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INTEGRATION OF TOPOLOGY AND SHAPE OPTIMIZATION INTO THE PROCESS OF THE DESIGN OF MECHANICAL STRUCTURES ELEMENTS

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Abstract: *Rapid development of science and engineering demands of modern mechanical engineers not only the knowledge of classic techniques of mechanical structures design, but also the knowledge of methods and techniques that enable the making of optimal structures or the structures that are close to optimal. This paper presents shape and topology optimization on the example of double-sided hook. Initial shape is a flat plate, having only holes for hanging the hook and the load. At the end of the optimization process, the volume is decreased by 80.92%. The original idea is to perform the whole analysis within one software application - starting from the design of the model, through the preparation of the model for the calculation by finite elements method, calculation and optimization to the analysis of the obtained results. In this case, software CATIA was used. Integrated approach to structural optimization within one CAD software application saves time and money. With this approach, in the early phase of the design, we tend to create mechanical structures elements with optimal characteristics. As the result, we get a real structure, which could be improved further, if necessary.*

Key words: *integrated structural optimization, shape optimization, topology optimization, FEM, CAD*

1. INTRODUCTION

Traditional approach to structural optimization of mechanical structures implies size optimization. Main flaw of this approach to the problem of determination of optimal dimensions is that shape and topology of the structure are predetermined and no changes are made on them. Without a doubt, changes in shape and topology of mechanical element or a structure can lead to significant improvements of mechanical characteristics. For that reason, formulation of the problem, which includes determination of geometry (including dimensions and shape), topology and distribution of material in the process of optimization, will probably give structures with significantly better characteristics. Such general approach requires a model that is simple enough to enable efficient solving of optimization problem, and include details enabling the change of geometric shape at the same time. In structural optimization, model symmetry should be used when possible [1].

Structural optimization is applied in many fields. For example, apart from engineering, it is applied in civil engineering, for the optimization of carrying elements [2, 3, 4]. Paper [5] presents topology optimization of bridges with constraints regarding stress, displacement and frequency. This is especially interesting because all possible flaws are predicted and eliminated in advance.

Apart from mechanical engineering and other related industries, structural optimization is applied in medicine, as well, e.g. optimization of stent built into human bloodstream [6, 7].

It is well known that parts of an airplane must be as light as possible and that optimization of any kind is desirable, to decrease the weight of an aircraft. Paper [8] presents the problem of structural optimization of airplane parts. Structural optimization based on CAD environment for airplane parts is presented in paper [9].

In automobile industry, and in many other industries, engineers meet the challenge regarding carrying components of a structure. They need to design carrying components so they can endure various loads, depending on the structure (static, dynamic, impact, cyclic etc.). Nevertheless, apart from that, those same structure components should not, and sometimes must not, be oversized. In most cases, this problem lies not only in the price of used material, but also in the fact that a structure with larger weight requires more energy-generating products. As the market offers various types of products, nuances decide on their competitiveness. Optimization of any kind, whether it is connected with the saving of material, optimization of time needed for production or optimization of design process, decreases the price, which could lead to the increase of sales [10].

Structural optimization can be divided into size optimization, shape optimization and topology optimization.

This paper presents the integration of topology and shape optimization into the process of design, where the flaws are seen in the early phase of the design process.

Complete preparation of the model, finite elements analysis and optimization are done in software CATIA.

2. FORMULATION OF THE PROBLEM

Optimization is a mathematical technique for minimizing or maximizing an objective function while satisfying the constraints, or:

optimize $f(x)$

subject to $g_i(x) \leq 0, i = 1,...,m$

and $h_j(x) = 0, j = 1,...,l$

Optimization requires definition of design variables (x), objective function $f(x)$, and constraints functions $g_i(x)$ and/or $h_j(x)$. [11]

In engineering practice, it is common to design several versions of the solution. The procedure of solving of optimization tasks consists of the following eight phases [12]: formulation of the problem, gathering of data about the system, definition of criteria for the evaluation of alternative solutions, formulation (and making) of alternative solutions, evaluation of alternatives, optimization – selection of the best alternative, final design and implementation.

3. TOPOLOGY OPTIMIZATION

Before starting size or shape optimization, it is necessary to have an initial shape of the structure. Design process can start with known loads, boundary conditions and maximal space that certain component can occupy. Then, based on known concept of the structure, certain requirements are met, such as necessary stiffness and durability. Unnecessary areas are removed from the given design space.

