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Strategy for Optimal Configuration Design of Existing Structures by Topology and Shape Optimization Tools

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***Abstract*—**A strategy is implemented to find the improved configuration design of an existing aircraft structure by executing topology and shape optimizations. Structural analysis of the Initial Design Space is performed in ANSYS under the loads pertinent to operating and ground conditions. By using the FEA results and data, an initial optimized layout configuration is attained by exploiting nonparametric topology optimization in TOSCA software. Topological optimized surfaces are then smoothened and imported in ANSYS to develop the geometrical features. Nodes at the critical locations of resulting voids are selected for sketching rough profiles. Rough profiles are further refined and CAD feasible geometric features are generated. The modified model is then analyzed under the same loadings and constraints as defined for topology optimization. Shape at the peak stress concentration areas are further optimized by exploiting the shape optimization in TOSCA.shape module. The harmonized stressed model with the modified surfaces is then imported in CATIA to develop the final design.

***Keywords*—**Structural optimization, Topology optimization, Shape optimization, Tail fin

I. Introduction

A. Topology Optimization

TOPOLOGY or layout optimization is an important gradient of structural optimization. Its application at the early design phase has gained the paramount importance for the successful development of a novel product [1]. For topology optimization only know loads and constraints on FE model are requisite for generating the initial configuration design. Explicit objectives like maximizing the stiffness or minimizing the compliance can be attained under a single or multiple load cases.

Mainly there are two types of topology optimization, discrete and continuous [2]. Topology optimization for discrete type of structures is concerned with determining the optimum number, positions, and inter-connectivity of the structural parts. For continuum structures topology optimization deals with the shape of the external as well internal boundaries of a structure.

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The continuum approach to topology optimization has now matured enough. This was first developed by Bendose and Kikuchi [3]. Presently, the problems related to topology optimization like checker board, mesh dependency, porosity etc have also been resolved to a great extent [4]. The main research contributions for developing the topology optimization as a successful tool are by the Bendsoe, Kikuchi's, Rozvany and Sigmund [5], [6], [7], [8]. The important manufacturing constraints like casting and extrusion [9, 10], minimal hole size, symmetry constraints [11] and minimum member size control [12] constraints have also been incorporated into topology optimization codes. Through these constraints topology optimization generates more reliable and pragmatic design proposals. Altair and FE design companies have incorporated these capabilities in Optistruct [13] and TOSCA [14] structural optimization softwares respectively.

At present, applications of topology optimization have become quite diverse. It is being used in biomedical, automotive, aerospace engineering, nano technologies, machine design, electronics etc [15]. Commercial aircraft industries have also exploited the benefits of topology optimization in their component design process. Particularly, Airbus employed this tool in the design of A380 aircraft leading edge and inboard inner leading edge ribs [16], [17] and attained a substantial weight saving up to 1000 Kg per aircraft. It was employed to design the fuselage tail sections of A330, A350 and rear fuselage of A400M military transport planes [18], compact fittings and flat metallic web panels of F-35 strike fighter [19] etc. Similarly, design of rear fuselage of A400M aircraft by EADS Military Aircraft was accomplished with the aid of topology optimization.

B. Shape Optimization

In shape parameterization, boundaries of the component geometry are modified while the topological connectivity among geometric sub domains remains constant [3]. Compared with the sizing optimization the shape optimization is more complex. It is used at the late stage of the product development process. The basic concept of shape optimization is to homogenize the stresses in component by placing the material in boundary areas that truly need it and thin out the unnecessary material from boundary areas that are least important for correct function. Its main perspective is to achieve the minimum shape that satisfies all the necessary functional requirements, such as strength, stiffness and rigidity. Usually the surface modifications through optimization are small and these do not effect the already fixed manufacturing processes. The neighboring components are also not affected by this. Although the modifications in shape optimization are very small but they have significant effects concerning the strength, stiffness, lifetime etc.

Shape optimization methods can broadly be divided into parametric and nonparametric optimization. The coordinates of the surface nodes are regarded as design variables that are modified during the optimization process [20]. Based on the specified stress objective function, specified design nodes locations are modified and a homogenized stress distribution is achieved [19]. This usually leads to large number of design variables that cause considerable mathematical difficulties. Because the component geometry changes significantly in the specified design domain, it requires an automatic remeshing of finite element model during the optimization processing.

