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Proceedings of the Workshop on Advances in the Analysis and Design of Composite Structures

A FULLCOMP Training and Networking Event

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Organized by Alfonso Pagani, Marco Petrolo and Enrico Zappino

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PREFACE

The FULLCOMP project is funded by the European Commission under a Marie Sklodowska-Curie grant for European Training Networks. FULLCOMP provides intersectoral, interdisciplinary and international training to 12 Ph.D. students to develop advanced numerical models for composite structures with reference to aeronautics, automotive, mechanical, wind energy, and space engineering. The design of composites leads to challenging tasks, because those competences that stemmed from the adoption of metallic materials are often inadequate for composites. As a matter of fact, insights on many different disciplines and tight academic/industrial cooperation are required to fully exploit composite structure capabilities. The aim of this project, hence, is to overcome such limitations in the training process of Ph.D. students. The intersectoral approach is pursued by including secondments and specific industrial training requirements in each project. The full spectrum of the design of composite structures will be dealt with - manufacturing, health-monitoring, failure modelling, multiscale approaches, testing, prognosis and prognostic - to develop integrated analysis tools to improve the design and production of composites.

The present workshop is one of the training and networking events within the FULLCOMP project. The aim of this workshop is to provide insights on the latest advances in the development of models for the analysis, design, and manufacturing of composite structures. Fourteen speakers present their research activity in four thematic sessions; namely, (i) structural models, (ii) analysis and design, (iii) impact, damage and monitoring, and (iv) applications, manufacturing and testing.

The structural model session presents activities related to the development of refined beam, plate, and shell models for composite structures. Particular attention is paid to axiomatic/asymptotic techniques for refined structural models [1], meshless approaches [2], variable kinematic models [3], multifield analyses [4] and functionally graded materials [5].

The analysis and design session focuses on novel approaches for the non-linear dynamic analysis of composites [6] and optimization for variable angle tow structures [7]. Also, new requirements for stress engineers in the automotive and aerospace industry are presented [8].

The impact, damage and monitoring session consists of works on the modeling approaches for impact and crash [9], the application of the boundary element method to predict delamination within the domain of structural health-monitoring [10], and fracture mechanics [11].

The applications, manufacturing and testing session presents activities on the explosive blast damage [12], the design of adaptive structures for flow regulation [13], and the virtual modeling of polymer matrix composites accounting for manufacturing and in-service performances [14].

The organizers thank the FULLCOMP coordinator, supervisors and Ph.D. students for their efforts towards the success of this workshop. Also, the organizers acknowledge the effort and availability of the invited speakers and the supporting actions of Politecnico di Torino and the Italian Association of Aeronautics and Astronautics.

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[3] E Zappino, “Finite Elements with Node Dependent Kinematics applied to metallic and composite structures”.

[4] G Giunta, “A hygro-thermal stress finite element analysis of laminated beam structures by hierarchical one-dimensional modelling”.

[5] F Fazzolari “A comprehensive analysis of porous functionally graded thermal beam structures: stability, free vibration and dynamic response”.

[6] E Jansen, R Rolfes, “Low dimensional models for nonlinear dynamic analysis of composite shell structures”.

[7] M Montemurro, “A new multi-scale optimisation strategy for designing variable angle tow composites by integrating manufacturing constraints”.

[8] S Czichon, “From Lightweight Design to Cost-Out – New Requirements for Composite Stress Engineers”.

[9] B Falzon, “Predicting impact damage, residual strength, and crashworthiness using computational analysis: progress and challenges”.

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[14] M Maiarù, “Virtual modeling of Polymer Matrix Composites (PMCs) from manufacturing to in service performances”.

The Organizers

Alfonso Pagani, Marco Petrolo and Enrico Zappino

Table of Contents

Refined structural models via axiomatic/asymptotic analyses and best theory diagrams

Marco Petrolo

MUL[2] Group, Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Italy

marco.petrolo@polito.it, www.mul2.com

The Carrera Unified Formulation [1] is a well-established framework to develop refined structural models. Via the CUF, the 3D structural problem is reduced to a 2D or 1D one. In other words, the 3D unknown variables become 2D or 1D, and expansion functions along the thickness or the cross-section of the structure define the order of the model, or computational cost, and its accuracy. Using a hierarchical structure, the problem equations do not depend on the order of the expansion. In the case of 1D models, the displacement field is

$$\boldsymbol{u}(x,y,z;t) = F_\tau(x,z)\boldsymbol{u}_\tau(y;t), \qquad \tau = 1,2,\ldots,M \quad (1)$$

F_τ are the expansion functions over the cross-section and $\boldsymbol{u}_\tau$ is the vector of the 1D unknown variables. The choice of the expansion functions and their order is problem dependent and various techniques are available, such as the axiomatic and the asymptotic methods. While axiomatic models are easier to build, asymptotic ones allow the accuracy of the models with respect to the exact solution to be evaluated.

In the CUF framework, the axiomatic-asymptotic method (AAM) has been recently proposed by the authors as an attempt to retain the advantages of both methods [2] [3]. In the AAM, in fact, a starting model is used with a full expansion of variables. Then, the influence of each variable, or groups of variables, on a given problem is evaluated by deactivating it. Only those variables exhibiting an influence are retained and reduced models are built in which the number of unknown variables are less or equal to the starting, full model. The method can be iterated to evaluate the influence of characteristics parameter such as thickness or orthotropic ratios. Examples of reduced models via AAM are the following:

- Static and free-vibration analyses of beams [3] [4].
- Static analyses of plates and shells [2] [5] [6] [7] [8] [9] [10] [11].
- Multifield problems [12] [13] [14].

The systematic use of CUF and AAM has then led to the definition of Best Theory Diagrams (BTD) in which, for a given accuracy and problem, the minimum number of required unknown variables can be read [6], see Figure 1. The BTD can be seen as a tool to evaluate the accuracy and the computational efficiency of any given structural model against the best available. The BTD has been recently obtained for plates [15] [16] [17] and shells [18].

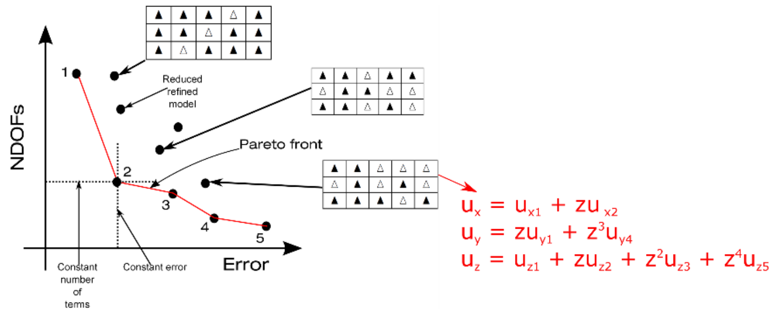

Figure 1 The Best Theory Diagram.