Topology optimization is usually done according the criterion of maximal stiffness or minimal elastic deformation. The objective here is to distribute the material in certain area to get a structure with maximal stiffness. Paper [13] presents the problem of topology optimization of beam cross section, to spot places where reinforcements must be placed, to increase stiffness. Likewise, topology optimization with constraints regarding the stress is presented in papers [14, 15]. Constraints regarding stress can be local or global. Local constraints can be given in certain points of the structure. The influence of local constraints is examined by defining global function that takes into account all local constraints [16].

To reach the best solution, or the solution close to the best, it is necessary to modify the topology during the optimization procedure. Research related to topology optimization is most commonly connected with finite elements analysis. Final optimized shapes are very much dependable on the density of the mesh used in finite elements analysis. Emphasis is on the removal of parts that are loaded under a certain limit, in order to decrease weight. Nevertheless, it is possible to set allowed displacement as a constraint, as shown in papers [17, 18]. It is also possible to have requirements related to allowed vibrations. Topology optimization is used in the initial phase of design procedure, while shape and size optimization is used for detailed design.

Most commonly used technique in topology optimization is treating of the problem as the set of large number of building blocks that make up a mechanical part. The procedure starts with the definition of the set of possible parts and the definition of maximum size and shape of the structure, known as design space. As the procedure of optimization progresses, the parts are allowed to disappear and reappear, thus updating the structure topology. Each part is represented by one variable. If the value of design variable is 1, it means that the part exists and if the value is 0, the part does not exist. In some optimization methods, design variables can be of value between 0 and 1, which shows that there is lower density material in the relevant part.

As an example of topology optimization, optimization of beam element cross-section can be considered. In this, most general case, it is possible to have more different solutions than it is the case with other methods. Basic flaw of this method is that it is rather complicated analytically. In some cases of optimization, the design space can be much larger than in other two types of structural optimization. If the design space is divided into more parts, the search space is increased.

Fig. 1 shows the design area discretized to a large number of parts and one of possible results of optimization procedure.

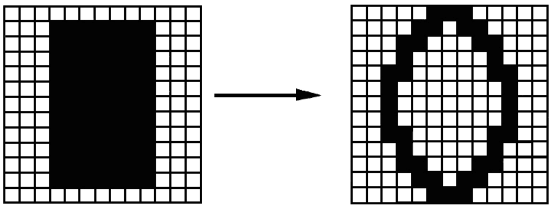


Fig. 1: Example of topology optimization

4. SHAPE OPTIMIZATION

Optimization variables that can be modified are usually surface coordinates. One of shape optimization tasks can be the modification of surfaces, to remove stress concentration. Therefore, reliability and service-life of a structure can be increased thanks to finding optimal shape or the shape that is close to the optimal.

Shape optimization has become an important tool for the minimization of weight in the design of new structures. There is a growing tendency to perform optimization in CAD environment [19, 20].

Parametric shape optimization requires integration and full association between CAD model and FEM model. Any change of solid, e.g. change of dimensions, must reflect on FEM model. Such association enables the use of any parameter of the solid as possible variable in shape optimization. Greatest advantage of such approach is that, at the end of the process, the design engineer gets final dimensions of the solid and this model can be directly used in applications for the analysis of machining, planning process and so on. Besides, this kind of approach enables geometry to stay consistent, i.e. a straight line remains a straight line, inclined surfaces are kept etc., while structure shape is changed. Nevertheless, such approach requires careful building of the model. Boundary conditions and loads must be defined on geometry and not directly on FEM model. Geometry of the solid must be carefully parametrized to ensure that the change of the shape of the model is in accordance with the designer's ideas. Finally, parametric optimization, changes of variables that cause changes and regeneration of finite elements mesh, significantly increase the complexity of the problem. This increases calculation time needed to form the mesh with a large number of finite elements and many variables.

On the other hand, non-parametric shape optimization is directly done on FEM model. Variable quantities are defined by selecting nodes on finite elements mesh. In addition to that, the positions that nodes can take after the coordinates are changed are also defined. That is the advantage of this kind of approach. First, the mesh stays the same (number of nodes and elements is not changed). Second, no special actions are required for the taking of positions where loads and boundary conditions are defined. Third, the geometric or solid modeler and the mesh generator are not invoked during the shape changes. The greatest challenge is to guarantee that the mesh distortion is neutralized as much as possible, because the update of the model (after the mesh distortion) requires the interaction with the user.

