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MASS REDUCTION OF PLATE FRAMES

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Abstract: *Mass reduction of the frames of machines is quite important. One possibility to reduce frame's mass is to use sandwich structures. Mechanical properties of sandwich structures are characterized by higher strength-to-weight and stiffness-to-weight ratios than those of stiffened steel plate structures. The proposed welded steel structures consist of walls and ribs welded in between these walls. In this paper we have examined strength properties of such structures depending on ribs configuration and the length of welds. Manufacturing of such structures requires new technological approach. Some technological adaptations for construction of sandwich frames are described in this paper. As an example we investigate the design and mass reduction of chain-cutting machine's body.*

Keywords: *FEM, Topological optimization, sandwich structures.*

1. INTRODUCTION

An important problem in industry is how to achieve better design concepts by considering product performance and manufacturing costs in the early design stages of product development. It must be possible to manufacture the final optimal product economically, and the product should consist of standard and simple geometric shapes instead of arbitrary complex shapes.

The topology of a product has a significant effect on product performance and manufacturing costs. The initial design concept may lead to inefficient structural design and manufacturing costs if the topology is not optimal. The design of optimal topology allows design goals to be reached faster, accurately, and cost effectively. It provides an initial design concept for subsequent applications following the design stage, such as shape optimization, machining, etc. Therefore, it is important to choose the optimal structural layout during the early design stages of product development.

The support structures of many machines are designed as frames or plates. Often they are made of steel plates that have been strengthened with various elements (pipes, angles etc.). As an example we studied a chain-cutting machine's body (Fig. 1). The mass of such a structure can be reduced by using a sandwich structure.

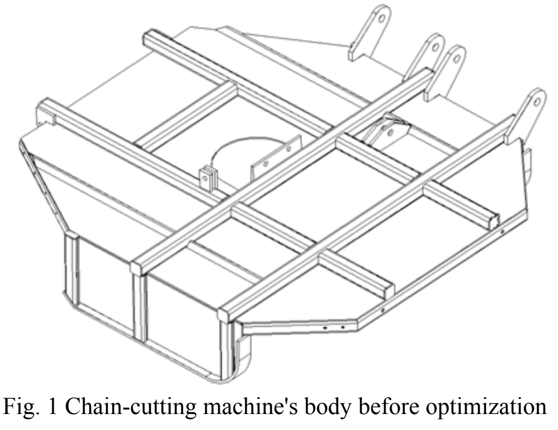

Fig. 1 Chain-cutting machine's body before optimization

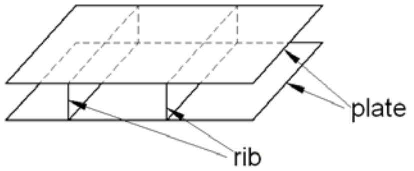

Fig. 2 Sandwich structure

One possibility to build sandwich structures is to place ribs between the two covering layers. Forces influencing the structure in working state differ by direction, character and power. The problem is how to place the ribs so that the usage of material is optimal. A good way to solve this problem is to use topology optimization.

2. TOPOLOGY OPTIMIZATION

Topology optimization, which was introduced by Bendsoe and Kikuchi [Bendsoe & Kikuchi, 1988], is usually used to find the optimal distribution of material in a given design region that meets a predefined criterion [Leiva et al., 1999]. With topology optimization, regions of the structure that have the least contribution to the overall stiffness or natural frequency can be identified. Thus, it enables identification of the regions, which should be taken out from the structure to minimize the mass with the least impact on the performance of a structure. Of the various optimization techniques, topology optimization has proven to be very efficient, especially when used to strengthen existing designs [Chen & Usman, 2001].

Unlike traditional optimization, topological optimization does not require the explicit definition of optimization parameters (i.e., independent variables to be optimized). In topological optimization, the material distribution function over a body serves as optimization parameter. The user needs to define the structural problem (material properties, FE model, loads, etc.) and the objective function (i.e., the function to be minimized or maximized) and the state variables (i.e., constrained dependent variables) must be selected among a set of predefined criteria.