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Meshless and closed-form solutions of metallic and composite structures accounting for refined kinematics

Alfonso Pagani

MUL[2], Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Italy

alfonso.pagani@polito.it, www.mul2.com

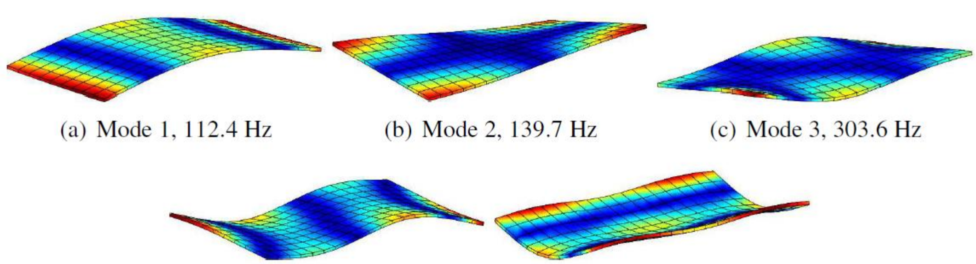
This work discusses the solution of the strong-form governing equations of higher-order beam models in exact as well as numerical forms. In the case of former, the differential equations are transformed into algebraic problems specially by imposing simply supported boundary conditions [1]. Inherently, the transcendental governing equations can be simplified into an algebraic system of equations if the axial motions are decoupled from the transversal ones. This is only possible if the material coupling is absent, i.e. if the structure is homogeneous or the laminae of the composite beam are isotropic or the resulting laminate is symmetric and balanced cross-ply. As a further limitation, only prismatic beams whose material characteristics are homogeneous along the axis can be addressed in the case of closed-form exact solutions. Conversely, approximate solutions of the strong-form equations of refined beam models can be developed by using many numerical methods, such as collocation schemes. In this work, we also discuss the use of Radial Basis Functions (RBFs) for representative purpose, see Pagani *et al.* [2]. With this method, boundary conditions and stacking sequences for composites can be chosen with no limitations by accepting numerical uncertainties.

Table 1 Natural frequencies (Hz) of the unconstrained symmetric 32-layer composite thin plate.

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
		Reference solutions			
Plate FE model	112.3	138.8	302.2	313.4	479.3
Experimental	110.8	138.6	299.6	309.9	475.3
		Present 1D CUF - DSM solutions			
$N=6$	112.4	139.7	303.6	314.3	480.4
$N=5$	112.5	140.1	303.8	314.4	484.5
$N=4$	112.5	140.5	305.6	315.3	484.8
$N=3$	112.6	141.3	307.7	316.9	560.4
$N=2$	113.4	141.6	311.2	326.9	564.8
$N=1$	99.8	1484.3	2968.6	274.7	–
TBM	99.9	–	–	274.7	–
EBBM	99.9	–	–	275.3	–

Owing to the rapid developments in computer technology in recent years, tremendous progress has been made in computational methods as applied in engineering. RBFs and, in general, collocation schemes are not necessarily the most effective tools to tackle the problems under consideration. Among the methods based on weak form solutions (which are, however, out of the scope of this work), the Finite Element Method (FEM) has been probably the most popular. Although FEM is versatile and applicable to arbitrary geometries, boundary conditions and material variations, it can be sometimes very expensive from a computational standpoint. There are other limitations of FEM as well. For example, the conventional FEM (and the majority of numerical methods, including RBFs) may not capture all necessary high frequency wave modes of interest, which can play an important role in the correct characterization of the entire vibration pattern of a structure. One of the reasons for this is that FEM uses assumed (frequency-independent) shape functions.

An alternative approach to improve the solution accuracy is to use frequency dependent shape functions, i.e. dynamic shape functions. As the dynamic shape functions can capture all necessary high frequency wave modes, much accurate solutions can eventually be achieved. This elegant approach has led to the development of the *Dynamic Stiffness Method* (DSM), whose application to strong-form governing differential equations in conjunction with *Carrera Unified Formulation* (CUF) is the main subject of this contribution, see Refs. [3] and [4]. In essence, CUF, by employing an index notation, allows the unification of all the theories of structures in one single formula. In other words, differential governing equations can be formulated in a compact and unified manner by employing CUF [5]. On the other hand, DSM makes use of dynamic shape functions that are derived from the exact wave solutions of the governing differential equations to formulate the Dynamic Stiffness (DS) matrix. To obtain the exact wave solutions in the frequency domain, the unified governing equations are transformed into the frequency domain by assuming harmonic solutions of a single frequency. Thus, the dynamic stiffness matrix is frequency dependent, consisting of a mixture of inertia and stiffness properties of the structure. As the dynamic stiffness matrix is constructed by using the exact solutions of the governing equations, it is clear that it deals with continuous mass and stiffness distributions in a structure exactly. As a consequence, coupling CUF and DSM guarantees exact solutions of the governing equations in the frequency domain for any refined structural theory, with no limitations of geometry, boundary conditions or material couplings. It should be recognized that DSM results in a non-linear eigenvalue problem, which requires the adoption of an iterative algorithm for which the known best method is the application of the Wittrick-Williams algorithm [6]. The algorithm has certainly enhanced the applicability of DSM. It allows one to automatically calculate undamped natural frequencies (or critical loads in the case of buckling problems) within any desired accuracy.



(a) Mode 1, 112.4 Hz (b) Mode 2, 139.7 Hz (c) Mode 3, 303.6 Hz

(d) Mode 4, 314.3 Hz (e) Mode 5, 480.4 Hz

Figure 1 First five modes of the unconstrained symmetric 32-layer thin plate; sixth-order CUF/DSM model.

For the sake of completeness, Table 1 shows the first natural frequencies of a 32-layer composite plate by the present CUF – DSM methodology, experimental tests, and a plate model by a FE commercial software. Figure 1, moreover, shows the same mode shapes by a sixth order refined beam model. Further results will be discussed for both free vibration [7], static and buckling [8] analyses of metallic and composite structures, with the aim to underline strengths and weaknesses of all the resolution methods considered.

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Finite Elements with Node Dependent Kinematics applied to metallic and composite structures

Enrico Zappino

MUL2 Group, Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Italy

enrico.zappino@polito.it, www.mul2.com

Improvements in the performances of next-generation structures will require the use of new computational tools that are able to deal with multifield problems and to provide increasingly accurate results. Classical one dimensional structural models are used widely in the design of complex structures but they are limited by their fundamental assumptions [1]. The introduction of refined structural models, e.g. [2] [3], allows the limitations introduced by the fundamental assumptions of the classical models to be overcome and the stress singularities due to local effects to be dealt with. In most cases, refined models are required to describe local effects, in other cases, the classical model assumptions are not satisfied just in some regions of the structure. The use of a refined beam model over the whole domain therefore requires more computational costs than those necessary.

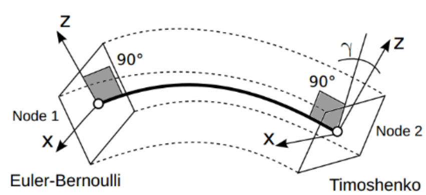

Figure 1 Example of node-dependent kinematic element.

