Title:
Automatic Construction of Structural CAD Models from 3D Topology Optimization

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Introduction:
The development and use of topology optimization (TO) methods [1] has been a very important subject of academic and industrial interest for 25 years. The fact that TO is now well mastered in 3D and that optimization is fully automated opens the path for very interesting developments in mechanical design. Indeed integrating and automating the use of TO inside 3D CAD environments allows extending it towards the automatic creation of parts and structures as shown in Fig. 1.

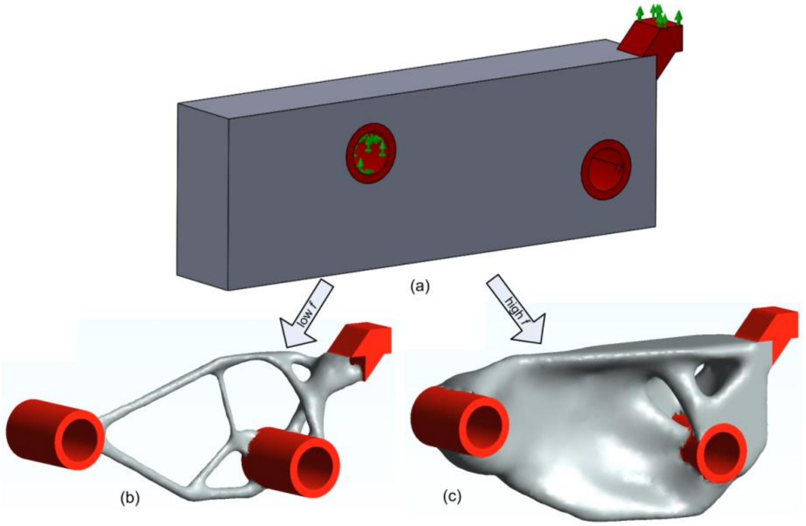

Fig. 1: Two types of TO results (a) Initial CAD model with BCs (b) TO result as a beam-like structure (c) TO result as a massive solid shape.

However, filling the gap between 3D TO results and conventional manufacturing processes still remains a major challenge. The work presented in this paper is aimed at filling this gap for TO results that tend towards beam-like structures such as the one shown in Fig. 1b. Indeed, depending on parameters used in TO, optimized geometry generated from it can be very different as illustrated in Fig. 1. The TO method used in Fig. 1 is Solid Isotropic Material with Penalization or SIMP [1, 6] and the parameter modified between Fig. 1b and Fig. 1c is SIMP volume fraction *f*. Fig. 1a shows the initial CAD model (before optimization) along with boundary conditions (BCs) and specification of *design* (grey) and *non-design* material (red). Non-design material refers to material that should not be modified or removed by the optimization process since it is generally related to other components. SIMP volume fraction f represents the fraction of initial design material (in %) that is allowed for generating the optimized geometry. If f is low (Fig. 1b), the optimized geometry tends to beam-like structures, while higher f values generate more massive shapes (Fig. 1c). It is obvious that, from these two types of TO results, an engineer would produce very different designs. In the first case, he would generally produce an assembly of structural beams while, in the second case, he would generally produce a molded and/or machined solid part.

Whatever the TO method used, raw TO results cannot be used as is for reconstructing optimized CAD models and deriving CAD models from raw TO results, requires intensive and complex post-processing. A few approaches are proposed in the literature, in this direction, and three main strategies can be distinguished for post-processing TO results as CAD geometry. The first strategy is based on computing iso-value sets (iso relative density for SIMP based methods for example), which leads to discrete representations of geometry (triangulated surfaces, discretized curves) which can be derived into CAD curves and surfaces. The second strategy is based on trying to fit pre-defined shapes, referred to as primitives, to sub-sets of TO results. The approach starts with identifying subsets of the optimized result and comparing and best-fitting these subsets with pre-defined shapes (primitives). Once parameters of these primitives are calculated, the optimized CAD model is represented as a Boolean combination of primitives. The third strategy is based on interpreting TO results using methods inspired by black and white and grayscale image processing algorithms. Indeed, once a TO result is represented as sets of cells filled of void or solid material or filled with a varying quantity (relative density for SIMP based results) extracting boundaries of optimized results can be considered as quite similar to image segmentation problems.

