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Analysis of thin-walled beam-shell structures for concept modeling based on higher-order beam theory

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ABSTRACT

Many engineering structures consist of thin-walled beams and shells. Especially for fast design in an early design stage, a simplified analysis using beams for load-carrying members and shells for panels is very useful, but there appears no accurate beam-shell combined finite element model. The main reason is that the Timoshenko or Euler beam elements are incapable of representing significant sectional deformations near beam joints or near beam-panel interfaces. Although some progress has been made in developing higher-order beam elements that can accurately capture the sectional deformations, there is no investigation to develop higher-order beam and shell combined models useful to analyze various engineering structures. The main contribution of this work is to present the first attempt to model structures made of thin-walled closed beams and shells in terms of higher-order beam elements and shell elements and to establish the matching conditions between the dissimilar field variables of higher-order beam and shell elements along their interfaces. For the finite element analysis of a whole structure, the interface matching conditions are imposed through Lagrange multipliers. High accuracy of the proposed higher-order beam-shell method is demonstrated through static and modal analyses of various structures including a simplified model of a vehicle body-in-white (BIW).

1. Introduction

In an early stage of the design process for complex structural systems, a fast but reliable analysis method is very useful. Especially for structures made of thin-walled beams and panels, such as a vehicle body-in-white (BIW), which refers to an automobile body before assembly of moving parts such as doors and hood, the engine, chassis sub-assemblies, and trim, the use of beam elements will be certainly preferred over detailed shell or solid elements. The main problem is that if the classical beam elements such as the Timoshenko or Euler beam elements are used to model thin-walled load carrying beams, the resulting structural behavior is quite inaccurate because significant sectional deformations, such as warping and distortion, of thin-walled beams cannot be represented by the classical beam elements. Nevertheless, there were many attempts to incorporate beam elements in the structural analysis of complicated structures, especially vehicle structures.

Donders et al. [1] and Mundo et al. [2] proposed a reduced beam and joint modeling procedure to analyze and optimize the NVH performance of an automotive structure in the concept design phase. Nakagawa et al. [3] used Euler beam elements for a first-order analysis of a vehicle subframe. To deal with joint stiffness, they used nonlinear springs for which a database had been stored for various cases [4]. Mihaylova et al. [5] achieved rapid optimization to improve static and dynamic stiffness of a BIW by constructing response surfaces for cross-section parameters of arbitrarily-shaped cross sections with respect to the dimensions of the boxes that enclose the cross sections. More simplified standardized cross sections, such as boxes or tubes, can be employed for the beam modeling of BIW [6,7].

Although simplified models in the studies listed above were successful to some extent for the optimization of existing vehicles (or predecessor vehicles), vast improvements are required in terms of analysis accuracy. In particular, the complicated behavior of beam joints has been one of the most difficult issues, for which many solutions have been proposed, such as static condensation [1,2], dynamic reduction [5], and torsional spring attachment [3,4,8,9]. However, most of these require corrections of joint stiffness and thus cannot ensure accurate analysis consistently during the optimization of simplified models.

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Recently, adopting the higher-order thin-walled beam analysis by Kim and Kim [10–12], flexibility of joints is naturally derived by introducing higher-order cross-section deformations such as warping and distortion. In Jang et al. [13] and Jang and Kim [14], matching conditions at a joint among one-dimensional beam deformation measures are found by considering the continuity of three-dimensional displacements. Coupling behavior at a joint among beam cross-section deformations can be derived in their research without introducing any artificial stiffness. Choi et al. [15] derived a joint transformation matrix to match arbitrarily-oriented thin-walled box beam elements for out-of-plane bending problems. Joints connected with three box beams, such as T-joints, were analyzed in [16–18] for out-of-plane bending problems, and the results were shown to be significantly close to those obtained by pure shell elements. The joint matching conditions for higher-order thin-walled beams in [13–18] are, however, valid only for rectangular cross sections. Higher-order cross-section modes are also considered by other recent beam theories such as the generalized beam theory [19–22] and the Carrera unified formulation [23–25]. Nonetheless, accurate stiffness calculation of a joint between thin-walled beams is not seriously investigated in these studies.