The best solution would be to use refined models only in the region in which they are required and classical models elsewhere. The present work has the aim to improve the efficiency of the well-known refined one-dimensional models introducing a node-dependent kinematic formulation able to adopt advanced kinematics only where required. This approach, in contrast with classical FE models, allows the accuracy to be improved using a refinement in the kinematic assumptions without any mesh refinement of the FEM model. When this model is adopted, the beam theory can be different at each node of the same element. For instance, in the case of a 2-node beam element the Euler-Bernoulli theory could be used for node 1 and the Timoshenko beam theory could be used for node 2, as shown in Figure 1. The approach can be easily included in the CUF [4] formulation and extended to any order beam model [5]. The displacement field of the one-dimensional element with node-dependent kinematic can be written as:

$$\boldsymbol{u}(x,y,z;t) = N_i F_\tau^i(x,z)\boldsymbol{u}_{i\tau}(y;t), \quad \tau = 1, \dots, M^i \qquad (2)$$

The term $F_\tau^i(x,z)$ states that the function expansion is not a property of the element, but of the node, that is, the index i is included in the notation. The number of terms in the expansion, M, can be different at each node, and the notation M^i is used to underline this aspect. Figure shows how the use of LE model leads to very accurate results with respect to TE models but requires a quite high computational cost. The

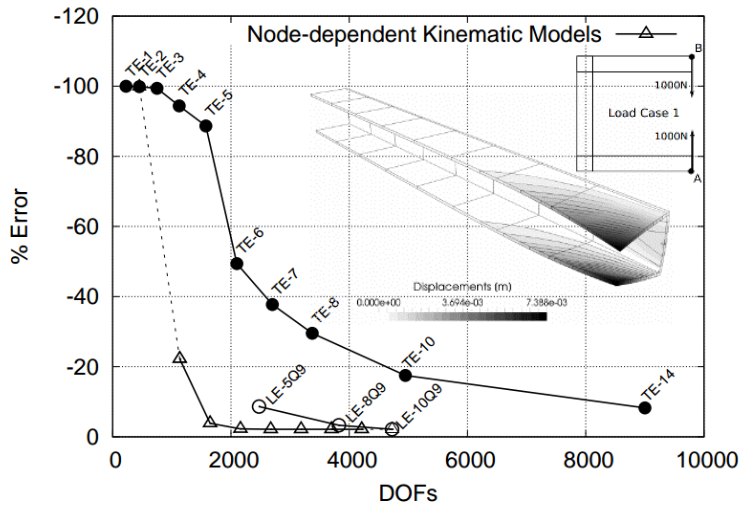

Figure 2 Convergence analysis using TE, LE and node-dependent TE/LE kinematic models.

introduction of node-dependent kinematic models could lead to a fast convergence of the solution to the reference one with a lower number of degrees of freedom. In short, the present node-dependent kinematic model can be considered a breakthrough with respect to uniform kinematic elements. The use of these elements could lead to benefits in several applications, such as in the analysis of local effects, global to local analyses, variable section beams and when beam should be connected to other structural models.

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A hygro-thermal stress finite element analysis of laminated beam structures by hierarchical one-dimensional modelling

Gaetano Giunta

Luxembourg Institute of Science and Technology, Luxembourg

gaetano.giunta@list.lu, www.list.lu

Composite structure operating under severe temperature conditions and/or wet environments are very common in several engineering fields such as aeronautics, space and transportation. Hygro-thermal solicitations of beam-like structures result in a three-dimensional response that classical one-dimensional models are not always capable to describe it effectively. An accurate prediction calls, then, for refined higher-order theories making this subject of research relevant and up-to-date.

In this work, laminated composite three-dimensional beams subjected to thermal and hygroscopic stresses are analysed. Several beam models are hierarchically derived by means of Carrera's Unified Formulation [1, 2] that allows for a theoretical derivation of several finite elements assuming a generic displacements polynomial approximation order over the cross-section as well as the number of nodes per element. Elements' stiffness matrix is derived in a compact form ("fundamental nucleus") via the Principle of Virtual Displacements. As a result, a family of several one-dimensional finite elements accounting for transverse shear deformations and cross-section in- and out-of-plane warping can be obtained. Temperature and humidity profiles are obtained by directly solving the corresponding diffusion equation (Fourier's heat conduction equation for temperature and Fick's law for moisture). These fields are, then, accounted as sources terms in the elastic analysis through Hooke's law.

Simply supported and cantilever configurations are considered. Numerical results in terms of temperature, moisture, displacement and stress distributions are provided for different beam slenderness ratios. Three-dimensional finite element solutions developed within the commercial code Ansys are presented for validation. The numerical investigations show that the hygro-thermo-elastic problem presents a complex three-dimensional stress state that can be efficiently obtained by a suitable choice of the approximation order over the cross-section: the accuracy is comparable to the reference solutions whereas the computational costs can be reduced.

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A Comprehensive Analysis of Porous Functionally Graded Thermal Beam Structures: Stability, Free Vibration and Dynamic Response

Fiorenzo A. Fazzolari

Department of Engineering, University of Cambridge, United Kingdom

ff305@cam.ac.uk,

The functionally graded materials (FGMs) can be produced by continuously varying the constituents of multi-phase materials in a predetermined profile defined by the variation of the volume fraction. Being ultra-high temperature-resistant materials, they are suitable for aerospace applications, such as aircraft, space vehicles, barrier coating and propulsion systems. Moreover, they have several advantages over other types of advanced materials like fibre-reinforced composites, indeed, problems like delamination, fibre failure, adverse hygroscopic effects due to moisture content etc are effectively eliminated or non-existent. Understandably with their potential applications, FGMs are steadfastly making headway in aerospace design. Thus, there is the need to fully analyse their mechanical and thermal characteristics when operating in harsh environments.
The variation of the FGM material properties is commonly described by using a power-law. If the difference between the material properties of the FGM constituents is relatively small, as in the case of the present analysis, it is then possible to successfully apply Voigt's model, also known as the rule-of mixture (ROM), with no loss of accuracy with respect to the Mori-Tanaka method.

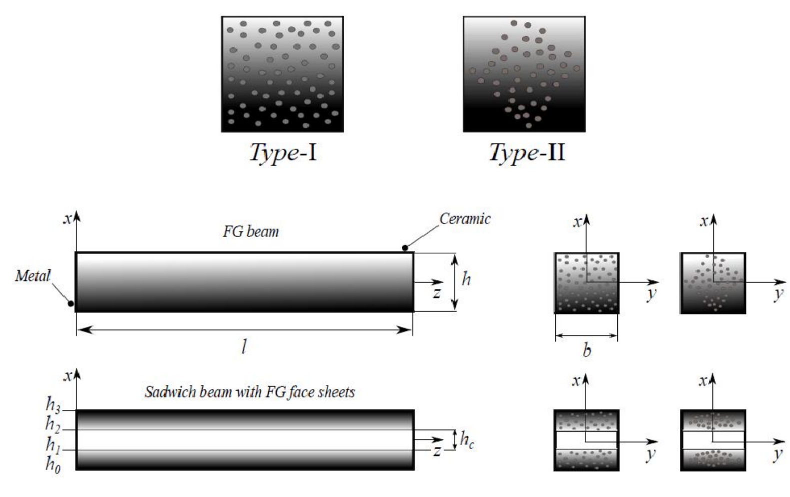
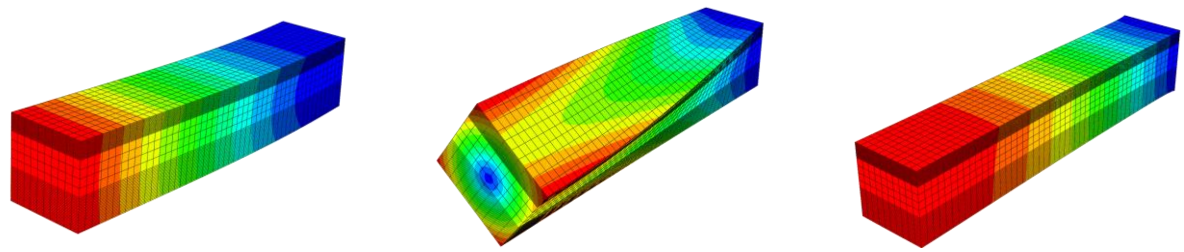


