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Finite element mesh deformation with the skeleton-section template

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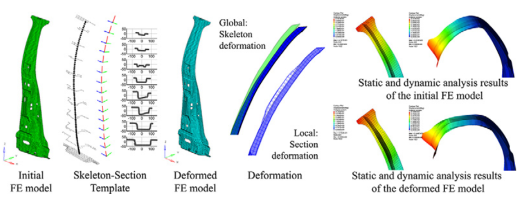
GRAPHICAL ABSTRACT



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ABSTRACT

To develop fast finite element (FE) adaptation methods for simulation-driven design optimization, we propose a radial basis functions (RBF) method with a skeleton-section template to globally and locally deform FE meshes of thin-walled beam structures.

The skeleton-section template is automatically formulated from the input mesh and serves as a hierarchical parameterization for the FE meshes. With this hierarchical parameterization, both the global and the local geometries of a thin-walled beam can be processed in the same framework, which is of importance for designing engineering components. The curve skeleton of the mesh is constructed with Voronoi decomposition, while the cross-sections are extracted from the mesh based on the curve skeleton.

The RBF method is employed to locally and globally deform the mesh model with the cross-sections and the skeleton, respectively. The RBF method solves the spatial deformation field given prescribed deformations at the cross-sections. At the local scale, the user modifies the cross-sections to deform a region of the surface mesh. At the global level, the skeleton is manipulated and its deformation is transferred to all cross-sections to induce the mesh deformation.

In order to handle curved mesh models and attain flexible local deformations, the input mesh is embedded into its skeleton frame field using an anisotropic distance metric. In this way, even strip-like features along arbitrary directions can be created on the mesh model using only a few cross-sections as the deformation handles. In addition, form features can be rigidly preserved at both deformation levels.

Numerical examples demonstrate that intuitive and qualified FE mesh deformations can be obtained with manipulation of the skeleton-section template.

1. Introduction

Simulation-driven design optimization has become a trend in computational engineering analyses and is a promising paradigm for product development [1]. Design optimization requires iterative evaluations of groups of models, either to compute the sensitivity or the gradient, or to perform stochastic evolutionary optimizations. Current parametric modeling techniques are inflexible to unexpected changes during design exploration, especially at

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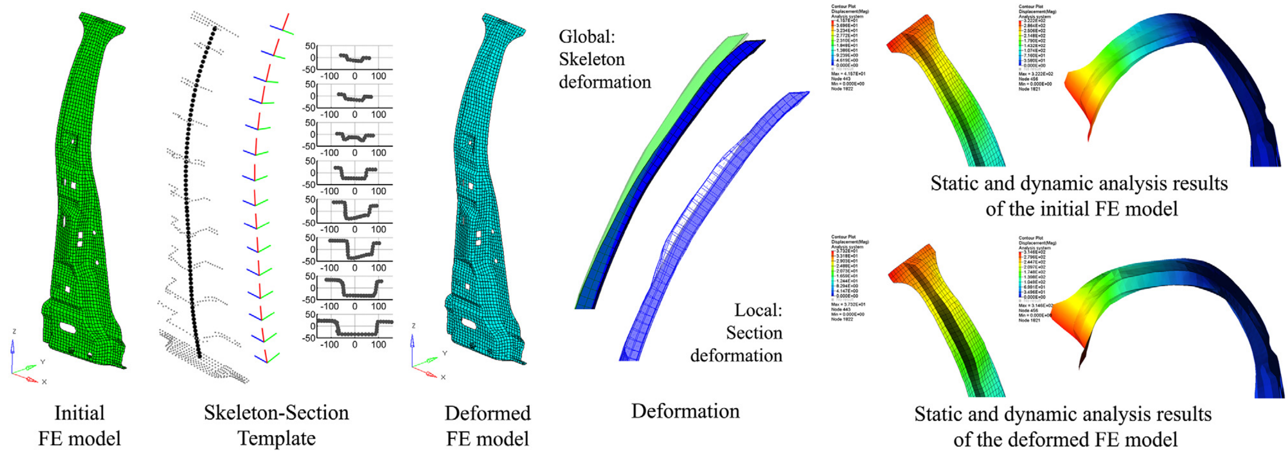

Fig. 1. Deforming the FE model of a thin-walled beam with the RBF method based on the skeleton-section template.

the stage where the definitions of features, constraints and sizes (or dimensions) are vague. Also, requirements of expertise for modeling and model transfer between Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) systems may slow down the overall development process. Therefore, a method that is native to CAE environment for rapid mesh model adaptation is necessary for optimization of the design concept.

