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TOPOLOGY OPTIMIZATION OF THE LOAD-CARRYING ELEMENT UNDER A CONCENTRATED LOAD

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Highlights

- Finite element methods (FEM) are very effective, and give reliable results in the analysis of engineering designs.
- Optimization methods can reduce the processing time.
- By use of the topology optimization, the weight of the designs, thus, the manufacturing costs can be reduced. The optimum design can be lighter and cheaper with the desired parameters.

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Abstract

Topology optimization (TO) is an important method for the conceptual design of the products. Traditional design methods generally depend on the knowledge and experience of the designer. In an optimization problem, the determination of the optimum design is a time consuming and challenging task, especially when the results are obtained by the trial and error method. Finite element based topology optimization methods have proven to be a robust algorithm in order to achieve the optimum geometries, and have been widely applied in computer aided design (CAD) software. In the study, initially, the static analysis of the load-carrying element has been carried out and the maximum von Mises stresses are obtained. Then, the topology optimization has been performed under the same operating and loading conditions. In the optimization process, minimum weight and maximum rigidity have been chosen as the design parameters, and then the load-carrying element is redesigned due to the results obtained after the optimization process.

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1. Introduction

The main goal of the manufacturing process is to obtain the best product in the shortest time with the minimum cost. In the design process, the best design is expected to be able to satisfy the all conditions in the most appropriate way. Although there are too many solutions, the most important point is to have the optimum one among them. The purpose of the optimization process performed in any machine element, structure or system is to obtain the best design in the most appropriate way. In general, the structural optimization problems can be classified into four groups such as size, shape, topology and topography optimization. The oldest structural optimization method in the literature is size optimization which is also called as the parametric optimization. In structural optimization, the optimum design is obtained by changing the material distribution or the shape of the boundaries, starting from a given design topology, under certain boundary conditions and constraints. The design process is implemented in three stages. First, the optimum initial topology is created with the existing methods, then the topology is processed and converted into designs with the help of computational methods. Finally, shape optimization is applied to give a smooth shape to the contours and holes of the structure, and if necessary, the final dimensions of the structure are determined by the size optimization. Structural optimization has the potential to reduce not only the manufacturing costs, but also the manufacturing time. It has been widely applied in the engineering designs in recent years. Hajare and Jadhav designed a load-carrying mechanism that includes a hook. Afterwards, by use of the finite element method, the design of the hook was optimized by a specific engineering software (Hajare and Jadhav, 2020).

Niteen and Malbhage designed and optimized an excavator boom for the maximum reliability, considering the minimum weight and cost. A finite element analysis was used in order to keep the design safe under all loading conditions (Niteen and Malbhage, 2017).

Ramesh et al. performed the topology optimization to reduce the lower arm weight of the excavator. To improve the lower arm model, low weight and high strength values were taken into consideration as the optimization parameters (Ramesh et al., 2017).

Sarode and Sarawade investigated the weight optimization of heavy-duty excavators within the certain limits. After the target values were obtained, the optimized model was manufactured and tested by a universal testing machine (Sarode and Sarawade, 2017).

Topology optimization in continuous structures can be performed by various methods. Generally, two important methods are used in most of the commercial engineering software.

The first method is the homogenization method which was initially developed by Bendsoe and Kikuchi. This method assumes that the finite elements that construct the model, contain gaps. In topology optimization, these gaps and their orientations are used as design variables (Bendsoe and Kikuchi, 1988).

The second method is the density method which was developed by Yang and Chung. They considered the material of each finite element as isotropic, and normalized the density of each element, and chose them as the design variables (Yang and Chung, 1993).

Rozvany et al. initially proposed a mathematical method used for the topology optimization which is called as the solid isotropic material with penalization (SIMP) method. The SIMP method estimates the optimum material distribution within a given design space for certain load situations, boundary conditions, production constraints, and performance requirements (Rozvany et al., 1992).

Eschenauer and Olho investigated the topology optimization of continuum structures. They searched for the parameters that improve the quality and reliability in a manner without exceeding a certain cost limit. The topology of a design was chosen by the engineer by inspiration of the previous designs traditionally, and the structure could then undergo shape or sizing optimization (Eschenauer and Olho, 2001).