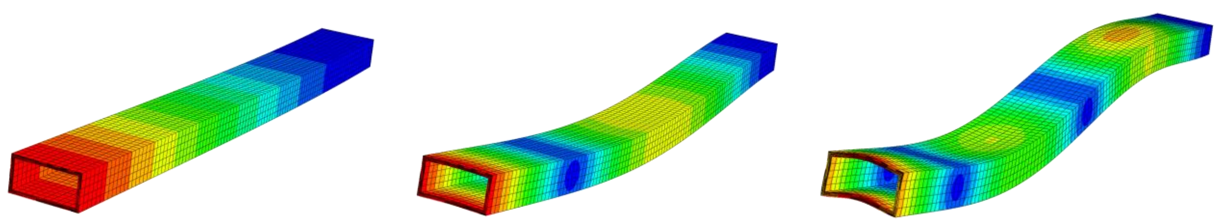
Figure 1: Even and uneven porosity distributions in FG isotropic and sandwich beam structures: coordinate system and nomenclature.

The present investigation will mainly focus on the linearised elastic stability, free vibration and dynamic response analyses of three dimensional functionally graded thermal beam structures featured by two different types of porosity (see Fig.1) and with arbitrary boundary conditions. The investigation is carried out by using the method of series expansion of displacement components. Various hierarchical refined exponential, polynomial, and trigonometric higher-order beam theories are developed in a generalized manner and are validated and assessed against 3D FEM results. The weak-form of the governing equations (GEs) is derived via Hamilton's Principle. The GEs are then solved by using the Ritz method, whose accuracy is significantly enhanced by orthogonalizing the algebraic Ritz functions by virtue of the Gram-Smith process. Convergence and accuracy are thoroughly analysed by testing 86 quasi-3D beam theories.



Mode 1: $f_1 = 47.525$ Hz   Mode 3: $f_3 = 242.01$ Hz   Mode 6: $f_6 = 449.82$ Hz

Figure 2: The first, third and sixth vibrational modes of a short (*l/h=5*) FG unsymmetric sandwich beam with CF boundary condition.



Mode 1: $f_1 = 9.4921$ Hz   Mode 3: $f_3 = 55.739$ Hz   Mode 6: $f_6 = 139.84$ Hz

Figure 3: The first, third and sixth vibrational modes of a FGM box (*l/h=10*) with CF boundary condition.

More specifically, the linearized buckling, free vibration and dynamic response characteristics of porous FG isotropic/sandwich beams and porous FG thin-walled beams in thermal environment are further investigated while resting on full and/or partial Winkler-Pasternak elastic foundations. Two examples of free vibration analysis of unsymmetric FG sandwich beam and FGM box structures are given in Fig.2 and Fig.3, respectively. In both cases the first, third and sixth modes are shown. Various nonlinear temperature gradients through-the-beam-thickness direction, are taken into account. Moreover, the effect of significant parameters such as slenderness ratio, volume fraction index, porosity coefficient, FG sandwich beam typology, boundary conditions, elastic foundation coefficients and cross-section type, is examined.

Low dimensional models for nonlinear dynamic analysis of composite shell structures

Eelco Jansen and Raimund Rolfes

Institute of Structural Analysis, Leibniz Universität Hannover, Germany

e.jansen@isd.uni-hannover.de, www.isd.uni-hannover.de

Composite shells are basic components in mechanical and aerospace engineering. These thin-walled structures are prone to buckling instabilities under static and dynamic compressive loading. Moreover, under dynamic loads they may be directly or parametrically excited into resonance at their natural frequencies. The notorious discrepancy between the experimental results and the theoretical predictions for the buckling load of a cylindrical shell under axial compression led to an enormous research effort since the 1960s. The important problem of the nonlinear vibration behavior of cylindrical shells has also been studied since that time and has received a considerable amount of attention. Several important effects are understood reasonably well, including "secondary" modes and modal interactions [1].

The nonlinear behavior of shell structures can be studied by means of Finite Element analysis, but in particular in the area of nonlinear dynamics it has been recognized, that low-dimensional models (i.e. models with a relatively small number of degrees of freedom) are indispensable for design purposes and in order to gain insight into the nonlinear behavior of the structure. Work in the field of nonlinear dynamics is therefore often rooted in a semi-analytical framework based on the governing differential equations. In earlier work, semi-analytical models for buckling and vibration of composite cylindrical shells have been developed and were presented in a unified, simplified analysis framework based on Donnell-type governing equations using a Galerkin-type approach [2]. These low-dimensional semi-analytical models are believed to capture important characteristics of the nonlinear static and dynamic behavior of composite cylindrical shells. Several reduced-order models for the nonlinear, large amplitude vibration analysis of composite shells are available [2, 3, 4]. These models can be used in a systematic, three-level hierarchical approach, based on the level of complexity of the description of the spatial behavior of the structure:

- Level-1 Analysis (Simplified Analysis) [3]: Semi-analytical approach based on a limited number of assumed spatial modes, approximately satisfying simply supported boundary conditions at the shell edges. The Method of Averaging is used to approximate the temporal behavior;
- Level-2 Analysis (Extended Analysis) [4]: Semi-analytical approach in which the boundary conditions at the shell edges are satisfied accurately. A perturbation method is used to approximate the temporal behavior;
- Level-3 Analysis: Numerical analysis corresponding to a detailed Finite Element discretization.

In recent years, reduced-order, low-dimensional models for the nonlinear buckling and vibration analysis of composite structures have also been developed within a Finite Element context, see e.g. [5]. The corresponding reduced-order method is based on a Koiter-type perturbation approach and has been used in order to gain insight into the characteristics of the nonlinear static and dynamic behavior of thin-walled composite structures and to reduce the computational effort involved in the nonlinear Finite Element calculations. The usefulness of these reduced complexity models based on perturbation-type approaches has been demonstrated.

In particular, a multi-mode Finite Element implementation of Koiter's initial post-buckling analysis has been achieved in earlier work. The capability to simulate the elastic post-buckling behavior of composite structures under axial compression via the reduced-order model based on Koiter's perturbation approach was shown. A modal-based reduced-order model for dynamic buckling of imperfection-sensitive structures was presented as a subsequent step, while an extension of this reduced-order modelling approach to dynamic response analysis is currently under development [5]. In parallel, Finite Element based reduced order-models for nonlinear, large amplitude vibrations of thin-walled structures have been developed and applied to composite cylindrical shells [6].

