Proc. Estonian Acad. Sci. Eng., 2004, **10**, 4, 300–307

Design of sandwich support structures

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Received 1 July 2004, in revised form 8 September 2004

Abstract. In modern engineering industry the weight reduction of support structures of machines is important. One possibility to reach that is to use sandwich structures. Mechanical properties of sandwich structures are characterized by higher strength/weight and stiffness/weight ratios than those of stiffened steel plate structures. This paper studies the possibility of replacing welded structures by sandwich ones using topology optimization. In the conceptual phase, topological optimization has been performed that allowed to find a structurally sound initial model for further design and parametrical optimization. Topological and parametrical optimization has been performed using a commercial FEM software system. This method is flexible by designing products with different configurations that is important by shortening the time to market new products. Welded steel structures, consisting of walls and ribs, are considered. Strength properties, depending on the ribs' configuration and on the length of welds, have been examined. Technology of manufacturing sandwich frames are described. As an example, the design and reduction of mass of a brush-cutting machine has been investigated.

Key words: metal structures, optimization, FEM.

INTRODUCTION

By developing a product, one of the goals is to consider its performance and manufacturing costs in the early stages of product design. The topology of a product has significant effect on the product performance and manufacturing costs. The design of optimal topology allows design goals to be reached faster and cost-effectively. Therefore it is important to choose the optimal structural layout during early stages of product development.

The support structures of many machines are frames or plates. Often they are made of steel plates that have been strengthened with various elements (pipes, angles, bars, etc.). As an example, we consider the body of a brush-cutting machine (Fig. 1). Using a sandwich structure, the mass of such a structure can be reduced.

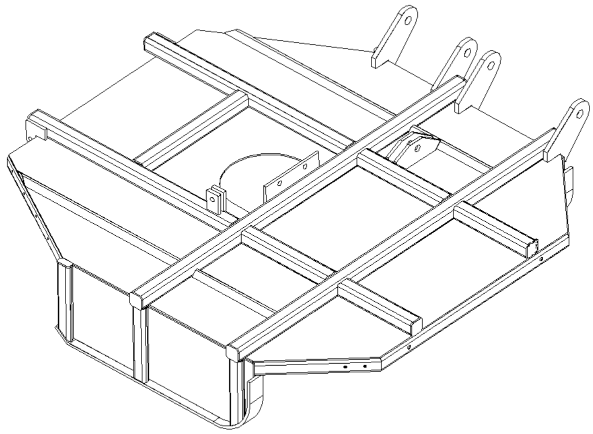

Fig. 1. Body of a brush-cutting machine before optimization.

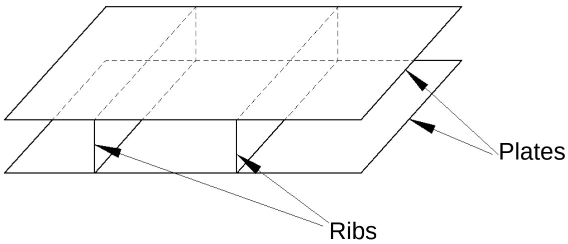

Fig. 2. Sandwich structure.

One possibility to build sandwich structures is to place ribs between the two covering layers (Fig. 2). The problem is how to place the ribs so that the use of the material is optimal. A way to solve this problem is topology optimization.

2. TOPOLOGY OPTIMIZATION

Topology optimization, which was introduced by Bendsoe and Kikuchi [1], is mainly used to find the optimal distribution of material in a given structure that meets a predefined criterion [2]. With topology optimization, regions of the structure that have the least contribution to the overall stiffness or natural frequency, can be identified. Thus it permits to find the regions, which should be excluded from the structure to minimize the mass with the least impact on the performance of the structure. Of the various optimization techniques, topology optimization has turned out to be very efficient, especially when used to strengthen existing designs [3].

Unlike traditional optimization, topology optimization does not require explicit definition of the optimization parameters (i.e., independent variables to be optimized). In topology optimization, the material distribution function over the structure serves as the optimization parameter. The user has to define the structural problem (material properties, loads, etc.) and the objective function (the function to be minimized or maximized) and the state variables (constrained dependent variables).

The theory of topology optimization seeks to minimize or maximize the objective function F subject to the constraints. The design variables η_i are internal pseudo-densities that are assigned to each finite element i in the topological problem. The pseudo-density for each element varies from 0 to 1; $\eta_i \cong 0$ represents material to be removed and $\eta_i \cong 1$ represents material that should be kept [4].

