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A complete development process of finite element software for body-in-white structure with semi-rigid beams in .NET framework

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ABSTRACT

At the conceptual design stage, simplified finite element (FE) model of body-in-white (BIW) structure focuses on its specific merit to provide early-stage predictions for detailed FE model of that. This paper exploits a semi-rigid beam element (SRBE) that consists of a beam element with two semi-rigid connections at the ends to simulate the flexibility of joint. Guyan reduction method condenses the SRBE as a super element. A special finite element software for structural modeling and analysis of BIW (SMAB) is developed in .NET framework. The Unified Modeling Language is employed to depict the classes and their relationship. The design patterns are identified and applied in the framework design to facilitate communication and system expansion. Microsoft DirectX and GDI+ implement graphics display of spatial BIW frame and planar thin-walled cross section. Based on multi-threaded technology in .NET, subspace iteration method is paralleled to speed up the mode analysis. As a result, the efficiency of the SRBE is demonstrated by a benchmarking automotive body. Multi-threaded parallel is effective and useful, especially for frequency optimization.

1. Introduction

Generally, the design process of body-in-white (BIW) structure should be divided into two stages: conceptual design stage and detailed design stage. A BIW structure can be simplified as a thin-walled frame structure consisting of joints and beams with complex cross section, i.e. a finite element (FE) model of space frame, showed in Fig. 1. The simplified FE model can thus be analyzed rather than detailed FE model (meshed by shell elements) for the global stiffness and vibration modes in the early design process of the main load-carrying components. At the conceptual design stage, no sufficient computer-aided-design (CAD) geometry information is available; moreover, the level of detail is not yet needed in the design process. Simplified model currently focuses on its specific merit to provide early-stage predictions.

At the conceptual design stage, how to accurately simulate the flexibility of joints and conveniently design the thin-walled cross section is a vital part of a finite element analysis (FEA) of BIW frame. Toyota Central R&D Labs have begun to study the conceptual design of BIW structure since 2000 and the first order analysis (FOA) conception for BIW designer was first proposed [1]. Although the FOA is easy to use, the software framework is based on Microsoft/Excel, so the expansibility and maintainability of the program become poor. Torstenfelt and Klarbring extended classical structural optimization from single-product optimization to optimization of a whole family of products that have common modules [2]. It utilizes beam elements with rigid connection without considering the flexibility of joints, so the global stiffness and frequency of simplified BIM structure are 50–100% larger than those of detailed BIW structure or real vehicle [3]. Donders et al. proposed a “reduced beam and joint modeling” approach to analyze and optimize the global bending and torsion modes of a vehicle body [4], in which all the complex beam sections were oversimplified as rectangular tube. In terms of BIW engineering, thin-walled frame structures are fabricated from a number of sheet metal parts. As shown in Fig. 2, multiple press-formed sheet metal parts are spot-welded together along two edges [5]. So complex shape of cross section should be drawn and properties of that should be calculated. Hyperbeam integrated in Altair’s Hypermesh software is a remarkable design and calculation module for cross section, but graphics drawing and editing features are not easy to attain by mouse click. Finally, SFE Concept [6] is a commercially available program, which makes use of an implicitly parametric modeling technique to create concept model based on simple geometrical descriptions. First, the user defines a set of base points and lines to indicate the position of joints, beams and pane ledges. Then, beam sections are defined and assigned to the lines. Parametric joints between the beams are automatically created and the shell

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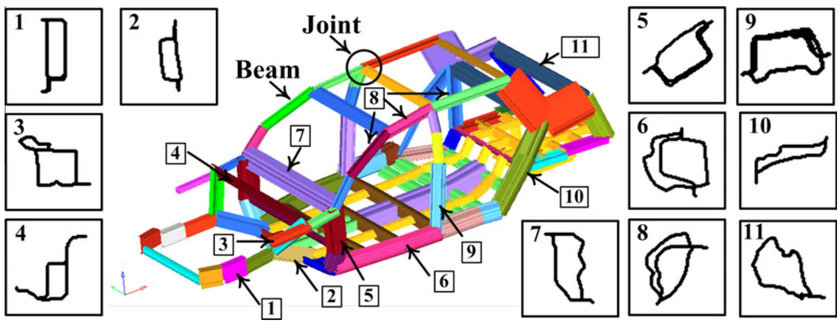

Fig. 1. BIW frame structure and its thin-walled cross section.

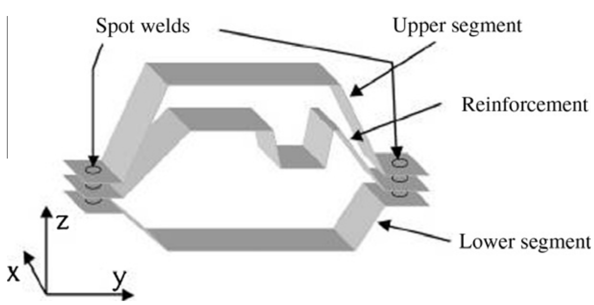

Fig. 2. Thin-walled cross section of BIW structure using pressed sheet metal.

components (wind screen, roof, etc.) are added. The procedure is fully parameterized, so that one can modify some base point coordinates and update the model to assess the effect on the structural behavior. The flexibility of joints in SFE Concept is dependent on the geometric shape beam element, so it may take much time and hard work to create concept model at conceptual design stage.

