled next April 2020. The main goal of AFS project is the investigation and validation of technologies for active flutter suppression and includes both numerical and experimental phases. This paper summarizes the activities and results carried out, with a special emphasis on the results collected during the last phase of the test campaign on the complete F-XDIA wind tunnel model, in both open and closed loop.

ABSTRACT

Despite the first studies on active flutter suppression date back to end of '70s, still today aircraft have to be certified as flutter free on the entire flight envelope. However, recent enhancements of the capabilities and reliability of aircraft control system hardware and software, combined with the growing structural flexibility typical of modern transport aircraft, and hence potential for flutter problems and for related weight reduction of optimized composite airframes, seem to have made the implementation of Active Flutter Suppression (AFS) technology closer than ever before [1]. This makes the experimental study of the current state of the art of AFS important, especially from the perspective of uncertainty, reliability, and the safety of flight vehicles in which this technology will be used.

Contributing to both aeroelastic active control and AFS technology development for many years, DAER-POLIMI developed in the mid-2000s a scaled actively controlled aeroservoelastic model of a three-surface passenger airplane [2-5] and tested it in its large low-speed wind tunnel. Motivated by the need to return to the wind tunnel with an aeroservoelastic model of a configuration that would better capture the aeroelastic behavior of current and emerging commercial passenger and cargo flight vehicles that may benefit from AFS, a research program has been launched by the Politecnico di Milano and the University of Washington to focus on the reliability and safety of AFS-dependent flight vehicles using a wind tunnel model that would be representative in complexity and aeroelastic characteristic to real aircraft.

The F-XDIA aeroservoelastic model has been thoroughly modified, by changing the configuration and by the addition of wind tunnel model features that would allow the study of the effects of uncertainty on the performance and reliability of AFS. The experimental activity has been divided in two main PHASES: the first one focused on the wing only, while the second one dedicated to the complete model and carried out in the POLIMI's Large Wind Tunnel. While the activity and results obtained during PHASE I have been extensively described in [6,7], this paper describes in more detail the activities carried out to complete the model as well as the results collected during PHASE II in both open and close loop configurations. The model is entirely aeroelastic, and the active control system has been designed ad realized in house from both the hardware and software point of view. A dedicated anti-flutter system installed in a wing tip pod has been realized to automatically stop the flutter when the wing acceleration exceeds a pre-defined threshold for global safety purpose. Different active flutter suppression laws have been developed and successfully tested in an extended experimental campaign inside the large POLIMI's wind tunnel.

The model, and especially the instrumentation and onboard data acquisition system and controllers appeared as very reliable allowing to completely manage the test remotely from the control room. The anti-flutter device worked properly enabling safe testing near the flutter point without breaking the model. The flutter identification results confirmed the numerical predictions. Finally, the results in close loop configuration demonstrates the validity of the approach adopted. The final part of the AFS project will be focused on the robustness aspects analysis related to the experimentation of advanced controllers, aiming at the derivation of a series of best practices to be followed in the future to implement these technologies on real aircraft.

Figure 1: Onboard computer (a), GVT of complete model (b), final validation WT flutter test (c)

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MAGNETOMETRY OF BALL CHAINS GRANULATED MATERIAL

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ABSTRACT

In accordance with the physical model of the channel-by-channel magnetization of the granulated medium (the model of effective chains of granules), such a medium consisting of ferromagnetic spheres of chains of contacting granules (spheres) are responsible for this magnetization - as self-sufficient channel-conductors of the magnetic flux Φ [1-3].

Each of the chains is characterized by a pronounced redistribution of this flow on the cross section of the conductor-channel. This can be found if in a chain consisting of spheres with radius R, one core with a radius r is conditionally selected. Then, for the corresponding measurements Φ, surround core by flux-measure loop, placed in the gap between the contacting spheres. Loops in the form of conductive circuits on the printed circuit board were used for this purpose.

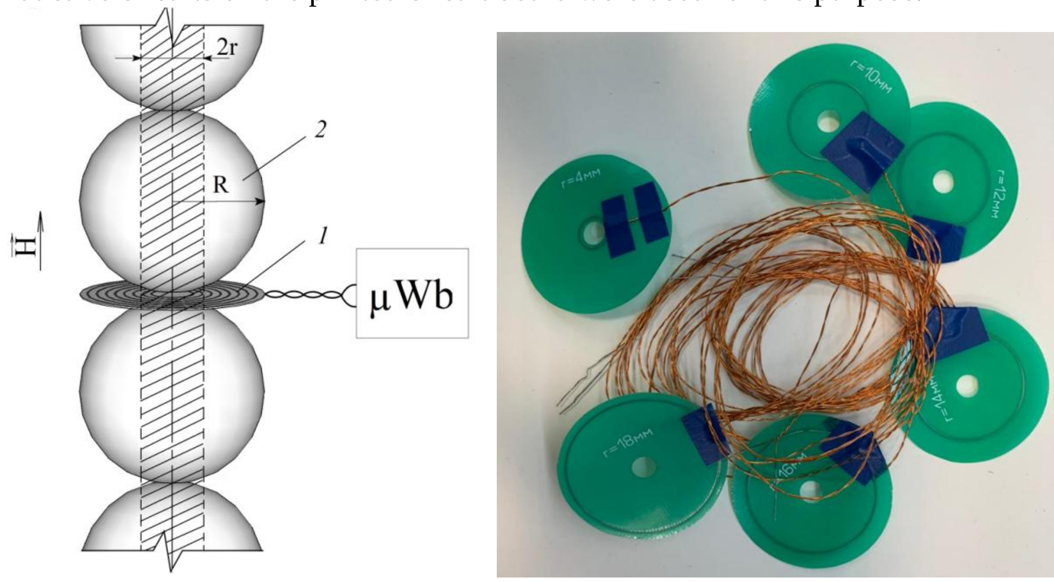

Fig.1. Illustration of the positioning of the loop *1* (from the concentric loop sensor block as loops on the printed circuit board, shown on the right) radius r in the plane of the symmetry of the volume between the contacting spheres *2* of the magnetized chain (corresponding to r, i.e. covered by loop, the core of the chain shaft is shaded).

From the measured data Φ the magnetic flux density is found, i.e. the average induction value B in the core. A conceptual position of the model expressed in how an increase in r decreases the flux density (induction B) in the core, has got an experimental confirmation. It requires the use of quite representative r/R numbers of different r loops (and the corresponding number of cores covered by them). And chains differing in the radius R should be used in experiments to obtain results that would indicate their versatility.

Thus, by confirming the conceptual positions of the physical model, these results contribute to the development of this model, which may be useful in solving a number of scientific and practical problems. Examples include creating technology and fine magnetic separation technology, i.e., separation of filtration type using such working bodies as ferromagnetic granular mediums.

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IMPACT RESPONSE OF VISCOELASTIC PLATES MADE OF MATERIALS WITH NEGATIVE POISSON RATIOS

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Summary: A mathematical model based on the utilization of fractional order operators for describing shear and bulk relaxations has been proposed for problems of impact response of thin plates, materials of which could possess negative Poisson's ratios.

ABSTRACT

Nowadays material engineers are looking for methods rising physical and mechanical characteristics of traditional materials via creating the structures possessing essential abnormal deformational features. As shown by experimental results, materials with negative Poisson's ratio (auxetics) belong to such abnormal materials [1]. There are a lot of papers devoted to auxetic materials, however, the majority of them are dealing with the internal structure of auxetics, experimental determination of Poisson's ratios, as well as with the description of features of different auxetics [2-4]. Papers discussing the mathematical models describing the behavior of viscoelastic auxetics and structures made of them are rare [5].

In the present paper, the problem on impact of a rigid spherical impactor upon a linear viscoelastic Kirchhoff-Love plate, made of viscoelastic auxetic material possessing fractional viscosity, has been formulated for the case, when the shear operator and bulk extension-compression operator are governed by the fractional derivative Kelvin-Voigt model, what allows one to take into account not only the shear relaxation but the volumetric relaxation as well.

It has been shown that the behavior of Kirchhoff-Love plate made of viscoelastic auxetic is different from the behavior of the viscoelastic plate lacking auxetic properties. This is due to the fact that the auxetic's Poisson's ratio is a time-dependent value changing from negative to positive magnitudes with time. The solution out of the contact domain is found via the Green's function, and within the contact domain via the generalized Hertz theory. Using the algebra of dimensionless Rabotnov's fractional operators, integral equations for the contact force and the local indention have been derived, and their approximate solutions have been obtained.

Acknowledgement
This research was supported by the Ministry of Science and High Education of the Russian Federation, Project # FZM-0641-2020-0007.

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FINITE ROTATION SOLID-SHELL ELEMENT FOR 3D ANALYSIS OF LAYERED PIEZOELECTRIC STRUCTURES USING SAS FORMULATION

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Summary: The paper presents a robust nonlinear exact geometry or geometrically exact (GeX) four-node piezoelectric solid-shell element through a sampling surfaces (SaS) formulation. The SaS shell formulation allows calculating transverse components of the second Piola-Kirchhoff stress tensor in layered piezoelectric doubly-curved shells with high accuracy.