The steps of topology optimization are the following:

- identify the design space for the analysed body,
- create the topology optimization model,
- formulate the optimization problem based on design requirements,
- perform topology optimization,
- create an optimized design based on the optimization results.

In this paper the objective is to maximize stiffness of the body of a brush-cutting machine, satisfying the mass reduction constraint. The topology optimization problem can be formulated as follows:

$$\text{maximize } F(\eta_i) \text{ subject to } m \le m_0 - m^*, \quad 0 < \eta_i \le 1 \quad (i = 1,2,3,\ldots,N),$$

where F is stiffness, N is the number of elements, m is mass, m_0 is original mass and m^* is the amount of material to be removed.

3. FEM MODELLING AND SIMULATION

A plate 1.4 × 1.4 m was investigated. The opening in the centre of the plate is typically used for fastening an engine or another device or structure. For this purpose a 0.3 × 0.3 m opening has been made in the centre of the plate. The plate is supported at two sides and by one additional constraint or at four corners. The most typical cases of loading are:

- force is directed to the centre of the plate (e.g., booms of a lift, Fig. 3, a and b),
- force is directed onto one corner (when a tree or a rock hits the plate, Fig. 3, c),
- torsion loading (Fig. 3, d),
- force is directed to the centre of one side (Fig. 3, e),
- moment applied to the centre of the plate (e.g., boom of a lift, Fig. 3, f and g),
- simultaneous influence of different loads (Fig. 3, h).

Corresponding topology was found for each load. Also the best topology of the structure for the combined loads was found. As large models may take long time to solve, it is preferred to use several simple models to study the physical phenomena involved and to find important parameters of the construction (for

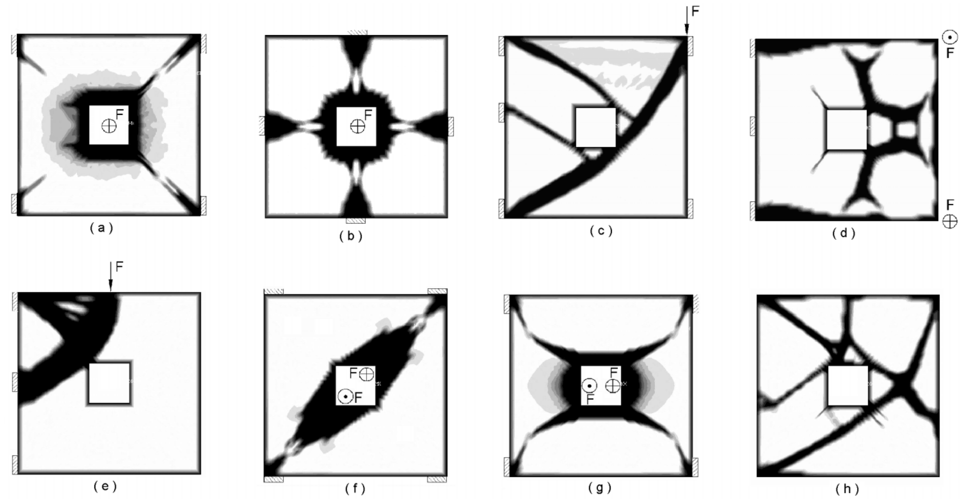

Fig. 3. Topology of a square plate for different load cases; darker areas mean greater density; shaded rectangles mark supports.

example contact parameters, parameters of the elements, etc.) in order to avoid simulation with large models [5].

Topology optimization was performed with the FEA software Ansys 7.1. For simplifying the task, the structure was modelled as a thin plate with a thickness of 10 mm. 2D shell elements were used for modelling. During optimization, global structural stiffness was maximized by reducing the volume of the structure by 80%. It is not allowed to modify the material on the edge of the plate and the edge of the opening. Modifying the rest of the material is allowed. The selection criteria for the loads, influencing the plate, were the following:

1) stress should not cause yield stress (380 MPa),

2) deformations caused by the force should remain small.

After calculation, the results should be critically evaluated and the model should be updated [6], if necessary. One possibility to verify the model is to set up a test and examine how the structure behaves under real conditions [7]. Nowadays the experimental modal analysis [8] is widespread, especially in solving problems of structural dynamics.

In the case of only one force, influencing the structure (Fig. 3, a–e) the results correspond to expectations – the force should be directed away by the shortest possible route. In the case of simultaneous influence of different loads (Fig. 3, f–h), the result is more complicated. In the examined case all forces were considered having equal weights. Still it can be seen that loads, shown in Fig. 3, c and e, have more significant influence. The results depend greatly on the application point of the force and the location of supports.