Design variables used to vary boundary lines and are known as "Shape Design Variables". In comparison with size optimization, the calculation is more complex due to larger number of variables.

Shape optimization can be done in two ways:

- By varying parametric variables and
- By varying boundaries.

In variation of parametric variables, design variables define the shape and/or important dimensions by parameters. In variation of boundaries, parts of the solid boundary are treated as design variables. For example, nodal coordinates that are located on boundary surface can be used as design variables (*Fig. 2*) [21].

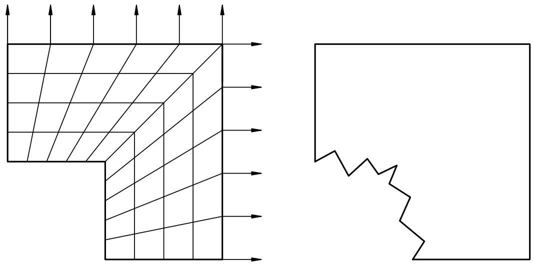


Fig. 2: Shape optimization using nodal coordinates [15]

During the optimization procedure, a shape that is included in previously defined topology is created. Therefore, shape optimization converges towards different optimal shapes for different initial topologies. Finite elements model must be constantly updated, to keep the mesh undistorted. The task is difficult, because the mesh must be automatically redefined in each step during the optimization procedure.

Other example of shape optimization would be the optimization of cross-section of a structure element by using B-spline or Bezier curves to define the cross section shape (*Fig. 3*). In given case, the section may vary, but it can never include holes afterwards.

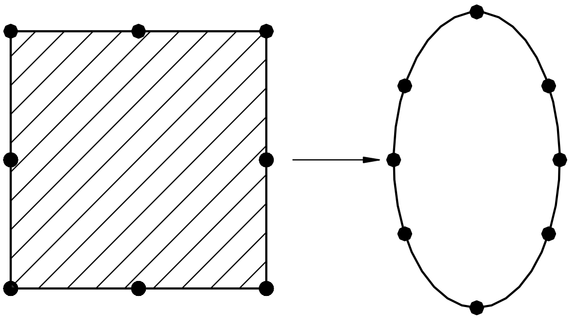


Fig. 3: Shape optimization of cross section of a truss structure element

5. SIMULATED ANNEALING ALGORITHM

Common flaw of majority of algorithms is their incapability to differentiate local and global minimum (or maximum). Many problems of structural optimization have more than one local extremum and, depending on the starting point, the algorithms converge towards one of them. The simplest way to check whether a certain extremum is local or global, in algorithms that are based on random search, is to begin the search from another starting point. In this way, it is checked whether other solutions, except the one initially obtained, are possible. Problems that contain a large number of variables carry a risk that global extremum is not found. The efficiency of the solving of the process is significantly deteriorated as the number of variables increases. Besides, these problems require more iteration during optimization process. Simulated annealing algorithm was suggested by Nicholas Metropolis. The algorithm consists of the following phases:

1. Define initial structure.
2. Examine whether it is necessary to improve the initial structure,
    - if yes, start the algorithm from a new starting point,
    - if not, define objective function and give initial values of the parameters.
3. Select each design variable only once in random order and create a new structure.
4. Check whether the solution obtained in this way is better than the previous one
    - if not, apply Metropolis test and, if the new structure is better than the previous one, accept it.
    - if yes, accept the new structure and automatically replace the old one.
5. Examine whether the design variables for the creation of a new structure are selected
    - if not, repeat the loop.
    - if yes, examine whether all interior loops are finished.
6. Go to the next search level.
7. Check whether all the cycles are finished
    - if yes, finish the algorithm.
    - if not, repeat the cycle.

6. INTEGRATION OF OPTIMIZATION INTO DESIGN PROCESS

By applying the integrated approach in the early phase of the development of a structure or an element of a structure, some possible flaws are identified. According to that, a correction of the structure is made until optimal characteristics are achieved. It is possible to develop several design versions simultaneously, with sufficient speeds of performing structural analyses and, depending on objectives, select the most favorable solution.

