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Topological optimization processes

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Abstract

The method of topological optimization is based on a mathematical algorithm, which is based on the distribution and intensity of detail stress on the investigated component. It was developed using the Rhino-Grasshopper theory. This is a complicated FEM analysis with the help of the Nastran solver in the Siemens NX software environment. The topology detail is controlled by the degree of iteration of the algorithm, changing the size and distribution of the elements in relation to the incoming force stresses of the FEM simulation. The goal of topological optimization is a clearly defined shape of the component for a given design solution.

Keywords: Topology optimization; NX; nastran; lattice; SIMP; Pareto

1. Introduction

Topological optimization processes are used not only in mechanical, but also in other industries in order to reduce the amount of material used and the deformation energy of construction details, while maintaining mechanical strength. It is a mathematical method that spatially optimizes the distribution of structured elements within predetermined boundary conditions. Boundary conditions can be understood as, for example, the incoming loading forces of the system, the physical and mechanical properties of the material used, the safety coefficients etc. The result of such optimization is a targeted shape, as the most optimal for a given construction detail.

There are a number of topological optimization methods in the scientific literature. The two most popular methods are the solid isotropic material (SIMP) technique and the structural optimization (ESO) technique. Solid Isotropic Material with Penalization (SIMP) technique The SIMP method was defined by Bendsoe - Kikuchi (1988) and Rozvany - Zhou (1992).

The method performs the optimal distribution of the material within the basic proposed space within the boundary conditions. According to Bendsoe (1989): "Optimizing a shape in the most general setting should create a shape at every point, whether or not the material is in it." Traditionally, topology optimization is solved by discretizing the domain into a finite element network, the so-called isotropic solid microstructures. Each element is then either filled with material in the areas required by the material or stripped of material in those areas where removal is possible (cavities). The material density distribution within the design domain ρ is discrete, each element is assigned a binary value:

$\rho(e) = 1$ where material is mandatory (black)
$\rho(e) = 0$ where material is removed (white)

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The following figure shows the optimal distribution of the embedded beam material under load. Solid particles with densities *ρ(e) = 1* are clearly visible as black, empty particles with densities *ρ(e) = 0* are collected particles.

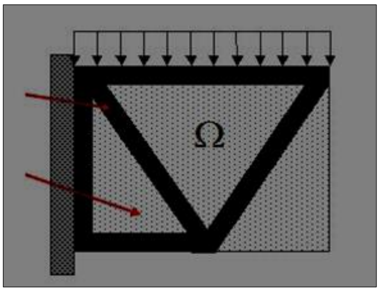

Figure 1 Example of an embedded beam

For each element, the assigned relative density can be between the minimum value of *ρmin* and 1, which allows the addition of intermediate element densities, also referred to as porous elements. *ρmin* - is the minimum allowable value of relative density, for empty elements, which is greater than zero. This density value ensures the numerical stability of the finite element analysis (FEM).

$$E(\rho_e) = \rho_e^{p} E_0$$

Formula 1 Relative density of the material

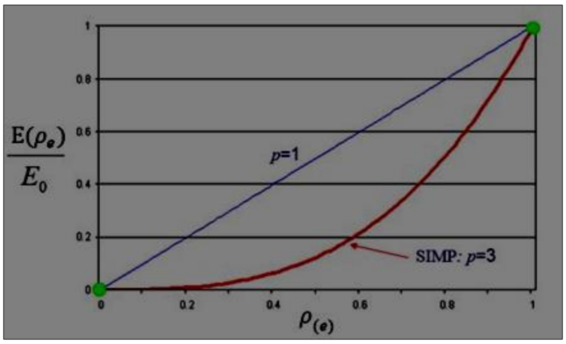

Figure 2 Penalty factor graph

Because the relative density of the material can vary continuously, the Young's modulus of the material of each element can also vary continuously. For each element, the relation between the relative density factor ρe and the Young's modulus of elasticity of the assigned isotropic material model *E0* is calculated based on the law of forces.igure 2 Penalty factor graph.

The penalty factor *p* reduces the contribution of particles with intermediate densities (gray elements) to the overall stiffness. The penalty factor directs the optimization solution to particles that are either solid and black *(ρe = 1)* or empty and white *(ρe = ρmin)*. Computational experiments indicate that the value of the penalty factor *p = 3* is satisfactory. Reduction of the elastic modulus of the element material leads to a reduction in the stiffness of the element. When calculated by the SIMP method, the global stiffness is modulated according to the following formula:

$$K_{SIMP(\rho)} = \sum_{e=1}^{N} [\rho_{min} + (1 - \rho_{min})\rho_e^{p}]\, K_e$$

Formula 2 Modular global rigidity

where *Ke* is the element stiffness matrix, *ρmin* is the minimum relative density, *ρe* is the element's relative density, *p* is the penalty factor and *N* is the number of elements in the proposed domain. For example, for an element with an assigned relative density *ρe = 0.5,* a penalty factor *= 3* and *ρmin = 0.001*, the global stiffness matrix is modified by a factor, then *KSIMP (0.001 + (1 - 0.001)* 0.5 ^3) = 0.12587*.

