KEY TOPICS IN TOPOLOGY OPTIMIZATION TRAINING FOR ENGINEERS

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Design of lightweight load-carrying structural parts is becoming increasingly demanding due to ever-tighter requirements on structural weight, performance, and durability. Topology optimization is the most recent and most promising tool supporting the development of such high-performance load-carrying parts – at least in theory. In practical applications, however, engineers are struggling to formulate and run topology optimization tasks in a way that would result in good and actually usable results. For this purpose, the pitfalls met in this process are reviewed and discussed in a systematic way. These mistakes range from deficiencies in FEA model preparation, over uncritical optimization process monitoring and management, to bad practices employed in resulting model finalization. As it turns out, careful FEA model preparation and its corrections based on a feedback information from the ongoing optimization process are keys to success. Keeping this in mind should prevent a superficially (and not precisely enough modeled) support condition or a missed load case, which may otherwise very quickly result in a useless final design.

Keywords: Lightweight structures, Load-carrying parts, Low-stress design, Prolonged service life

1 INTRODUCTION

Design of load-carrying structures is becoming a challenging task due to increasingly tight requirements related to higher structural durability and lower weight. To meet these requirements, it becomes unavoidable to engage and combine two advanced numerical procedures, namely the finite element analysis (FEA) and topology optimization (TO). Numerical FEA systems are well established and commonly used in modern engineering practice. However, the same cannot be claimed for TO. In fact, one can say that TO is rather modestly used in current industrial environment. This seems to be somewhat paradoxically, since minimization of structural strain energy, which is a conventional TO problem, exhibits a rather simple form; moreover, its solution requires a relatively simple numerical procedure, Bendsøe (1989) and Huang and Xie (2010).

TO is a FEA-driven numerical process by which the most efficient design (in terms of stiffness and actual stress levels) can be determined. The reasons for its modest engagement can mostly be related to disappointing and practically unusable designs frequently obtained in industrial practice. What is often not recognized, however, that bad results may not be attributed to poor TO performance, but rather to inadequate consideration of many of the tricky details embedded in the whole TO procedure. This paper aims to review briefly perhaps the most
important aspects that need careful consideration in order to ensure a valuable TO result. A much more detailed elaboration of these aspects is available in Harl and Kegl (2020).

2 TOPOLOGY OPTIMIZATION METHOD

The TO method involves the following three procedures:

• Model preparation: preparation of the FEA model, which is derived from an adequate geometrical (CAD) model. This necessitates domain discretization (meshing) and preparation of material, support, and loading data.
• Optimization process: numerical optimization is a cyclic process where each cycle contains FEA of all load cases and improvement of topology parameters.
• Model finalization: generation of an adequate triangulated geometrical surface. This includes procedures like surface smoothing, refinement, and simplification.

Note that these procedures may need to be engaged several times and interchangeably to get a good TO result. Most notably, the optimization process typically reveals flaws in the FEA model; this necessitates to go back and make adequate corrections of the FEA model. Anyhow, to get a good TO result, all details in these procedures have to be addressed and resolved carefully in order to avoid many of the common pitfalls. Any training aimed to prepare an engineer for TO must go through all these details in a way to illustrate the consequences and identify the reasons for all possible mistakes. A brief review of the most pressing issues is given in the following sections.

2.1 Model Preparation

A FEA model suitable for TO can be prepared in a similar way as an analysis-only FEA model. However, for TO, careful consideration of some model preparation details is needed. Most of all: The underlying CAD model must be adequately partitioned into volume regions so that optimization objectives and constraints can be taken into account.

• The set of the basic load cases must be expanded with additional load cases which must reflect all possible variations of load and support conditions.
• The finite element meshing must be performed in such a way that minimum quality requirements related to mesh density and uniformity are met.

In TO the optimized part has to be adequately partitioned into volume regions with the aim to enable and control various activities of the optimization process. In other words, adequately defined volume regions are needed to:

• Enforce various optimization attributes such as the region type, which can be defined as either fixed or free for optimization.
• Enforce various technological constraints such as various opening or symmetry design requirements.
• Enable the engagement of special modeling techniques, for example, for contact and fastening situations.