By applying integrated approach during the development process of a product, the following phases can be seen: building of a model for structural analysis, development of the model for structural analysis, discretization of the model to finite elements, structural analysis, the analysis of the results, and optimization of the structure. [22]

A problem of double-sided hook was reviewed as an example in this paper. Initial shape was a flat plate that contained only a hole for the suspension of the hook and a place for the suspension of load. The problem of optimization is divided into four phases:

- topology optimization of the upper half of the model,
- topology optimization of the lower half of the model,
- shape optimization of the upper half of the model and
- shape optimization of the lower half of the model.

In all four cases, volume was the objective function. Initial value of the objective function – volume was $V = 276292.037 mm^3$. Constraint was in relation to maximal Von Mises stress $\sigma_{VM} \leq 250 MPa$. Likewise, the parameters had upper and lower constraints. In defining upper and lower limits of the parameters, care should be taken about that the search area is not to narrow, because absolute optimum will not be obtained in that case. Likewise, the limits should not be too wide, because in that case, search area is broadened and the convergence to the optimal solution is slowed down. To solve the problem, simulated annealing algorithm was used. The elements used in structural analysis were parabolic tetrahedrons. Global sensor that measures maximal Von Mises stress was used as the sensor in this analysis. For each of the four mentioned phases, there were 5 optimizations with 500 iterations each. Likewise, optimization was done in two parallel procedures, to check the obtained results. Material used for the model was steel.

The procedure of integrated shape and topology optimization consisted of several phases. First, a model was created within the module *Part Design* and then the model was discretized to a certain number of finite elements within module *Generative Structural Analysis*. After that, optimization was done in module *Product Engineering Optimizer.* During the analysis, module *Knowledge Advisor* was used too, to define certain constraints and rules.

The model is axisymmetric and the change of parameters on one side reflects to the change of the parameters on the other side of the model. In defining the number of parameters, it should be noted that with the increase of the number of parameters, the search area increases as well, and with that, the convergence speed to the wanted solution decreases. It is not recommended to use more than a dozen parameters. *Fig. 4* shows the change of volume during the topology optimization of the upper half of the model.

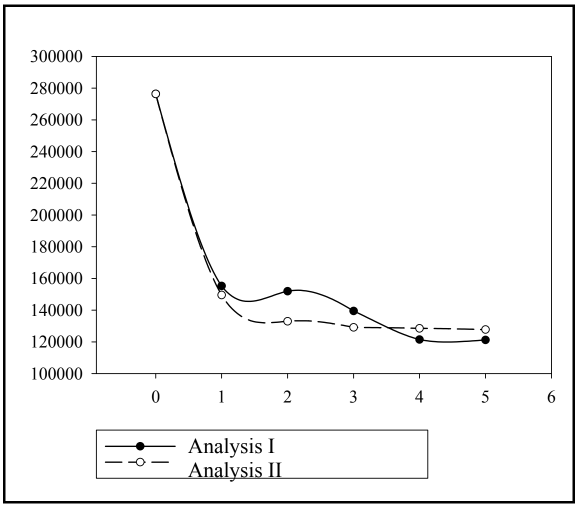


Fig. 4: Change of volume – topology optimization of the upper half of the model

For each optimization phase, two parallel analyses were done, to confirm obtained results. The volume during Analyses I and II was changed in approximately the same manner. During the topology optimization of the lower half of the model, there were 11 parameters, while the volume decreased from initial value of $V_0 = 276292.037 mm^3$ to $V_1 = 121150.127\ mm^3$, i.e. it decreased by 56.15%.

Fig. 5 shows the change of Von Mises stress during the optimization of the upper half of the model. Given constraint $\sigma_{VM} \leq 250 MPa$ was satisfied during all five procedures of optimization. There is a deviation during optimization 3, which means that the algorithm found a local optimum and dwelled there.

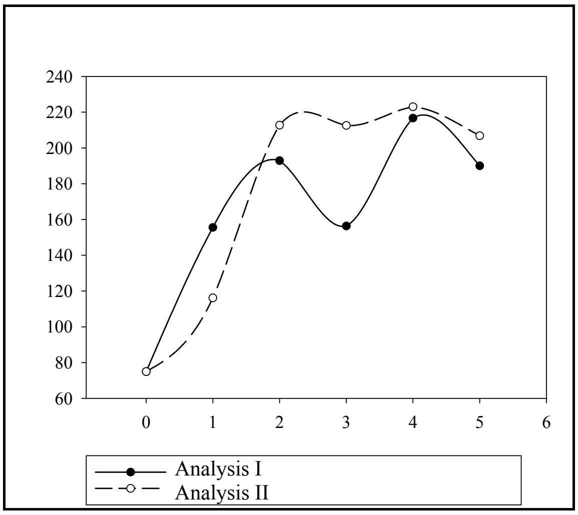


Fig. 5: Change of Von Mises stress – topology optimization of the upper half of the model

The reason for five optimization procedures in two parallel analyses was to overcome the problem of local optimum.