In the study, the topology optimization of the load-carrying element has been performed by use of a computational software. Minimum weight and maximum rigidity have been chosen as the design parameters. Firstly, the static analysis of the load-carrying element has been carried out for a specific material, and the maximum von Mises stress and safety factor values have been calculated. Then, the topology optimization process has been performed, and non-parametric void model has been obtained. The model is revised according to the topology optimization results, and after the validation process, the maximum von Mises stress and safety factor values have been calculated once again, and compared with the initial results.

2. Optimization Method

Topology optimization was firstly explored in 1904 by an Australian engineer Anthony Michell. It is a mathematical method that optimizes a specific design area for a given set of load, boundary conditions, and constraints in order to maximize the system performance. The main objective of the topology optimization is to find out optimum shape of the structure with the highest strength or natural frequency while reducing the weight. Especially in recent years, due to the computers with high processors and the desire to make lighter but more durable parts, the use of this method has increased. Until recent years, the use of topology results in manufacturing fields required major changes, and it was almost impossible to put them into production. Today, it is possible to obtain the topological results by many manufacturing methods such as casting, extrusion. The topology optimization algorithms have proven to be versatile, and been applied to many design problems in the engineering fields. In an optimization process, the optimum design should be in the exact dimensions, light in weight and have a long operating life. The models are often developed from an existing design or concept. In such cases, the dimensions or other inputs are defined by the design parameters. Thus, by use of the topology optimization in an optimization problem;

- The reliability of the design, and the performance of the product can be improved.
- The weight of the design can be lightened.
- The amount of chips and the processing energy in the product can be reduced.
- The product can be manufactured by use of a wide range of materials.

The workflow of topology optimization is presented in Figure 1.

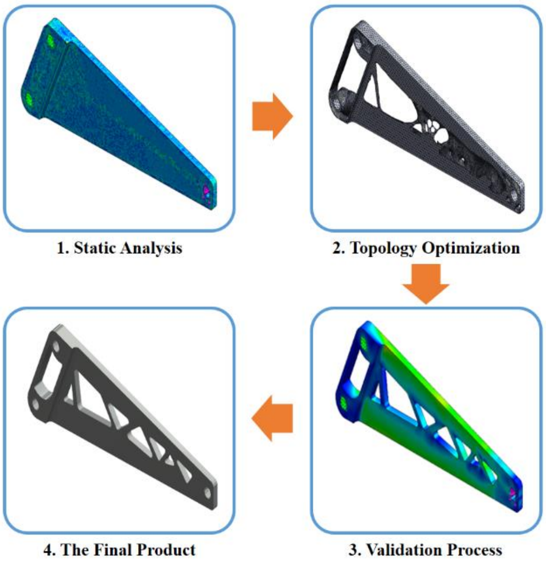

Figure 1. The workflow of topology optimization

Firstly, a finite element static analysis is applied to the product. The static analysis results are evaluated, and then the topology optimization analysis is performed. After the topology optimization, a validation process is performed by subjecting the new model revised by the designer to the static analysis to verify. Finally, the design of the new product is created.

The topology optimization of a design can be summarized as in the following way:

- Selection of the commercial software that satisfies the required conditions.
- Static analysis of the design, and evaluation of the targeted values.
- Performing the topology optimization after the static analysis.
- Examining the geometrical properties after the topology optimization, and interpreting the results.
- Application of the geometrical properties to the new design.
- Evaluation of the targeted values.

The geometry produced by the topology optimization procedures is often complex and difficult (sometimes impossible) to be manufactured by traditional methods. Additional manufacturing methods, or 3D-printing technologies have undergone a rapid development in recent years which is often more relevant for engineering purposes (Posch et al., 2017).

The main advantage of the additive manufacturing is the freedom that it provides to the designer. Therefore, by use of the combination of topology optimization and additive manufacturing methods together, the parts can be optimized and manufactured accurately (Saadlaoui et al., 2017).

