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Simplified crashworthiness method of automotive frame for conceptual design

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ABSTRACT

The crashworthiness design of automotive structure is crucial to ensure the safety of passengers. Lumped parameter models, multi-body models, plastic frame models and detailed shell element models were all introduced to simulate the collision process of automotive structure. However, plastic frame models were only confined to use box beams. Therefore, this paper presents a comprehensive crashworthiness design of plastic frame model, which can innovatively create complex thin-walled beams with arbitrary cross-sectional shapes, such as open, single-cell, double-cell, three-cell and four-cell sections. Numerical example verified that the proposed model can effectively replace detailed shell element model to accelerate the crashworthiness analysis of automotive structure, especially for the conceptual design.

1. Introduction

The design of automotive structure includes active and passive safety. Passive safety addresses the collision from the moment that an accident starts until automobile stops. During this process, the automobile is out of the control of the driver, but the safety devices, such as seat belts, airbags and automotive body structures, start to protect the occupants and pedestrians. This collision process can be tested by physical experiment or numerical simulation [1–4]. To reduce the experimental cost and period, numerical simulation is extensively used to aid the crashworthiness design [5]. In general, there are four types of finite element model (FEM) to simulate the collision process.

(1) Lumped parameter models were the first numerical method for one or two-dimensional crashworthiness analysis of automotive structure [6,7], by using lumped mass and nonlinear springs. These models introduced lumped and rigid blocks to represent the mass of the automotive parts, and nonlinear springs to represent the deformation of the automotive parts. These models were effectively applied on the initial stage of the automotive design, but this method is inaccurate.
(2) Multi-body models were proposed to simulate the three-dimensional collision of automotive structure and occupant protection [8–10]. The drawback on the use of multi-body models is the cumbersome modelling process and the difficulty of their validation. This problem is aggravated by the fact that automotive manufacturers are generally unable to release their automotive detailed data, even to contracted partners, due to commercial and legal restrictions. A solution to this problem is to use the generic automotive models that have all the passive safety data of the real automobile. However, the current automobile does not match exactly any existing one, so it is difficult to ensure the accuracy of the model.
(3) Detailed FEMs, meshed by plate or shell elements, can achieve accurate crash results, including deformation, collision force, energy absorption, etc. FEMs used in automotive crashworthiness analysis usually have millions of degrees of freedom. The computational cost, for simulations of 1 s on workstation computers, is measured in days. Especially, for the structural repeated modification or optimization problem [11–14], such a large computational cost is impractical in automobile engineering.
(4) Frame models used thin-walled beams (TWBs) and plastic joints to reduce the computational cost [15–17]. As an example of the effectiveness of TWBs and plastic joints, Park and Yoo [18] studied the modelling and crashworthiness analysis of simplified bus structures by using beam elements and nonlinear springs, but only employed box beam elements. Liu [19] presented a crashworthiness design of thin-walled curved steel beams with only box and channel cross sections, and did not apply it into the crashworthiness design of the automotive body model. How to acquire the plastic tension, compression, bending and torsional properties for plastic joints is the crucial issue in frame model [20,21]. The main findings have

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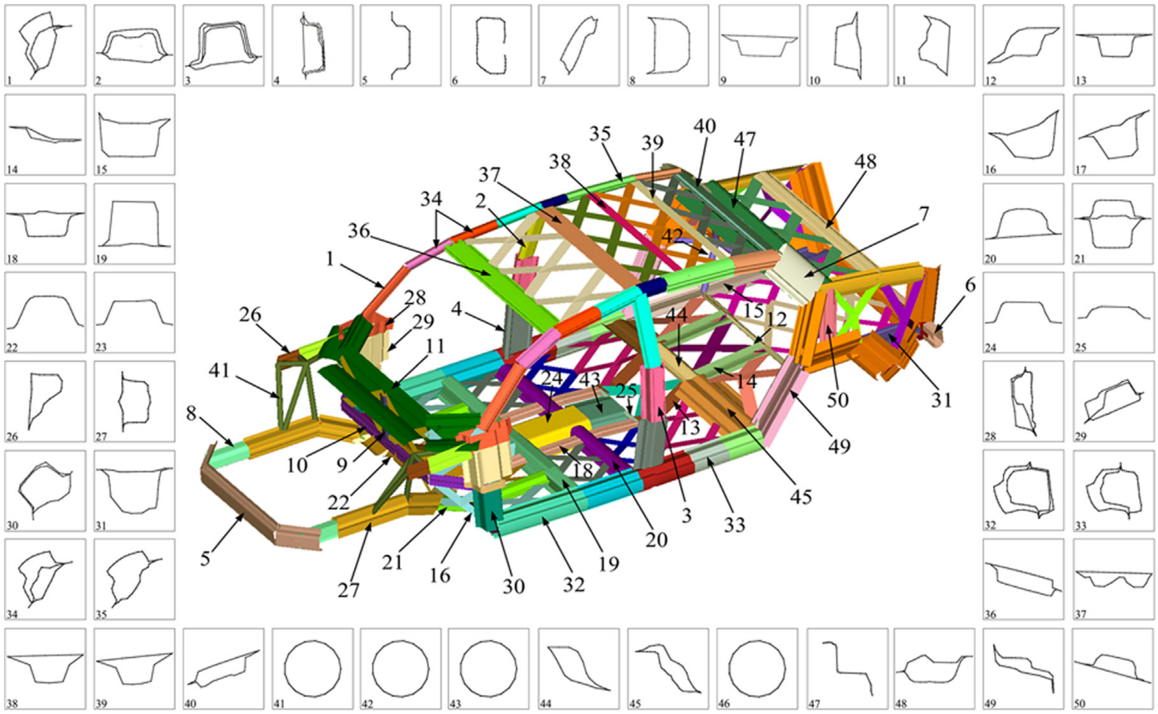