The present progress of shape optimization is attributable to the cumulative spurs research efforts by mathematicians, software developers and researchers since many decades. Baud in 1934 [22] first investigated the connection between outer surface geometry and stress concentrations of notches. He proposed a hypothesis that if the surface contour of the outer surface is changed in such a way that the tangential stress are constant, then the minimization of the maximum tangential stress at the outer surface can be achieved. Neuber [23] extended the research work of Baud and enhanced his hypothesis. He proposed a fade-away law and explained that stresses in a notch are mainly influenced by the configuration of geometry nearby the stress peaks. He also described the relation and dependence of the magnitude of stress concentrations on local curvature.

Polynomials have been used to describe the surface boundaries. Fox example, describing the thickness distributions by polynomial coefficients as design variables was undertaken by Stroud et al. (1971) [35]. Dems (1980) [36] also described the piecewise linear boundaries by using a set of prescribed shape functions. With the passage of time it was comprehended that use of higher order polynomials to describe the boundaries may result in oscillatory boundary shapes. After this, inclination was drifted to use the splines because these diminish the probability of creation of oscillatory boundary shapes. Splines are composed of low order polynomial pieces that result in more smoothed boundaries. Yang and Choi [37] also worked out that use of splines to represent the boundaries have better sensitivity accuracy than a piecewise linear representation of the boundary. Braibant, et al. (1923) [38] used Bezier and B-spline blending functions to describe the boundaries. For geometrical description blending functions provide great flexibility.

The emerging finite element method was first applied to the shape optimization problems by Zienkiewicz and Campbell [24]. By using a mathematical programming approach they varied the coordinates of nodes on the design boundary.

The term, gradient-less refers to zero order optimization methods. This means there is no need to calculate the sensitivities like the gradients of objective function and constraints with respect to the design variables. A gradient-less shape optimization method for stress concentration problems was proposed by Schnack [25]. He proposed several theorems by using the Neuber's fade-away law and applied the FE method to calculate displacements and stress distributions. He also implemented an iterative optimization scheme that gives the displacement quantities with sufficient accuracy in a single step. In his research, shape optimization was accomplished by moving the maximum stressed nodes outwards and minimum stressed nodes inwards. The other nodes in the design area were changed by using the linear dependency of the arc distance on the boundary with respect to the minimum and maximum stress nodes. The node displacement was found from the mean element edge length.

The reviews of Ding [26], Haftka and Grandhi [27] summarize the progress of shape optimization up to 1986. Kikuchi et al. (1986) [28] proposed the optimality criteria method for stress-minimization problems that was based on the Kuhn Tucker conditions. For a geometrically unrestricted problem, they worked out that optimality condition is satisfied if the strain energy along the design boundary remains constant.

By extending the work of Schnack [25], Sauter (1991) [29] proposed a nonparametric gradient-less method for shape optimization. The method was called CAOS and later CAOSS. As compared to the work of Schnack, he calculated the node displacements on optimization boundary by local stresses rather than calculating with maximum and minimum stresses. Recently, the method was extended and used in the commercial finite element software's. For example, this method is used in the optimization code of TOSCA.

In 2000, Pedersen [30] formulated an expression in the energy formulation form. It proves that stiffest design exhibits the uniform energy density along the design boundary. The expression also establishes that minimization of the compliance leads to a homogeneous energy density as far as geometrical constraints allow for this. If the highest energy density of the boundary of the optimization domain is found then the stiffest design will be the strongest design.

The deterministic gradient-based methods for shape optimization are also used [31], [32] extensively. In some papers genetic algorithms (GA) and simulated annealing methods have also been investigated to deal with the shape optimization problems [33], [34].

II. METHODLOGY

A. Topology Optimization

An existing aircraft vertical tail fin rib (adaptive design) is selected for finding its optimal configuration design by topology and shape optimization tools. This is shown in Fig. 1. TOSCA topology optimization module is used in a batch-