ABSTRACT

This paper focuses on the development of a GeX four-node solid-shell element using the SaS method [1] for the three-dimensional (3D) stress analysis of laminated piezoelectric structures. The term GeX reflects the fact that the parametrization of the middle surface is known and, therefore, the coefficients of the first and second fundamental forms and Christoffel symbols are taken exactly at element nodes. The SaS method is based on choosing inside the *n*th layer I_n SaS parallel to the middle surface in order to introduce the displacements and electric potentials of these surfaces as basic shell unknowns. Such choice of unknowns with the consequent use of Lagrange polynomials of degree $I_n - 1$ in assumed approximations of displacements, electric potential, strains and electric field through the layer thickness yields the efficient higher-order piezoelectric shell formulation. The inner SaS are located inside each layer at Chebyshev polynomial nodes that permits to uniformly minimize the error due to Lagrange interpolation. As a result, the SaS solid-shell element can be applied to obtaining the numerical solutions for piezoelectric structures, which asymptotically approach the solutions of electroelasticity when the number of SaS tends to infinity.

In the SaS shell formulation, the Green-Lagrange strain tensor, which exactly represents the arbitrarily large rigid-body motions of a shell in any curvilinear coordinate system [2], is utilized. This makes it possible to calculate the second Piola-Kirchhoff stresses in piezoelectric doubly-curved shells with a high accuracy. The developed GeX solid-shell element is based on a hybrid-mixed method that allows the use of load increments, which are much larger than possible with the displacement-based finite elements. The tangent stiffness matrix is evaluated through effective 3D analytical integration as suggested in [3].

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On layerwise user-elements in Abaqus for free vibration analysis of variable stiffness composites and piezoelectric composite laminates

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Summary: In response to the still limited number of available literature on advanced structural models implemented as Abaqus user-elements, this study is devoted to the evaluation of layerwise user-elements for free vibration analysis of variable stiffness composites and piezoelectric composite laminated plates. The models predictive capabilities are demonstrated through a comparison with benchmark finite element solutions and 3D exact solutions.

ABSTRACT

The multidisciplinary subject of smart composite structures finite element modelling, namely for the analysis of piezoelectric sensors and actuators integrated in composite laminates, has experienced a remarkable advent in terms of research in the last three decades, underlying the development of the next generation of smart and multifunctional structural systems. Additionally, the recent advances in automated manufacturing techniques have shed light on the capability of tailoring variable stiffness composites, with curvilinear fibre paths, to further improve the performance of the conventional straight fibre composites. However, the implementation of Abaqus user-elements (UEL), assigning refined structural models for the analysis of such multilayered structures, remains not fully unveiled.

Therefore, a family of layerwise user-elements in Abaqus is developed and validated for free vibration analysis of purely elastic variable stiffness composites - in the form of variable-angle tow laminates - as well as piezoelectric multilayered composite plates. For the analysis of purely elastic variable stiffness composite laminates, two layerwise user-elements, assigning the first-order shear deformation theory (FSDT) or the third-order shear deformation theory (TSDT), for three discrete layers, are compared with available finite element solutions in the literature. Both thin and moderately thick plates are considered, either simply supported or clamped. In the case of simply supported straight fibre composite laminates, the models accuracy assessment is carried out through a comparison with 3D exact solutions. On the other hand, for the two layerwise electro-elastic user-elements [1], each of the three discrete layers is described by a first-order shear deformation displacement field combined with a linear or quadratic *z*-expansion of the electric potential. The models predictive capabilities on the evaluation of the first twelve natural frequencies of laminated plates with surface bonded piezoelectric layers (PZT-4 or PVDF) are assessed by a comparison with 3D exact electro-elastic solutions for simply supported plates and native Abaqus solid elements.

Overall, the underlying numerical results demonstrate fairly accurate and computational efficient predictions of the lower natural frequencies and mode shapes.

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V-STACK PIEZOELECTRIC BASED ADAPTIVE CONTROL OF INCOMPRESSIBLE AIRFOIL FLUTTER

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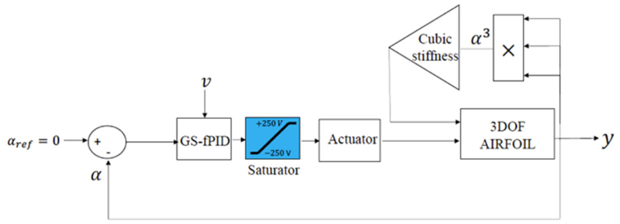
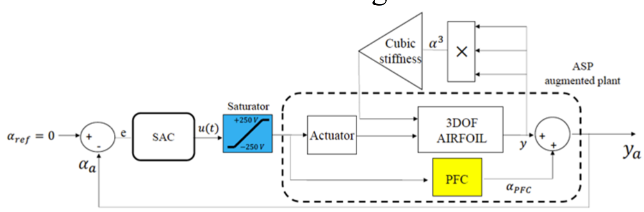
Summary: A comparison of the Simple Adaptive Control SAC and the Gain scheduled filtered PID GS-fPID controller for the suppression of airfoil flutter is presented in this work. Based on Theodorsen unsteady aerodynamic theory, the numerical model of an airfoil in incompressible flow is used in order to tune a SAC-based and f-PID based flutter suppression systems taking into account stiffness non-linearities, actuator dynamics and saturation, parameters variation, and pitch only measurements. The stochastic robustness analysis of the influence of structural parameters uncertainties on the closed loop systems response has been carried out.

ABSTRACT

The 3-DOF airfoil aeroelastic model has been extensively used over the years to predict flutter characteristics of lifting structures [1] and for preliminary active control systems design. In this work, the non-dimensional equations of motion of a 3-DOF airfoil in unsteady flow are taken into account [2]. Moreover, the FEM model of a high-bandwidth V-stack piezoelectric actuator is included in the closed loop system taking into account its input voltage saturation [3]. Therefore, a GS-fPID controller tuned by a Population Decline Swarm Optimizer P_DSO [3] is applied to the plant. Moreover, a SAC algorithm is applied to the plant that is made Almost Strictly Passive ASP by means of a Parallel Feedforward Compensator PFC, following the procedure described in [4]. The SAC invariant gains are tuned once again using the P_DSO procedure that minimize the Integral of Time Absolute Error ITAE of the pitch angle α. The two control schemes considered are shown in Figure 1.



a) GS-fPID control scheme



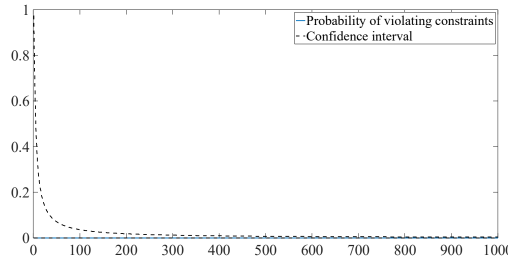
b) SAC control scheme

Figure 1 – Control systems schemes

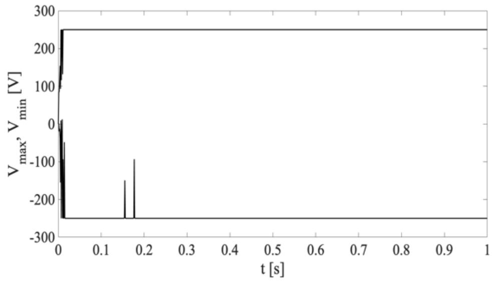
The first performance difference between the two flutter suppression systems is the closed loop flutter boundary; in fact, the open loop flutter speed is $v_f^{OL} = 19\,m/s$, the GS-fPID one is $v_f^{GS-fPID} = 28\,m/s$, and the SAC one is $v_f^{SAC} = 40\,m/s$. Robustness to inertia, stiffness, and aerodynamic uncertainties is verified by means of a stochastic approach. A variation of the $\pm 5\%$ around the nominal inertia and stiffness values is taken into account [5] [6], while aerodynamic uncertainties are included by means of four different exponential approximations of the Wagner function [7] [8] [9] [10]. For the closed loop systems Stochastic Robustness Analysis SRA, the airstream speed is also considered as a variable and it is let varying within the range $v = [19 \quad 28]\frac{m}{s}$; thus, the pitch boundary envelope defined in eq. (1) is considered while the airfoil is perturbed with a pulse disturbance on α of 2.7 deg amplitude that lasts 0.1 s.

$$E:\begin{cases} \mathrm{U(t)} = 0.05 + 0.95\mathrm{e}^{-5\mathrm{t}} \\ L(t) = -0.05 - 0.95\mathrm{e}^{-5\mathrm{t}} \end{cases} \tag{1}$$

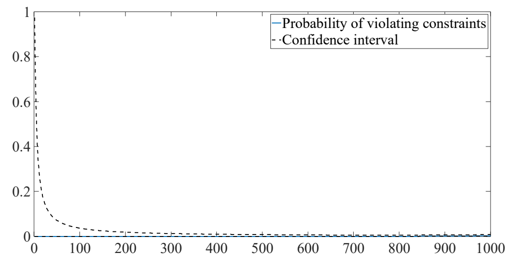
Then, 1000 Monte Carlo MC evaluations are performed and the results in terms of probability of violating the constraint $\hat{P}$ are shown in Figure 2(a)(c), while in Figure 2(b)(d) the actuator input Voltage maximum and minimum envelopes are reported.