Fig. 6 shows the change of volume during topology optimization of the lower half of the model.

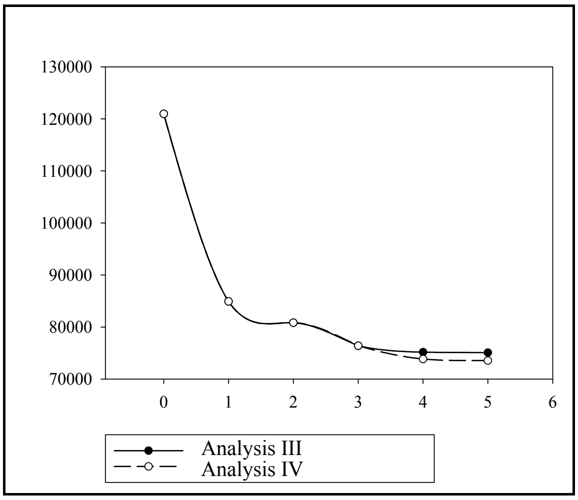


Fig. 6: Change of volume – topology optimization of the lower half of the model

The value of volume at the end of the previous optimization procedure was taken as the initial value.

6 parameters were used and the volume decreased from $V_0 = 276292.037mm^3$ to $V_2 = 73540.600\,mm^3$, i.e. it decreased by 73.38% in comparison to the initial value of the objective function. *Fig. 7* shows the change of Von Mises stress during the procedure of topology optimization of the lower half of the model. It can be seen that the constraint regarding Von Mises stress was violated during optimization 4 – Analysis IV, but during the following optimization, this constraint was satisfied.

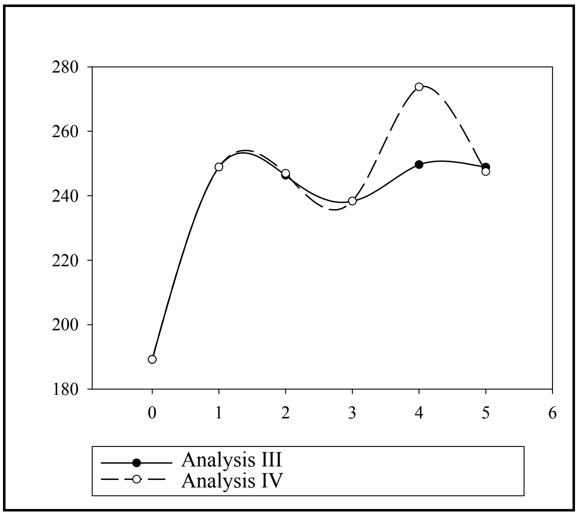
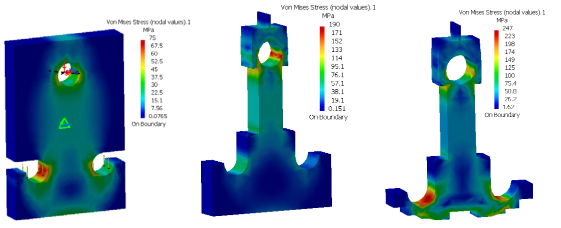


Fig. 7: Change of Von Mises stress – topology optimization of the lower half of the model

Fig. 8 shows the initial shape of a two-sided hook. Likewise, the figure shows that there is a large area where the stresses are minimal and which should be removed. Figure b shows the model after topology optimization of the upper half, while figure c shows the model after optimization of the lower half.

After topology optimization, there were sharp edges left, which is not good, because they represent a stress concentration source. Nevertheless, topology optimization procedure ends here.



a. b. c.

Fig. 8: Topology optimization

Models obtained in this way can be optimized further, but not according to this criterion. After this, shape optimization of upper and lower halves of the model is done.