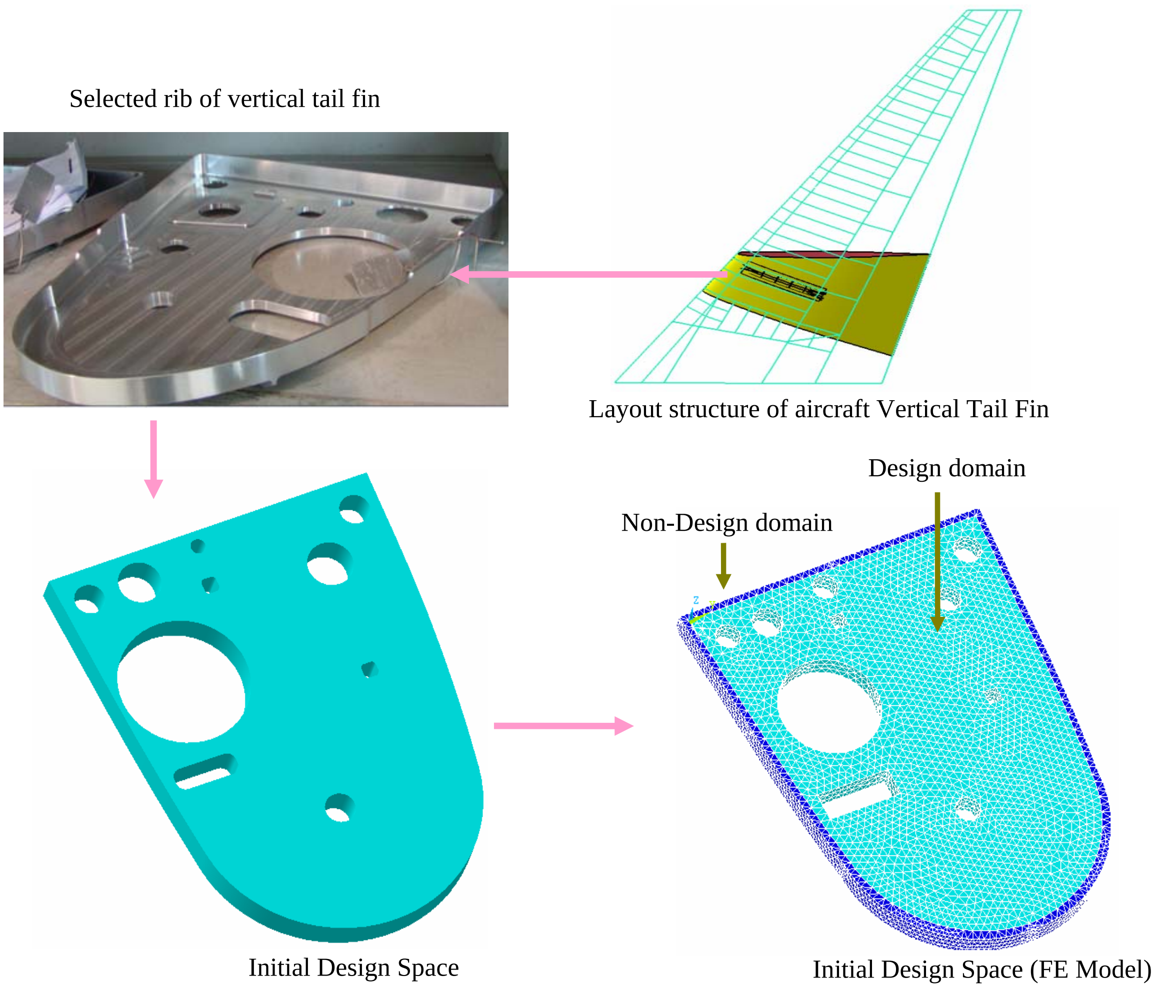

Fig. 1 Development of Initial Design Space from existing used structure

process mode with ANSYS solver. Based on the existing used structure, Initial Design Space is calculated and developed in CATIA software. FE Model of Initial Design Space is developed in ANSYS software. This is shown in Fig.1. The main steps performed for topology optimization are:

- Design loads and constraints specified for the existing used structure are applied on the FE model of Initial Design Space. Then the model is solved and analyzed for structural analysis.
- FE data is imported into TOSCA.pre module via .cdb file. This data is used as FE input deck for the definitions of elements, nodes and material properties.
- Attributes of the element groups in non-design domains are defined as frozen elements that have no contribution in the optimization process.
- Objective function is selected as to maximize the stiffness and reduce volume up to 50 percent maximum.
- A controller based algorithm is used for topology optimization. TOSCA.post is used for post processing of optimization results. Results were analyzed through TOSCA.view module in GL view express.

First, the topology optimization is executed without any manufacturing constraints into the optimization preprocessor. The optimized layout design proposal attained after 16 iterations is shown in Fig 2(a).