Results of the two semi-analytical approaches (Simplified Analysis and Extended Analysis) for the nonlinear vibrations of specific composite cylindrical shells will be presented. Moreover, results of the Finite Element based reduced-order modelling approach for various composite cylindrical shells illustrate important characteristics of the dynamic buckling and nonlinear vibration behavior of these shells.

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A new multi-scale optimisation strategy for designing variable angle tow composites by integrating manufacturing constraints

Marco Montemurro

Arts et Métiers ParisTech, I2M CNRS UMR 5295, F-33400 Talence, France
marco.montemurro@ensam.eu, http://i2m.u-bordeaux.fr/

In this work a multi-scale two-level (MS2L) optimisation strategy for optimising variable angle tow (VAT) composites is presented. In the framework of the MS2L methodology [1], [2], [3] the design problem is split and solved into two steps. At the first step the goal is to determine the optimum distribution of the laminate stiffness properties over the structure (macroscopic scale), while the second step aims at retrieving the optimum fibres-path in each layer meeting all the requirements provided by the problem at hand (mesoscopic scale).

The MS2L design strategy is characterised on the one hand by the refusal of simplifying hypotheses and classical rules usually employed in the framework of the design process of laminates, and on the other hand by a proper and complete mathematical formalisation of the optimum design problem at each characteristic scale (meso-macro).

The MS2L strategy relies on the use of the polar formalism (extended to the case of higher-order theories [4], [5]) for the description of the anisotropic behaviour of the composite. The real advantage in using the Verchery's polar method is in the fact that the elastic response of the structure at the macro-scale is described in terms of tensor invariants, the so-called *polar parameters*, having a precise physical meaning (which is linked to the elastic symmetries of the material) [4]. On the other hand the MS2L strategy relies on the use of a particular genetic algorithm (GA) able to deal with a special class of huge-size optimisation problems (from hundreds to thousands of design variables) defined over a domain of variable dimension, i.e. optimisation problems involving a *variable number* of design variables [6].

The MS2L strategy has been improved in order to integrate all types of requirements (mechanical, manufacturability, geometric, etc.) within the first-level problem [3]. Several modifications have been introduced in the theoretical and numerical framework of the MS2L design procedure at both first and second levels [2], [3]. At the first level (laminate macroscopic scale) of the procedure, where the VAT laminate is modelled as an equivalent homogeneous anisotropic plate whose mechanical behaviour is described in terms of polar parameters (which vary locally over the structure), the major modifications focus on: 1) the utilisation of higher-order theories (First-order Shear Deformation Theory (FSDT) framework [4], [5] for taking into account the influence of the transverse shear stiffness on the overall mechanical response of VAT composites; 2) the utilisation of B-spline surfaces for obtaining a continuous point-wise variation of the laminate polar parameters; 3) a proper mathematical formalisation of the manufacturability constraints linked to the AFP process in the framework of the B-spline representation and in terms of laminate polar parameters. Regarding the second-level problem (laminate mesoscopic scale, i.e. the ply level) the main modifications is the utilisation of B-spline surfaces for obtaining a continuous point-wise variation of the fibres-path within each ply.

Accordingly, the second-level problem (the lay-up design) can now be formulated as an unconstrained minimisation problem as all the requirements (geometrical, technological, mechanical, etc.) are satisfied since the first step of the MS2L strategy. All of these modifications imply several advantages for the resolution of the related optimisation problems (both at first and second level of the strategy) as detailed in [3]. The effectiveness of the MS2L strategy is proven through a numerical example on the maximisation of the first buckling factor of a VAT plate subject to both mechanical and manufacturability constraints.

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From Lightweight Design to Cost-Out – New Requirements for Composite Stress Engineers

Steffen Czichon

ELAN-AUSY GmbH, Germany
Steffen.Czichon@elan-ausy.com

Light weight design has been a main focus in Automotive and Aerospace industries and is usually the main driver for the use of composite materials such as GFRP and CFRP. This has also been mirrored in the efforts of engineers to develop material models and analysis tools. Main focus of most numerical approaches is to determine the onset of failure and final failure of structures as precisely as possible, in order to carry the maximum load with the minimum structural weight.

Two trends within the last years have led to new needs in the development of numerical models. On the one hand, large scale production as practiced in automotive industry is only possible with optimized manufacturing techniques. On the other hand, decrease in oil prices have reduced the pressure for extreme light weight construction and shifted the main focus towards cost optimization and design-to-cost approaches.

Both developments lead to new requirements for engineering simulation. Instead of only determining the structural response, manufacturing simulation becomes increasingly important. In the domain of composite materials, this includes – but is not limited to – simulation of forming and draping, braiding, cutting, cooling and heating as well as assembly and disassembly.

In this presentation, several examples of how this shift in engineering requirements is influencing work of stress and design engineers are shown. The first example is forming of thermoplastic composite materials for the automotive industry. Secondly, simulation of braiding composite materials is discussed. Finally, an approach for the simulation of cutting CFRP is shown.

Predicting impact damage, residual strength, and crashworthiness using computational analysis: progress and challenges

Brian G. Falzon

School of Mechanical and Aerospace Engineering, Queen's University Belfast, UK

b.falzon@qub.ac.uk

The development of the latest generation of "all-composite" wide-body carbon-fibre composite passenger aircraft has heralded a new era in the utilisation of these materials. The premise of superior specific strength and stiffness, corrosion and fatigue resistance, of composite aerostructures, over their metallic counterpart, is tempered by high development costs, slow production rates and lengthy and expensive certification programmes. Substantial effort is currently being directed towards the development of new modelling and simulation tools to mitigate these shortcomings. One of the primary challenges is to reduce the extent of physical testing, in the certification process, by adopting a 'certification by simulation' approach. In essence, this aspirational objective requires the ability to reliably predict the evolution and progression of damage in composites. Moreover, there is also a need to ensure a level of crashworthiness commensurate with that of similarly-sized metallic aircraft. Even though there are no aircraft-level survivable crash conditions specified in airworthiness regulations, experience has shown that there is a high probability of occupant survivability within certain impact parameters for metallic aircraft and that a similar level of safety should be expected of composite aerostructures.

The desire for such modelling capability has equal relevance in other sectors. As the automotive industry also transitions to the use of lightweight composite materials in mass-produced vehicles, to meet increasingly strict emission guidelines, the issue of crashworthiness is arguably of even greater importance. To date, even high-end road vehicles with carbon-fibre composite passenger cells resort to metallic elements for their primary energy absorbing capability. The railway industry, while recognising the considerable potential advantages of adopting composite materials in load bearing passenger rail cabin sub-structures, is prevented from doing so by current European legislation, citing a lack of suitable certification procedures.

It is often claimed that carbon-fibre composites have higher specific energy absorption than steel and aluminium but this is not an intrinsic material property. Composites will deliver superior energy absorption provided that structural elements are designed to fail in a manner which maximises energy dissipation. Add to this the currently incurred high development costs and relatively slow production rates, associated with composite structures in general, and it becomes apparent that there is an urgent need to address these shortcomings if the level of utilisation is to continue on an upward trajectory. The extent of physical testing currently required in development programmes, to meet certification or statutory requirements, is seen as a primary factor hindering their wider utilization across sectors and industries.