Initial shape for shape optimization is defined based on the model obtained during the topology optimization procedure.

Shape optimization was also done in two phases. Shape optimization of the upper half of the hook was done in the first phase and the shape optimization of the lower half of the hook was done in the second phase. Initial values of the parameters represent the values of the parameters that were obtained at the end of topology optimization of the upper and lower halves of the model.

During the shape optimization procedure of the upper half of the model, 11 parameters were used and the volume decreased from initial value of $V_0 = 276292.037mm^3$ to $V_3 = 61501.254mm^3$, i.e. it decreased by 77.74%. As the optimization progresses, the objective function is decreased less and less, which is a logical thing, because we move from rough optimization to a finer optimization of the model.

Fig. 9 shows the change of volume during the procedure of shape optimization of the upper half of the model.

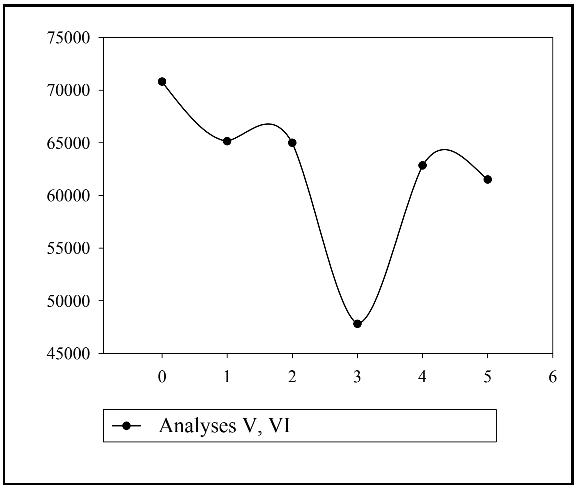


Fig. 9: Change of volume – shape optimization of the upper half of the model

Fig. 10 shows the change of Von Mises stress during the shape optimization of upper half of the model.

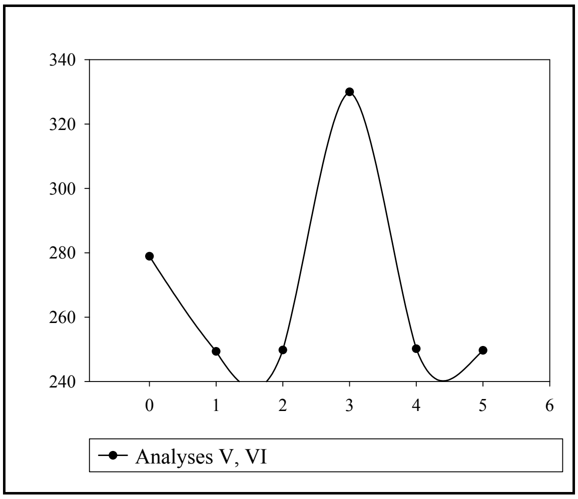


Fig. 10: Change of Von Mises stress – shape optimization of the upper half of the model

Two parallel analyses were done for this phase of optimization too, but the same results were obtained. *Fig. 9* shows that during optimization 3 the volume largely decreased, but this is not realistic because the constraint regarding Von Mises stress was violated (*Fig. 10*).

During the shape optimization of the lower half of the model, 7 optimization parameters were used. Objective function at the end of optimization was $V_4 = 52726.769 mm^3$, which means that it decreased by 80.92% when compared to the initial value.

Fig. 11 shows the change of volume during the shape optimization of the lower half of the model.

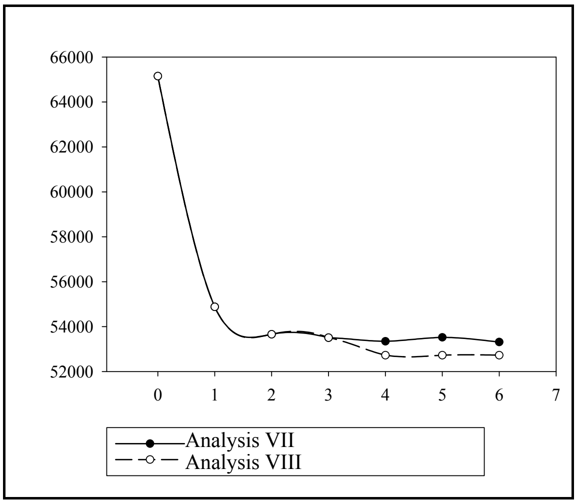


Fig. 11: Change of volume – shape optimization of the lower half of the model

Fig. 12 shows the change of Von Mises stress during the procedure of shape optimization of the lower half of the model.

