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Assembly of semi-analytical models to address linear buckling and vibration of stiffened composite panels with debonding defect

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ABSTRACT

The substitution of conventional mechanical fasteners by adhesive joints has been advocated by the aircraft and aerospace industries due to the weight saving potential. Flaws such as debonding of the adhesive layer between the skin and the stiffener may greatly affect the structural behavior of composite panels. Within this context, this work presents a semi-analytical approach for the numerical investigation on the effects of skin-stiffener bonding flaw size on the vibration and linear buckling behavior of T-stiffened composite panels. Skin and stiffener have been modeled using an assembly of curved and flat panel components, with each domain approximated using a set of hierarchical polynomial functions. A penalty-based approach has been used to assemble the various domains and to model the debonded region between the stiffener flange base and the plate. This approach ensures full compatibility in terms of displacements and rotations between the stiffener's base top face and the panel bottom face allowing to model different skin/stiffener debonding lengths. The results obtained using the proposed semi-analytical models have been compared and verified against numerical predictions based on finite element analyses.

1. Introduction

Flat and curved composite panels constitute a major portion of aircraft structures. They are found in aerospace structures such as wing surfaces, horizontal and vertical stabilizers, and fuselage sections as well as in spacecraft and missile structural applications [1]. Nowadays there exist many methods for bringing together stiffeners and skin in terms of the joining technique. Conventional mechanical joints such as bolted, pinned or riveted are preferred due to their simplicity and disassembly capability for both metallic or composite parts. However, mechanical joints are prone to local damage at the fastener holes due to stress concentrations [2–4], leading to the degradation of the joint which ultimately jeopardizes the structural integrity of the assembled structure. The demands for designing lightweight structures without any loss of stiffness and strength have turned many researchers and design engineers to seek for alternate joining methods. Adhesive bonding is a material joining process in which an adhesive placed between the adherent surfaces solidifies to produce an adhesive bond. The field of structural adhesive bonding has matured with the development of a wide range of adhesives from the chemical industry. Both adhesive bonding or co-cure offer several advantages over conventional joining technologies which includes [5]: (a) Often, thinner gage materials can be used with attendant weight and cost savings; (b) The number of production parts can be reduced, whereas the design is more simplified; (c) The need for milling, machining and forming operation of details is reduced; (d) Large area bonds can be made with a minimum work force without special skills; (e) Adhesive bonding provides a high strength to weight ratio with three times higher the shearing force of riveted joints; (f) Improved aerodynamic/hydrodynamic smoothness and visual appearance; (g) Use as a seal, and/or corrosion preventer when joining incompatible materials.

Most of the work reported in the open literature have focused on the effects of the skin-stiffener interfacial debonding flaws on the static behavior of stiffened composite panels. Previous studies on the effects of the skin/stiffened delamination in co-cured stiffened panels uniaxially loaded in compression in the post-buckling regime are presented in Refs. [6–9]. Ambur et al. [9] presented a similar study for composite panels loaded in shear. Rijn and Wiggenraad [10] investigated experimentally the strength of the skin-stiffener interface in composite aircraft panels using the seven-point bending test apparatus. Closed-form [11–14] and

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semi-analytical approaches [15–17] to deal with the local buckling of stiffened panels and plates have been presented in the literature, but a semi-analytical approach that takes into account global buckling modes and debonding flaws are currently not available.

The skin/stiffener interface behavior plays an important role in the overall dynamic characteristics of the stiffened panel, such as natural frequencies, mode shapes, and non-linear response characteristics to external excitations. The joint represents a discontinuity in the structure and results in high stresses that often nucleate failure [18]. The stresses and slip in the vicinity of contact regions determine the static strength, cyclic plasticity, frictional damping, and vibration levels associated with the structure. The need for developing methodologies for constructing predictive models of structures with joints and interfaces has recently been discussed by Dohner [19].

Modern mechanical design and analyses are based on deterministic finite element (FE) and multi-body dynamics computer codes [20]. The main objectives of these codes are to estimate the system eigenvalues, system response statistics, and probability of failure [21,22]. Ibrahim and Pettit [22] presented an assessment of the role of joint uncertainties and relaxation in the design and dynamic behavior of structural systems. Basic considerations in the design of joints of composite structures are discussed by Agarwal and Broutman [23].

The main goal of this paper is to present a semi-analytical approach to investigate the effects of skin-stiffener bonding flaw size on the linear buckling and vibration behavior of T-stiffened composite panels subjected to any static loads. Various laminate configurations for the skin and stiffener as well as different geometric configurations were investigated in an attempt to map the general behavior of such panels under the presence of a skin/stiffener debonding flaw. The problem is solved using an assembly of semi-analytical models that can be adapted to a large variety of problems, producing efficient parameterized tools for the investigation of various types of structures. The Ritz Method is chosen to derive the equations for each semi-analytical domain using the weak form, with each semi-analytical domain and their assembly formulated using the kinematic assumptions from the Classical Laminated Plate Theory (CLPT). Finite element models were used to verify the obtained results and the convergence behavior of the approximation functions here adopted.