Fig. 1. Automotive frame of TWBs with complex cross-sectional shape.

been analytically derived by using the Wierzbicki's axial collision theory [22] and Kecman's bending collapse theory [23], respectively. Furthermore, most of the past studies have still only studied the properties of TWBs with common cross sections, including circular [24], rectangular [1], triangular [25], regular multi-cell [26–28], variable thickness [29–32], foam/ honeycomb filled thin-walled structures [2,3,33,34] under axial or oblique impact loading. These researches have been conducted to find the optimal crashworthiness design of the various TWBs, which focus on cross-sectional shape [35–37], geometrical modification [28], multi material [38] and filling condition [39]. Additionally, Sun et al. [40] explored the parameterization of criss-cross configurations for multi objective crashworthiness optimization, thereby generating the best possible parameterized sectional shape. For all the above studies of TWBs, only common cross sections are introduced to represent the automotive frame for collision analysis [8,41]. However, TWBs with complex cross-sectional shapes are extensively used in automotive engineering practice, as shown in Fig. 1.

Visual Crash Studio (VCS) [42] software focuses on the solution of the properties of complex cross sections. It is a powerful tool for the predesign stage of product development using Macro Element Method [43]. Compared to a detailed FEM, the VCS macro element model generates accurate results in a few seconds, which in consequence reduces modelling and solving cost. Besides, the VCS software calculates the crashworthiness of frame structures using multi-body dynamics (i.e. rigid beams with joints). However, this paper calculates the frame structures using elastic beams (i.e. Belytschko-Schwer beams) with joints, which are more accurate when dealing with the large deformation problems.

Additionally, we attempt to solve the frame model using explicit dynamics method. Thus, besides the plastic deformation of joints, the geometric nonlinear deformation of TWBs can also be calculated. In contrast, the deformation of TWBs in multi-body models can not be obtained, because the TWBs are all regarded as rigid body. LS-DYNA software is used to solve the frame model. Therefore, the main contribution of this paper is to develop a novel frame FEM for crashworthiness design and analysis, which consists of TWBs with complex cross sections and plastic joints.

2. Finite element model of automotive frame

2.1. Thin-walled Belytschko-Schwer beam

During the collision process of automotive frame, the plastic deformation occurs at the connection position (i.e., joint) between TWBs, so TWBs will rotate around the joint. In this case, TWBs generate large deformation, including rigid body rotation displacements and deformation displacements. Belytschko-Schwer (BS) beam element [44] successfully employs a “co-rotational technique” to separate the deformation displacements from the rigid body rotation displacements. However, BS beam element in LS-DYNA is unable to calculate the mechanical properties of complex cross-sectional shapes, as shown in Fig. 2. So we summary the formulations of mechanical properties [45–47], including cross-sectional area and moments of inertia for open-cell section, single-cell section and double-cell section, as shown in Figs. 3 and 4. Additionally, the torsional moment of inertia for three-cell and four-cell sections is derived, as shown in Figs. 5 and 6, because three-cell and four-cell sections are usually applied in the automotive B-pillar structure to serve as the main load-bearing part.

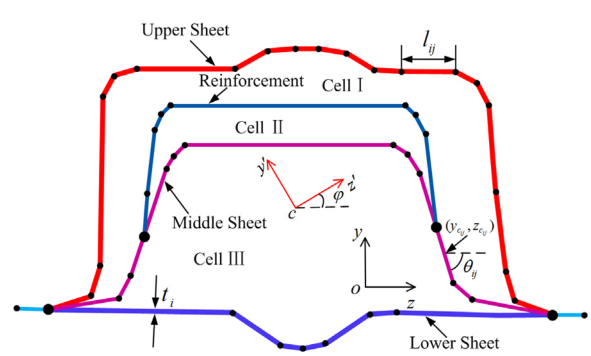

Fig. 2. Typical complex cross section.