The theory of topological optimization seeks to minimize or maximize the objective function (f) subject to the constraints (g_j) defined. 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; where $\eta_i \cong 0$ represents material to be removed; and $\eta_i \cong 1$ represents material that should be kept [Ansys, 2003].

The steps of optimization approach using topology optimization can then be stated as:

- identify the design space for the analyzed 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.

3. FE MODELLING AND SIMULATION

The selected plate has side measurements 1.4 x 1.4 m. Very typical is the bigger opening in the centre of the plate for fastening an engine or another device/structure. For this purpose an 0.3 x 0.3 m opening has been made in the centre of the plate. Usually bodies are supported from two sides plus one additional constraint, or from four corners. The most usual load cases are:

- a) force is directed to the centre of the plate (e.g. Booms of a lift, Fig. 3 a, b);
- b) force is directed onto one corner (when a tree or a rock is hit, Fig. 3 c);
- c) torsion loading (riding on uneven landscape, Fig. 3 d);
- d) force is directed to the centre of one side (Fig. 3 e);
- e) moment loading on the opening in the centre of the plate (e.g. boom of a lift, Fig. 3 f, g).

A corresponding topology was found for each load case. Also the best topology of the structure was found for the combined loads. Similar task was solved for a round plate with a diameter D=1.4m (Fig. 4).

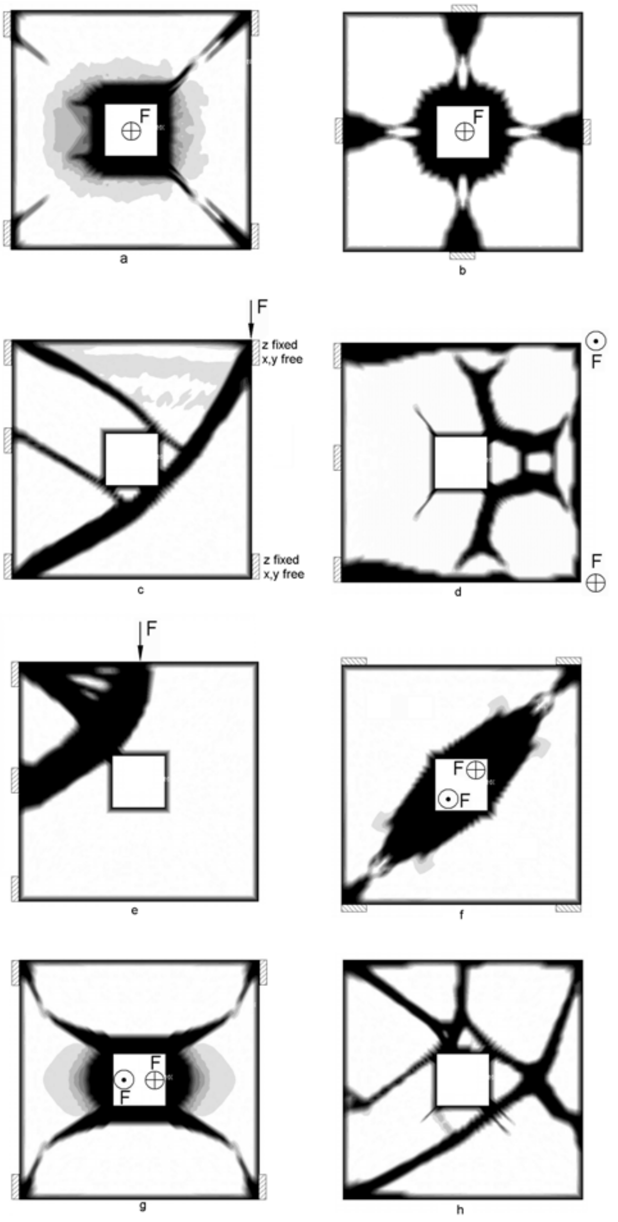

Fig. 3 Square plate topology optimization results of different load cases. Darker area means greater density.