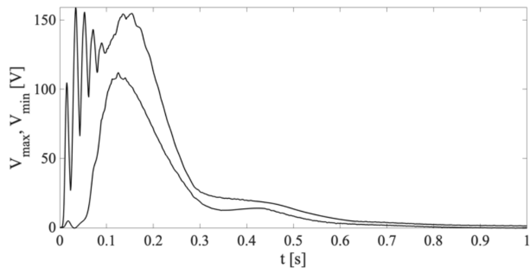
(a) $\hat{P}$ and confidence interval for the GS-fPID controller



(b) Actuator voltage envelopes for the GS-fPID controller



(c) $\hat{P}$ and confidence interval for the SAC controller



(d) Actuator voltage envelopes for the SAC AFS system

Figure 2 – Results of the Monte Carlo evaluations in the GS-fPID controlled speed range

It can be noted from Figure 2(b)(d) that the SAC algorithm is able to face the actuator saturation limit better than the GS-fPID thus allowing the aforementioned higher closed loop flutter boundary.

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On the Modeling of Large Deformation and Hysteresis in Ferroelectric Materials

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Summary: We present recent developments on the modeling and simulation of ferroelectric materials. Our focus lies on methods to describe irreversible changes in the state of remanent polarization. In this context, we have pursued two directions: On the one hand, we aim to account for geometric non-linearities. Inspired by other problems that are characterized by an inelastic constitutive response, the concept of a multiplicative decomposition of the deformation gradient is repeatedly adopted in our approach. We derive a constitutive model using a thermodynamically consistent framework based on a material description of the governing equations of electro-mechanics. Our second focus lies on efficient simulation of ferroelectric continua by means of a mixed finite-element formulation, which we have extended towards the electro-mechanical coupling including irreversible domain switching processes. The fundamental idea of TDNNS elements is to relax selected continuity requirements in fields involved in order to reduce locking phenomena that occur for adverse element aspect ratios typical of thin-walled structures.

ABSTRACT

Ferroelectric materials are characterized by the presence of a spontaneous electric polarization that can be irreversibly re-oriented under a sufficiently strong electric field or mechanical loading. In the poling process, the initially random distribution of the spontaneous polarization on the microscale gets aligned with an external field, which results in a non-vanishing state of remanent polarization on the macroscopic level [1]. The "smartness" of poled ferroelectrics is based on their pyroelectric and piezoelectric properties, which enable their usage both as sensors and as actuators. The state of remanent polarization is typically assumed to be constant in engineering problems. To extend the operational range of ferroelectric transducers and open perspectives for novel applications, we seek for an accurate understanding of the evolution of the state of polarization in ferroelectrics, which requires both physical and geometric non-linearities to be considered in the modeling. Macroscopically, changes in the state of remanent polarization manifest in ferroelectric and ferroelastic hystereses. To describe irreversible changes of the polarization in ferroelectric materials, we transfer phenomenological models for domain switching to the geometrically non-linear regime. For this purpose, we first recall the fundamental governing equations of reversible non-linear electro-mechanics, for which a material description proves beneficial. We make use of concepts and algorithms of elasto-plasticity along with ideas of damage modeling, where the notion of a multiplicative decomposition of the deformation gradient plays a pivotal role in geometrically non-linear problems. In particular, the proposed approach for the constitutive modeling of ferroelectrics [2] relies on a decomposition of the deformation gradient into three parts: The irreversible part accounts for the evolution of a poled intermediate configuration from the initially unpoled referential state. The second part locally describes the reversible response of ferroelectrics subjected to externally applied electric loads. The third part is related to the elastic stress response of the material. To describe the dissipative response in a thermodynamically consistent manner, the principle of maximum dissipation is adopted [3]. As in elasto-plasticity, the evolution equation for the dissipative internal forces then follows as an associated flow rule. To simplify the algorithmic treatment, we introduce the notion of a dissipation function, by which the constrained optimization problem is converted into an unconstrained optimization problem, which can be efficiently solved by standard means. The proposed approach allows us to study the poling process of deformed structures as, e.g., the cantilever subjected to a tip-load shown in Fig. 1.

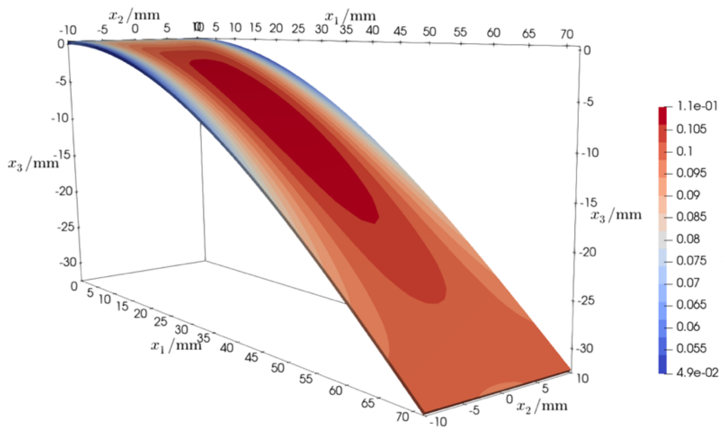

Figure 1: Deformed configuration and state of polarization of a ferroelectric cantilever subjected to a transverse tip-load: The top surface is grounded; the voltage at the bottom surface is gradually increased in the poling process, which is initiated from the deformed equilibrium configuration.

Pechstein and Schöberl [4] proposed the tangential-displacement normal-normal-stress (TDNNS) method, which is based on the key idea to relax continuity of displacement and stress fields. Across faces of adjacent elements, only the tangential component of the displacement field and the normal component of normal stress are required to be continuous, whereas discontinuities may occur in the respective complementary components. Based on this idea, we have developed an energy-based model of the ferroelectric polarization process, in which the dielectric displacement and strain (or displacement) are the primary independent unknowns. The vector of remanent polarization enters the model as additional internal variable. The constitutive response is governed by two thermodynamic functions, i.e., the free energy and a dissipation function. We derive a variational formulation, which is subsequently discretized using conforming finite elements for each quantity. We discuss continuity requirements and provide corresponding finite elements. The elements are chosen such that Gauss' law of zero charges is satisfied exactly. The discretized variational equations can be solved for all unknowns at once within a single Newton iteration.

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ANALYSIS AND DESIGN OF SENSING STRUCTURES THROUGH REFINED KINEMATIC MODELS

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Summary: The present paper presents an advanced modelling approach to study and design layered structures with sensing capabilities. Advanced kinematic models based on the Carrera Unified Formulation and innovative numerical techniques, e.g. the node dependent kinematic, has been used to derive high-fidelity models for laminated structures. A multifield formulation able to consider the piezo-electric effects has been adopted to predict the sensing capabilities of the considered structures. The models have been used to investigate different sensing mechanisms, including piezoelectric, piezoresistive and capacitive sensors. Sensing and self-sensing structures have been considered. The results show that the use of refined models is mandatory for designing multifunctional structures.

ABSTRACT

The possibility of giving sensing capabilities to classical structures is desirable for many engineering applications. The recent development of new materials and innovative manufacturing techniques supports the development of innovative design solutions and may have a significant impact on the development of multifunctional structures [1]. Embedded piezoelectric sensors have been investigated in many works and adopted in the health monitoring of composite structures [2]. Recently the variation of the capacitance in piezo-electric sensors has been adopted to give sensing capabilities to laminates structures [3]. Although embedded or surface-mounted sensors are common in engineering, external devices could affect the structural integrity, and their use is still a challenge in high-performance structures, e.g. aerospace structures. The development of self-sensing structures aims to avoid the use of external devices and to exploit the sensing capabilities of the structural elements, e.g. the piezoresistive properties of the carbon fiber [4].

