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An efficient semi-analytical simulation framework to analyse laminated prismatic thin-walled beams

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ABSTRACT

An efficient semi-analytical simulation framework is presented, that allows a highly systematic analysis of the mechanical behaviour of laminated prismatic thin-walled beams. It is excellently suitable for extensive case studies and can serve as a key ingredient for the optimization of shape, geometry and stacking sequences of laminated beams. The proposed method can be coded as a stand-alone solution and easily and directly be embedded in existing numerical optimization tools, without the overhead of common simulation tools (like FE-codes). Thus, long-winded and time consuming data transfers are avoided. Additionally, as a consequence of the structural clearness of the proposed method, the simulation framework can also be used as an environment for the development and testing of new beam models. By analogy with existing models for thin-walled beams, the kinematic of the cross-section is described by a proper set of deformation modes. There are no restrictions regarding these modes, i.e. rigid body modes (axial extension, mayor- and minor-axis flexure, and torsion) as well as higher-order modes (involving warping, distortion and transverse bending of the cross-section walls) can be considered. It is shown that for each given set of modes, the resulting system of equations can be derived - both analytically and systematically - in a straight-forward manner. In contrast to common beam formulations, the introduction of both stress resultants and cross-section values is not required.

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1. Introduction

Light-weight structures become more and more attractive in different fields of structural engineering. This trend can be traced back to both mechanical reasons and the increased sensibility due to the stewardship of available resources. Carbon fibre reinforced plastics (CFRP) show a big weight-saving amount and an increase in fatigue strength in comparison to steal and aluminium. This results in a longer service life and maintenance intervals. CFRP have a good corrosion resistance. Recent progress in the production process of laminates, allows the application of laminates in real engineering structures with a dimension of meters and more; e.g. bridges, aircraft parts and truck trailers, portal milling machines or overhead travelling cranes. In Sedlacek and Trumpf [20] a light weight bridge was constructed out of pultruded profile elements. In the context of light-weight structures, a typically distinction is made between shell-and beam-like structures. The focus in this paper lies on beam-like prismatic structures, where the beam cross-section consists of individual plane segments that are linked together, see e.g. Fig. 1. The cross-section shapes of such light-weight structures are typically geared to those of common steel or concrete structures. Each individual segment represents a plane laminate, which is built up from a certain number of transversal-isotropic (unidirectional) layers with individual orientations.

In order to design and to dimension such engineering structures, numerical methods are required, as experimental investigations are less flexible, more time-consuming and more expensive. The numerical methods must be able to detect reliably, the stressing of individual members of the structure as well as the collapse load of the entire structure. Existing numerical methods for the structural analysis of such thin-walled beam-like structures are usually based either on shell- or beam-theories.

In case of arbitrary thin-walled structures, shell models are more flexible, especially when considering the deformation of the cross-section shape, which cannot be taken into account by classical beam theories. However, in the context of prismatic thin-walled structures of interest here, it turns up that the extended beam theories with additional kinematics are more suitable. This is due to the fact that the meshing procedure considering 1D beams is less time-consuming than the procedure considering 2D shells. This is particularly significant if extensive parameter studies

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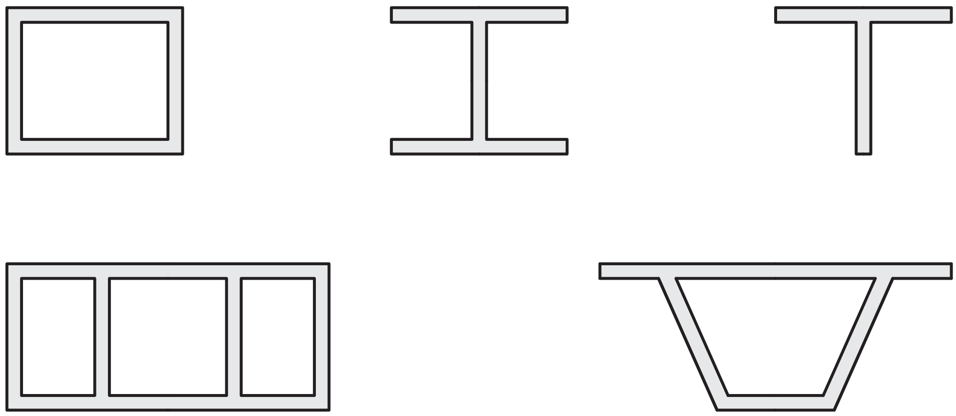

Fig. 1. Different type of prismatic folded plate structures of open and closed cross-sections.

have to be performed in order to optimize the dimension of the cross-section and/or the laminate-stack sequences.