As large models may take long time to solve, it is preferred to use many several simple analyses to study the physical phenomena involved and to find out parameters (for example contact parameters, element parameters etc) in order to avoid unsuccessful simulation with large models. [Adams & Askenazi, 1999]

Topology optimization was performed with the FEA software suite Ansys 7.1. For simplifying the task the structure was modelled as a thin plate with thickness 10 mm. Shell 93 elements were used for modelling. 3D solid elements are planned to be used in future work. During optimization global structural stiffness was maximised 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 following:

1) stress should not cause yield stress (<380MPa);
2) deformations caused by the force should remain small.

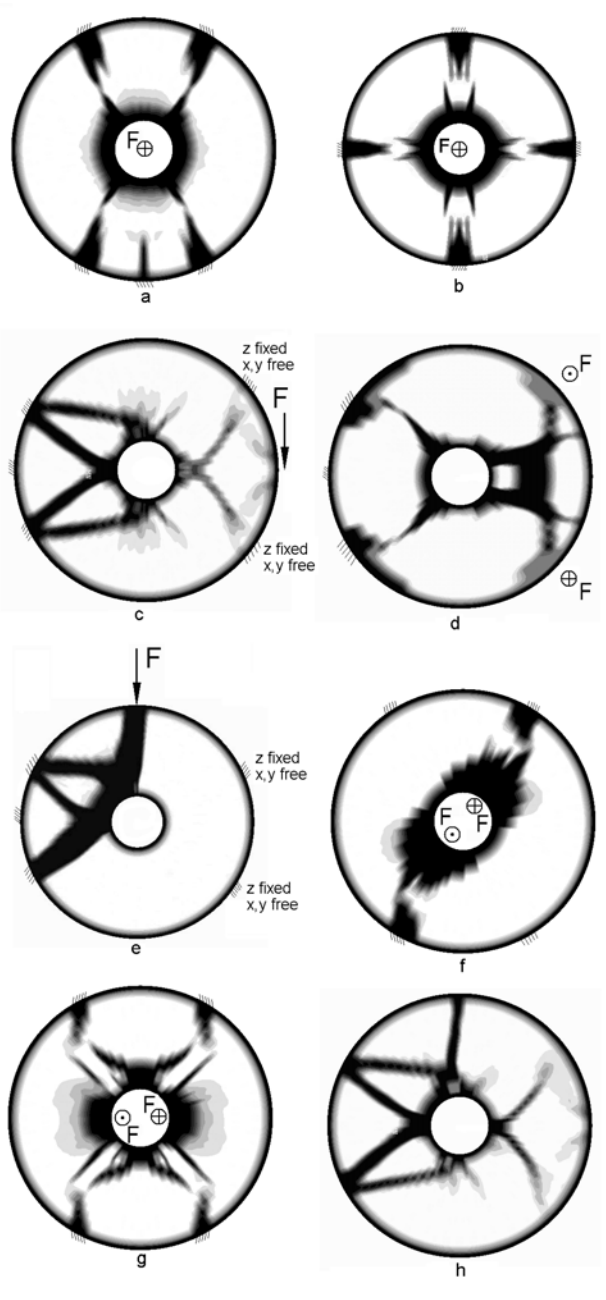

Fig. 4 Round plate topology optimization results of different load cases. Darker area means greater density.

After calculation the results should be critically evaluated and the model should be updated (Friswell & Mottershead, 1996) if necessary. One possibility to verify the model is to set up a test (Computer Aided Testing) and examine how the structure behaves under the real conditions (Montgomery, 1991). Nowadays the experimental modal analysis (Cyril et al. 1986) is widespread, especially in solving problems of structural dynamics.