The smoothened surfaces are generated in TOSCA.smooth module with an ISO value 0.3. This is shown in Fig. 2(b). Analysis of the optimized configuration demonstrates that it is not feasible with reference to manufacturing perspectives. This is because of the ambivalent features like non-smooth thin supports, undercuts and non symmetrical features. Results of this optimized configuration are difficult to extract in form of CAD parametric features.

Considering the previous optimization results, topology optimization is executed again by incorporating minimum member size control constraint in the optimization preprocessor. The minimum thickness is selected as 10 mm that is 3 times more than the element size. Optimization solution converged after 16 iterations. The new optimized configuration with minimum member size control constraint is shown in Fig. 3.

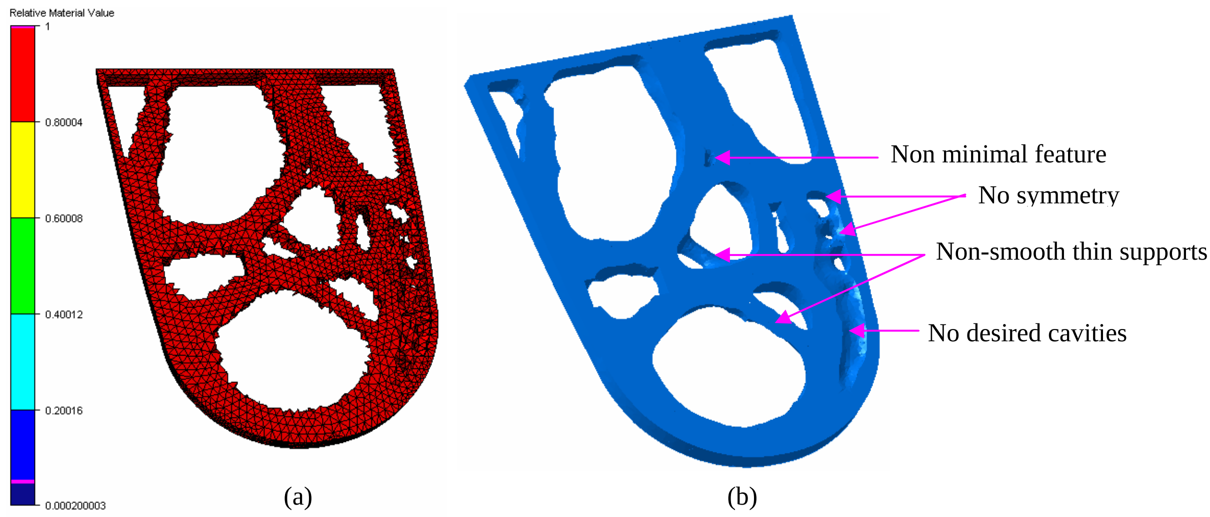

Fig. 2 (a) Topological optimized configuration without manufacturing constraints (b) Smoothened surfaces with TOSCA.smooth