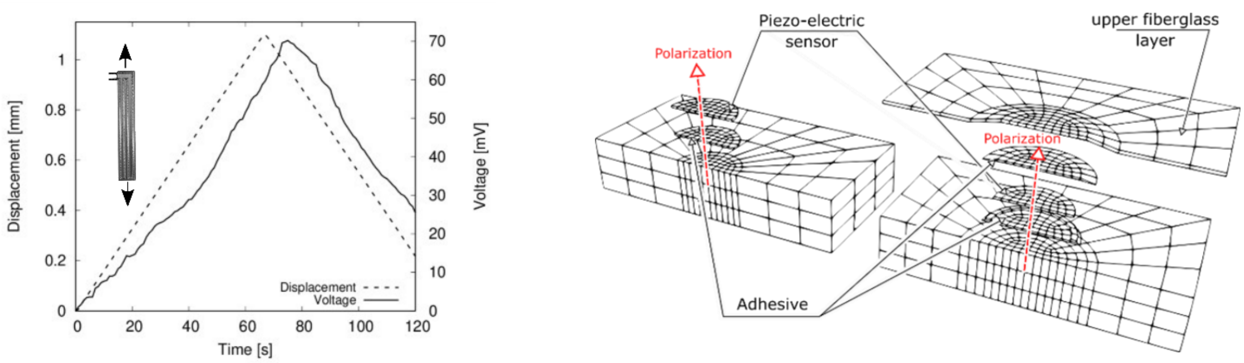

Figure 1 Examples of sensing structures. On the left side, is the response of a self-sensing 3D printed structure manufactured in the MUL2 Lab. On the right side, the models of a surface mounted and embedded piezoelectric sensor [2].

Whatever the nature of the sensing capabilities, the design of multifunctional structures requires the prediction of complex stress and strain distributions and the possibility of including extra physical fields, e.g., the piezo-electric. The Carrera Unified Formulation has been demonstrated to be accurate in the analysis of multifield problems and provide a full range of kinematic models that can be used to address simple and complex configurations [5,6].

The present work exploits the capability of the Carrera Unified Formulation for the analysis and design of sensing structures. Refined kinematic models based on an Equivalent Single Layer (ESL) and layer-wise (LW) formulations have been used to describe the strain and stress field accurately.
A fully coupled piezoelectric multifield formulation has been employed to predict the sensing capabilities of the considered structures. The node-dependent kinematic approach has been used to reduce the computational costs when possible. Different structural configurations have been considered. At first, classical piezoelectric sensors/actuators have been studied, both embedded, and surface mounted layouts have been accounted for. The possibility of exploiting the capacitive properties of the piezoelectric sensors as a sensing mechanism has been investigated. Finally, the self-sensing properties of 3D printed composite structures have been considered. The results have been compared with those from literature and, where possible, with experimental tests.

The outcomes of this research activity highlight the importance of refined models in predicting the sensing capabilities of intelligent structures. The advantages of using layer-wise models for the analysis of layered structures are even more significant when active materials are considered. The presence of discontinuities and interfaces make the use of refined models mandatory. The accurate prediction of the through-the-thickness stress has been demonstrated to be of great importance when capacitive sensors are considered. The present tool's high efficiency and high fidelity make it a good candidate for future applications for the development of digital twins able to support the design of multifactional structures.

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Algebraic aspects of variable kinematics plate models based on RMVT

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Summary: The modeling of composite plates is discussed based on Reissner Mixed Variational Theorem and variable kinematics assumptions expressed in Generalized Unified Formulation. The analysis of the algebraic properties of the resulting mixed model allows to identify necessary relations between the displacement and the transverse stress unknowns. An attempt is made to find the ``best'' model in view of an accurate transverse stress response.

ABSTRACT

Reissner Mixed Variational Theorem (RMVT) is a variational tool expressly dedicated to composite structures, in which displacements and transverse stresses can be independently assumed [1,2]. It has been used in conjunction with variable kinematics approaches in Unified Formulation to formulate Equivalent Single Layer (ESL) as well as Layer-Wise (LW) models with arbitrary expansion orders for the displacement and stress unknown functions [3—5]. It is well known that any mixed approach of Hellinger-Reissner type requires a careful choice of the static and kinematic field variables in order to avoid an excessively stiff response as well as spurious zero-energy modes and oscillations, such as those depicted in Figure 1. The analysis of the algebraic properties of the mixed matrix allows to identify relations that are required to hold for avoiding such pathological responses [6].

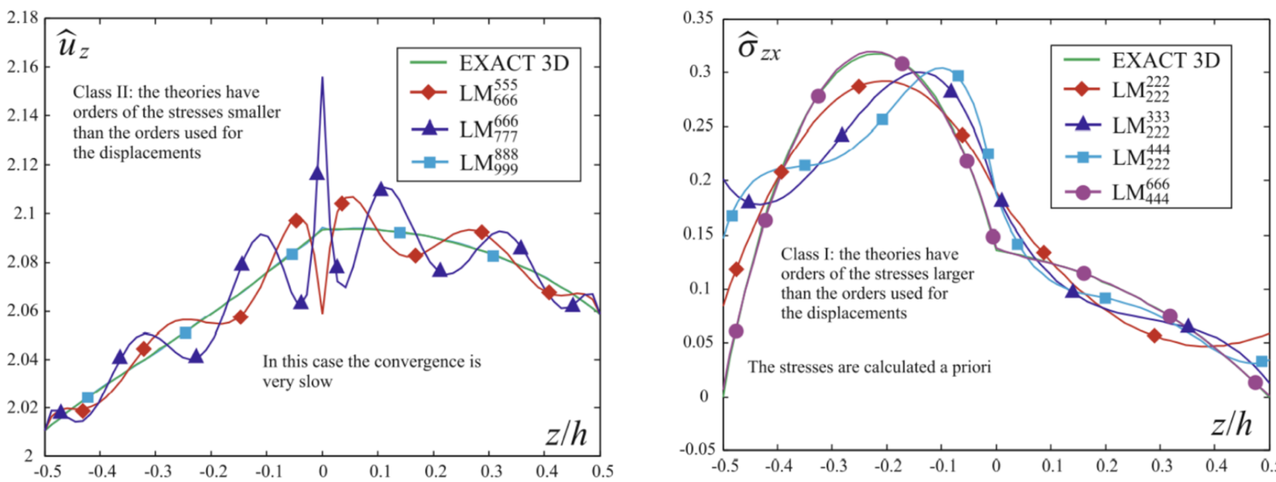

Figure 1. Spurious oscillations of displacements (left) and transverse stresses (right) that may occur in RMVT-based plate models with arbitrary expansion orders for the static and kinematic field variables [results taken from [7].

This work is a first attempt for establishing a general rule for selecting the approximations for displacement and transverse stress variables so to obtain an optimal RMVT-based plate model in the framework of the Generalized Unified Formulation variable kinematics approach [4]. GUF allows to adopt different orders of expansion and descriptions (ESL/LW) for each variable, which shall be regrouped in in-plane displacements, transverse displacement, transverse shear stresses and transverse normal stress. The algebraic system obtained in the framework of Navier-type solutions is considered. Results on homogeneous plates (or, equivalently, full ESL models) are first presented which allow to shed light on the meaning of Fraejis de Veubeke's "Limitation Principle" [8], the possibility of enforcing stress boundary conditions at the plate's top and bottom planes, and on the origins of oscillations and excessive stiffness. The analysis is subsequently extended to composite plates (or, equivalently, to models including a LW description) and a modified version of the original RMVT is discussed in view of an accurate transverse stress response.

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Finite Plate Elements for Viscoelastic Sandwich Structures based on Sublaminate Generalized Unified Formulation

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Summary: The aim of this paper is to present a robust finite plate element for the analysis of sandwich structures, characterized by the presence of a viscoelastic layer. The FEM implementation is based on Sublaminate Generalized Unified Formulation (SGUF) for both PVD and RMVT formulations [1].

ABSTRACT

Viscoelastic materials are of a great interest for automotive and aerospace applications due to their high level of energy dissipation, which leads to a direct reduction of structural vibrations and noise. For this reason there is interest in manufacturing composite structures including viscoelastic materials. It is therefore necessary to dispose of a numerical tool able to accurately predict the response, while keeping the computational effort to the minimum.

In this paper a FEM implementation of SGUF is proposed for both displacement-based and mixed (based on Reissner Mixed Variational Theorem) formulations. The variable kinematics approach allows to adapt the complexity of the model to the desired level of accuracy and computational cost. The Sublaminate extension of GUF, also named mixed ESL/LW approach, allows to reduce the problem size by regrouping several plies into one numerical layer and choosing a different kinematic for each of them. In this way a richer one can be exploited only when a three-dimensional state of stress actually occurs. This approach is particularly useful for sandwich panels, for which different models can be used for the thick core and the thin skins.
An enhanced 4-node plate element has been implemented in order to avoid the shear locking pathology for thin plate and to reduce the convergence loss rate for distorted mesh [2].

Several numerical test have been performed in order to validate the model. Initially the viscoelastic core of the sandwich structure is represented by a constant complex modulus. The complex nature of the stiffness matrix has also allowed to shed light on the reliability of the *Modal Strain Energy* (MSE) resolution method. This method allows to estimate the modal loss factor by neglecting the imaginary mode shapes. On the other hand in the *Direct* method the modal loss factor is directly calculated from the ratio between the imaginary and the real part of the eigenvalue. It has been proved that for moderate loss factors the differences between the *MSE* and *Direct* methods are negligible.
Subsequently the viscoelastic analysis has been extended to materials with a frequency-dependent behavior. The shear modulus can be represented by generalized Maxwell or Fractional Derivative models. The results obtained in [3] and [4] have been used to prove the robustness and the efficiency of the proposed numerical tool.

