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The Pitfalls of Reverse Engineering Topology Optimised Load-Carrying Structural Parts into Parametric Models

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Abstract: In this paper, we will show the topological optimization of a load-carrying structural parts and the errors that can occur when the topological solution in the form of a triangulated mesh of the surface of the optimized part is reconstructed into a parametric CAD form. Such a reconstruction always introduces geometric errors in the resulting optimal structure of the structural element. A numerical example will be used to show how quickly stress concentrations are reproduced on surfaces where they should not be. The numerical results are also supported by experiment. In the conclusion, it is suggested how, with a specific topological model, the obtained stress concentrations at the edges of the structure can be reduced.

Keywords: load-carrying structural parts; reverse engineering; stress concentrations; topology optimization

1 INTRODUCTION

Optimization of mechanical systems is a key step in the design process. The aim of optimization is to find the most efficient shape, dimensions, material distribution and other parameters that will ensure optimum load capacity and minimize material and production costs. Achieving optimum design of mechanical systems requires the use of a variety of methods and tools. Advanced numerical methods such as the Finite Element Method (FEM) and genetic algorithms [3] allow engineers to simulate the behavior of mechanical systems under different loads and conditions. These tools allow an iterative process to find the optimal design over several iterations, with the parameters of the mechanical systems being changed and adjusted according to the results of the analysis. It is important to note that optimization often leads to lighter and more efficient mechanical systems that also have a longer service life, which can have a positive impact on the environment.

Structural optimization of mechanical systems can be divided into three main fields:

- sizing optimization, where the optimisation task aims to reduce the weight of the structure. The optimisation parameters can be lengths or cross-sectional sizes of the structure;
- shape optimization, where an optimisation task is used to change the geometry of the structure to obtain smooth contours without stress concentrations;
- topology optimization, where a mathematical model is typically used to reduce the total strain energy of the structure by adding or removing material in the optimisation domain of the structure.

The paper will discuss about the topology optimization (TO) and mechanical systems will be the load-carrying structural parts. Topology optimization of the load-carrying structural parts has been the most developed area in recent years, also due to the rapid development of 3D printing and related materials. These processes can produce complex shapes of load-carrying structural parts, but problems still arise because the printing materials are sensitive to cracks and, as a consequence, can lead to the failure of the mechanical part. Topology optimization is very important, because it can allow stress concentrations to be absent in the optimization domain, or to occur only in the compression zones of the part as shown in Fig. 1.

Figure 1 Higher stress in compression zones of the part

Topological optimization process (Fig. 2) is complex [4, 5] and consist of:

- CAD model preparation – adjust regions that will be further optimized or fixed,
- FEA model preparation – adjust mesh, materials and load cases,
- optimization model preparation – adjust design configuration (shell, lattice, or mixed structure,) and technological constraints (Plane Symmetry, Opening…),
- optimization process – run optimization and monitor progress,
- output results – adjust shape optimization or smoothing tools for a triangulated geometrical surface.

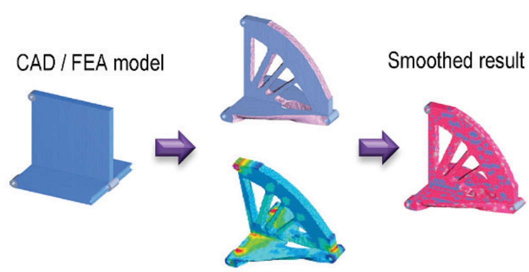

Figure 2 Topology optimization process

The goal of topology optimisation is to obtain a load-carrying structural part that exhibit lightweight (performance), durable (low crack initiation probability), low stress levels and no stress concentrations in the area where the process can remove or add material (reliability, safety). The resulting output should be ready for CNC machining, casting and molding or 3D printing.

Although in most cases the TO result is the best in terms of stress concentrations and associated product lifetime, some results are not considered by designers to be suitable for manufacturing. Fig. 2 shows an example of a not "flat enough" surface (Fig. 3a) and an "overcomplicated" structure (many small connections) for fabrication (Fig. 3b).