In this study, the interface matching conditions between thin-walled beam elements and shell elements are established to solve static and modal analysis problems of thin-walled beam-shell coupled structures. Fig. 1 illustrates a vehicle body-in-white as an example of a higher-order beam-shell coupled structure, which will be solved using the proposed beam-shell modeling method. The frame of the structure, regarded to be generally curved in three-dimensional space, is approximated by using higher-order thin-walled beams with quadrilateral cross sections. Joints or panels are modeled by using MITC4 shell elements [26], and are attached to the thin-walled beam elements. The field variables of higher-order beam and shell elements are matched through the interface matching conditions. Because the matching conditions at a joint between higher-order beam elements are not available for cross sections with general quadrilateral shapes, the so-called joint region is defined at the joint, modeled by using shell elements, and connected with higher-order beam elements using the interface matching conditions. In this study, we establish the interface matching conditions between higher-order beam elements and shell elements by imposing the continuity of three-dimensional displacements and rotations. The validity of the proposed interface matching conditions is investigated for the cases of the following beam-shell connections: flat beam and flat shell connection, curved beam and curved shell connection, and beam and joint connection.

This paper is organized as follows. First, a brief overview of the higher-order beam theory used to analyze thin-walled beams having quadrilateral cross sections is presented in Section 2. The interface matching conditions between higher-order beam elements and shell elements are presented in Section 3, and those for the beam-joint interface are presented in Section 4. The effectiveness of the proposed beam-shell modeling method is verified by several numerical examples in Section 5.

2. Higher-order beam theory for thin-walled beams with quadrilateral cross sections

In the higher-order beam theory, three-dimensional displacements of the centerline of a cross section are described as [27]

$$u^B_\alpha(s,z) = \sum_{i=1}^{N_\psi} \psi^i_\alpha(s) d_i(z) = \boldsymbol{\psi}_\alpha \mathbf{d}, (\alpha = n,s,z), \tag{1}$$

where s is the tangential coordinate along the contour of the cross section, n is the outward normal coordinate, and z is the axial coordinate. In Fig. 2(a), s and n are edge-wisely defined.

In Eq. (1), d_i denotes one-dimensional deformation measures of the cross section for not only conventional rigid body deformations but also higher-order deformations. The associated cross-section deformations (or modes) for d_i are ψ^i_α, which will be obtained using the beam frame model in Fig. 2(a). Higher-order cross-section deformations consist of distortions for in-plane deformations, and warpings for out-of-plane deformations. As a result of the coupling effect among the one-dimensional deformation measures, a number of higher-order cross-section deformations are needed for accurate analysis especially for curved or jointed beam structures. In this investigation, the cross-section deformation is

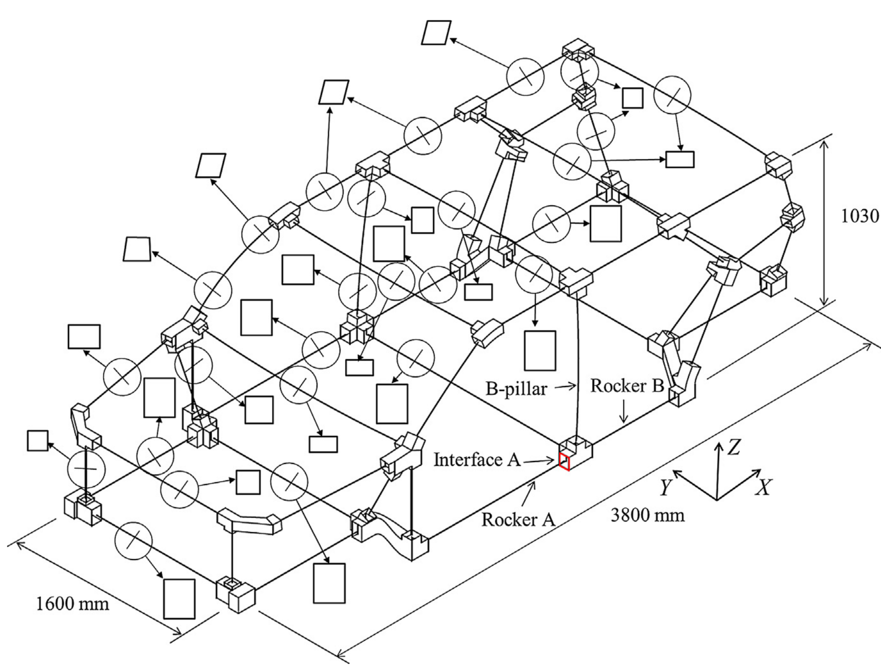

Fig. 1. Simplified beam-shell model of a vehicle body-in-white (joint regions defined at the joints are modeled using shell elements).