Main idea:

This synthesis of existing methods towards fully automating the reconstruction of CAD models from TO results brings about the conclusion that it represents a very complex challenge in a general context. The work presented here targets automating this reconstruction for results that tend towards beam-like structures (like in Fig. 1b). Ideally, the process should start from a rough initial CAD model along with boundary conditions (BCs), design/non-design material specification and optimization objectives (typically a low volume fraction here since the SIMP method is used). From that, it should automatically produce a CAD model of an optimized structure that fulfills these objectives, without any other user interaction. Fig. 2 presents a flowchart of our approach, which introduces its main steps: TO with SIMP, automatic construction of a smooth 3D solid shape from raw SIMP results, automatic construction of a 3D beam structure from this solid shape through curve skeletonization and validation, based on finite element analysis (FEA) results performed on both the 3D solid shape and the 3D beam structure. In the following paragraphs, these steps are illustrated starting from the initial rough CAD model shown in Fig. 3a.

The first step in the process is SIMP optimization. The initial CAD model is first automatically meshed (see Fig. 3b), with linear tetrahedrons through a specific adaptation of the advancing front method developed by our team [5]. SIMP topology optimization itself follows, which is basically an iterative process that updates, at each iteration, a relative density field $\rho(x,y,z)$ represented on this mesh. This relative density varies from 0 (no material) to 1 ("full" or actual material). Update of $\rho(x,y,z)$ is performed through FEA iterations that globally tend to minimize total compliance $\tilde{C}$ (and by the way maximizes stiffness). Practically, $\tilde{C}$ is calculated from FEA total strain energy $\widetilde{W}$ as $\tilde{C} = 2.\widetilde{W}$. Thus, SIMP optimization minimizes $\tilde{C}$ while keeping volume fraction f constant throughout iterations. SIMP convergence is classically formulated with respect to the evolution of $\tilde{C}$ (see [6] for details). Fig. 3c shows $\rho(x,y,z)$ obtained after convergence of SIMP iterations ($f = 4\%$ is specified in this case).

As introduced in Fig. 2, the second step in our approach is deriving a 3D optimized solid shape from SIMP results. Fig. 4a illustrates that this is performed by discarding tetrahedrons for which $\rho(x,y,z)$ exceeds a threshold ρ_{th} ($\rho_{th} = 0.2$ in this case). This threshold is adjusted so that solid design material remains continuous and that f_{3D}, the actual volume fraction obtained after construction of the optimized 3D solid shape, is as close as possible to target f.

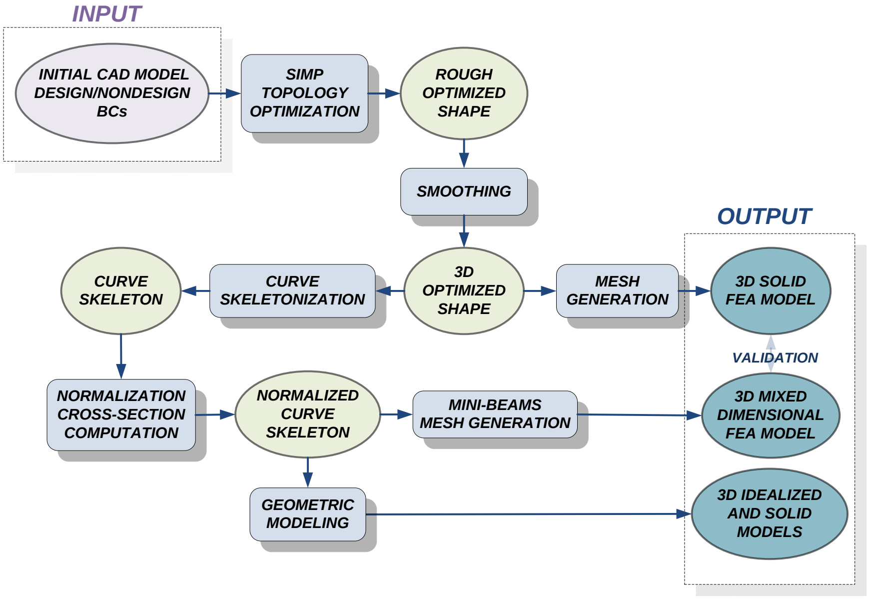

Fig. 2: Flowchart of the approach proposed.

