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Response of sandwiches undergoing static and blast pulse loading with tailoring optimization and stitching

U. Icardi *, F. Sola

Dipartimento di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

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ABSTRACT

A numerical study is presented where tailoring optimization and stitching are applied to improve the structural performances of sandwich plates undergoing static and blast pulse pressure loading. The purpose is to recover the critical interlaminar stresses at the interface with the core and contemporaneously keep maximal the flexural stiffness. Optimized distributions of the stiffness properties for the faces are obtained solving an extremal problem whose target is the minimization of the energy due to transverse shear and bending stresses under spatial variation of the stiffness properties, along with the maximization of the energy due to in-plane stresses. The contribution of stitching is computed through 3D finite element analysis and it is incorporated as modified elastic moduli into the refined, hierarchic zig-zag model employed as structural model to carry out the analysis accurately accounting for the layerwise effects of the out-of-plane transverse shear and transverse normal stresses and deformations. Approximate solutions giving the ply fibre orientation at any point (compatible with the current manufacturing technologies) are considered in the numerical applications. The numerical results show that stitched sandwiches incorporating optimized low-cost glass-fibre plies can achieve the same bending stiffness as sandwiches with uniform stiffness carbon-fibre faces, with a consistent reduction of critical out-of-plane stresses. The amplitude of vibrations under blast pulse loading can be consistently reduced with a proper choice of the curvilinear paths of fibres incorporated in the faces.

1. Introduction

Sandwiches with laminated faces find use as primary structural components in aerospace and other branches of engineering, thanks to an outstanding specific bending stiffness compared to monolithic composite structures (see, e.g., Heimbs et al. [9]). Also their high energy absorption, thermoelastic, thermal insulation, damping and fatigue properties are of great practical interest.

Regrettably, composites suffer from strong out-of-plane stress concentrations at the interfaces, which can have harmful effects on structural performances and service life as exhaustively explained among many others by Liu and Islam [30] and Vachon et al. [45].

Various technical skills have been developed (Heimbs et al. [9], Potluri et al. [40], Judawisastra et al. [26], Wang et al. [47], Vaidya et al. [46] and Nilanjan [36] and Cox and Flanagan [4]) with the aim of improving the damage tolerance of composite aircraft structures, their strength under impact loading, their fatigue behaviour and the detrimental effects of out-of-plane stress concentrations.

However, stitching is the most effective technique and it is easy to use with the current manufacturing technologies as discussed by Dow and Dexter [6] within the framework of the Advanced Composites Technology (ACT) program by NASA.

Another effective way in mitigating the out-of-plane stress concentrations at the interfaces is the tailoring optimization. As examples, the recent papers by Liu et al. [31] and Sliseris and Rocens [43] are cited dealing with optimization design of layup configuration, fibre distribution and discrete varying stiffness. Generally, the optimal lamination stack-up is found for the chosen objective function, under the pertinent constraints, solving the problem through gradient based search techniques or genetic algorithms (see, e.g., Pholdee and Bureerat [39] and Badallò et al. [2], respectively). Both finite element and closed form analytic are used as structural models. To limit the computational burden, often the fibre orientation angle is assumed constant throughout the plies and the core properties are assumed uniform across the thickness. In addition, also simplified structural models like smeared laminate models are adopted, despite they cannot accurately describe the structural behaviour of laminates. With the advent of automated fibre placement techniques (see, e.g., Martin et al. [32] and Evans [7]), variable stiffness composites in which the fibres follow curvilinear paths started to be considered, as they can offer consistent advantages over uniform stiffness plies, such as improvement

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* Corresponding author. Tel.: +39 (0) 110906872; fax: +39 (0) 110906899.
E-mail addresses: ugo.icardi@polito.it (U. Icardi), federico.sola@polito.it (F. Sola).

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of structural performances and damage tolerance. The papers by Sliseris and Rocens [43], Khani et al. [27], Honda et al. [10], Sousa et al. [44] and Nik et al. [35] are cited as recent examples. Because automated fibre placement used to manufacture variable stiffness composite laminates can lead to the formation of gaps or overlaps, embedded defects that can deteriorate strength and stiffness properties, should be taken into account as considered in [35].

At the authors' best knowledge, no papers can be found where optimization is carried out using structural models that accurately account for the layerwise effects, the transverse shear deformations and the out-of-plane stresses as their complexity can make the computational effort unaffordable for the optimization process. In this paper, the tailoring optimization technique developed and successively refined by the authors in Refs. [15,17–20,22] is employed to determine the optimal fibre angle variation over the faces of sandwiches, using as structural model the refined zig-zag model with hierarchic representation of displacements across the thickness recently developed by the authors [23]. It can accurately describe the transverse shear deformations and the out-of-plane stresses, therefore the optimization procedure could attain more realistic results than with simplified models. In order to further improve the structural performances, the optimization procedure is coupled with stitching through-the-thickness. The aim here is to assess through a numerical study whether stitching of faces and stitching through-the-thickness of sandwiches coupled with the tailoring optimizations of their face plies can be effective for recovering the critical interlaminar stress concentrations at the interface with the core, but keeping maximal the flexural stiffness. It could be remarked that stitching and variable stiffness optimization have been always treated separately in the literature. The final goal is to verify whether sandwiches with variable stiffness glass-fibre faces and stitching can achieve the same bending stiffness of conventional sandwiches with carbon-fibre reinforced faces having spatially uniform properties, recovering the critical stress concentrations at the interfaces with core.