An important purpose of optimization is, first and foremost, to maximize the overall rigidity of a given system, structure, or to minimize compliance with a targeted amount of material taken in order to reduce a certain weight. Flexibility can be understood as the overall flexibility, the softness of the system. Then global compliance is equal to the sum of elastic or deformation energies. The minimization of global compliance, *C*, is equivalent to the maximum global stiffness. The optimization algorithm, using iterative cycles, seeks to resolve the density of elements that minimize the global flexibility of the system or structure:

$$minC(\{\rho\}) = \sum_{e=1}^{N} (\rho_e)^p[u_e]^T[K_e][u_e]$$

Formula 3 Global flexibility

where *ue* is the nodal displacement vector of element *e*, *Ke* is the stiffness of element *e*, and vector *{ρ}* contains the relative density of element *ρe*. In order for the topological optimization system to run logically, each stage of the iteration must always meet the global balance of stiffness forces with the required constraint function (variable).

$$\sum_{e=1}^{N} \{v_e\}^T \rho_e \leq M_{target}$$

Formula 4 Global balance of power

where *ve* is the volume of the element and *Mtarget* is the target optimization weight.

At each stage of the optimization iteration, the algorithm performs a so-called sensitivity analysis. It is a process in which the impact of different material densities on the function of the purpose of the system is evaluated, in order to maximize the stiffness. Mathematically, it can be said that the sensitivity analysis is expressed as a derivative of the function of the purpose with respect to the material density of the construction detail.

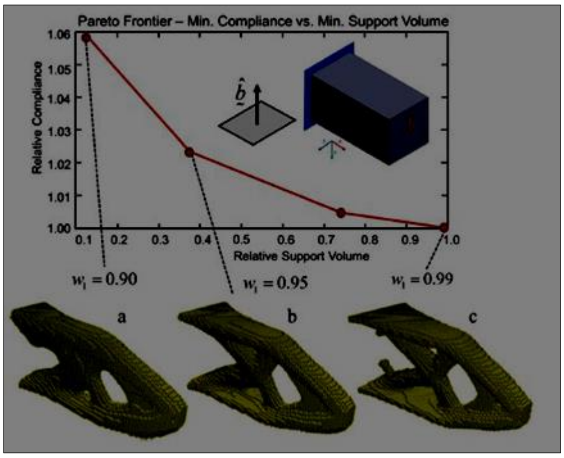

Figure 3 Pareto principle, example of an anchored beam

During the sensitivity analysis process, elements that are loaded with low material density coefficients eventually lose their structural importance and are subsequently eliminated in subsequent iteration stages. If we calculate the sensitivity of the individual elements independently and do not take into account the connection between these elements, this can lead to the formation of certain volumes that are not connected to the main geometry of the system or structural detail. This state is then called the checkerboard effect. This is an undesirable state, forming discontinuous, illogical volumes of the overall topological optimization.

This checkerboard effect is minimized by averaging the sensitivities of the elements during iterative cycles. Iterations continue until the deviations of the purpose function converge and the degree of iteration does not reach the necessary convergence criteria.

Another tool of Topological Optimization is Pareto Front, also called as a set of solutions. It is a set of all effective Pareto solutions. This tool is widely used especially in mechanical engineering. It allows the designer to narrow down a set of effective options. The iterative cycle of topological optimization is the result of the nearest effective set subject to a certain input parameter in a given stage of iteration.

The sensitivity of the Pareto set is modifiable in the optimization process. If specific inputs are placed on the designer, it is possible to design certain construction details to the edge of the effective set.

FEM simulation software tools, such as Nastram, NX, Ansys and the like, offer optimal settings for these sets.

Particle optimization filtering technique is used according to the theories of Sigmund & Petersson, 1998. The whole process involves three phases, construction of interpolation models, concurrent topology optimization and creation of a geometric database of lattice structures, to generate a CAD model. In the first phase, the basic structure of the grid is created. The equivalent properties of the new grid are then parameterized and the properties are fitted based on the boundary conditions of the given interaction. In the second phase, a concurrent topology optimization is performed to obtain optimal distributions of the relative density of the elementary gratings. In the last phase, the optimized structural grids are reconstructed by taking over pre-created geometric models and stored in a geometric database. The database contains grids with extremely anisotropic properties. The 3D CAD model is then compiled by binary matrices of database structural grids with subsequent transformation into a * .stl format model.