2. T-Stiffened panel with debonded region

Fig. 1. shows a T-Stiffened panel with the respective coordinate system for the skin (x, y, z), stiffener's base (x', y', z') and flange (x'', y'', z''). A debonding defect exists and it is assumed to always extend all over the stiffener's base width (b_b) and has its length δ measured by its extent along coordinate x. The T-Stiffener is assumed to extend all over the skin panel length, parallel to x, with the origin of coordinate system x'', y'', z'' located at $y = b/2$. All dimensions necessary to define the T-Stiffener cross section and the skin thickness are also shown in Fig. 1.

In order to compute linear static displacements, linear buckling modes and vibration modes for the stiffened panel of Fig. 1, the authors have first attempted to apply a semi-analytical model for which the skin region was modeled using a single domain, with just one set of continuous approximation functions. For those attempts Legendre's hierarchical polynomials of orders as high as 24 for each coordinate were used as approximation functions for the displacements u, v, w, leading to an insufficient resolution of the displacement field. The successful strategy herein explained in details consists on dividing the skin, stiffener's base and stiffener's flange in subdomains, as illustrated in Fig. 2, where each subdomain has its own set of approximation functions and the assembly is accomplished using connection matrices based on compatibility relations. The unsuccessful single domain approach could theoretically be improved by higher order polynomials, but the 24th order polynomials already started to become computationally expensive and prone to numerical instability with a numerical precision of 64-bits (double), whereas the multi-domain approach allows the use of considerably lower order polynomials for each domain, keeping the computational cost low and the numerical stability high even for complex and displacement fields, verified nearby the debonded region. Note that in the assembly scheme of Fig. 2 the debonded region is the connection between panels P05 and P12, and the defect is produced when this connection is omitted. Since non-linear analyses are not performed in the current study, contacts between panels P05, P12 and P13 at

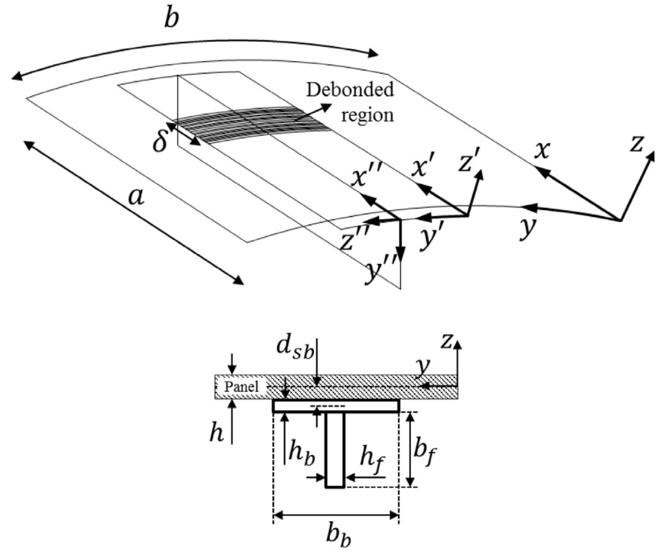

Fig. 1. T-Stiffened Panel.

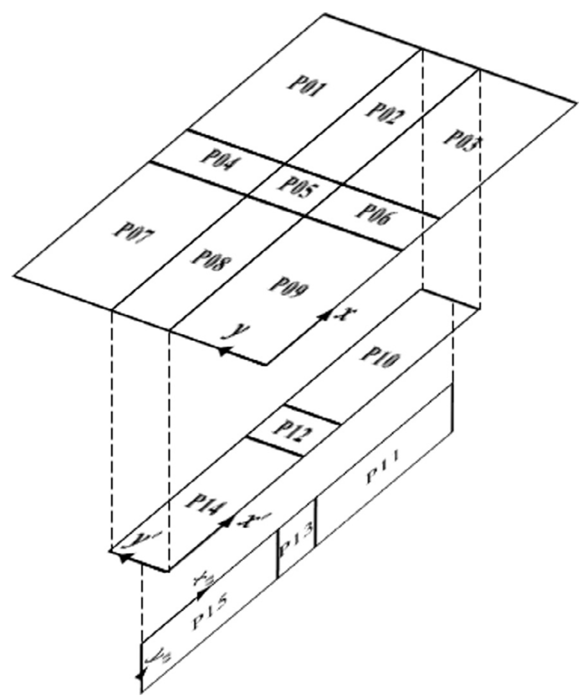

Fig. 2. Assembly scheme for semi-analytical models.