According to the discussion above, we developed a new finite element software for structural modeling and analysis of BIW (SMAB), constructed from semi-rigid beams with thin-walled cross section. This special CAE software can solve the problems in the following way. (1) The FE model of BIW structure can be quickly built up using semi-rigid beam elements (SRBEs), which is a new hybrid element. (2) This special CAE software integrated graphics/analysis environment is developed based on Microsoft's .NET framework. The design patterns are identified and applied in the framework design to facilitate communication and system expansion. Object-oriented programming (OOP) method for finite element analysis is adopted. GDI+ and DirectX implement the two dimensional (2D) and three dimensional (3D) graphics for Windows, respectively. (3) In order to speed up the frequency optimization of BIW structure, subspace iteration method (SIM) is parallelized and implemented by System.Threading class in .NET framework. In the following section, the details of each component are discussed.

2. BIW structure modeling using semi-rigid beam elements

The 3D semi-rigid beam with a joint at both ends is modeled by a beam element with a connection element at each end, as shown in Fig. 3. This hybrid element contains four nodes: two internal nodes m_{in} and n_{in}; two external nodes m_{ex} and n_{ex}. The thin-walled beam of the BIW structure is short and thick in the length and height, so classic Timoshenko beam theory should be introduced to consider the transverse shear, whose element stiffness matrix is denoted by $\mathbf{K}^e$ (12×12 dimension) [7]. The connection element consists of three tensional springs and three rotational springs, which are all zero-length and massless. At the local coordinate system, the stiffness matrix of spring element at m node is as follows:

$$\mathbf{K}_m^i = \begin{bmatrix} r_m^i & -r_m^i \\ -r_m^i & r_m^i \end{bmatrix} \quad i = u,\ v,\ w,\ x,\ y,\ \text{or}\ \ z \tag{1}$$

where r_m^u, r_m^v and r_m^w are the stiffness of tensional spring along the u, v, w local axes, respectively; r_m^x, r_m^y and r_m^z are the stiffness of rotational spring around u, v, w local axes, respectively. And then the stiffness matrix of the connection element at m node is assembled as

$$\mathbf{K}_m = \begin{bmatrix}
r_m^u &&&&&& -r_m^u &&&&& \\
& r_m^v &&&&&& -r_m^v &&&& \\
&& r_m^w &&&&&& -r_m^w &&& \\
&&& r_m^x &&&&&& -r_m^x && \\
&&&& r_m^y &&&&&& -r_m^y & \\
&&&&& r_m^z &&&&&& -r_m^z \\
-r_m^u &&&&&& r_m^u &&&&& \\
& -r_m^v &&&&&& r_m^v &&&& \\
&& -r_m^w &&&&&& r_m^w &&& \\
&&& -r_m^x &&&&&& r_m^x && \\
&&&& -r_m^y &&&&&& r_m^y & \\
&&&&& -r_m^z &&&&&& r_m^z
\end{bmatrix} \tag{2}$$

The following stiffness relations of SRBE can be obtained by considering equilibrium of the members:

$$\begin{bmatrix} \mathbf{K}_{11}^m & \mathbf{K}_{12}^m & & \\ \mathbf{K}_{21}^m & \mathbf{K}_{22}^m + \mathbf{K}_{11} & \mathbf{K}_{12} & \\ & \mathbf{K}_{21} & \mathbf{K}_{11}^n + \mathbf{K}_{22} & \mathbf{K}_{12}^n \\ & & \mathbf{K}_{21}^n & \mathbf{K}_{22}^n \end{bmatrix} \begin{bmatrix} \mathbf{u}_m^{ex} \\ \mathbf{u}_m^{in} \\ \mathbf{u}_n^{in} \\ \mathbf{u}_n^{ex} \end{bmatrix} = \begin{bmatrix} \mathbf{R}_m^{ex} \\ \mathbf{R}_m^{in} \\ \mathbf{R}_n^{in} \\ \mathbf{R}_n^{ex} \end{bmatrix} \tag{3}$$

where $\mathbf{K}_{ij}^m$, $\mathbf{K}_{ij}^n$ and $\mathbf{K}_{ij}$ ($i = 1, 2$; $j = 1, 2$) are respectively the stiffness matrix of the connection element at m node; the stiffness matrix of the connection element at n node; block matrix of beam element stiffness matrix $\mathbf{K}^e$. The column vector of displacement and load (forces and moments) at external and internal m node are respectively

$$\mathbf{u}_m^{ex} = \left[u_m^{ex}, v_m^{ex}, w_m^{ex}, \phi_{xm}^{ex}, \phi_{ym}^{ex}, \phi_{ym}^{ex}\right] \tag{4}$$

$$\mathbf{u}_m^{in} = \left[u_m^{in}, v_m^{in}, w_m^{in}, \phi_{xm}^{in}, \phi_{ym}^{in}, \phi_{ym}^{in}\right] \tag{5}$$

$$\mathbf{R}_m^{ex} = \left[X_m^{ex}, Y_m^{ex}, Z_m^{ex}, M_m^{ex}, M_m^{ex}, M_m^{ex}\right] \tag{6}$$

$$\mathbf{R}_m^{in} = \left[X_m^{in}, Y_m^{in}, Z_m^{in}, M_m^{in}, M_m^{in}, M_m^{in}\right] \tag{7}$$

Those of n node can be obtained by replacing subscript m with n.