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Potential error factors in 1D beam FE modeling for the early stage vehicle design

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ABSTRACT

When creating simplified models of the vehicle structure, 1D beam elements are normally used to obtain a small-sized and parametric representation of all beam-like parts. Despite its undoubted advantages, such an approach can introduce certain modeling errors. They are influenced by various factors such as cross-section deformations, spot welds, flanges, discontinuities and beam cross-section geometry. The aim of this paper is to perform a systematic study of these error factors and their potential impact on the model accuracy. Consequently, guidelines are given on good practices for overcoming the intrinsic limitations of 1D beam concept modeling techniques. For this purpose six different beam structures with idealized geometry are studied. Furthermore, three beam-like parts of a vehicle body are also investigated. The derived good modeling practices are applied to a couple of industrial case-studies, both at car body level. By giving a better insight of the potential pitfalls and their possible solutions, 1D beam concept modeling can become more accurate and reliable.

1. Introduction

The automotive virtual prototyping process is becoming more and more demanding in terms of time, costs and product quality. Vehicle concept modeling is increasingly recognized as an important part of the design chain. It is used to identify and apply modifications already in the early design stages, leading to shorter development time, lower cost and better products. Thus various concept modeling methodologies are being actively developed. The methods based on concept Finite Element (FE) equivalent of the structure are among the most popular ones [1–14]. They principally aim to create a simplified beam, joint and panel (BJP) representation of the detailed FE model of an existing vehicle. In some cases it is also possible to start with a concept model "from scratch". The resulting small-sized and parametric concept models are then used to perform fast structural optimization in order to improve the vehicle static and dynamic performance.

Despite their advantages, the methods using simplified structure layout can introduce some errors related to the modeling of beams, joints, panels and the connections between them. This work is focused on the error resulting from the concept representation of beams. They are an important component group used to simplify the main load-carrying structure of the vehicle. Beam-like members are often the first to be simplified and added to the concept model and, normally, they are substituted with 1D beam elements [1–13]. This simplification leads to a significant reduction in the number of elements and nodes with respect to the initial shell mesh. However, it can cause various discrepancies between the detailed FE model and its concept equivalent. Concept models with 1D beams result stiffer than their detailed FE counterparts as they do not take into account the local cross-section deformations. Additional differences can occur because of factors such as flanges, spot welds, stiffeners and discontinuities in the reference FE model, which are heavily simplified or not considered in the concept model. The type of the 1D beam cross-section is also important as it influences the accuracy of approximating the real cross-section properties. Various solutions have been proposed to tackle these issues: better modeling alternatives [2,3,6,12], model updating [2,7–9], correction factors [1,5,6,13]. However, in all these works, the problem is only partially addressed and solved. Still no holistic approach exists. The purpose of this paper is to serve as a basis to improve 1D beam concept modeling by giving a better insight into its major bottlenecks. Based on the systematic study of various beam typologies, general guidelines are derived to reduce the modeling errors. Thus, the already fast BJP methods can also become more accurate and they can result in more reliable early-stage predictions.

This paper is organized as follows. The used methodology is described in Section 2 and it is then applied to various idealized and non-idealized case-studies in Section 3. Based on the derived guidelines, an existing body-in-white (BIW) concept model is studied in Section 4.1. Finally, a hybrid detailed-concept FE model of a BIW is created and analyzed in Section 4.2.

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2. Methodology

This section focuses on the quality of the 1D beam models. The main criteria to evaluate it are considered, as well as the major error factors that can deteriorate it.

2.1. 1D beam concept modeling

To assess the performance of a specific 1D beam concept model, two main aspects must be taken into account. On one hand, its structural behavior must be as close as possible to the one of its corresponding detailed FE model, thus resulting in better prediction capabilities. On the other hand, a geometry match between the detailed and the concept model must be also ensured. The fulfillment of this second condition is especially important for optimization studies so that the optimized concept model could be used to find the optimized detailed FE model [12]. These two important considerations are discussed hereafter.

2.1.1. Beam theories

1D beam models are simpler and computationally more efficient than models with 2D shell or 3D solid meshes. In consequence, beam theories are extensively used for various engineering applications regarding the static and dynamic analysis of structures [15]. Many methods have been proposed each of which relying on different assumptions and simplifications and resulting in different accuracy of the concept models.

The beam theories of Euler–Bernoulli [16,17], de Saint-Venant [18,19], and Timoshenko [20,21] represent the group of classical approaches. In contrast to its two predecessors, Timoshenko's model accounts also for transverse shear deformations. However, none of the three considers non-classical effects such as in- and out-of-plane cross-section deformations and torsion-bending coupling. The application of the classical methods for cases in which such effects are present can lead to wrongly estimated structural stiffness. This has been the main motivation for the further development of refined beam theories during the last years.