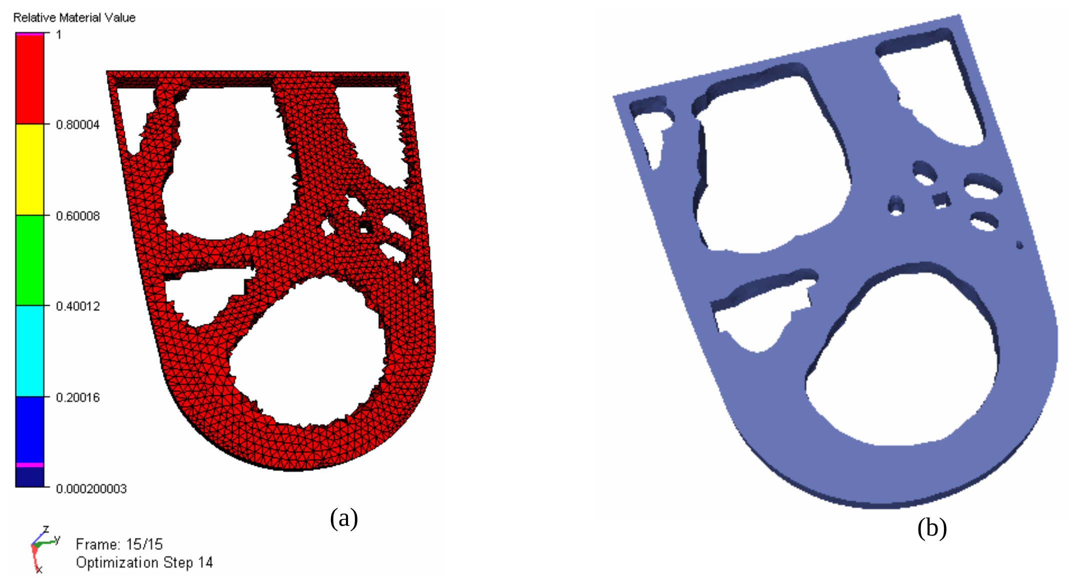

Fig. 3 (a) Topological optimized configuration with minimum member size constraint (b) Smoothened surfaces with TOSCA.smooth

Optimization results reveal that the novel design configuration attained with the minimum member size control constraint is feasible from manufacturing perspectives. Inside ribbing and voids are well-defined with no undercuts or intricate cavities. All the features thickness is more than the defined minimal feature size. Being a feasible design proposal, this optimized configuration was selected to transform into CAD model. Evolution of the objective function and volume (weight) reduction is shown in Fig. 4.

The smoothened ISO surfaces are then imported in ANSYS software to develop the geometrical feasible model. For this purpose, nodes at the top surface are selected. Then the nodes making the boundaries of voids are filtered and rough profiles are sketched with the aid of line, arc and splines. The model is further refined to develop the CAD feasible geometric features. This process is shown in fig 5. The FE model is developed with 10 node SOLID 92 element type. The material properties of the model are Al7075-T6. The model is discretized into 39003. Then a structural analysis is performed under the same loading and constraints previously defined on the initial design space. This is to check the intended structural performance under the stipulated loads and constraints. This is shown in Fig.6. After the structural analysis, von Mises stress distribution is shown in Fig 7. The highest stress found is 36.6×103 psi. It is located at the contour of smaller void, highlighted with circle in the Fig 7.

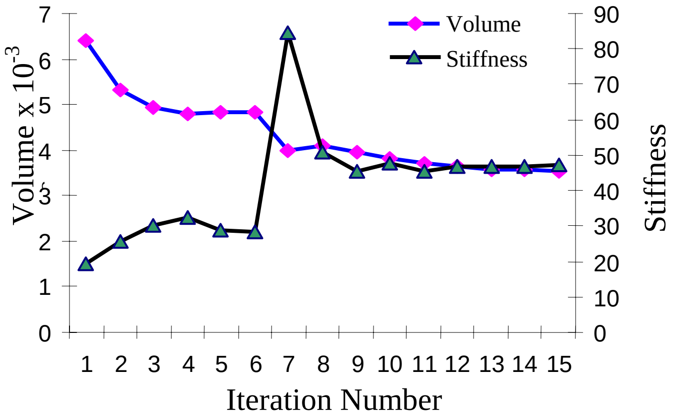

Fig. 4 Evolution of objective function (stiffness) and constraint (volume)