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Design criteria for soft-hard active-passive composites

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Summary: In the design of active-passive composites, the stiffness ratio between the components plays a crucial role in the final actuation capabilities. Starting from a simple cantilever setup, we present different cases for the resulting composite behavior and give examples from our current research related to hydrogel composites.

ABSTRACT

Combinations of active and passive materials in the form of active composites provide special opportunities [1, 2]. In the design and modeling of such systems, the pairing of stiffness is the most important part: Many active materials are *soft* in comparison to *hard* construction materials that are used in engineering. For example, the elastic modulus of hydrogels ranges between 10^3 and 10^5 Pa [3, 4] whereas steel features $E \approx 210 \cdot 10^9$ Pa. Therefore, hydrogel-steel combinations are very difficult to actuate. However, the geometry plays a role as well, i.e., very thin layers of a hard material can still interact with a soft material to form a combined behavior.

The actuation of hydrogel composites can be classified as follows: (i) Constrained swelling, (ii) combined behavior and (iii) free swelling. In the extreme cases, it is possible that for Case (i) the hard component or for Case (iii) the soft component dominates the behavior of the overall structure. Only the case (ii) leads to composites that can be actuated to obtain an advantage over the single material.

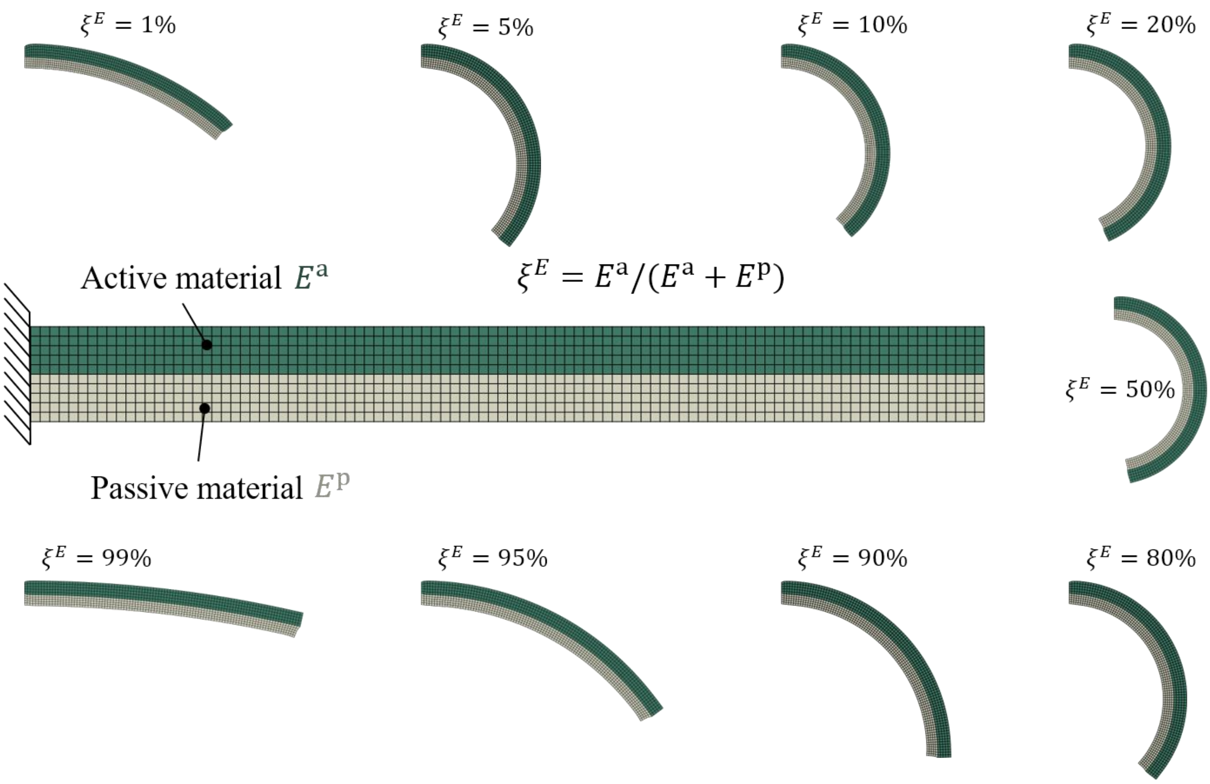

Figure 1 *Active cantilever composite beam with equal heights of the active and passive layer and with varying ratio of elastic moduli.*

In the present research, a simple cantilever beam with an active hydrogel top-layer and a passive bottom layer is presented. Its length is ten times higher than its height. In our example, the active layer is actuated in a way that the isotropic swelling strain reaches $\varepsilon^{\mathrm{swelling}} \approx 40\%$, which is a usual value for hydrogels [4].

When the ratio of elastic moduli $\xi^E = E^{\mathrm{a}}/(E^{\mathrm{a}} + E^{\mathrm{p}})$ of the active material E^{a} and the passive material E^{p} is varied, different cases of combined bending behavior can be achieved, see Figure 1. A very similar relationship can be observed when varying the layer thickness ratio $\xi^h = h^{\mathrm{a}}/(h^{\mathrm{a}} + h^{\mathrm{p}})$, see Figure 2. Quantitatively, they differ because the bending stiffness in a cantilever setup scales with different orders of magnitude: $[h]^3$ and $[E]^1$. In the simple cantilever setup, the case of constrained swelling (i) is approached at the ratio $\xi^E \approx \xi^h \approx 1\%$. The free swelling case (iii) is obtained for the ratio $\xi^E \approx \xi^h \approx 99\%$.

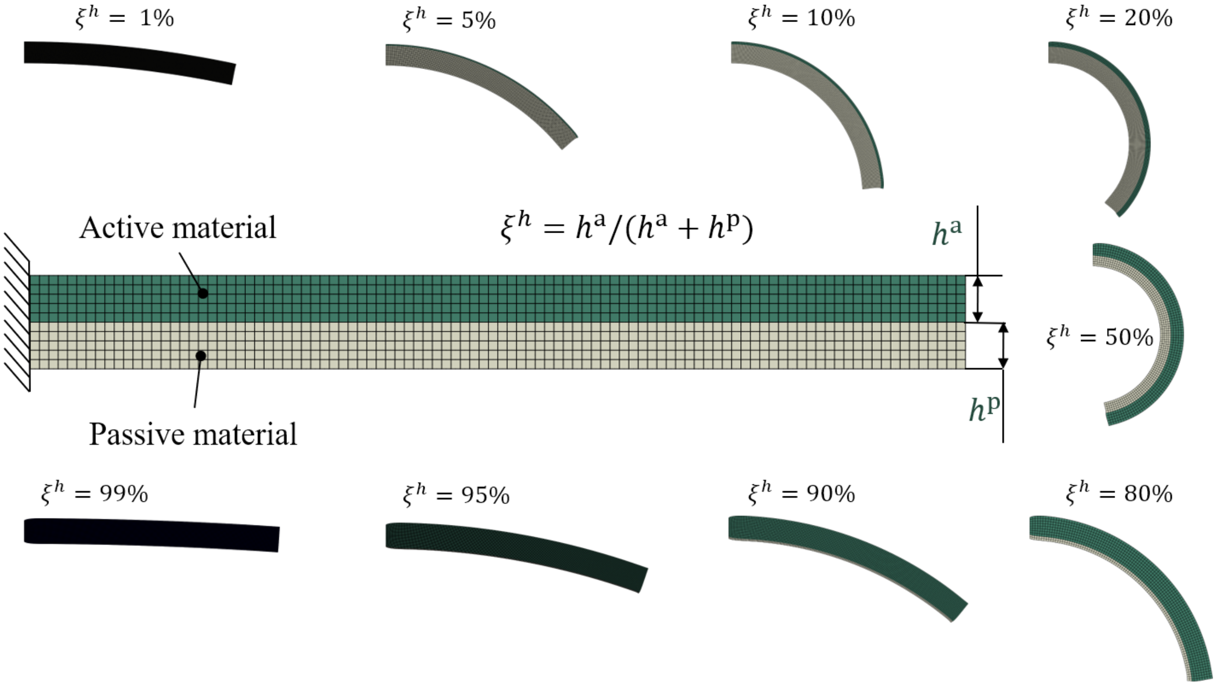

Figure 2 *Active cantilever composite beam with equal elastic moduli of the active and passive layer and with varying height ratio.*

In the current work, we present active hydrogel composite systems for all three cases. We highlight their potential applications and give insights into analogy modeling using the Temperature Expansion Model [5].

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Multiscale modeling of compressible magneto-active polymers based on numerical homogenization techniques

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Summary: This work presents a microstructure-guided framework for the macroscopic, continuum-based modeling of non-dissipative magneto-active polymers in an energy-based setting based on numerical homogenization techniques.