The increased use of simulation at all stages of the development cycle provides an opportunity to meet these shortcomings. The aerospace and automotive industries have been at the forefront of incorporating computational tools in development programmes but the emergence of load bearing (primary) composite structures has brought with it new challenges in ensuring the reliability of such tools. The prediction of composite damage arising from impact events and the subsequent residual strength, or the crushing of composites for crashworthiness assessments, is seen as particularly challenging but an indispensable requirement if these materials are to be fully exploited and if we are to move away from the high level of conservatism currently practiced in industry.

This presentation reports on the development of a finite-element-based composite damage model, for predicting impact damage, residual strength and energy-absorbing capacity, which mitigates the need for model calibration to match physical testing. A number of validation cases, based on experimental results reported in the literature and on in-house experimental test programmes, confirm the model's predictive capabilities. This will be followed by a brief overview of a new Horizon 2020 European project, 'ICONIC – Improving the Crashworthiness of Composite Transportation Structures' under the coordination of the presenter. ICONIC brings together a consortium of nine partners, across six European countries, to explore new and innovative strategies for enhancing the energy absorption of composite materials and structures; develop improved experimental techniques to enable the reliable characterisation of novel materials, improve on the state-of-the-art in the virtual testing of composite structures under crushing loads; assess the role of fasteners in energy absorption; and develop new optimisation tools for the effective design of crashworthy structures.

Application of the Boundary Element Method to delaminated composite structures and SHM system for composite flange-skin delamination detection

Andrea Alaimo

Faculty of Engineering and Architecture, University of Enna Kore, Italy

andrea.alaimo@unikore.it, www.unikore.it/index.php/responsabile-marta

The present abstract summarizes the research activities fully described in the work of Alaimo et. al [1] [2] and deals with the application of the Boundary Element Method to the analysis of delaminated composite structures and to the numerical modeling of a structural health monitoring system able to identify the occurrence of delamination in a drop-ply composite structure. The research is then focused in a 3-D Boundary Element Formulation able to study the fracture mechanics behavior of composite structures by means of the multi-domain technique, allowing to model layered configurations as well as the crack occurring at bi-material interface. Moreover, a boundary element code, implemented in the framework of dynamic piezoelectricity, is applied to model a structural health monitoring configuration where the adhesive layer between the damaged structure and the piezoelectric sensor is modeled by means of the multidomain technique coupled with an interface spring model.

On the aforementioned basis, the main purpose of the present document is then to highlight the potentiality of the Boundary Element Method in the modeling of composite structures in presence of delamination [3] as well as in the modeling of Smart Structures, i.e. piezoelectric materials, to be applied in the framework of the Structural Health Monitoring – SHM [4].

Multidomain BEM and interface Spring Model

The Boundary Element Method (BEM) [5] allows to solve numerically the boundary integral equations that governs the analysed problems by solving the following linear algebraic system.

$$\mathbf{H}\boldsymbol{\delta} = \mathbf{G}\mathbf{t} \qquad (1)$$

where $\boldsymbol{\delta}$ and $\mathbf{t}$ are the vectors collecting all the boundary displacement and traction nodal values, respectively, while $\mathbf{H}$ and $\mathbf{G}$ are influence coefficients matrices. When the problem involves layered heterogeneous structures, cracks, or the need to assemble a piezoelectric sensor into a host structure by modelling the adhesive layer at the interface, the multidomain technique can be used. It is implemented by writing the equation (1) for each of the N homogeneous sub-region as

$$\mathbf{H}^{(k)}\boldsymbol{\delta}^{(k)} = \mathbf{G}^{(k)}\mathbf{t}^{(k)} \qquad k=1, 2\ldots, N \qquad (2)$$

The global system of equation pertaining the overall assembled structure is then obtained by applying the compatibility and equilibrium conditions along all the sub-regions interfaces.

$$\boldsymbol{\delta}^{(i)}_{\partial\Omega ij} - \boldsymbol{\delta}^{(j)}_{\partial\Omega ij} = \Delta\boldsymbol{\delta}^{ij} \qquad i=1, \ldots, \text{N-1} \qquad \boldsymbol{t}^{(i)}_{\partial\Omega ij} = \boldsymbol{t}^{(j)}_{\partial\Omega ij} \quad j = i+1, \ldots, N \qquad (3)$$

where the subscript $\partial\Omega ij$ indicates quantities associated with the nodes belonging to the interface between the ith and jth sub-regions. Eq. (3) allows to assemble heterogeneous sub-regions by considering both rigidly and elastic connection among them.

3D Skin Stringer debonding configuration

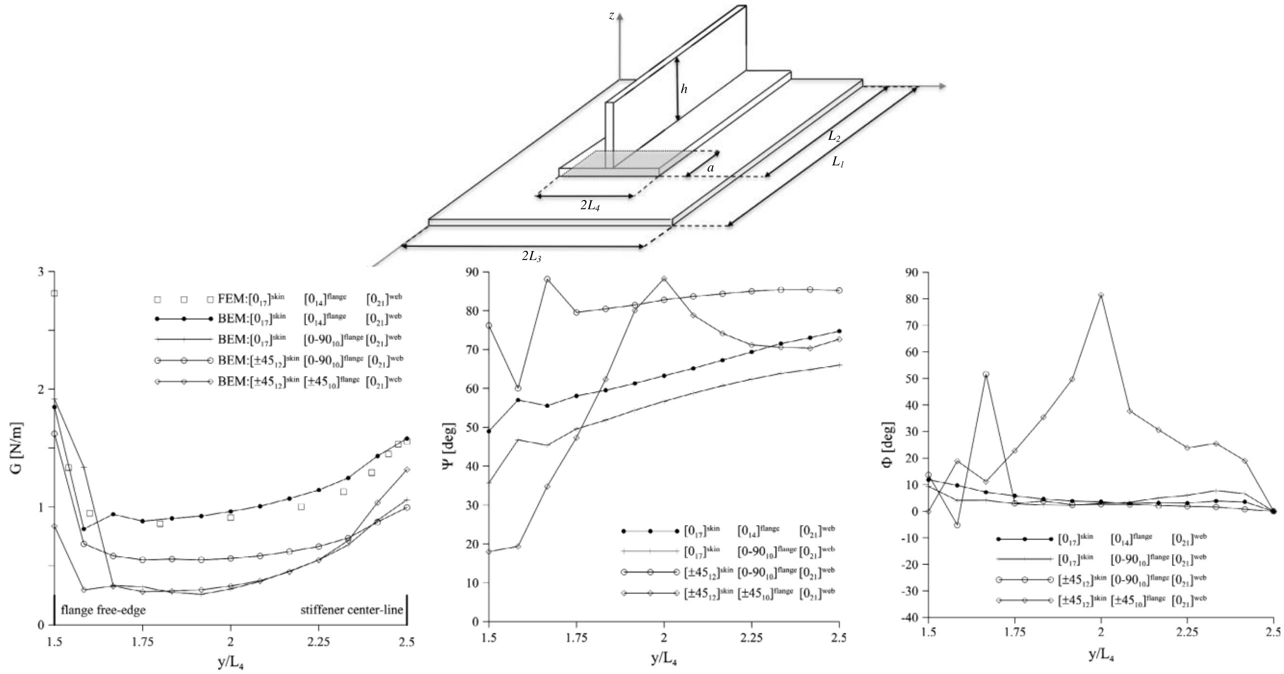

Figure 1: Stacking sequence effect on the Fracture parameters for skin – stringer delamination configuration

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Modelling of fracture in composite structures: application to photovoltaic modules

Marco Paggi

IMT School for Advanced Studies Lucca, Italy

marco.paggi@imtlucca.it, http://musam.imtlucca.it/

Photovoltaic (PV) modules are laminates composed of a glass or a PET protective cover, a layer of Epoxy Vynil Acetate (EVA), Silicon solar cells, another layer of EVA, and a backsheet. Traditionally, methods to increase the solar energy conversion efficiency of Silicon solar cells have been subject of an intensive research from the applied physics community. However, important issues such as durability and reliability of PV modules have to inevitably consider the composition of the laminate structure which embeds the solar cells, and this topic is becoming increasingly important for future applications of PV to new climate zones and its building integration.