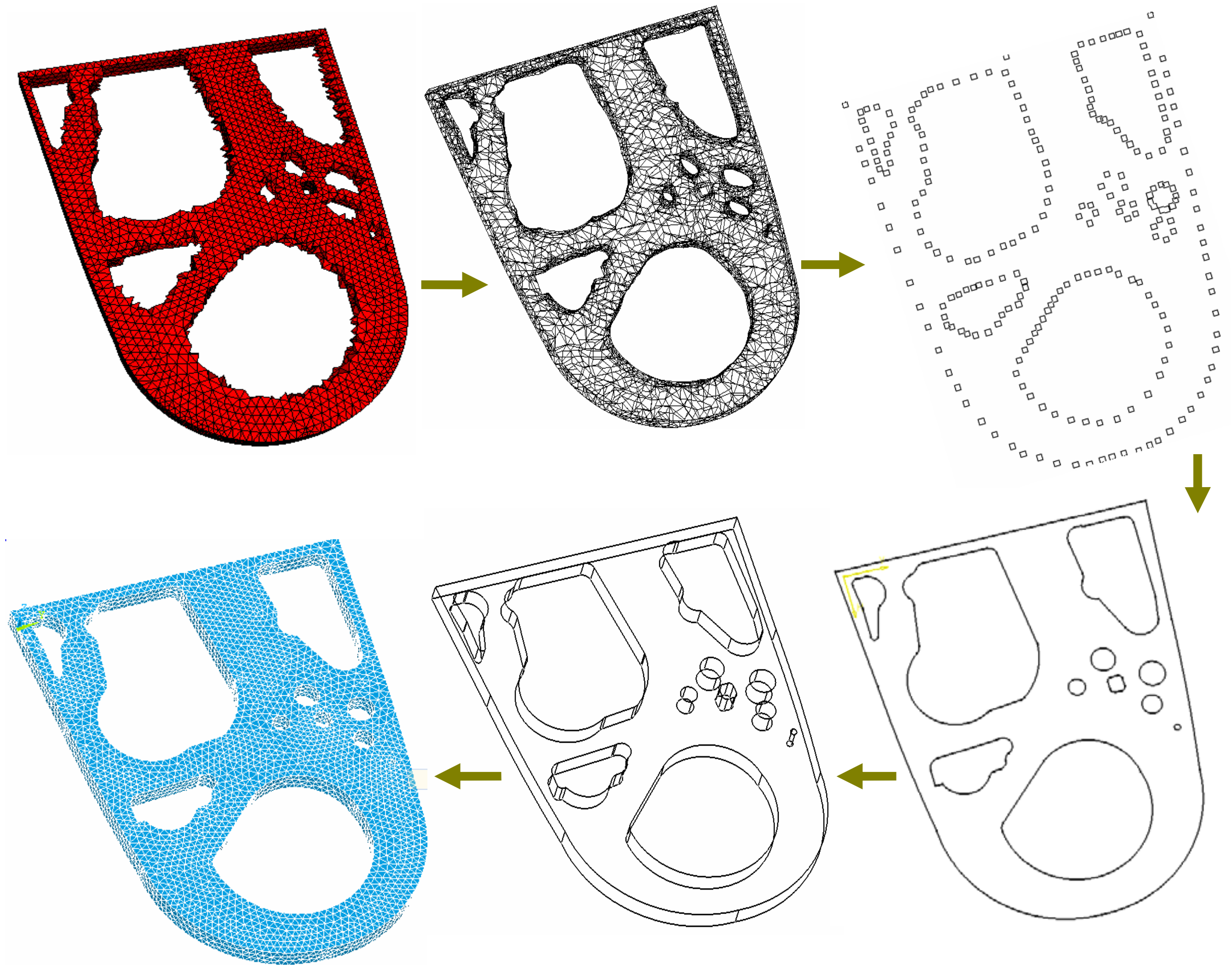

Fig. 5 Extracting CAD feasible geometry from topological optimized results

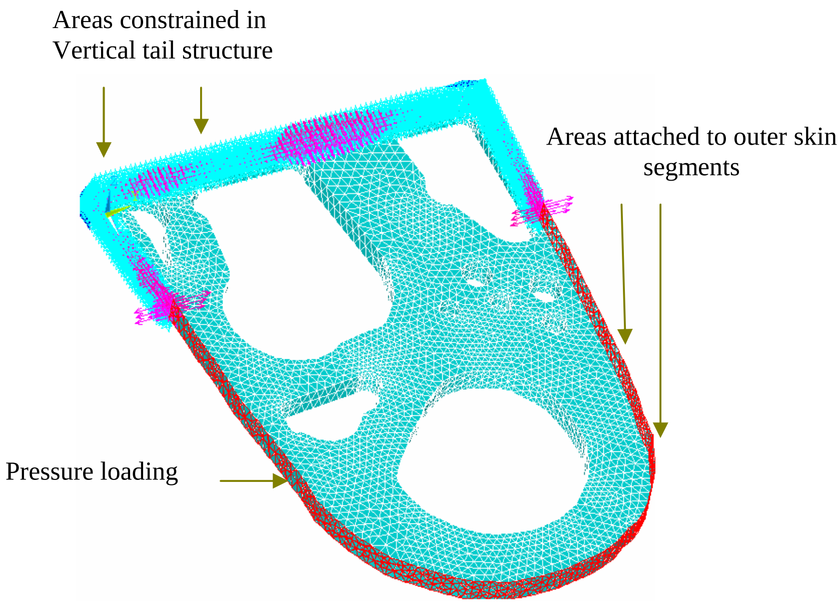

Fig. 7 Loading and constraints on initial optimized model

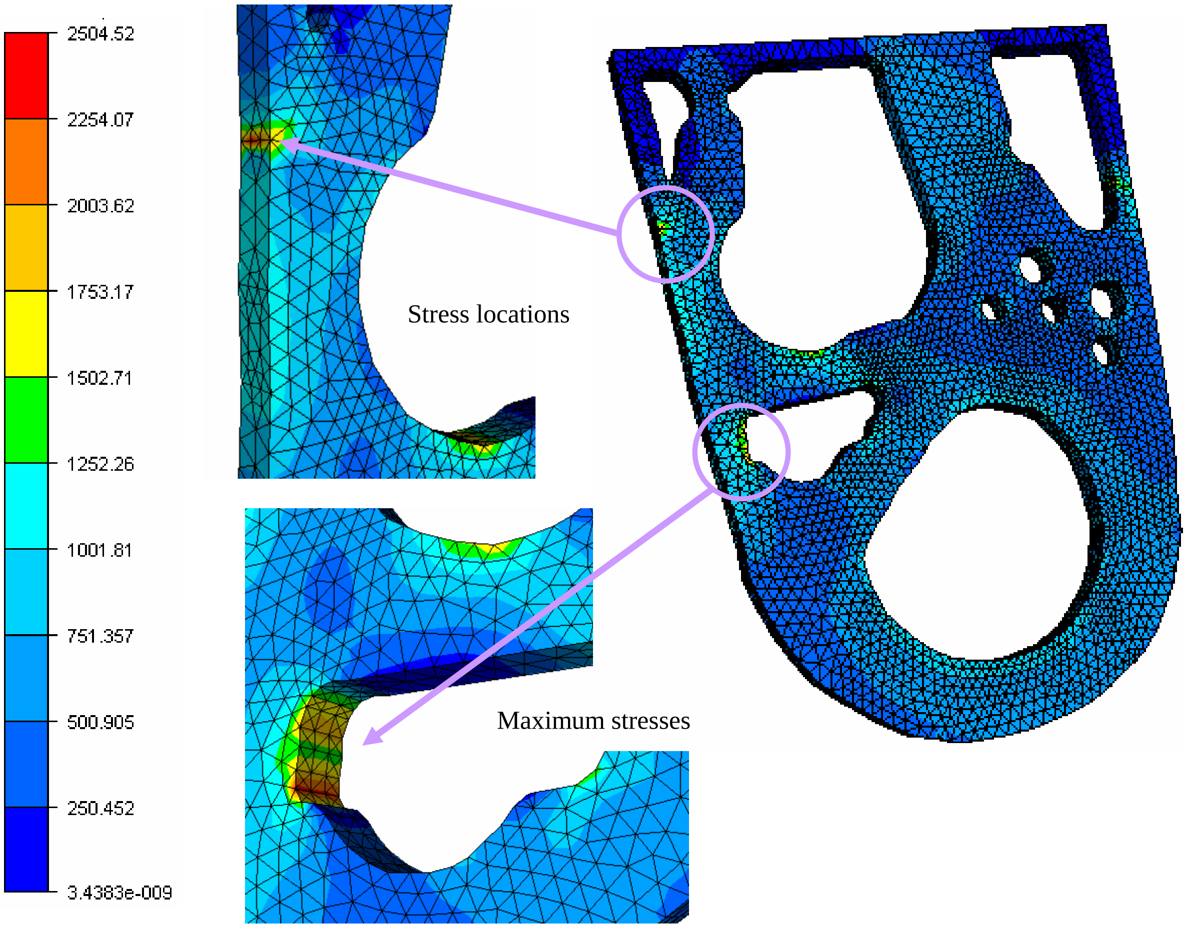

Fig. 6 Structural analysis of the initial optimized configuration

B. *Shape Optimization*

TOSCA.shape is based on a non-parametric approach. It generates the optimum shape of the component with respect to its mechanical behaviour. It is based on the methods of

