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Research paper

A novel approach to analyze beam-like composite structures using mechanics of structure genome

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ABSTRACT

A novel approach to the analysis of beam-like composite structure is introduced in this paper. New software Gmsh4SC is developed based on two well-known open source codes Gmsh and CalculiX. One-dimensional Euler–Bernoulli and Timoshenko type finite elements are derived based on the constitutive models obtained by using Mechanics of Structure Genome (MSG). Gmsh4SC is connected to a general-purpose composites software SwiftComp^{TM}, which implements MSG to carry out the constitutive modeling. The software can be executed in the cloud at https://cdmhub.org/tools/scstandard. Several beam-like composite structures are analyzed by this newly developed software. The accuracy and efficiency of the proposed method are verified by three-dimensional (3D) finite element model using the commercial code ABAQUS.

1. Introduction

Beam-like structures are widely used in various industries, such as civil, aerospace, and mechanical engineering. Although finite element methods have been widely and successfully used in the analysis of beam-like structures, there are still some issues when the structure has complex geometries or made of multiple anisotropic materials. For beam-like composite structures, significant computational effort is required in order to get the accurate results (e.g. stress and strain fields) due to the heterogeneity and anisotropy of material.

In order to analyze beam-like composite structures, many refined beam theories have been proposed. Generalized beam theory is introduced to analyze various problems in thin-wall beam structures, such as non-linear, elastoplastic [1,2] and buckling problems [3]. Vidal et al. [4] developed a finite element based on the Proper Generalized Decomposition, which expresses the displacement as a separated representation of two one-dimensional (1D) space functions to simplify original three-dimensional (3D) problems. Carrera et al. [5] developed a hierarchical formulation that can be used to reduce 3D problems to two-dimensional (2D) or 1D ones in a unified manner, and a detailed literature review can be found in Carrera et al. [6]. Berdichevsky and his coworkers [7,8] introduced the variational asymptotic method (VAM) for three-dimensional beam modeling. The original 3D beam problem is decoupled into a 2D cross-section analysis which provides the elastic constants and an 1D beam problem to calculate the beam structure global responses. Based on VAM, a cross-sectional analysis tool named variational asymptotic beam section analysis (VABS) was developed by Hodges and his coworkers [9–11]. Recently, Yu [12,13] developed Mechanics of Structure Genome (MSG) as a generalization of VABS to deal with all types of structures including beams, plates (shells) and 3D structures. MSG is implemented in a general-purpose multiscale constitutive modeling software SwiftComp^{TM}. SwiftComp^{TM} takes the geometry and material characteristics of a Structure Genome (SG) described using a finite element mesh as the input and computes the constitutive models for the macroscopic structural analysis. After analyzing structural responses, SwiftComp^{TM} can also compute the local fields within the SG based on structural global behaviors.

Currently, the license of commercial finite element software packages is very expensive, which somehow limits the development of advanced structures. On the other hand, more and more open source software codes appear in the recent years, which provides new tools to analyze engineering structures. Two open source codes are used to implement the concept of MSG into structural analysis: Gmsh and CalculiX. Both of them are widely used in both industries and academic research [14,15]. Gmsh is an 3D finite element grid generator with a build-in CAD engine and post-processor developed by Geuzaine and Remacle [16]. Gmsh geometry module is modified to provide a set of common SGs [17], which will greatly reduce the time for building the geometry of the structure. A new module SwiftComp is added into Gmsh which is con-

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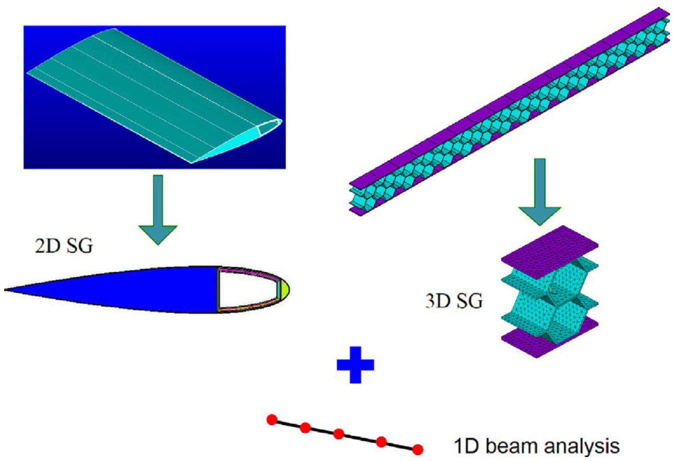

Fig. 1. SG for beam-like structure.

nected with SwiftComp™ to carry out homogenization and dehomogenization analysis. Another open source code CalculiX CCX is developed by Dhondt [18], which is added in a new module to serve as the finite element solver that carries out structural analysis of composite beams.