In the case of only one force influencing the structure Fig.3 a-g and Fig.4 a-g the results correspond with expectations – the force should be directed away by the shortest possible route. In the case of simultaneous influence of different load cases Fig 3h the result is more complicated. The topology depends significantly on the proportion of single force's influence in the whole solution. In the examined case all forces were considered having equal weights. Still it can be seen that load cases Fig.3c and Fig.3e have more significant influence. The proportions of individual loads are better shown on Fig.4 c, e, h.

By comparing the results on Fig. 3 and Fig. 4 it becomes clear that the importance of the plate's shape is minimal for the topology of sandwich structure. The results depend greatly on the application point of the force and the location of support structures. Thus we can design the shape of the covering plate smoothly from round to square. This gives freedom to a designer to design the shape of the structure.

Calculations with exact measurements confirm 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. TECHNIQUES OF MANUFACTURING

In manufacturing process we have to secure the joint between the covering layers and ribs by welding. To achieve this we have to plan for technical openings in the covering layers which can be used for welding. There are two possibilities:

- the first case is to weld the ribs to the lower plate and after that the upper plate is welded to the existing structure. The plate has openings a little bit wider than the ribs and through these openings the upper plate is welded to the ribs. The disadvantage is the complexity of assembly.
- In the second case the plates have slots to the direction of ribs. Slots can be made easily on the sheet metal processing centre. A rib is a plate with teeth that are L_h long and have stepping L_s (Fig. 4). During the assembly ribs are placed into slots using the teeth and point-welded. Then the upper plate is put into place. Ribs' teeth reach higher than the lower surface of the plate or higher than the thickness of plate. Ribs are connected to the upper plate by welding the teeth.

It is possible to optimize the length and stepping of teeth but this remained outside the scope of this work. LE

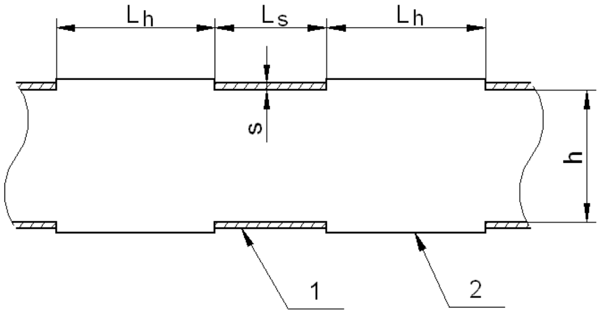

Fig. 5 Toothed rib, the measurements of tooth are L_h and L_s , where 1- plate; 2 – rib;

5. CONCLUSION

This research studies the possibility of replacing welded structures with sandwich structures by using topology optimization. Applying optimization algorithms enables to design structures with the best mass and stiffness.

Manufacturing sandwich structures requires special methods which are described in this article.

Topology optimization is very sensitive to load situation. 3D topology optimization tools should be applied in the future.

In our example we were able to reduce the mass of a chain cutting machine's body by ~35% (Fig. 6).

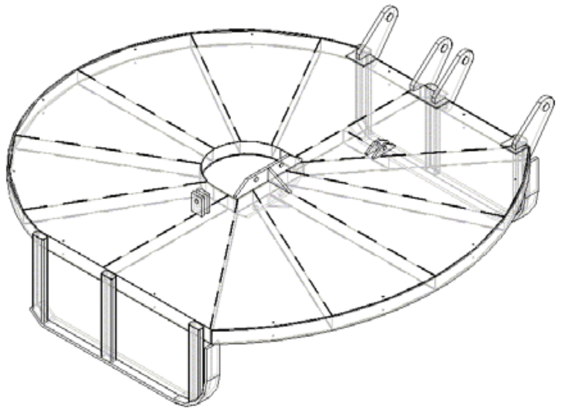

Fig. 6 Chain-cutting machine's body after optimization

6. ACKNOWLEDGEMENTS

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