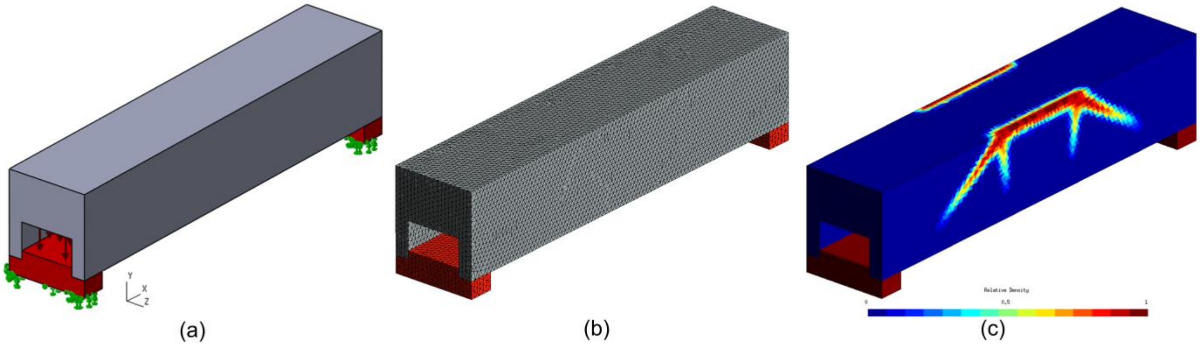

Fig. 3: SIMP optimization: (a) model with BCs (b) mesh of design/non-design material (c) relative density obtained at convergence.

As emphasized in Fig. 4a, the 3D optimized shape generated this way is extremely irregular. Post-processing is applied to derive a smooth boundary (shown in Fig. 4b) from such an irregular result. This post-processing involves removing non-manifold patterns and smoothing the irregular boundary triangulation. Many triangulation smoothing methods are available in the literature but none is completely satisfying for fulfilling all requirements of this work, which are generating smooth and good quality triangles (for FEA) while preserving some sharp features from extremely irregular input triangulations. In the case of the work presented here, we use a combination of Taubin [8] and Laplacian-based smoothing [3]. Taubin smoothing indeed overcomes a major drawback of Laplacian based smoothing methods referred to as shrinking. In Taubin's approach, smoothing is performed as a low-pass filter that decreases curvature variations without shrinking. Taubin smoothing iterations are followed by a couple of Laplacian-type smoothing iterations for obtaining a smoother boundary as in Fig. 4b. As emphasized in the enlarged view, resulting triangulation feature excellent element quality, which is mandatory for performing 3D FEA from it.

The next step in our automatic model construction process is transforming this 3D smooth solid shape into sets of straight standard beams, which is principally based on curve skeletonization techniques, as described in [2]. Curve skeletons (see [7] for a thorough survey) can basically be defined as centered curvilinear structures that approximate topology and geometry of 3D volumes. The algorithm used in our work is inspired by the fact that Laplacian-based smoothing naturally leads to mesh shrinking. Thus, by using constrained implicit Laplacian iterations, followed by a farthest-point sampling process and topology thinning (see reference [2] for details) a curve skeleton can be automatically generated as shown in Fig. 4c. This curve skeleton is then normalized by transforming each branch of the skeleton into a straight standard beam with constant circular cross-section (Fig. 4d). Fig. 4d also shows the distribution of cross-section radii, which is computed from mean distances between boundaries of the 3D smooth solid shape and curve skeleton branches. Finally, a 3D solid model of the 3D beam structure (see Fig. 4e) can be automatically created from the normalized skeleton and cross-section radii.