Our overarching goal is to develop a fast finite element (FE) mesh deformation method, for the design optimization loop as well as for human interactive modeling, which does not depend on the mesh types of the models (e.g. triangular meshes or quadrilateral meshes) or the modeling techniques (e.g. feature modeling, parametric modeling or direct modeling). In this way, even legacy FE meshes without prior parameterizations can be adapted and reused in the design optimization process. However, it would be too ambitious to include all kinds of FE meshes, thus we narrow our scope to thin-walled beam structures, a class of primitive building blocks for complex engineering systems such as aircraft and vehicle structures. As thin-walled structures are often modeled as surface meshes (in the CAE content, shell element meshes), our discussion is limited to surface meshes.

We proposed a radial basis functions (RBF) deformation method based on the skeleton-section template, in order to adapt the FE meshes of the thin-walled beams (see Fig. 1). The RBF method is adopted in this paper as it can handle arbitrary polygon meshes, directly manipulate the mesh vertices, and preserve the mesh structure (i.e. the number of the mesh vertices and the mesh connectivity) as much as possible before inevitable remeshing.

The skeleton-section template is designed to represent the global shape of the mesh with the *skeleton* and the local geometry with the cross-*sections*. It is constructed automatically given the input mesh. With the template parameterizing the input mesh, the proposed method enables both local and global deformations of the complex curved mesh model.

For the local deformation, the input mesh is embedded in the skeleton frame field with a directionally scaled distance metric. The deformation field of some specified local region of the mesh model is computed in the embedding space and mapped back to the original space. Then the deformed mesh is obtained by adding the deformation field to the corresponding mesh vertices. With the directionally scaled distance metric, we can achieve local deformations aligned with prescribed directions by manipulating only a few cross-sections.

At the global level, the skeleton deformation made by the user is first transferred to the associated cross-sections. The cross-sections are rigidly moved accordingly, and it is by taking the changes of all cross-sections as input that the global deformation is computed.

During both global and local deformations, form features can be preserved as follows. Firstly, we estimate the target positions of form features during the initial deformation with prescribed boundary conditions. Then, we iteratively minimize the residuals to the target positions of the features in the subsequent deformations.

The global deformations using the skeleton and the local deformations using the selected cross-sections as driving handles are necessary for designing thin-walled beam structures, since mechanical properties of the beam structures mainly depend on the global and sectional geometries. In particular, adding strip-like features amounts to introducing the reinforcements to the component in the engineering content. This can further extend the design space and lead to diverse results in both design optimization and interactive modeling.

In summary, our method enables hierarchical and flexible modifications of FE meshes of thin-walled beams using the skeleton-section template as a parameterization of input meshes. With the embedding space and the associated directionally scaled distance metric, various local deformations of the complex curved surface mesh can be achieved by using only a few cross-sections. Meanwhile, intuitive global deformations are obtained with the resulting rigid motions of all cross-sections induced by the skeleton modification. Therefore, the proposed method can adapt legacy FE models of thin-walled beam structures to new design variants at both local and global levels.

The remainder of the paper is organized as follows. The related work is reviewed in Section 2. In Section 3, the framework of the proposed method is introduced. The construction of the skeleton-section template is presented in Section 4. In Section 5, the local and global deformations are described in detail, along with the RBF method as preliminary and the feature preservation method as complementary. The numerical experiments are demonstrated in Section 6. Finally the conclusion is drawn in Section 7.

2. Related work

Generic templates are useful in geometric modeling and design as they bridge models used in different fields [2], abstract and cluster of models into same classes [3], or synthesize and generate new models from databases [4–6]. The generic template is summarized as an inherent structure that represents the relations among its constitutional parts via parameters [7].

Skeletons and cross-sections have long been used as effective tools for analyzing, designing and modeling mechanical components with slender geometries. The reduced-beam model, resembling the skeleton of the thin-walled structure, is used to construct