Various solutions have been proposed to overcome the intrinsic limitations of the conventional approaches. They rely on different techniques: the introduction of shear correction factors, the use of warping functions based on the de Saint-Venant's solution, the variational asymptotic solution, generalized beam theories and higher-order beam models. A comprehensive state-of-the-art can be found in [15]. Despite the attempts to extend the applicability of 1D beam modeling, few of these works have led to a fully functional and tested commercial software to be used by the engineering community. The proposed approaches are often developed and validated for specific academic case-studies, but their performance in more general cases is not guaranteed.

For the purposes of this work Timoshenko's beam theory was used, extended with an additional DOF accounting for warping [22,23]. Thus 1D beams have 7 DOFs at each end node—three translations T, three rotations R and one DOF approximating the cross-section deformation due to torsional warping. A commercial solution was chosen—MD Nastran 2010 [24]. On one hand, the limitations of this approach restrict also the current study. On the other hand, it is widely used in the automotive industry. Moreover, the choice of a single method can be considered reasonable because of the impossibility to apply and compare the numerous beam theories in a single paper.

2.1.2. Geometrical similarity

Regarding the geometry description of the 1D beam cross-sections, three main approaches can be distinguished using standard cross-sections (STCS) [2,3,7–11], arbitrary cross-sections (ABCS) [3,12] and generic cross-sections (GNCS) [1,4–6,13]. An extensive state-of-the-art can be found in [12]. Fig. 1 shows an example of simplifying the A-pillar of a Ford Taurus FE model with 1D beams having STCS, ABCS and GNCS. In this figure the STCS and the ABCS beams are visualized in detailed 1D element display to evidence the difference with respect to the GNCS.

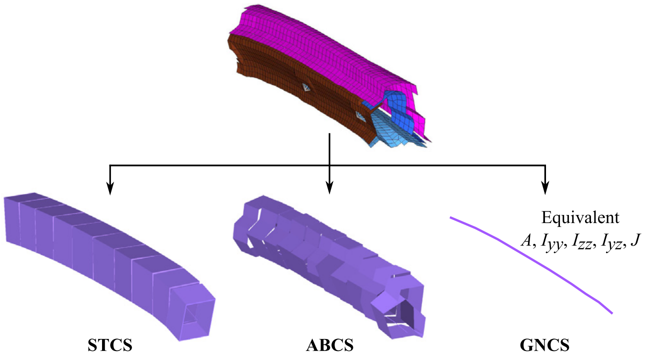

Fig. 1. A-pillar detailed FE model and 1D beam simplifications.

The STCS method offers a predefined library with simplified versions of the most common cross-section typologies (e.g. box, tube, I-, C-shape). For each 1D beam element the STCS shape is chosen that best approximates the projection of the real cross-section on a plane perpendicular to the 1D beam axis (Fig. 1). Given the irregularity of the beam cross-sections in a car body, this approach is not always appropriate, despite its simplicity. Moreover, the backward transition to the optimized detailed FE model can become problematic.

In the ABCS approach the real cross-section is described with points, segments and their corresponding thicknesses (Fig. 1). Thus it is possible to control the degree of detail. The cross-section description can range from a simple rectangle enclosing the real shape to a geometry that matches it almost perfectly. A fully detailed ABCS will have the same geometry and cross-sectional properties as the projection of the reference cross-section. This facilitates the transition from the optimized concept model to the optimized detailed FE model.

In contrast to the previous two methods, the GNCS approach keeps no information about the geometry of the cross-section. Instead, it is substituted with its equivalent cross-sectional properties such as area and moments of inertia (Fig. 1). Although this equivalent generic cross-section can be still accurate, the direct relation with the detailed FE model is broken.

2.2. Potential error factors

There are many factors which could influence the accuracy of the concept model regarding its structural behavior and geometrical similarity with the reference structure. Those considered as the most important ones are discussed hereafter. They will be subject of a detailed study in Section 3.

2.2.1. Cross-section deformations

As out-of-plane deformations are approximated by the employed beam theory [22,23], they are not a subject of study in this work. Regarding the in-plane cross-section distortion, a new measure is hereby proposed to quantify it. The procedure for its calculation is the following:

- A control node C is defined for the cross-section under study (reference detailed FE model). It can be positioned in the cross-section centroid or shear center, as well as in any other point.