The primary material and structural-related failure modes affecting PV modules involve quasi-brittle Silicon fracture, corrosion of the electric gridline deposited over the solar cell due to moisture diffusion in the encapsulant, also enhanced by cracks, and browning of EVA, promoted by the simultaneous action of moisture and temperature. To effectively simulate these important sources of damage and electric power losses, a novel computational framework has been proposed within the ERC Starting Grant CA2PVM "Multi-field and multi-scale computational approach to design and durability of photovoltaic modules" supported by the European Research Council (http://musam.imtlucca.it/CA2PVM.html).

Research results presented in this lecture regard the development of a novel multi-physics simulation method of PV modules integrating: (i) advanced structural mechanics models to compute the stress and deformation fields in PV laminates, including global-local approaches [1,2] and solid shell finite elements [3,4]; (ii) geometrical multi-scale numerical schemes to solve thermal and moisture diffusion problems [5,6]; (iii) nonlinear fracture mechanics formulations to simulate crack propagation in the solar cells [7]; (iv) electric models to quantify the electric output of the device, also in the presence of moisture degradation and cracks in Silicon [8]. Target applications concern not only traditional ground-mounted PV modules, but also novel building-integrated PV solutions. Both traditional technologies based on mono- and poly-crystalline silicon semiconductors and innovative semi-flexible PV modules are discussed.

Acknowledgements

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Improving the Explosive Blast Damage Resistance of Composites

Adrian Mouritz

School of Engineering, RMIT University, Australia

adrian.mouritz@rmit.edu.au, www.rmit.edu.au

The presentation describes recent experimental research into the explosive blast response of fibre-reinforced polymer composites. Composite materials are used extensively in a wide variety of military assets, including fighter aircraft, naval ships and submarines, and armoured land vehicles, which all require high damage resistance against an explosive blast. Similarly, composites are used in civil and commercial applications such as passenger aircraft, rail carriages, buses and buildings, which have been attacked by terrorists using improvised explosive devices. The aim of the study is to determine the material design parameters needed to improve the damage resistance of composite materials when impulsively loaded by an explosive blast. The improvements to the explosive blast resistance via control of the fibre architecture, fibre type, polymer matrix and fibre-matrix interfacial strength was investigated.

Blast tests using plastic explosive charges were performed on different types of composite materials. The materials include 2D woven laminates containing glass or carbon fibres, 2D woven laminates with vinyl ester or polyester matrix, 2D woven laminates with weak or strong interfacial bonding, and 3D woven composites. The laminates were dynamically loaded by shock waves of increasing pressure and impulse generated by plastic explosive charges (Fig. 1). The dynamic deformation, damage and residual mechanical properties were determined.

The amount of blast-induced damage and the post-blast mechanical properties depend on the fibre reinforcement, polymer matrix and interfacial strength between the fibres and matrix. E-glass laminates have higher resistance to blast-induced delamination cracking than carbon fibre composites (Fig. 2). Furthermore, glass or carbon fibre laminates with a vinyl ester matrix have superior blast damage resistance compared to composites with a polyester matrix (Fig. 2). The higher damage resistance is attributed to the higher flexural strain energy capacity and interlaminar fracture toughness of composites containing glass fibres or vinyl ester matrix. The explosive blast damage resistance is also higher in composites with strong interfacial bonding between the fibres and matrix. 3D composites with through-the-thickness fibre reinforcement have superior explosive blast damage resistance of conventional 2D woven laminates.

The experimental results presented in this chapter reveal that the blast damage resistance of laminates can be improved by the judicious selection of fibre architecture, fibre type, matrix type, and fibre-matrix interfacial strength.

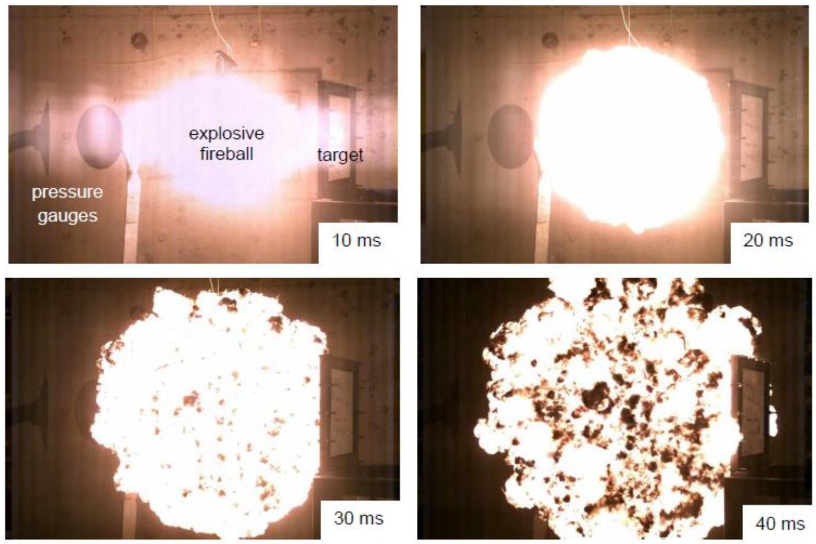

Figure 1. Time-lapse photographs showing explosive blast testing of composite.

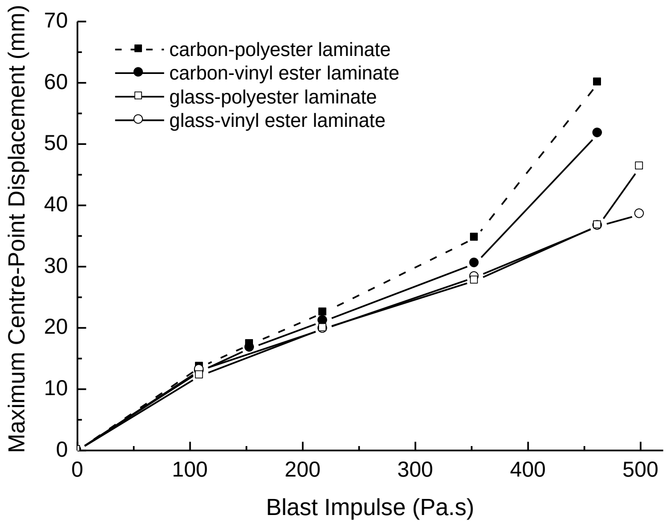

Figure 2. Effect of shock wave impulse on the amount of delamination damage to composite materials. E-glass composites have superior blast damage resistance to carbon fibre laminates. Vinyl ester composites are more damage resistant than polyester laminates.