ABSTRACT

Compressible magneto-active polymers (MAPs) are field responsive solids composed of a polymeric matrix with dispersed magnetizable particles. Due to this microstructural composition, these materials deform and alter their material behavior under the influence of magnetic fields.
These properties in combination with the tunability of specific material characteristics through the fabrication process makes MAPs attractive for a broad range of engineering applications. Experimental and numerical investigations have shown that the magneto-mechanical behavior of MAPs at the macroscale level strongly depends upon the macrostructural shape of the body [1,2,3].
This fact poses a major challenge in the accurate determination of the effective material properties of the composite. We make use of an energy-based variational framework embedded into a scale transition scheme to bridge between micro- and macroscale and compute the homogenized response of the underlying microstructure at the macroscale level. This methodology allows the in silico generation of a comprehensive data set and overcomes inherent difficulties in the experimentally based material characterization of MAPs. We outline ingredients of the constitutive theory in an energy-based arrangement and develop - guided by the comprehensive homogenization data - specific constitutive expressions that are able to accurately capture the highly nonlinear material response of MAPs at the macroscale level. Moreover, we propose an elegant three-level fitting algorithm for the precise parameter identification based on the generated homogenization data set and discuss poly-convexity of the developed constitutive model that ensures the material stability in the sense of the Legendre-Hadamard condition [3,4].

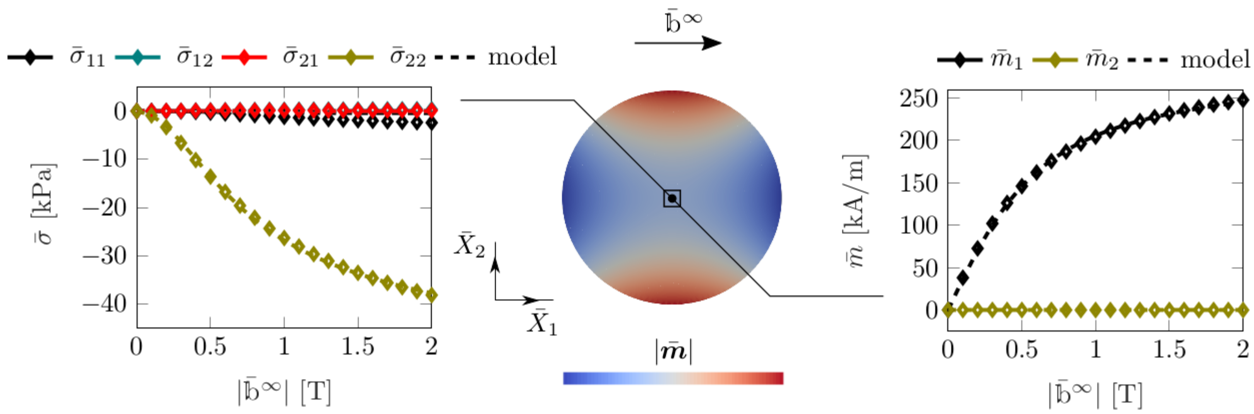

Figure 1: Decoupled multiscale analysis for the micro-macro evaluation of the magneto-mechanical behavior of the MAP at an integration point in the center of an initially circular specimen subjected to a homogeneous external magnetic field.

The accuracy of the developed constitutive macroscale model is demonstrated by the solution of some application-oriented boundary value problems along with the application of a decoupled multiscale scheme for the micro–macro evaluation of the magneto-mechanical behavior, see Figure 1. The main emphasis of the numerical studies lies on the investigation of the macrostructural magnetorheological and magnetostrictive effect.

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Non-conventional beam and plate finite elements based on CUF for non-orthogonal geometries

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Summary: When dealing with innovative materials - such as composites and metamaterials with complex microstructure - or structural components with non-orthogonal beam/plate geometry, the Finite Element Method can become very costly in calculations and time because of the use of very fine 3D meshes. By exploiting the Node-Dependent Kinematic approach of the Carrera Unified Formulation, this work presents the implementation of new non-conventional 1D and 2D elements mainly based on the computation of '3D Jacobian matrix' inside the element. These elements allow us to accurately study beam-like and plate-like components with non-orthogonal geometry by employing much less degrees of freedom with respect to the use of classical 3D finite elements.

ABSTRACT

The Finite Element Method (FEM) is a well-established method and yields accurate results for the structural analysis of any geometrical shape. However, when dealing with innovative materials - such as metamaterials with complex architected microstructure - or structural components with non-conventional beam/plate geometry, this method can become very costly in calculations and time. Indeed, classical beam and plate models cannot be clearly employed in the case of beam with variable section or section not orthogonal to the axis, as well as plate with variable thickness or edges not orthogonal to the midsurface. In these cases, the researchers have to resort to very fine 3D meshes encountering the following main drawbacks: (i) the high computational cost associated with the classical 3D elements that sometimes make the analyses infeasible; (ii) the difficulty to couple the different scales of the problem in the analysis of large components.

It is well known that 1D and 2D finite elements based on Carrera Unified Formulation (CUF) provide very accurate 3D-like solutions with much lower computational cost than the classical 3D elements. The unknowns of such FEs are defined over the physical surfaces of the real 3D body; this means that the definitions of mathematical reference axes (for beams) or reference surfaces (for plates) are not needed. Moreover, in the framework of CUF, a novel approach, called Node-Dependent Kinematics (NDK), has been proposed to further increase the numerical efficiency of the models and it implements local kinematic refinements on the selected FE nodes within the domain of interest [1,2].

This research aims to implement and assess enhanced CUF finite elements based on NDK approach for the analysis of beam-like and plate-like components having non-orthogonal geometrical features, as described above. The new elements are formulated on the basis of a simple idea: the computation of the Jacobian matrix inside the element in '3D form', by still employing one-dimensional or two-dimensional kinematics of the CUF. In this work, only Lagrange expansions are considered but the approach can be straightforwardly applied also to Taylor and Legendre expansions. The main advantage of these non-conventional 1D and 2D elements is represented by the possibility to adopt local refinements of the mesh where the geometrical features of the component, in addition to the kinematic behavior, require that.

An example is shown in Figure 1. An aluminium beam-like component having section with variable dimensions along the axis has been studied. The average dimensions of the square section are 1/10 of the axis length and the variation gradient along the axis is 0.2. A free-vibration analysis is performed by using both 3D classical elements (mesh 5x50x5 H27 elements, Figure 1a), and new four-node CUF beam elements based on 3D Jacobian matrix (mesh 20 B4 elements, Figure 1b). In the latter case, a 2x2 mesh has been adopted in the cross-section with variable order of expansion along the axis: four-node Q4, nine-node Q9 and sixteen-node Q16 expansions, as shown in Figure 1b. The results are provided in terms of natural frequencies, in particular the sixth modal shape is given in Figure 1.

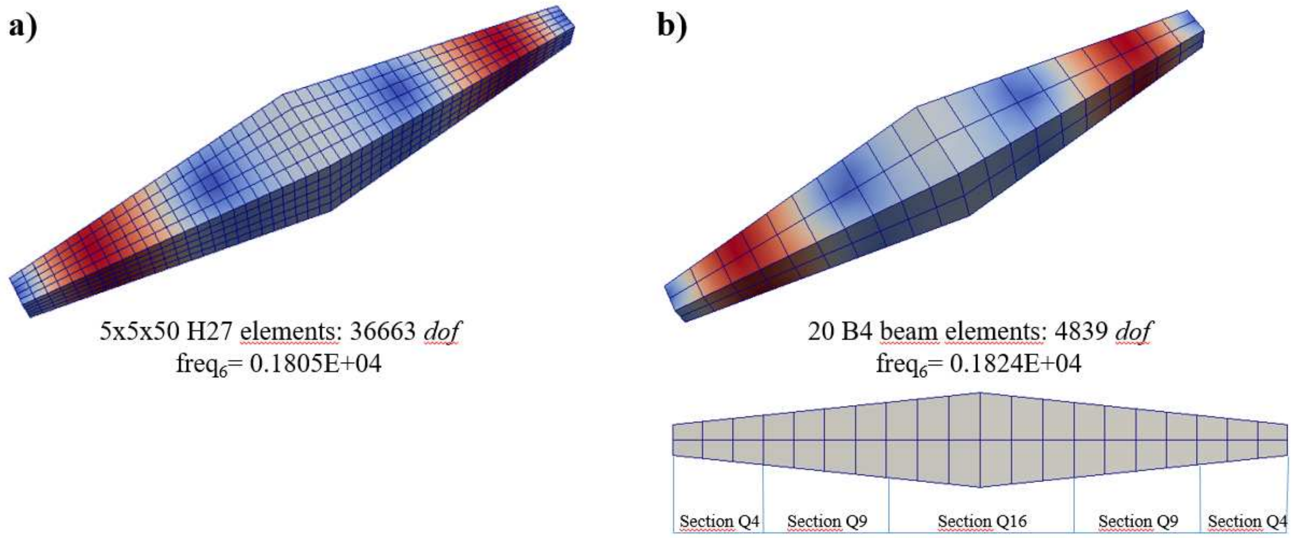

Figure 1 Sixth modal shape of an aluminium beam-like component with section variable along the axis obtained with: a) classical 3D elements and b) CUF beam elements based on NDK approach and 3D Jacobian.