3. Static Analysis

In the study, the total weight of the load-carrying element is 477 kg, and ST-52 steel is chosen as the material. The mechanical properties of ST-52 steel are presented in Table 1 with respect to the SI unit system.

Table 1. The mechanical properties of St-52 steel

Property	**Value**	**Unit**
Elastic Modulus	210000	N/mm^2
Poisson's Ratio	0.28	-
Shear Modulus	79000	N/mm^2
Mass Density	7800	kg/m^3
Tensile Strength	450	N/mm^2
Yield Strength	275	N/mm^2

In Figure 2, the solid model of the load-carrying element is presented. The design requirements of the model are chosen as 10000 kg for the maximum load capacity, and 3 as for the safety factor.

Figure 2. The solid model of the load-carying element

In Figure 3, the mesh quality plot of the load-carrying element is presented. A mixed curvature-based mesh with high accuracy is selected in the model, and the minimum and maximum element sizes are defined to the system. During the meshing process, 101539 nodes and 65236 elements are created.

The maximum von Mises stress value is obtained as 75 MPa when the diverging points are excluded from the analysis as presented in Figure 4.

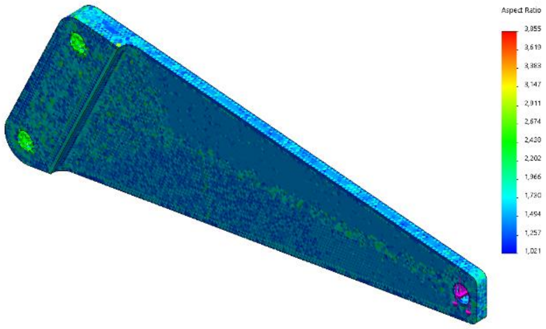

Figure 3. The mesh quality plot of the load-carrying element

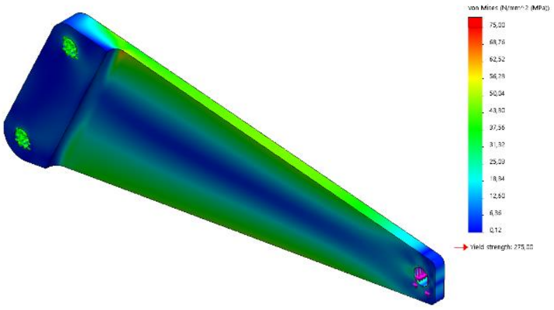

Figure 4. The stress distribution of the model after the diverging points are excluded

Considering the yield strength of the material (YSM) and the maximum von Mises stress ($MVMS$) obtained from the static analysis, the safety factor (SF) can be obtained as follows:

$$SF = \frac{YSM}{MVMS} \tag{1}$$

$$SF = \frac{273}{75} \tag{2}$$

$$SF = 3.64 \tag{3}$$

As the safety factor in Eq. 3 is higher than the limit value of 3, the topology optimization can be performed on the model.

4. Optimization Process

In the optimization process, the same design parameters with the static analysis, such as fixtures, loads and meshing, are directly transferred. A computer aided engineering software which is based on the finite element method is utilized for the computational solution. Considering the targets and limitations, the main objective of the design is to reduce the mass by maintaining the best stiffness and weight ratio, and to set the limitation to a safety factor of 3 and above. In Figure 5 and 6, a non-parametric void model, and the areas to be kept or removed from the model after the optimization process, are presented respectively. The decision of the areas which can be kept (yellow) or removed (blue) from the model is made by the software.

Figure 5. The non-parametric void model after the optimization process

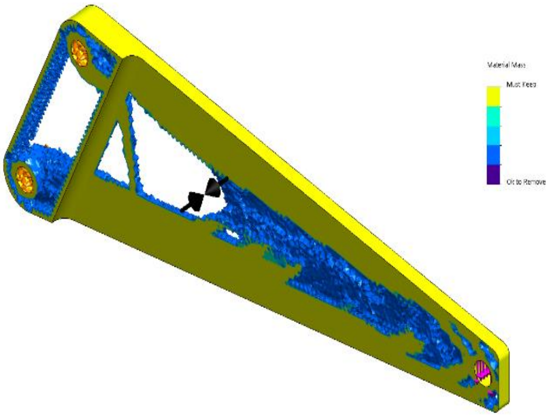

Figure 6. The areas to be kept and removed from the model after the optimization process

When the model is exported, it will be revised according to the results obtained from the topology optimization, and will be subjected to the validation process. After the validation process performed, the model takes its final form. Depending on the model obtained from the previous steps, the load-carrying element is revised as in Figure 7 with the necessary revisions.