Measurements confirm efficiency of the solution, reached by topology optimization. The best structure for given loads has 8 ribs, forming a cross, and a diagonal inside the structure.

4. DESIGN OF A SANDWICH STRUCTURE

There are two possibilities to weld ribs between upper and lower plates of the sandwich structure (Fig. 2). In the first case the ribs are welded to the lower plate and the upper plate is welded to the existing structure afterwards (Fig 4). The upper plate has holes, through these holes the upper plate is welded onto the ribs. Assembling is quite complex in this case.

In the second case the plates have slots. Slots are easy to make on the sheet metal CNC punch press. The rib plate is toothed (Fig. 5). During the assembly, teeth of the rib are placed into slots of the lower plate and fixed. After that the upper plate is positioned and both plates are welded to the ribs.

However, welds (tooth length L_h) must be long enough to ensure stability of the rib. Modal analysis was used to study the dependence of the rib stiffness on the tooth length and the number of the teeth. Rib stiffness was evaluated by analysing eigenfrequencies. Higher first eigenfrequency was considered as an indication of greater stiffness. Ignoring damping, eigenfrequency and stiffness are related as follows:

$$f = \omega^2 m, \tag{1}$$

where ω is the first eigenfrequency and m is mass.

Figure 6 shows how stiffness depends on the relative weld length L_w/L and on the number of teeth. Fully welded rib ($L_w = L$) has maximal relative stiffness 1. Increase of the number of teeth mostly affects the rib stiffness more than increase of the weld length. Therefore it is reasonable to use a number of short welds.

The question arises how many welds are reasonable and how long these should be. If modal analysis is used for studying the rib stiffness, it is possible to use modes for determining the optimal number of teeth. Minimizing distance L_s between welds reduces bending length of the rib. If L_s equals to rib height ($L_s = h$), the bendinglength of the rib becomes equal to the rib height. From Fig. 5 the following relationships can be found:

$$L = nL_h + (n-1)L_s,\ \ L_w = nL_h,\ \ C_w = L_w / L,\ \ C_h = h / L. \tag{2}$$

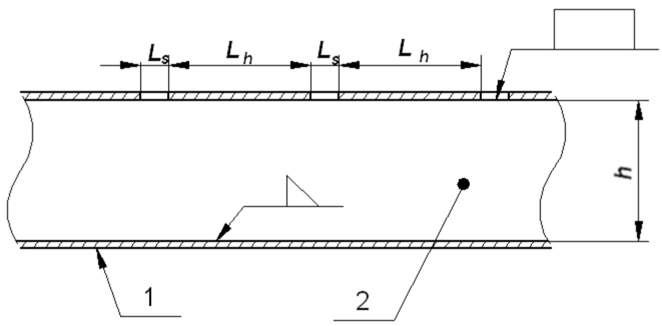

Fig. 4. Design type I; 1 – plate; 2 – rib; L_h – length of the weld; L_s – distance between welds.

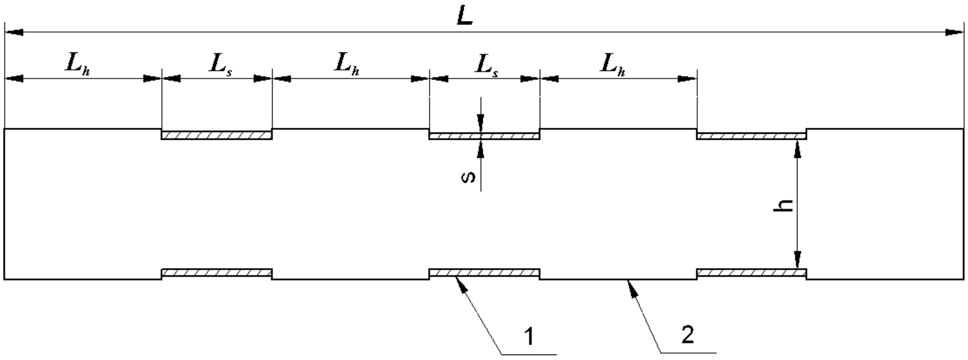

Fig. 5. Toothed rib: 1 – plate; 2 – rib.