In this study, new Euler–Bernoulli and Timoshenko type beam elements are derived based on the constitutive models provided by MSG, which can capture all the coupling effects in composite structures and deal with arbitrary beam cross-sections. Here the coupling effects refer to the elastic couplings among the fundamental deformation modes of the Euler–Bernoulli model or Timoshenko model. In other words, the beam elements developed in this study can deal with fully populated stiffness matrix, see Eq. (10) for the Euler–Bernoulli model and Eq. (26) for the Timoshenko model. The beam elements are coded into CalculiX to overcome its limitation in beam elements. A graphical user interface (GUI) named Gmsh4SC which incorporates Gmsh, SwiftComp™, and CalculiX is developed to provide an efficient way to analyze a structure using MSG. Several numerical examples show that using MSG to analyze beam-like composite structures greatly simplifies the modeling process while maintaining accuracy similar to 3D finite element analysis (FEA).

2. MSG for beam-like structures

2.1. SG for beam-like structure

SG is the smallest mathematical building block of a structure which contains all the constitutive information needed for this structure [13]. This implies that SG builds a connection between materials properties and structural analysis. SG is built upon the concept of representative structural element (RSE) [19], but highlights the fact that SG contains all the constitutive information needed for a structure, which is similar as genome which contains all the intrinsic information for an organism's growth and development.

For beam-like structures, we can use MSG to obtain 4 by 4 beam stiffness matrix for the Euler–Bernoulli type beam element or 6 by 6 beam stiffness matrix for the Timoshenko type beam element, and also the original 3D fields in terms of the global beam behaviors. The first step to analyze a beam-like composite structure is to identify the SG of the original structure according to its heterogeneity. As the structures in Fig. 1 show, if the beam has uniform cross-section along the beam reference line, its SG is 2D, which can be projected along the beam reference line to construct the entire structure. If the cross-section of the beam is not uniform along the beam reference line, then we need to use a 3D SG to construct the entire beam structure.

Beam constitutive modeling is often considered as one branch of the structural mechanics, but if we treat the beam reference line as a 1D continuum, then every material point of this continuum has a 2D SG or 3D SG as its microstructure. In other words, The constitutive modeling of beams can also be treated as a special case in micromechanics. So MSG unifies structural mechanics and mircomechanics in beam constitutive modeling [13].

2.2. Modeling framework using MSG

Traditional FEA analysis can easily handle isotropic homogeneous beam-like structures, but it is computationally more expensive in analyzing composite beams. In order to achieve accurate

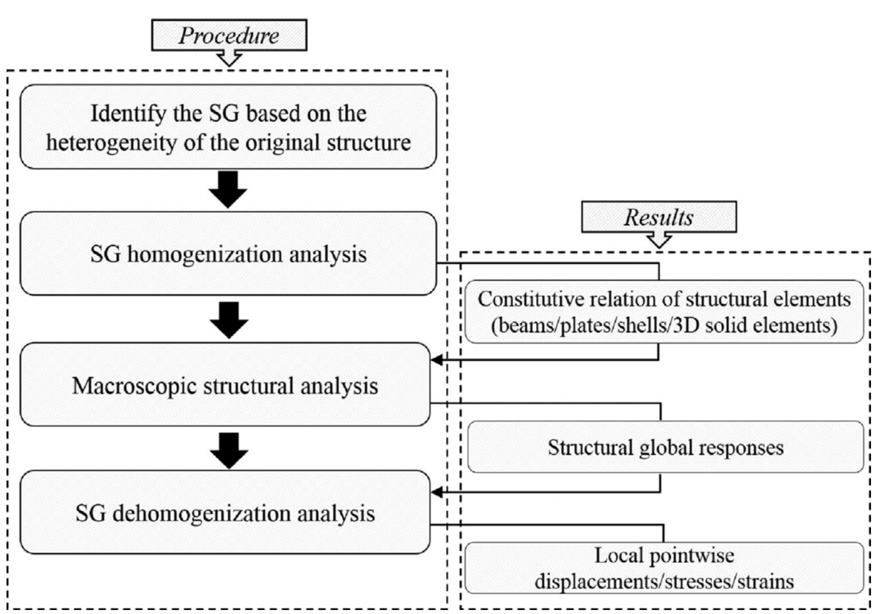

Fig. 2. Structural analysis using MSG.