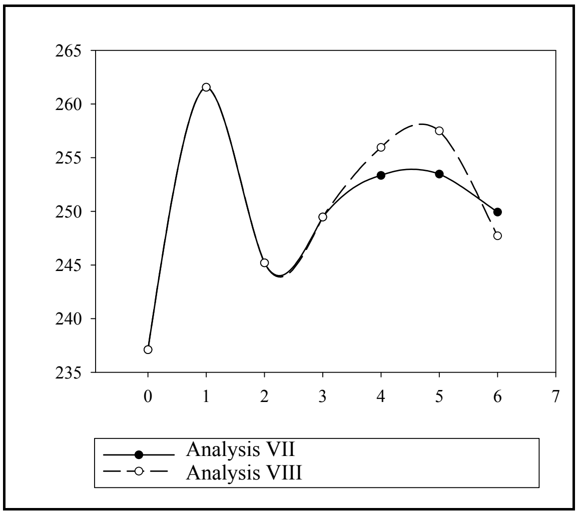
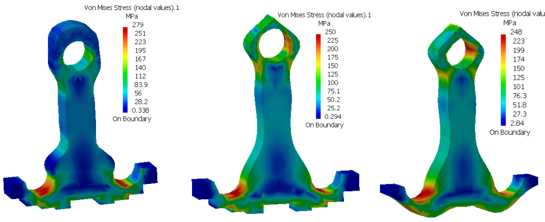


Fig. 12: Change of Von Mises stress – shape optimization of the lower half of the model

Fig. 13a shows the initial shape for shape optimization. *Fig. 13b* shows the model after shape optimization of upper half of the model and *Fig. 13c* shows the model after shape optimization of the lower half of the model.

At the end of all four procedures of optimization, the constraint regarding Von Mises stress was not violated.



a. b. c.

Fig. 13: Shape optimization

Initial value of objective function – volume of the model was $V_0 = 276292.037 mm^3$, while after four phases of optimization, the volume was decreased by 80.92% when compared to initial value, i.e. to $V_4 = 52726.769 mm^3$. *Fig. 14* shows the diagram of the change of the volume during individual phases of optimization.

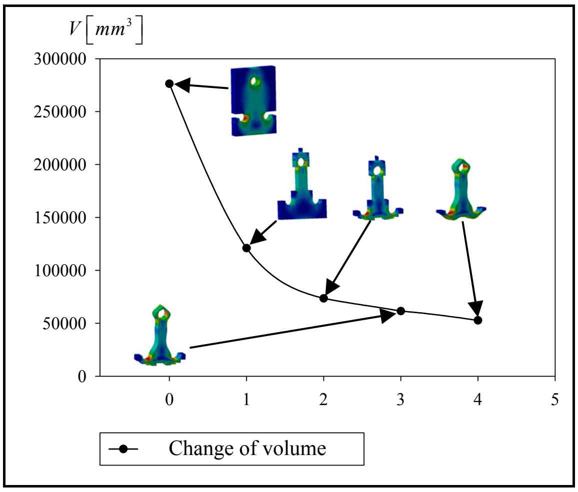


Fig. 14: Topology and shape optimization

It should be noted that the complete procedure of modeling, preparation of the model for structural analysis, the analysis itself and optimization were done in software CATIA.

7. CONCLUSION

This paper presents one of possible ways of integration of shape and topology optimization into the design process in software CATIA. Complete design procedure, starting from the creation of the model, through the generation of finite elements mesh, structural analysis to optimization itself was done in one software. By optimization, within CATIA software, the design engineer determines minimal values of certain parameters using optimization methods and techniques, so that the stresses are within allowed limits.

By applying this kind of approach in the early phase of the development of a structure, design flaws are identified. According to this, a correction of the structure is made until the optimal characteristics are achieved. It is possible to develop several design versions simultaneously, with structural analyses done fast enough, and depending on the objectives, it is possible to select the most favorable solution. As the result of such an approach, a realistic structure that can be developed further if necessary is obtained.