2. Results and discussion

As an example, the beam below is bent. Mathematical model, boundary conditions, dimensions, forces are shown in the figure. The size of the beam is *48 x 12 x 8 mm*. Load *60 N* with evenly distributed force along the surface. Beam support limits vertical displacement. A network of *2304 (24 × 12 × 8) 8* - nodal hexaedron particles is used to discretize the shape. The goal is to minimize the consistency of the volume macrostructure. Due to manufacturability constraints (SLA technologies), the upper and lower lattice density limits are set at $0.18 \le \rho v \le 0.93$, which corresponds to the upper and lower limits of the proposed variables $0.06 \le \rho\lambda \le 0.5$. The initial setting of the optimization process is a uniform fill with the proposed structures, grids with $\rho v = 0.5$ and $\rho\lambda = 0.22$.

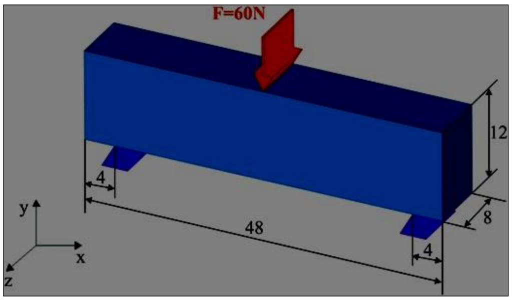

Figure 4 Beam, bending stress

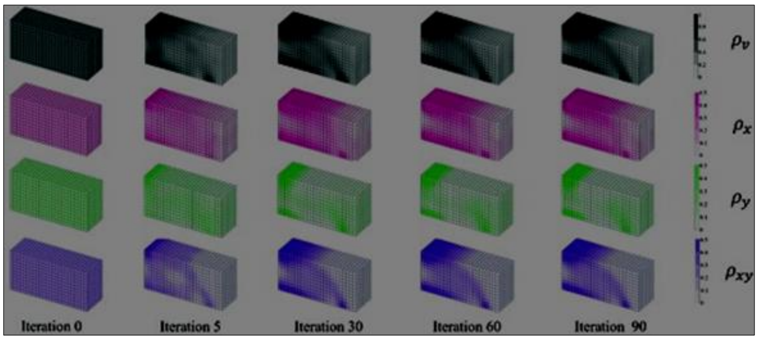

Figure 5 Development of the total density of structures, according to the degree of iteration

As further shown in the figure, a larger part of the volume of this beam is distributed around areas with a high concentration of deformation energy, which is logical in terms of strength. Due to symmetry, only the right half of the beam is shown in the figures. It can be assumed that the optimization process was successful. The strongly colored parts of the model in different degrees of interaction indicate the course of force stresses. Paler areas indicate excess optimization.

For comparison, the figure below shows three additional optimizations obtained by different methods under the same boundary conditions and volume fraction.

Figure 06 shows the geometric models of these samples:

The model in case *A* is evenly filled with a cubic lattice. The model in case *B* is obtained by the method of heterogeneous lattice microstructures composed of different cubic and X - shaped lattice particles according to the theory of Wang et al., 2020. The macrostructure filled with topologically optimized homogeneous microstructures is given in case *C*. It is clear that the multilevel design achieved by the proposed method , as demonstrated in case *D*, showed excellent agreement.

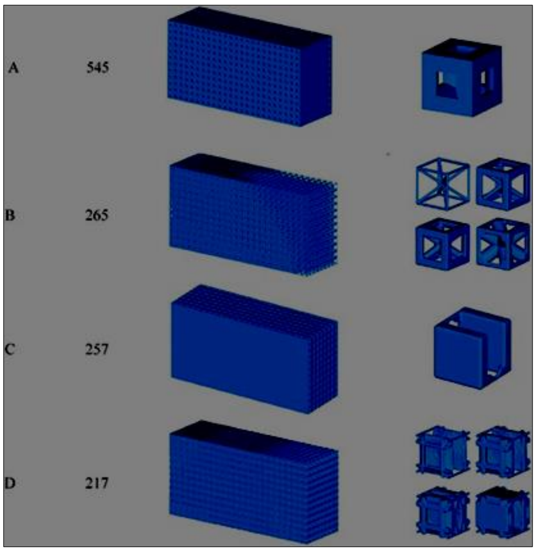

Figure 6 Comparison of different optimization results

3. Conclusion

In this article, we have briefly evaluated the method of topological optimization methodology. Its application is increasingly used in various branches of the engineering and automotive industries. The aim of this method is to optimize the existing system in order to increase the efficiency of this system in the given area of use. For various components, in series or mass production, the aim can be, thanks to the mentioned optimization, considerable material savings, while constantly maintaining the mechanical and strength properties. However, the production of components optimized in this way requires different manufacturing technologies.

Compliance with ethical standards

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Disclosure of conflict of interest

There is no conflict of interest.

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