Note that a poorly partitioned domain may have a vast of potentially detrimental consequences that will often be hidden until a certain stage of the optimization process is reached. Careful planning is therefore needed to account for possible future technological constraints or modeling tricks.

A load case (LC) is generally defined as an independent set of boundary conditions (it includes supports and loads) which are imposed on the structure exclusively at a given time. In a
typical FEA, the LCs are generated from the basic prescribed support and loading information only. In a TO scenario, however, these idealized LCs are typically insufficient, Harl et al. (2020). In reality, additional unexpected loading or support variations may occur during structural lifetime. Even if these variations are rather modest, they must be carefully identified, evaluated, and translated into additional LCs. Only after such an extended set of LCs is used, one can expect to get a robust and reliable design of the optimized part. Namely, only one missed LC may result in a design being extremely vulnerable to that particular LC. The consequence may be a quick and sudden failure of the load-carrying part.

Finite element meshing of a part to be shaped by TO should be done by considering a few issues related to mesh quality. The first issue is related to element size variations which should be as small as possible. More specifically, one should actively avoid largely variable element sizes, which are popular in order to reduce the required FEA computation time. Namely, the uniformity in element sizes determines the precision of the generated TO design. Consequently, large variations prove to be highly harmful in this context.

The second issue related to mesh quality is mesh fineness. On the one hand, the mesh should be fine enough to capture accurately fine design changes. On the other, there is another important reason for insisting on a fine mesh, which is related to technological constraints. Namely, constraints are enforced numerically by mapping material parameters. For a discrete FE mesh this means that the accuracy of the map will depend heavily on the mesh fineness. This is because the mapping error depends significantly on the distance measured from the mapped location to the nearest FE node. It should be obvious that with a finer mesh this error decreases.

Under the bottom line, in the scope of TO, model preparation is not an easy undertaken since a fully satisfactory FEA model can typically not be prepared in a one-step fashion, before running optimization. Instead, model preparation can only be successful by employing a cyclic interactive process where the underlying CAD and FEA models are modified and upgraded according to feedback information from the optimization process. This feedback loop should be based on observing the ongoing optimization process and using the partial results to identify any signs of poor FEA model preparation and the reasons for that. These reasons may have various origins, but mostly belong to the following two main groups:

- Geometry-related reasons. Inadequately prepared geometry may result in sharp edges present in the final design, if design domain boundaries prevent the optimizer to add material where it would be needed. The appearance of such under-sized and over-stressed regions may be difficult to predict in advance since it may depend on the material removal process.
- Boundary conditions and mesh-related reasons. These typically originate from standard practices such as adaptive domain meshing or simplified support conditions modeling, often applied in response-only FEA. In the scope of TO such practices usually show a detrimental effect on the final design. This follows from the fact that TO fully adapts the structural design to the imposed LCs. Consequently, even minor simplifications in boundary condition, mesh flaws, or underrepresented LCs, can lead to a disappointing final design.

2.2 Optimization Process

Since the initial FEA model can hardly be defined in a fully satisfactory manner, the optimization process has to be exploited as a feedback data provider for model corrections. Once a problematic design feature is observed, optimization should be stopped and the FEA model corrected adequately. This section outlines perhaps the most important design features to be monitored during the optimization process.
For this purpose, a simple and quasi-planar bracket structure is considered. It is supported by two pins and loaded by the third pin, Figure 1a. The supporting two pins are rigidly supported while a prescribed vertical force is applied to the third pin. The objective is to design a lightweight part which would exhibit high stiffness and low stresses at some prescribed structural volume.

![Simple bracket structure (a) and the first optimization result (b).](image)

**2.2.1 Domain partitioning and region types**

By preparing the model in a simplistic manner, typical for quick FEA assessment of stress states, the pins are not part of the model. Instead, to save time and effort, (fully rigid) support and (traction) loading boundary conditions are prescribed at the contact surfaces between the bracket and pins. If the whole bracket domain is defined as a free region, the optimizer will remove material as shown in Figure 1b. It is obvious at a first glance that the material was removed so that the bores, intended for the supporting pins, vanished. This necessitates to stop the optimization process and update the FEA model adequately.