In *classical* beam theories (e.g. Bernoulli beam and Timoshenko beam) it is assumed that the cross-section surface remains plane and that the cross-section shape remains unchanged during the deformation process. Upon consideration of these kinematic assumptions, the deformation of a spatial beam is restricted to 6 modes, which are finally represented by 3 translational and 3 rotational degrees of freedom. Beams with thin-walled cross-sections are especially outlined in Chen et al. [11], Alsafadie et al. [1], Goncalves et al. [12]. The cross-section deformation is considered in Goncalves et al. [12].

In *extended* beam formulations, the warping of the cross-section is also considered by using additional deformation modes, and additional degrees of freedom, respectively. Some finite element formulations, e.g. Simo and Vu-Quoc [24], Gruttmann et al. [13], Battini and Pacoste [4], Alsafadie et al. [1], use seven nodal degrees of freedom at each node. These are three displacement degrees of freedom, three rotations and one quantity which is related to the torsion-warping deformation. In Wackerfuß and Gruttmann [30,29] a beam formulation has been presented which is able to cover warping effects without the need of extra global degrees of freedom. In the so-called *generalized beam theory*, introduced by Schardt [19], further deformation modes are considered for prismatic beams. Those deformation modes allow the consideration of warping and deformation of the cross-section. Many fundamental and general contributions on beam theories have been made by Vlasov [27,28]. Altenbach et al. [3] summarizes the research work done before in the field of modelling thin-walled, beam-like elements. Their focus lies on the work done by Vlasov. The models were extended in order to include composite materials and also to cover geometrically non-linear effects, e.g. in Silvestre and Camotim [22,23], Camotim et al. [6], Silva et al. [21]. In the textbook of Altenbach et al. [2] a detailed overview of composite structures is given. The mechanics of laminated composite plates and shells is presented in the textbook of Reddy [18]. Nonlinear composite beams are addressed in a textbook of Hodges [14]. In the literature, several simple shear deformation theories exist for analyzing the global beam behaviour. Most of them are 1st order with no in-plane deformations of the cross-section. In Kroker and Becker [16] a higher-order theory for a composite box beam under bending load has been presented. They applied 2nd and 3rd order approaches for flanges and webs, respectively. Thereby not only out-of-plane deflections of a cross-section were taken into account but also in-plane deformations. For this case, a closed form analytical solution has been derived. Some higher-order theories are based on different shell elements and also include in-plane deformations of the cross-section [15,17]. In Suresh and Nagaraj [26] an higher-order shear deformation model for thin-walled composite beams has been developed, whereas the warping functions are derived form the equilibrium. In Carrera et al. [8] the Carrera Unified Formulation (CUF) has been introduced, enabling the development of 1D displacement fields in an arbitrary, but kinematically enriched manner. For recent developments on refined beam theories we refer to Carrera et al. [10].

The aim of this paper is to propose an efficient semi-analytical simulation framework that allows a highly systematic analysis of the mechanical behaviour of prismatic laminated thin-walled beams with arbitrary-shaped open- or closed cross-sections. Due to their semi-analytical character, it is excellently suitable to be applied in the context of extensive case studies that are required to optimize the shape, geometry and the stacking sequences of laminated beams. The proposed method can be coded as a standalone solution and easily and directly be embedded in existing numerical optimization tools, without the overhead of common simulation tools (like FE-codes). Thus, long-winded and time consuming data transfers are avoided. Additionally, as a consequence of the structural clearness of the proposed method, the proposed framework can also be used as an environment for development and testing of new beam models. For example, the influence of a certain deformation mode on the mechanical behaviour of the beam can be investigated separately. Like in existing beam models for thin-walled beams, the kinematic of the cross-section is described by a proper set of deformation modes. In general, there are no restrictions regarding these modes, i.e. rigid body modes (axial extension, mayor- and minor-axis flexure, and torsion) as well as higher-order modes (involving warping, distortion and transverse bending of the cross-section walls) can be considered. However, based on the deformation modes considered in this paper, the formulation is limited to 2D problems (without torsional effects) and simply shaped thin-walled cross-sections. It will be shown that for each given set of deformation modes, all matrices required to assemble the global system of equations can be – both analytically and systematically – derived in a straight-forward manner. A related workflow summarizing all steps required is explicitly presented. This approach results in a system of linear equations for the unknown deformation modes, which finally can be solved using a standard numerical solver. Analog to the CUF – and in contrast to the most existing beam formulations – the introduction of both stress resultants and cross-section values is not explicitly required.

In order to guarantee the semi-analytic character of the proposed method, the deformation modes are formulated by means of polynomial functions. In contrast to existing beam formulations

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