Figure 7. The revised solid model of the load-carrying element after the optimization process

The static analysis section is reapplied to the revised solid model, and the results are evaluated again to check whether there is an error during the design revision, or an extra element has been removed from the model. The static analysis is repeated by applying the same support and load conditions to the revised model as shown in Figure 8.

Figure 8. The revised model for the validation process

After the topology optimization, the total weight of the load-carrying element is reduced to 342 kg. When the diverging points are excluded again from the analysis, the maximum von Mises stress value is obtained as 85 MPa as presented in Figure 9.

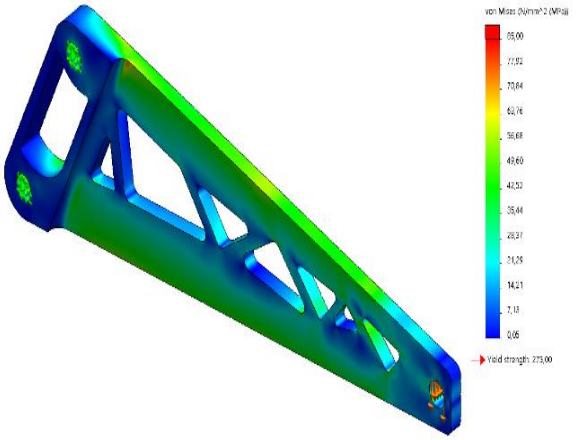

Figure 9. The stress distribution of the revised model after the diverging points are excluded

Considering the evaluation of the post-validated results after the optimization process, the safety factor can be calculated from Eq. 1 as in the following way.

$$SF = \frac{273}{85} \tag{4}$$

$$SF = 3.21 \tag{5}$$

The safety factor is still higher than the limit value, so it is obvious that the load-carrying element can safely withstand the prescribed loading and boundary conditions.

5. Results and Discussions

The determination of the optimum design by trial-and-error method will cause a lot of time waste and manufacturing cost.

For this reason, it is inevitable to use the topology optimization in order to obtain the optimum model in a shorter time, more easily and economically.

In Table 2, the weight, maximum von Mises stress and safety factor values of the load-carrying element are compared before and after the topology optimization.

Table 2. The comparison of weight, von Mises stress and safety factor values before and after the topology optimization

	Weight (kg)	**Maximum von Mises Stress (MPa)**	**Safety Factor**
Before TO	477	75	3.64
After TO	342	85	3.21

The percentage difference of the weight and maximum von Mises stress values before and after the topology optimization can be calculated in the following way:

$$d\% = \left|\frac{(iv - fv)}{iv}\right| \times 100 \tag{6}$$

where "$d\%$", "iv" and "fv" correspond to the "percentage difference", "initial value" and "final value" respectively.

After the optimization process, it can be concluded from Table 2 that the weight has been reduced by 28.3%. The load-carrying element has become lighter, but as it is expected, the maximum von Mises stress value has increased 13.33% due to the decrease in the weight of the load-carrying element. Although the maximum stress value has increased after the optimization process, the safety factor is still higher than the limit value.

The topology optimization should not be performed without the validation process, otherwise, the optimization process cannot be controlled, and generate unreliable results.

The study can be extended with different material and geometrical properties for various boundary and multi-loading conditions. For further studies, the dynamic behavior of the load-carrying element can be investigated. In this case, the fundamental natural frequencies and critical buckling loads can be obtained in order to prevent the resonance and deformation in a specific load-carrying element under various loading and boundary conditions.

Conflict of Interest

There is no conflict of interest.

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