This exploratory study will contribute to the discussion on whether low-cost materials like glass-fibre laminates, whose performances are improved through currently available technological skills like tailoring optimization and stitching, could offer a possible alternative choice to advanced carbon reinforced composites that may have unaffordable costs for many applications.

The numerical results will confirm the beneficial effects of variable stiffness composites and stitching found by other researchers using different modelling techniques. This paper will also show that sandwiches with variable stiffness glass-fibre faces and stitching can reach almost the same performances of the corresponding sandwiches with carbon-fibre faces.

2. Basic remarks

Necessary premise to the description of the structural model and of the optimization technique used in this paper, first their features and motivations are overviewed, along with the technique used for computing the properties of the stitched structure. The readers are referred to [22], [23] and [24] for further details.

The structural model developed by the authors in [23], which is a progressive refinement of those of Refs. [5,13,14,21], is aimed at reducing the computational effort keeping maximal the accuracy. It features a variable piecewise representation across the thickness of the three displacement components that *a priori* satisfies the continuity of the transverse shear and normal stresses at the material interfaces through continuity functions whose expressions are determined once for all. Its expansion order can be entirely different for any displacement and can vary from point to point across the thickness, in order to adapt to the variation of the material properties, though the number of functional degrees of freedom (d.o.f.) is kept fixed, being just the mid-plane displacements and the shear rotations.

It has the merit of solving the structural problems with the minimal number of unknowns, giving very accurate predictions of the piecewise variation of displacements across the thickness and of out-of-plane stress distributions directly from constitutive equations, as shown in [23], even for problems with different length and elastic scales. Since this model very accurately represents the strain energy, it is suited for the optimization technique here used. It is also suited for carrying out the analysis of optimized configurations being as accurate as the high-order layerwise plate models to date extensively employed, with a much lower computational effort, having less d.o.f. In fact, its memory storage dimension and its processing time are not considerably larger than those required by equivalent single-layer models. It also accurately predicts the through-the-thickness variation of the transverse displacement and of the transverse normal stress, which can have a significant bearing for keeping equilibrium in many practical cases (e.g., thermo-elasticity, cut-outs, free edges, crushing behaviour of sandwiches). The readers are referred to [23] for a more comprehensive discussion of the available structural models for laminates and sandwiches and of their relative merits and drawbacks in terms of accuracy and computational costs.

The tailoring optimization technique (Refs. [15,17–20,22]) here employed makes simultaneously extreme the strain energy contributions associated to in-plane and out-of-plane stresses and deformations under spatial variation of the stiffness properties. After having considered equilibrium and the boundary conditions of the problem (see Fig. 1), a set of equations are determined, the so-called Euler–Lagrange equations, whose solution in exact or approximate numerical or closed form, depending by the problem, represents the optimal distribution of stiffness properties. The purpose is to obtain plies with spatially variable properties that minimize the transverse shear stresses at the critical interfaces and the bending deformation. However, any other strategy of interest could be applied making minimal or maximal the strain energy contributions of interest, then solving simultaneously the resulting equations giving the optimal distribution of stiffness properties.

It could be noticed that the search of the optimal orientation of fibre paths is carried apart from the computation of the structural response and once for all. As a consequence, layerwise structural models that are impractical if used with the available optimization techniques, their computational effort being unaffordable, can be considered within the present approach in order to give more realistic predictions.

The optimization problem of variable stiffness composites is reduced to a simple problem of detecting the proper stacking sequence like with straight-fibre composites, which can be efficiently solved by the classical optimization techniques.

Differently to previous works by the authors, functionally graded foam core is not considered, being a potentially effective technology which is still under development. On the contrary, stitching and plies with variable fibre orientation are consolidated technologies (see, e.g., Refs. [40], [32] and [7]) that allow for an immediate application.

According to Prodromou et al. [41], the models accounting for the through-the-thickness reinforcements can be broadly classified as analytical methods (Refs. [25] and [34]), methods based upon inclusion method (Refs. [12] and [33]), methods based upon cell method (Refs. [41] and [1]) and finite element methods. The latter approaches are of general validity being capable of treating arbitrary reinforcement configurations and in the form of a material testing by a full scale finite element analysis (Refs. [28] and [29]) they are the most accurate method to date available. Hence, as in Ref. [24], 3D finite element analysis (FEA) is here