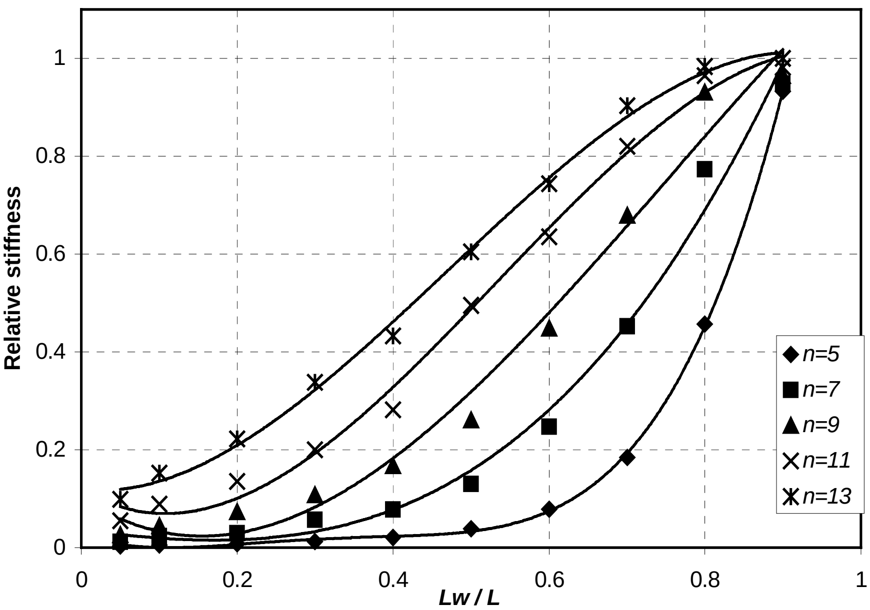

Fig. 6. Stiffness dependence on the relative weld length and on the number of the teeth *n*.

Since C_w and C_h are known constants, from Eqs. (2) follows

$$n = \frac{C_h - C_w + 1}{C_h}, \tag{3}$$

$$L_h = \frac{C_h C_w L}{C_h - C_w + 1}. \tag{4}$$

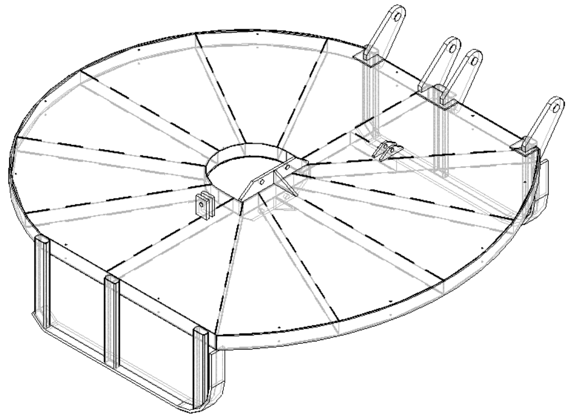

Fig. 7. Body of the brush-cutting machine after optimization.

Table 1. Strength properties of the initial and new design

	Initial design	New design
Max stress, MPa	132	61
Max deformation, mm	0.5	0.8
1^{st} eigenfrequency, Hz	73.6	69.5

Replacing stiffened plate by a sandwich structure the mass of the body of the brush-cutting machine was reduced by 35% (Fig. 7) without essential difference in strength properties (Table 1).

5. CONCLUSIONS

Topological optimization helps to improve product performance and to decrease manufacturing costs. It permits to design sandwich structures with a better stiffness/mass ratio. The design of optimal topology allows design goals to be reached faster, more accurately and cost-effectively.

In ribbed structures, the number of teeth affects the rib stiffness more than increasing the weld length; therefore it is reasonable to make a number of short welds.

ACKNOWLEDGEMENT

The authors would like to thank Estonian Science Foundation for supporting the research (grants Nos. 5600 and 5903).

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Kihiliste tugikonstruktsioonide projekteerimine

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Masinate raamide konstruktsioonide massi vähendamine on oluline ülesanne. Üks võimalus selleks on kihiliste struktuuride kasutamine. Tavapäraselt tugevdatud terasraamidega võrreldes on kihilistel struktuuridel parem tugevuse/massi ja jäikuse/massi suhe. Artiklis on uuritud võimalust asendada traditsiooniline plaadist ja jäikusribidest koosnev keeviskonstruktsioon kihilise konstruktsiooniga, kasutades topoloogia optimeerimist.

On vaadeldud kahest terasplaadist ja nende vahel olevatest terasribidest koosnevat konstruktsiooni. On uuritud sellise konstruktsiooni tugevusomadusi sõltuvalt ribide asukohast ja keevisõmbluse pikkusest ning käsitletud selle konstruktsiooni valmistamise võimalusi. On näidatud, et otstarbekas on teha palju lühikesi keevisõmblusi. Näitena on vaadeldud kettniiduki korpuse projekteerimist ja massi vähendamist.