It can be noted that the new beam elements provide accurate results, comparable to the convergence solution obtained with classical 3D elements, but the number of degrees of freedom employed is much lower: 4839 for the beam model and 36663 for the 3D model, almost one order less. This demonstrates that the present elements, with their adaptable refinement approach in the analysis of complex structures, can lead to high fidelity multi-scale FE models with optimal computational efficiency.

Further study cases will be presented in which the beam section is not orthogonal to the axis and plate-like structures with non-orthogonal geometrical features will be analyzed too.

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Progressive non-linear damage of variable angle tow composite plates by a Ritz approach

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Summary: In this work a Ritz model for progressive non-linear damage analysis of variable angle tow composite plates is presented. The damage is treated in the framework of continuum damage mechanics and its evolution is based on a linear softening law with which four damage indices are computed for degrading the mechanical properties of the material. A set of analyses have been carried out to investigate how damage evolves in VAT composite plates under progressive loading.

ABSTRACT

Modelling progressive failure analysis in composite materials is a challenge due to the large number of damage mechanism that must be considered. Depending on the scale of the idealization, from microscale through mesoscale to macroscale, damage can be modelled in different ways. In the microscale, a micromechanical approach is used where the damage in the form of cracks is represented using representative volume elements (RVEs) [1]. These micromechanical model approaches are typically used for representing the mechanical response before cracks localize at ply lever or at the larger scale. Instead, at macroscale level, the damage is represented as a hard discontinuity. At mesoscale level, where the individual plies are represented as homogenous, the damage process can be treated using different theories. The most common theory is Continuum Damage Mechanics. (CDM).

CDM models are based on the works done by Matzenmiller and Ladeveze among others [2, 3], where damage is treated at the meso-scale level and damage modes are represented as a reduction in the corresponding stiffnesses. A variety of models have been developed in the CDM framework using the finite element method [4, 5]. Such models generally suffer from mesh size dependency, which can be alleviated using crack band or non-local models [6, 7]. As an alternative to FEM, a damage model based on the Ritz method [8] is implemented in this work. The developed tool may be seen as a meshless method with some interesting features with respect to mesh size dependency issues.

The proposed model adopts a first order shear deformation theory and considers geometric non linearities through the von Karman assumptions. The onset of the damage is predicted using the Hashin's criteria. Four damage indices are computed and used for the degradation of the mechanical properties of the material, in fiber and matrix directions and both for tension and compression. The evolution of damage is based on a linear softening law, see Fig. 1, and the increase of damage is assessed by means of equivalent strains. Considering the capabilities offered by VAT laminates, i.e. the increase of the compressive buckling loads when compared to straight fiber laminated plates [9], this work focuses on how variable stiffness composite plates deal with the presence and evolution of damage. First some validation tests have been performed, for the uniaxial tensile load case, Fig. 2; then more analyses have been carried out, presenting novel results of progressive non-linear damage in variable angle tow composite plates.

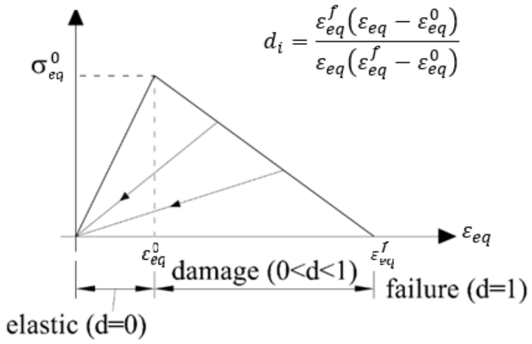

Figure 1 Linear softening law

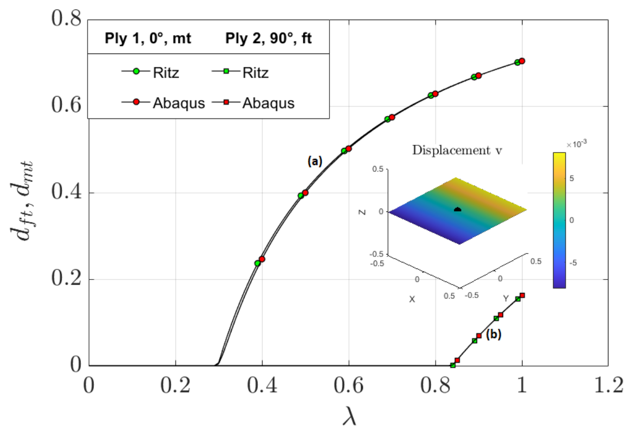

Figure 2 Damage index evolution for tensile test, comparison between Abaqus and present model using $[0,90]_s$ straight fiber composite plate (E_1 = 181.0 GPa, E_2 = 10.27 GPa, G_{12}= G_{23} = G_{13} = 7.17 GPa, ν_{12} = 0.28). (a) damage index for the matrix direction in tension; (b) damage index for the fiber direction in tension.

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Modeling of Functionally Graded Plates based on a variable separation method

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Summary: This study aims at developing an efficient numerical tool based on the separation of variables to analyze Functionally Graded Plates. The interesting features rely on the decreasing of the number of unknowns involved in the deduced problems to be solved. Firstly, an in-plane / out-of-plane representation is carried out. Secondly, an explicit solution with respect to the material gradation parameter *k* is built. The approach is assessed by comparing with reference solutions.

ABSTRACT

Functionally Graded Material (FGM) is a class of composite materials that has continuous and smooth variation of material properties from one surface to another, and thus eliminates the stress concentration found in laminated composites. Thus, it calls for the development of efficient numerical tools allowing us to predict accurate displacements / stresses for design purpose or in an optimization process involving many computations.

Since few years, some methods based on the separation of variables have shown interesting features to model composite structures and also to reduce computational cost in a reduced-order model (ROM) framework where many analyses have to be performed. For FGM material, the extended Kantorovich method has been applied in [1]. Another interesting way is based on the so-called Proper Generalized Decomposition (PGD). It has been successfully developed for the modeling of laminated / sandwich structures in [2–5]. In the present work, it is extended to the analysis of FGM plates. For that, the displacements are written under the form of a sum of products of bidimensional functions of (x,y) and unidimensional functions of z. Thus, the separation between the in-plane and out-of-plane coordinates is chosen. The deduced non-linear problem implies the resolution of 2D and 1D problems alternatively, in which the number of unknowns is smaller than a classical Layerwise approach. Considering the models developed in open literature, the modeling of this type of materials calls for a well-suited kinematics, i.e. a relevant shear strain shape function. The present work allows us to determine automatically the z-functions. The results will be assessed on plate structures constituted of FGM or combined FGM / classical laminated layers.

Then, an explicit solution with respect to a material parameter, k_{FGM}, is built based on the same approach. Thus, the displacement is expressed as follows:

$$\mathbf{u}(x,y,z,k_{FGM}) = \sum_{i=1}^{N} g^i_{FGM}(k_{FGM})\,\mathbf{f}^i(z) \circ \mathbf{v}^i(x,y)$$

where the "o" operator is Hadamard's element-wise product. The method is assessed through configurations involving one-layered and sandwich structures with different FGM laws. As our approach provides an explicit solution with respect to a parameter law, the assessment will be performed for some fixed values of the FGM law index. The present work, denoted VS-LD4, is illustrated in Figure 1 where the bending and transverse shear stresses depend on a law parameter. This computation is performed in a straightforward manner and does not need numerous numerical analyses.

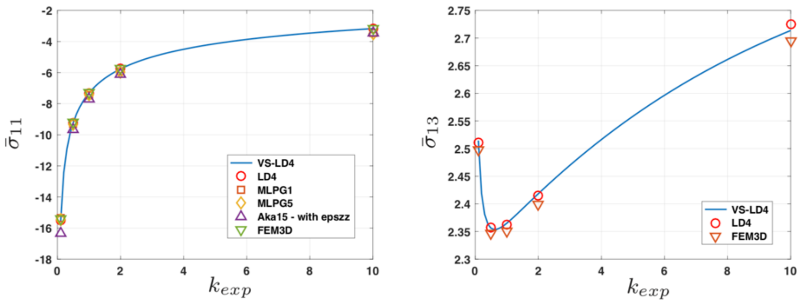

Figure 1 Variation of the stresses with respect to a FGM law parameter

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RVE-Homogenisation Approach To Characterise Additively Manufactured Porous Metals

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Summary: Additive manufacturing represents a great candidate to boost smart materials expansion in the Industry 4.0 era through 4D printing technologies. However, to fully exploit the benefits of these technologies, increasing knowledge is needed on how internal defects condition the overall behaviour of the component. In this work, the Representative Volume Element approach is presented to study, through different numerical analyses, the effect of size, number and spatial distribution of micro-voids on the stress-strain behaviour of additive manufactured SLM AlSi10Mg. An in-house code on the commercial software ANSYS Parametric Design Language APDL is used to model a random pore distribution inside the RVE; comparison with reference case studies from the literature are reported.