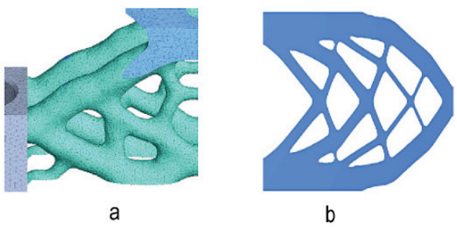

Figure 3 Topology optimized parts

Designers often carry out geometry reconstruction procedures to obtain a parametric CAD model, which is not an easy process. This can be done with the help of various software programs, but as a rule, a considerable amount of manual modelling cannot be avoided. The result of the reconstructed model is a geometry that always deviates slightly from the geometry of the original optimized part. The errors made in doing so may seem insignificant from a geometric point of view, but they can greatly increase the stress concentrations in the model. In fact, we know from the field of shape optimization that even a slight variation in geometry, which may otherwise appear to be quite insignificant, can lead to a significant increase in stresses. In the paper [6] an example of the effect of changing the geometry of an opening on a plate loaded as shown in Figure 4 is shown. A plate loaded with uniform but different loads along the outer edges has an optimum elliptical opening, which is then replaced by a circular one. This replacement causes the maximum stresses on the contour of the circular bore to increase by about 55 %. Such an increase can make a huge difference to the life of a cyclically loaded part.

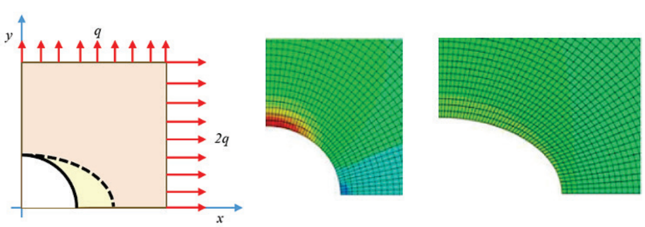

Figure 4 Plate with opening

A very difficult example to reconstruct the geometry are load-carrying structural parts with modelled lattice structures (Fig. 5).

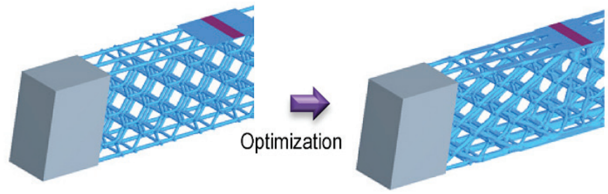

Figure 5 Optimized lattice structure

The authors are by themselves involved in the development of a professional TO software, enabling them access to invaluable feedback information from practicing engineers on their usage of TO procedures. The aim of this paper is to illustrate the pitfalls and possible solutions of reverse engineering topology optimized load carrying structural parts back into CAD models.

The structure of the paper is as follows. Section 2 outlines the structural TO fundamentals. Section 3 shows numerical example of topology optimization and reconstruction into CAD model. Section 4 shows the experimentation of the reconstruction models and the testing on the bending machine.

2 TOPOLOGY OPTIMIZATION

Topology optimization can be divided into three groups:

- First are homogenization methods - the foundations of the method were laid by [1]. These methods typically introduce a large number of design variables and mathematical programming methods are not well suited to solve these problems;
- Second are Solid Isotropic Microstructures with Penalization (SIMP) or Power-law methods [2]. These methods are based on an assumed and simple relation between the rigidity of the cell (elastic modulus) and the density of the cell. The number of design variables is smaller as in first methods, 1 variable per 1 finite element (FE) as in first 3 variables per FE.
- Third are Evolutionary Structural Optimization methods (ESO) [11] are based on some criterion as stress, strain energy density ... based on which a particular finite element can be eliminated or restored to its initial state.

Topology optimization is a powerful computational technique that enables engineers to determine the optimal material distribution within a given design space. The basic idea behind topology optimization is to start with a given design space, which represents the volume in which the structure will be located, and then use mathematical algorithms to determine the best possible configuration of material within that space. This is achieved by defining certain performance criteria that the structure must meet, such as maximum stress or displacement, and then iteratively refining the material distribution until the desired performance is achieved. Topology optimization problems of load-carrying structures are in general:

- non-linear,
- non-convex, and
- very flat,

problems.