As an example, shape and topology optimization of double-sides hook was presented. Optimization procedure was divided into four phases, to sufficiently narrow the search area in each phase and enable finding of absolute optimum. During the optimization procedure, the shape and topology of the part suffered great changes, while the volume was decreased by 80.92% when compared to the initial value.

REFERENCES

[1] Kosaka I., Swan C.C., A symmetry reduction method for continuum structural topology optimization, Computers and Structures 70, 1999., pp. 47-61.

[2] Balling R., Rawlings M.R., Collaborative optimization with disciplinary conceptual design, Structural and Multidisciplinary Optimization 20, 2000, pp. 232-241.

[3] Nadir W.D., Kim I.-Y., Hauser D., de Weck O.L., Multidisciplinary Structural Truss Topology Optimization for Reconfigurability, *10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, Albany, New York, 2004.

[4] Kaveh A., Hassani B., Shojaee S., Tavakkoli S.M., Structural topology optimization using ant colony methodology, *Engineering Structures 30*, 2008., pp. 2559-2565.

[5] Guan H., Chen Y.J., Loo Y.C., Xie Y.M., Steven G.P., Bridge topology optimization with stress, displacement and frequency constraints, Computers and Structures 81, 2003., pp. 131-145.

[6] Wu W., Yang D.Z., Huang Y.Y., Qi M., Wang W.Q., Topology optimization of a novel stent platform with drug reservoirs, Medical Engineering & Physics 30, 2008., pp. 1177–1185.

[7] Guimaraes T.A., Oliveira S.G.A., Duate M.A., Application of the Topological Optimization Technique to the Stents Cells Design for Angioplasty, Journal of the Brazilian Society of Mechanical Sciences and Engineering Vol. 30, No. 3, 2008., pp. 261-268.

[8] Good M.G. Development of a Variable Camber Compliant Aircraft Tail using Structural Optimization, Master Thesis, Blacksburg, Virginia, 2003.

[9] Ledermann C., Ermanni P., Kelm R., Dynamic CAD object for structural optimization in preliminary aircraft design, Aerospace Science and Technology 10, 2006, pp. 601-610.

[10] Wang L., Basu P.K., Leiva J.P., Automobile body reinforcement by Finite element optimization, Finite Elements in Analysis and Design 40, 2004, pp. 879–893.

[11] Marjanovic N., Isailovic B., Blagojevic M., Structural optimization in CAD software, Machine Design, 2009., pp. 27-32.

[12] N. Marjanovic, *Gear Train Optimization*, Monography, University of Kragujevac, Faculty of Mechanical Engineering, CADLab, Kragujevac, 2007.

[13] Kim Y.Y., Kim T.S., Topology optimization of beam cross sections, International Journal of Solids and Structures 37, 2000, pp. 477-493.

[14] Amstutz S., Novotny A.A., Topological optimization of structures subject to Von Mises stress constraints, Structural and Multidisciplinary Optimization, 2009.

[15] Victoria M., Marti P., Querin O.M., Topology design of two-dimensional continuum structures using isolines, *Computers and Structures 87*, 2009, pp. 101-109.

[16] Paris J., Casteleiro M., Navarrina F., Colominas I., Topology optimization of structures with local and global stress constraints, ICCEES – International Conference on Computational & Experimental Engineering and Sciences, vol. 2., no. 1, 2007, pp. 13-19.

[17] Lin C.–Y., Hsu F.–M., An adaptive volume constraint algorithm for topology optimization with a displacement – limit, Advances in Engineering Software 39, 2008, pp. 973-994.

[18] Liang Q.Q., Xie Y.M., Steven G.P., Optimal topology selection of continuum structures with displacement constraints, Computers and Structures 77, 2000, pp. 635-644.

[19] Blattman W.R., Generating CAD Parametric Features Based on Topology Optimization Results, Master Thesis, Brigham Young University, 2008.

[20] Lazzara D.S., CAD-Based Multifidelity Analysis and Multidisciplinary Optimization in Aircraft

Conceptual Design, Thesis Proposal, Massachusetts Institute of Technology, 2008.

[21] Kang K.T., Kwak B.M., Optimization of finite element grids using shape sensitivity analysis in terms of nodal positions, *Finite Elements in Analysis and Design 26*, 1997., pp. 1-19.

[22] Isailovic B., *Structural Optimization of Mechanical Design Elements in CAD Environment*, Master thesis, Faculty of Mechanical Engineering, Kragujevac, 2010.

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