ABSTRACT

The Industry 4.0 era, with the fourth industrial revolution, is based on the ability to integrate modern manufacturing technologies with big data information systems to create smart factories and products able to evolve with the request of the market. In this scenario, smart materials, advanced structured and responsive materials, are highly requested due to their vast applicability as they optimise their behaviour in response to external stimuli. Recent developments of AM technologies have seen the implementation of smart multi-material printing combining classical 3D printing with the possibility to modify the function, structure, shape or the material properties through an external stimulus in what is called 4D printing, enormously accelerating the introduction of smart materials [1]–[3].
Different applications can be exploited in different sectors such as self-assembling and deployable structures, compact configurations, stimuli-activated mechanisms in extreme environments, and programmable materials for the aerospace, biomedical and textile sectors [4], [5].
Since the overall final properties of AM components are strongly influenced by their microstructure, several efforts are constantly placed to understand how the process parameters and internal defects, intrinsically present in each product, will influence it. The overall behaviour of the component can be accurately predicted through numerical simulations if such defects are included at the expense of computational costs. The Representative Volume Element RVE approach is generally used to drastically reduce the complexity of such resource-intensive analyses.
The "micro-to-macro" modelling approach considers first microscale effects and, in a second step, an equivalent homogenised material to describe the overall mechanical response of the macro-dimensional components [6], [7].

In the present work, the Representative Volume Element approach is used to conduct an extensive campaign to study the effect of size, number, and spatial distribution of micro-voids on the stress-strain behaviour of additive manufactured AlSi10Mg. An in-house routine on the commercial software ANSYS Parametric Design Language APDL is used to model a random pore distribution inside the RVE.
All the Representative Volumes Elements are assumed as cubic whereas pores are modelled as spheres with different radii. According to reference literature studies, AlSi10Mg components produced with

modern additive manufacturing Selective Laser Melting technologies can reach nearly null porosity to a maximum of 5% [8]–[10]. To study the effect of distribution, size and coalescence of pores different numerical simulations are considered. First a single pore centred inside the RVE is considered, spatial position and pores coalescence are considered in subsequent analyses through a regular matrix pore distribution and through a random pore distribution.
The RVE is defined as the smallest volume element capable of statistically representing the overall constitutive response of the material with errors of less than 5%, and must contain sufficient heterogeneity for the apparent overall moduli to be independent of "macroscopically uniform" surface tension and displacement values [11], [12]. Multiple analyses with decreasing bulk volumes are performed to retrieve the smallest dimension of the RVE able to represent the overall constitutive response of the material respecting the reference pore distribution.
The stress-strain behaviour of the macro-dimensional component, through the equivalent homogenised material, is finally compared with literature references.
The in-house APDL code models the overall porosity of the RVE and the pores distribution accurately and can be easily implemented for different materials and manufacturing technologies.

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HIGHER-ORDER PLATE ELEMENTS FOR THE ANALYSIS OF PASSIVE DAMPED HYBRID LATTICE SANDWICH PANELS WITH COMPOSITE SKINS WITH CURVILINEAR FIBERS

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Summary: An advanced higher-order plate formulation for the frequency-response and damped free-vibration analysis of multilayered hybrid sandwich lattice structures with composite skins with curvilinear fiber paths is here proposed, see Figure 1. The multi-functional hybrid multi-layer sandwich and its damping properties can be modeled through an opportune homogenization procedure. The use of the composite skins with curvilinear fibers in conjunction with a lattice core leads to dramatically improve the structural performance of the panel structure with respect to a classical sandwich one.

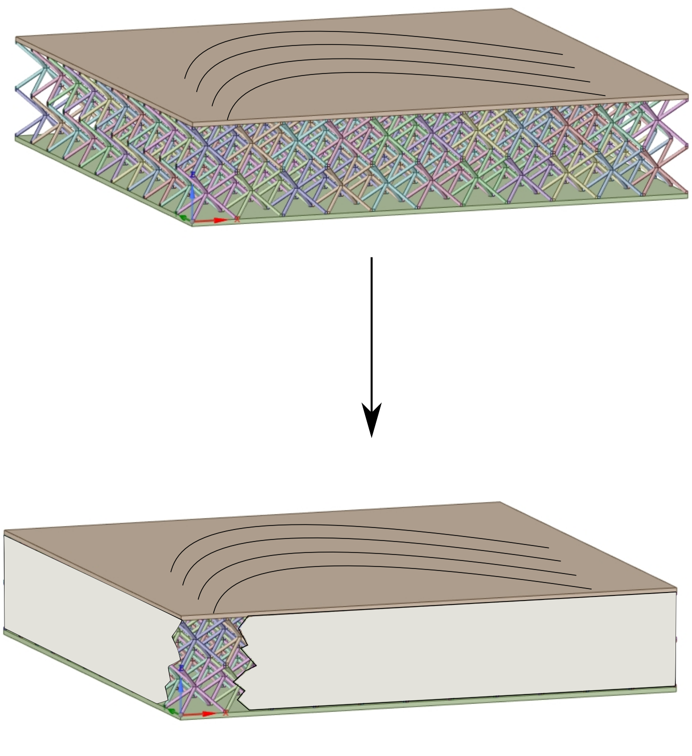

Figure 1: Sandwich lattice panels with composite VAT skins.

ABSTRACT

Nowadays new emerging technologies, such as additive manufacturing technologies, have permitted the increase of the tailoring in the industrial design process. In the aeronautical field, the continuous improving of the structural design techniques passed through the concept of multilayered panels structures, such as classical sandwich panels, the development of composite materials from the unidirectional lamina to the assembled multilayered unidirectional layers with different lamination

angles, ending to the more recent Variable Angle Tow (VAT) composites where the fiber path can follow a curvilinear trajectory [1]. This feature can be very useful with the aim to improve the tailoring of a structure. Moreover with the development of different additive manufacturing technologies new multi-functional materials have been developed in the last decades, one of the most popular applications is the study of different type of lattice structures in order to optimize the structural properties and response of a complex structure like the aeronautical ones [2].
Despite of the fiber orientation rules, the damping of structural vibration is always to be needed. The use of viscoelastic damping materials is among the established literature solution [3]. The damping materials can be included in the multi-functional lattice core structure in order to improve the damping properties of the sandwich core, see Figure 2. The damped free-vibration and frequency response solutions are obtained for the analysis of hybrid sandwich lattice VAT composite plates. The governing equations are derived from the Principle of Virtual Displacements and higher-order Layer-Wise models are used for the unknown variables description in the thickness direction. Numerical solutions are presented for the analysis of hybrid sandwich lattice plates with different boundary-conditions and various mechanical loads.

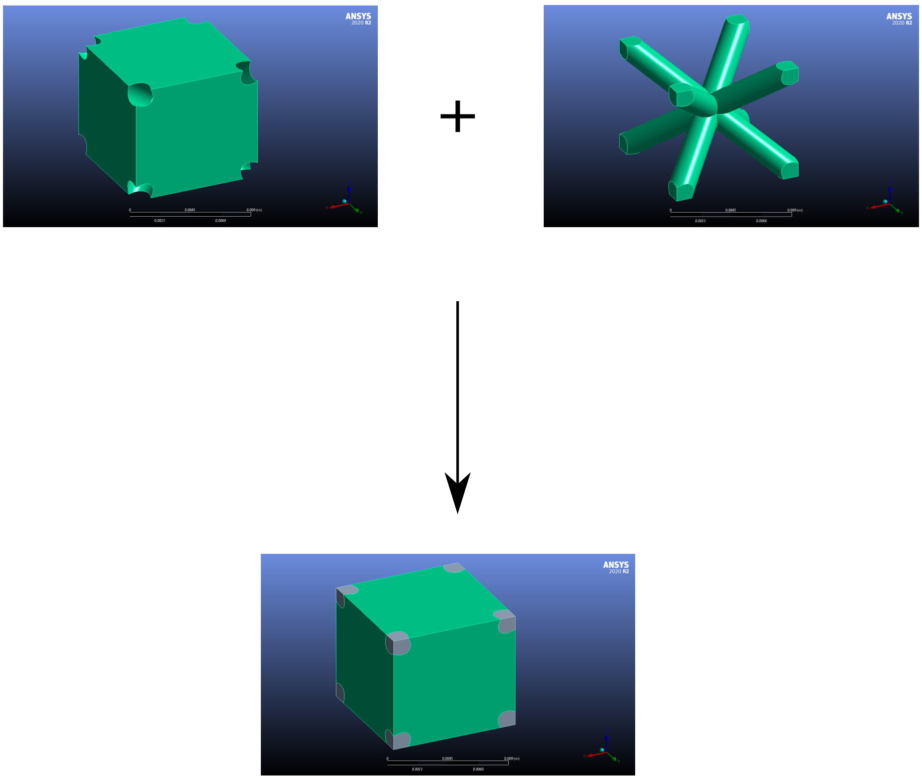

Figure 2: Lattice cell filled with soft viscoelastic material.

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