A consequence of non-linearity is that the optimization process is iterative and cannot be solved within a single cycle. Non-convexity, on the other hand means that the problem exhibits many local minima and that it is very difficult to check whether the obtained result is actually the global minimum or solution. The most confusion in practice, however, is the extreme flatness of topology optimization problems.

There is no single solution in TO, however the number of solutions can vary depending on how the optimization process was carried out (Fig. 6). In optimized parts below is the strain energy practically the same although the designs differ substantially.

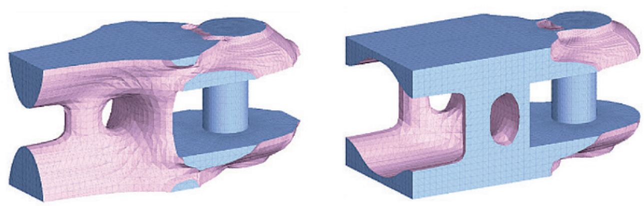

Figure 6 Topology optimization process – same strain energy

In topology optimization, the mathematical task is often defined as minimizing the total strain energy of the structure, taking into account the boundary conditions. The problem can be formulated as [4, 8]:

$$\min \int f(u, x). \quad (1)$$

In Eq. (1), u is the displacement field and x represents a parameter (e.g. the material distribution within a component) that affects the topology of the body under consideration. The value $u = u(x)$. For the optimization domain, dimensionless parameters x_i must be defined between 0 and 1 to allow material to be removed or added. Material removal or addition will be achieved by relating x_i to material properties such as density and elastic modulus, which can be written by the equation

$$x_i = x\rho_0, E_i = p_i E_0. \quad (2)$$

In Eq. (2), ρ_0 and E_0 are the density and modulus of elasticity of the material used in the structure, and p_i and E_i are the variables to be associated with the finite elements of the numerical model. In the numerical model, the parameters p_i represent material distribution in design space and are associated with nodes of FEA. Those parameters are defined in the range between 0 and 1, where 0 represents the void in design space and 1 the full material.

The mathematical problem of the TO is to distribute the material over the design domain in such a way that the minimum of the total strain energy is achieved. In this case, normally low stress levels and no stress concentrations in the design domain will reach. This will prolong the service life with low crack initiation probability of load-carrying structural parts. As mentioned before, the final design is fully adapted to given boundary conditions as loads, supports, theological constraints.

3 NUMERICAL EXAMPLE

The topology optimization and the geometry reconstruction will be demonstrated on a simple beam element. The beam represent the load-carrying structure where the middle section has to carry a large part of the vertical load, Fig. 7. The stand (middle section), which will be subject to topological optimization, represents a quasi-planar region, which will simplify the geometric reconstruction and the observation of the stresses on the cut surfaces.

Figure 7 CAD and FEA model

The beam element is centrally supported on the top side and loaded with uniform pressure 10 MPa on the underside. The CAD and the FEA models of this case were prepared using the PTC® Creo® software package [12]. A topology optimization-capable FEA model is normally prepared in a similar way as a usual FEA model, but there are some important issues that require careful consideration. The underlying CAD model must be adequately partitioned into volume regions [6, 8], the load cases must include all possible loads and supports variations and the finite element mesh must be prepared with some minimum quality requirements regarding mesh density and element size uniformity.

For topology optimization, proper prepared FEA model contains approximately one million linear tetrahedral finite elements and was imported in CAESS ProTOp® software package [13] (Fig. 8).

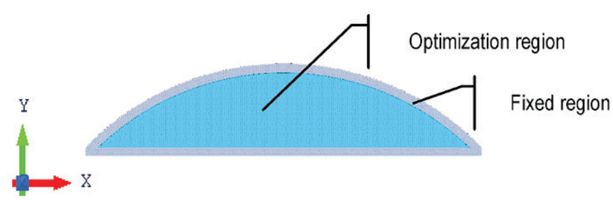

Figure 8 Topology model

Two optimization regions were set in ProTOp, where the light blue is a free region. This region can be optimized by removing or restoring material. The grey represent fixed region, which has to remain unchanged and is not optimized. Additional were added two technological constrains as plane symmetry on x and z axis, so the optimizer will distribute the material symmetrically to the prescribed plane.