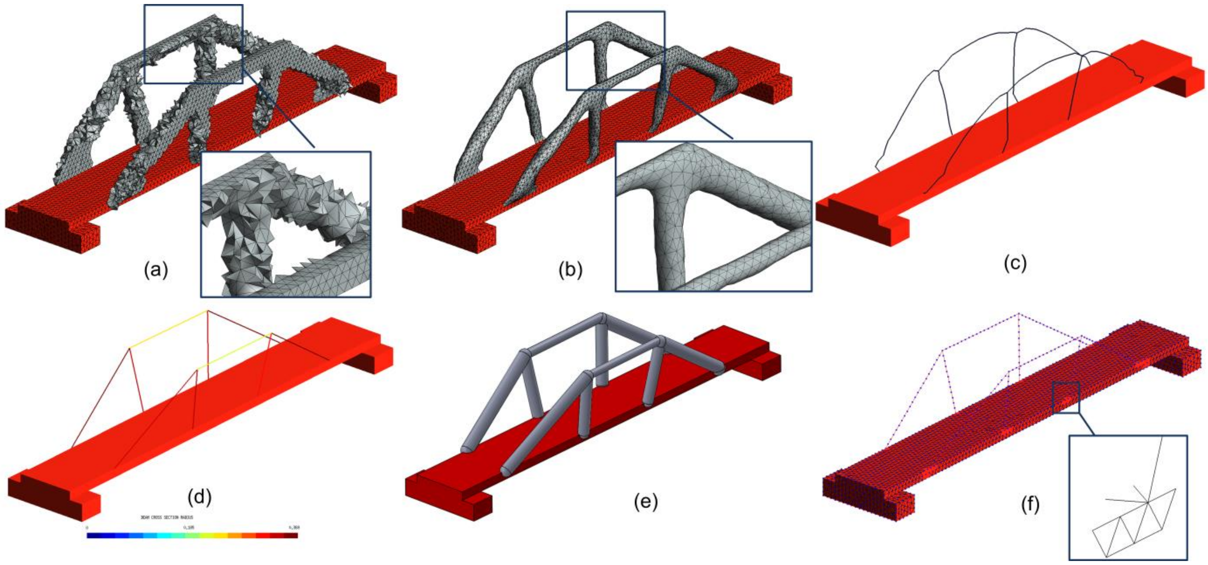

Fig. 4 Construction of a beam structure (a) Rough optimized shape: (b) 3D solid shape after smoothing (c) curve skeleton (d) skeleton after normalization and distribution of cross section radius (e) 3D CAD model of the beam structure (f) mixed-dimensional FEA model.

The last step in the process consists in generating and solving two FEA models: one based on the 3D solid optimized shape (Fig. 4b) and the other one on the 3D beam structure derived and cross-section information (Fig. 4d). Thus, as illustrated in Fig. 5, the first FEA model only features linear tetrahedrons while the second model is mixed-dimensional (Euler-Bernouilli 3D beam elements for the structure itself mixed with 3D linear tetrahedrons for non-design geometry). In this mixed-dimensional FEA model, specific connexion elements, referred to as *mini-beams* [4], are used for easily overcoming inconsistency between degrees of freedom of linear tetrahedrons and Euler-Bernouilli beam finite elements. These mini-beams locally introduce rigid connections between beams and non-design material (see details in Fig. 4f). Fig. 5 presents FEA results obtained with these two models through a comparison between resultant displacement distributions calculated from these two FEA models (Fig. 5b). For better comparison between these two displacement distributions, the same color scale is used, as well as the same amplification factor for deformed shapes. Maximum displacement for the created beam structure is 0.526 mm while that of the optimized solid shape is 0.462 mm. This slight difference is confirmed by calculating total compliance C_{beam} for this beam structure. Total compliance is calculated as twice the total strain energy W_{beam}, which is derived from FEA results obtained with the mixed-dimensional model. $C_{beam} = 2.W_{beam} = 288\,J$, which is slightly higher than that of the optimized solid $C_{3D} = 2.W_{3D} = 257\,J$.

<u>Conclusion:</u>

The proposed method automates 3D beam structures construction from TO results that tend towards beam-like structures. Comparing FEA results derived from 3D optimized solid shapes and 3D beam structures created, shows that these structures generally well reproduce mechanical behavior of TO results, which is very interesting since these beam structures can easily be edited for improving their performance. It also shows that these structures are always a little more flexible than optimized solid shapes from which they are generated. This is mainly due to the fact that, this automatic process generates beam structures featuring beam elements with circular cross-sections. Extending the approach to other types of standard cross-sections is a first natural improvement of the approach.

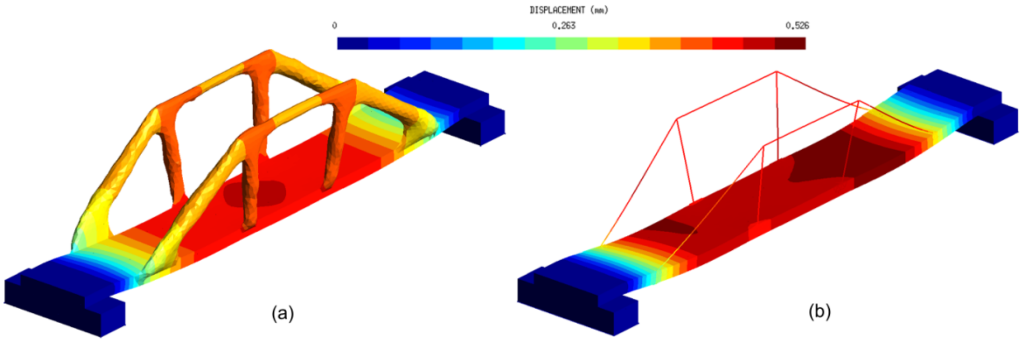

Fig. 5: Resultant displacement distributions (a) for the optimized solid shape (b) for the beam structure.

Acknowledgments:
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