![Result obtained by using proper: fixed regions (a) and support and loading modeling (b).](image)

More precisely, to prevent such unwanted removal of material, the free region around the pin bores has to be subdivided into fixed and free sub-regions. Note that the newly introduced fixed regions may become partially exposed as part’s outer boundaries during optimization, Figure 2a. Therefore, such regions should be adequately shaped to preserve smooth outer boundaries in the case of becoming exposed.

Note that in this simple example it was rather obvious what will happen right from the start. In real-life engineering problems, this will be way less obvious and careful examination of partial results is necessary.

**2.2.2 Support and loading modeling**

By optimizing the newly corrected model, the problem of missing material around the pin bores was resolved. However, it also became quite obvious that the modeling of support and loading conditions is flawed. Namely, a loaded or supported pin creates a sophisticated contact situation when loads are transferred to the bores. In analysis-only FEA such details are often neglected by
modeling the boundary conditions in a simplified manner, e.g., as done initially in this example. Since this cannot be done in the scope of TO, in the considered example the model’s region partitioning was changed by adding six new regions: three pins and three thin contact layers. A contact layer contains special semi-contact elements which are capable of simulating a contact situation with sufficient accuracy. The effect is clearly visible in the newly obtained design, Figure 2b.

2.2.3 Load cases

In TO the design is fully adapted to the underlying boundary conditions, i.e., loads and supports. In the considered example, only the prescribed vertical force was applied so far and the last optimized part reflects this well. However, in real-life working environment the bracket might be loaded by various circumstantial (unintended) loads. For a successful TO, all these loading conditions, must be carefully searched for, evaluated, and (if needed) added as additional LCs. With regard to structural durability and operational reliability, it is far better to add some possibly superfluous load cases than to miss only one, potentially important, LC.

In the considered example, the FEA model was enriched by adding two extra LCs, which simulate unintended but possible horizontal loads that may appear under some rare circumstances. After optimizing the LC-enriched model, the obtained result was visually much better than the old one, especially with respect to structural robustness, Figure 3a. Such a result indicates that the last updated FEA model is promising with a potential to deliver a good final design.

2.2.4 Technological constraints

Structural reliability and durability are for sure among the most important factors regarding the worthiness of the final design. However, the final design also needs to be manufactured somehow and that needs to be taken into account as well. Recent production technologies like additive manufacturing (AM) are very promising in this view, but they are often considered too expensive. So, CNC machining, forging, casting, or molding typically have to be engaged to manufacture the optimized part. To make this possible, however, the part’s design must fulfill certain production limitations. Such requirements have to be enforced by the so-called technological constraints.

In the considered example, two unidirectional opening constraints were introduced, both in the direction perpendicular to the central symmetry plane. This resulted in a part with similar strength as the foregoing result. Its geometry, however, enables the engagement of conventional production technology like molding, Figure 3b.
2.3 Model Finalization

By taking care about all of the before raised issues, the FEA model has a potential to deliver a good design. Nevertheless, one must realize that the quality of the actually delivered design depends significantly on the quality (fineness and uniformity) of the mesh. Keeping this in mind, a carefully and locally performed gradual mesh refinement and improvement can be used to get maximal design accuracy while keeping the computation time acceptably low, Figure 4. Namely, a too hasty and aggressive mesh refinement can very quickly result in model sizes being too big to be optimized with reasonable computation effort. Therefore, a much preferred option is to start by a moderately dense mesh. Afterwards, as the optimization proceeds and material is gradually removed, the mesh should be reasonably refined only locally (for example, along cut surfaces), as needed.

![Gradual mesh refinement](image)

Figure 4. Simple bracket structure (a) and the first optimization result (b).

Practical experience has shown that this procedure can hardly be automated, because it requires quite some practical experience to make the correct decisions which operations to perform at a particular optimization stage. But, if done properly, the reward is an accurately shaped optimal design that exhibits robustness and reliability under various operation conditions.

3 CONCLUSIONS

This paper elaborates on the most important issues being critical for successful engagement of modern TO procedures to design load-carrying structural parts. To run a successful TO, the model preparation and optimization processes are the most critical. They have to be engaged in a feedback loop, where the ongoing optimization delivers the data for the needed model corrections and updates. Within this context, the support and loading conditions are the one requiring most attention. A superficially modeled support condition or a missed load case may very quickly result in a useless final design. However, if everything is done carefully enough, one can be sure that TO is perfectly capable to deliver a very good result.

References