Firstly, the objective was to design parts by using 80 %, 60 %, 50 %, 40 % and 20 % of the material present in the initial design. The aim of TO is that the load-carrying structure with this amount of material has minimal stresses levels and maximal stiffness. Results are shown in Fig 9. The stress scale is set to 500 MPa max.

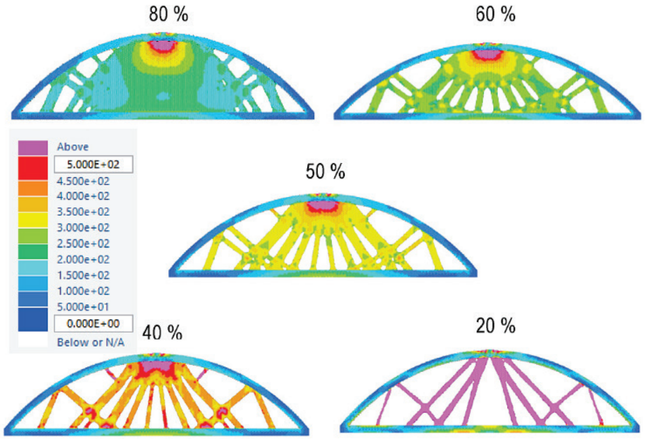

Figure 9 Optimized models with stress fields

Tab. 1 shows total volumes and calculated reference stress for optimized parts. Reference stress denote the maximum von Mises stress along the contours of all the openings in the rack.

Table 1 Reference stress for optimized parts

Volume (%)	80	60	50	40	20
Total volume (10^3 mm^3)	697	647	623	598	548
Reference stress (MPa)	253	275	332	425	904

Based on the topological optimization results, we decided to perform three variants of geometry reconstruction for the case of 50 % material removal, which illustrate the most commonly used techniques in practice. We did:

- Case A: we used only circles to cut the material. The size and position of circles are chosen to represent the inscribed circles for the openings of the optimal design.
- Case B: we used only ellipses to cut the material. The size and position are chosen to visually follow as closely as possible the openings of the optimal design.
- Case C: The material is cut by hand so that the curves used follow as closely as possible the actual shape of the optimal design.

The numerical results of stress fields are shown in Fig 10.

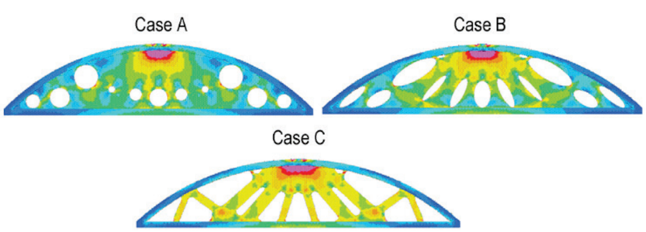

Figure 10 Cases A, B and C with stress fields

Tab. 2 shows total volumes and calculated reference stress for all three cases.

Table 2 Reference stress for Cases A – C

Volume 50 (%)	Case A	Case B	Case C
Total volume (10^3 mm^3)	694	671	623
Reference stress (MPa)	499	620	430

Fig. 11 shows calculated reference stress for all three cases.

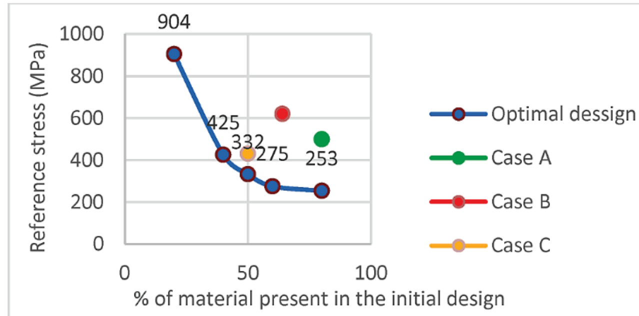

Figure 11 Reference stress for optimal design and Cases A – C

The diagram shows that it is best if the reconstructed geometry follows the optimal one as closely as possible. In this case, the increment is about 30 %. However, the geometry reconstruction performed poorly when using a circle and an ellipse. The stress increments in these cases were enormous.