Adaptive Compliant Structures for Flow Regulation

Gaetano Arena, Rainer M. J. Groh, Alex Brinkmeyer, Raf Theunissen, Paul M. Weaver, Alberto Pirrera

Advanced Composite Centre for Innovation and Science, University of Bristol,
Queen's Building, University Walk, Bristol, BS8 1TR, UK

alberto.pirrera@bristol.ac.uk

Abstract. *Conceptual design principles for a novel class of adaptive structures for flow regulation and control are introduced. Whilst of general applicability, these design principles, which revolve around the idea of utilising the instabilities and elastically nonlinear behaviour of post-buckled panels, are exemplified through a case study: the design of a shape-adaptive air inlet. The inlet comprises a deformable post-buckled member that changes shape depending on the pressure field applied by the surrounding fluid, thereby regulating the inlet aperture. By tailoring the stress field in the post-buckled state and the geometry of the initial, stress free configuration, the deformable section can snap-through to close or open the inlet completely. Unlike conventional flow controlling devices and thanks to its inherent ability to change shape in response to external stimuli—i.e. the aerodynamic loads imposed by different operating conditions—the inlet does not have to rely on linkages and mechanisms for actuation.*

Engineering systems are generally designed to meet multiple requirements that derive from the functionalities that a system is meant to fulfil and from the expected operating conditions/environment. Viewed in isolation, individual requirements can drive designs in opposing directions.

The goal of classical design philosophies is to find the best compromise between competing drivers. The disadvantage of such design philosophies is that a system's performance will be sub-optimal in most, if not all, of the individual operating conditions. In structural engineering, one possible refinement to this traditional design approach are the so-called morphing and adaptive technologies, which allow structures to change geometry and/or material properties in response to external stimuli [1]. Specifically, morphing and adaptive structures promise to enable less stringent trade-offs between stiffness, strength, weight and functionality [2–6]. Particularly attractive from a weight and minimal design philosophy perspective are passively actuated adaptive structures that do not rely on separate actuation devices to re-configure their geometry [7–9].

We present a novel design concept for an adaptive, variable geometry air inlet for flow control and regulation. The underlying working principle relies on the structurally nonlinear characteristics of a post-buckled beam. Figure 1 shows the design concept schematically.

The inlet comprises a deformable composite insert set between rigid components and a cover. These elements are arranged to form a channel that diverts part of the external flow to an outlet down-stream. The deformable component morphs in response to the pressure field caused by the fluid flow. Increasing air speeds create areas of low pressure that actuate the deformable component towards the cover, thereby closing the inlet. The morphing air inlet can therefore snap back and forth between an "open" and "closed" configuration, purely in response to air flowing at different speeds over the curved geometry. The kinematic characteristics of the shape adaptation depend on the nonlinear structural mechanics of the post-buckled member. In this study, we identify a taxonomy of nonlinear post-buckling behaviours and demonstrate their use for the design of adaptive air ducts by means of Fluid-Structure Interaction simulations.

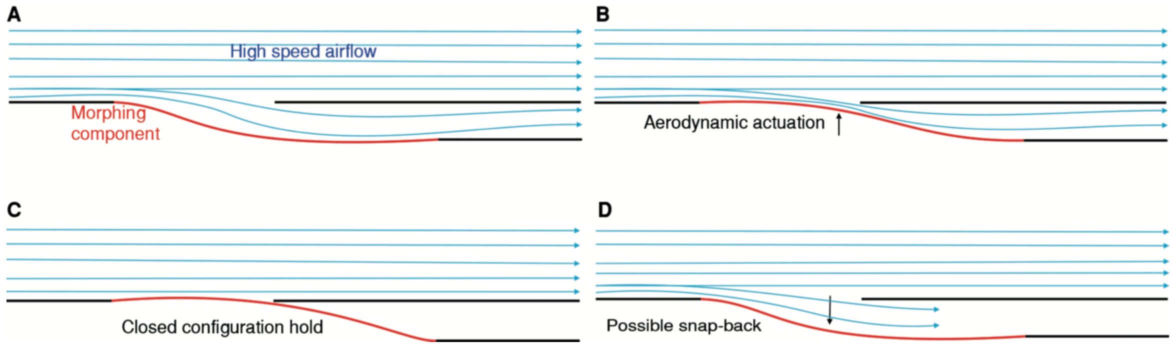

Figure 1. Schematic representation of adaptive air inlet. (A) The inlet, with the morphing component (in red) in its open configuration, can be actuated (B) by the pressure field applied by the fluid flow. The flow, fluid boundary conditions and properties of elastic stability of the morphing member, define the inlet's adaptive behaviour (C), (D).

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Virtual modeling of Polymer Matrix Composites (PMCs) from manufacturing to in service performances

Marianna Maiarù

Department of Mechanical Engineering, University of Massachusetts Lowell, Lowell, MA 01854, U.S.A.

Marianna_Maiaru@uml.edu, http://faculty.uml.edu/Marianna_Maiaru/

Polymer Matrix Composites (PMCs) provide significant advantages in performance, efficiency and cost for a wide range of engineering applications. Thermosets are a class of PMCs that during manufacturing undergoes chemical reaction, causing the polymer chains to cross-link and consolidate. When thermosets start to solidify, self-equilibrated residual stresses start building up. The curing process of the resin influences the microstructure and therefore, composite performances. Depending on the constituent chemistry of the matrix, the thermal cycle prescribed, the fracture and strength properties of a curing matrix, a fiber reinforced composite can and may undergo damage and cracking in the matrix during the cure cycle [1, 2]. Developments in computer hardware opened the way to sophisticated modeling tools for the analysis of composite structures and prediction of their performances. Integrated Computational Materials Engineering (ICME) is a new approach that uses virtual tests to reduce the cost and optimize the design of new generation composites [3, 4].

This talk will focus on the relationship between cure cycle and performances of virtually cured fiber-reinforced PMCs. Variations which occur during manufacturing will be discussed. Analyses are performed using the finite element method (FEM) at the micro-scale where Representative Volume Elements (RVEs) are studied. Damage mechanics is introduced to include the possibility of progressive damage and failure during curing and subsequent mechanical loading [5]. Simulations are composed by two parts, first the RVE is cured, then a set of boundary problems are solved to determine composite strengths and elastic moduli. Because of the dimensions of the RVE, temperature gradients within the matrix are neglected. Results are presented for two case studies in which respectively, damage occurs or not during curing. ABAQUS/Standard and ABAQUS/Explicit have been used as the solver for the analysis, supplemented by user written subroutines; UMAT and VUMAT. A computationally advantageous multi-scale model for virtually cured structures based on higher order 1D Finite Elements (1D-CUF) for progressive failure analysis will also be introduced [6, 7]. Developments toward the integration between scales from molecular- to structural- level analysis will be explored.

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