4 EXPERIMENTAL EXAMPLE

We also wanted to verify experimentally the numerical results of the reconstruction for Cases A – C. We were interested in whether they would crack under cyclic loading, where we numerically calculated the stress concentrations. For each reconstructed case, we prepared several Co-Cr test specimens with properties $R_{p0.2}$ = 900 MPa and R_m = 1100 MPa. The test specimens were 3D printed. The tests were carried out with a bending test where the force was increased up to 10 kN.

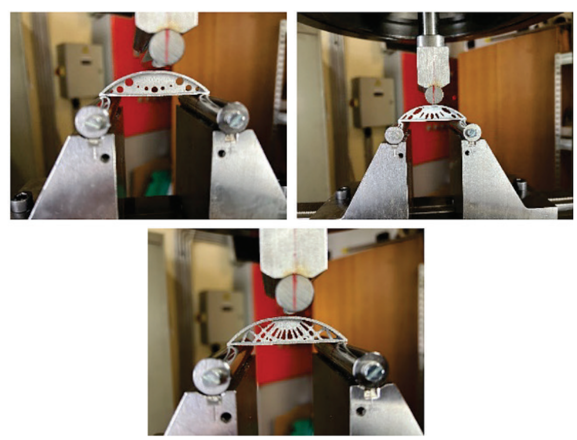

Figure 12 Experiment for Cases A, B and C

The results showed that the cracks occurred in the zones with the highest stress, as predicted. However, it should be said that, probably due to the porosity of the 3D printing material, some test pieces also cracked in places where we did not predict (dot).

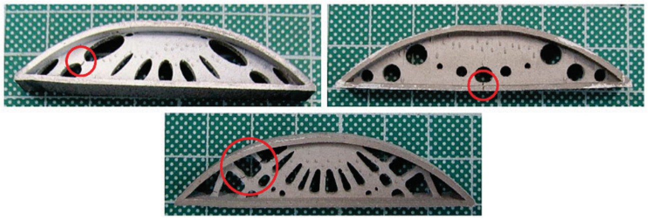
Figure 13 Some test results

5 CONCLUSION

In practice, the results of topology optimization are often processed back into CAD models. However, many engineers do not realize that they are thereby spoiling the favorable optimization results and introducing stress concentrations into the structure, despite the fact that they are adding material during the reconstruction process.

To avoid such errors and to prevent stress concentrations, we have developed a model in the TO software framework that can redistribute the material in the domain a little after reconstruction [10]. In such case, the stress concentration vanishes at the edges of plots (Fig. 14).

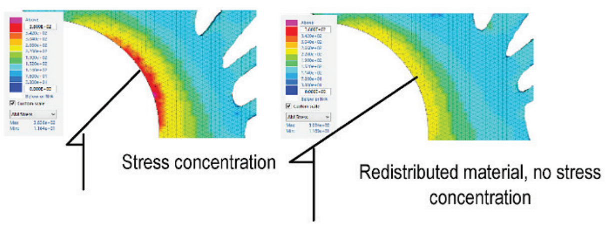

Figure 14 Redistribution of the material

By introducing such a model, we have been able to reduce the stress concentrations at the edges of the contours in cases A – C (Fig. 10), but it is important to remember that this has worsened the deformation energy of the system. But still thus preventing the formation of a crack, as shown in Fig. 15.

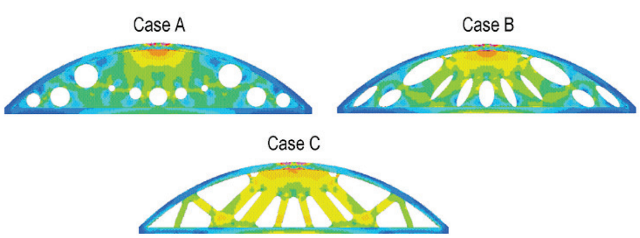

Figure 15 Cases A, B and C with stress fields

It must be stressed that the reconstruction of the geometry must be approached in a thoughtful way, so as not to reduce the load-bearing capacity and the service life of the load-bearing part.

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