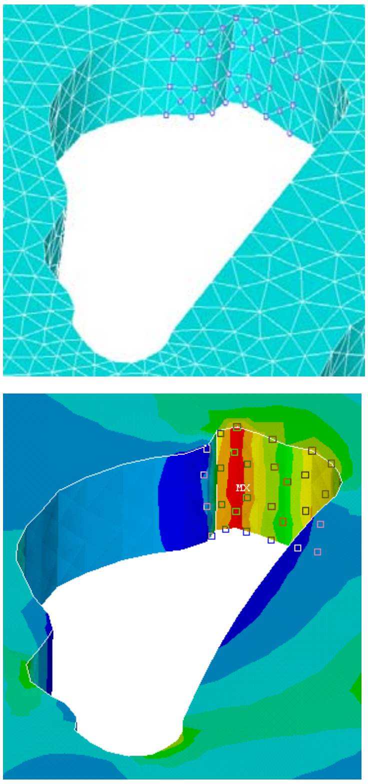

Fig. 8 Selection of design nodes group

optimality criteria. The optimal form and design of the component is made by a redesign formula. For the optimization process, parameterization of the mesh or the underlying CAD geometry is not required [39]. The FE data and analysis results are imparted directly to the optimization preprocessor. Design domain is defined in form of design node groups. The automatic mesh smoothing algorithms of controller ensures a good mesh quality during the surface modifications process. The overall surface modifications process leads to a homogenized stress distribution [22].

The optimized configuration obtained after refining the topology optimization results (Fig.5) is used as basis for the shape optimization. FE data, structural analysis, and model information is then archived as .cdb file and imparted into the TOSCA.shape preprocessor. The optimization domain is specified by selecting the nodes group at maximum stressed locations that make up the complete surfaces or contour. The list of design nodes groups is then defined in the optimization preprocessor by node numbers. In this case the selected design nodes group is shown in Fig.8.

Definition of the geometry-based parameters or shape basis vectors for restriction of the design space is not specified in the optimization preprocessing. The volume constraint is incorporated as 100 percent to remain close to the volume of the original model. This also ensures that no extra weight is added to the optimized structure and total stiffness of the component does not change too much. The optimization target is selected as to minimize the maximum von Mises equivalent stress along the design nodes. After 10 optimization cycles solution for the shape optimization converged and yielded a significantly improved design. Shape variations and stress distribution of the optimal design are shown in Fig 9.

In the optimized configuration, the highest stress is reduced to 30.5x103 psi. The shape of the contour at the design space is changed, exhibiting growth at that location. The overall stress distribution in design domain and other locations is homogenized. The maximum equivalent stress was reduced as 16.7 %. Fig 10 shows the convergence plot for the maximum stress during the optimization. Stress reduction at the critical spots is highlighted with circles. Although the geometrical changes are small, yet the improvement in the stress distribution is considerable. The modified geometry can be obtained either directly from the final FE-model or exported as surface mesh in IGES format and imported into the CAD system. The final optimized model is shown in Fig11.

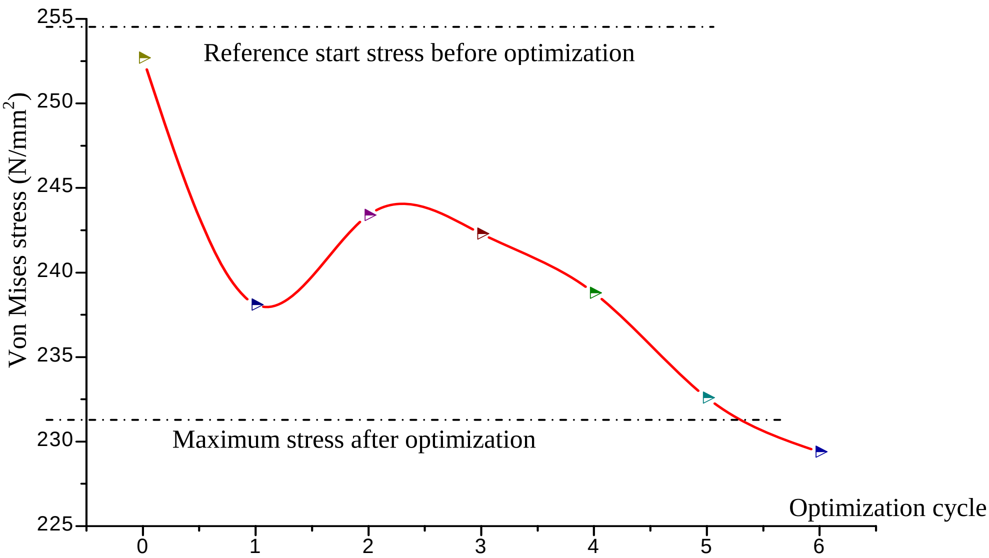

Fig. 9 Stress reduction by shape optimization

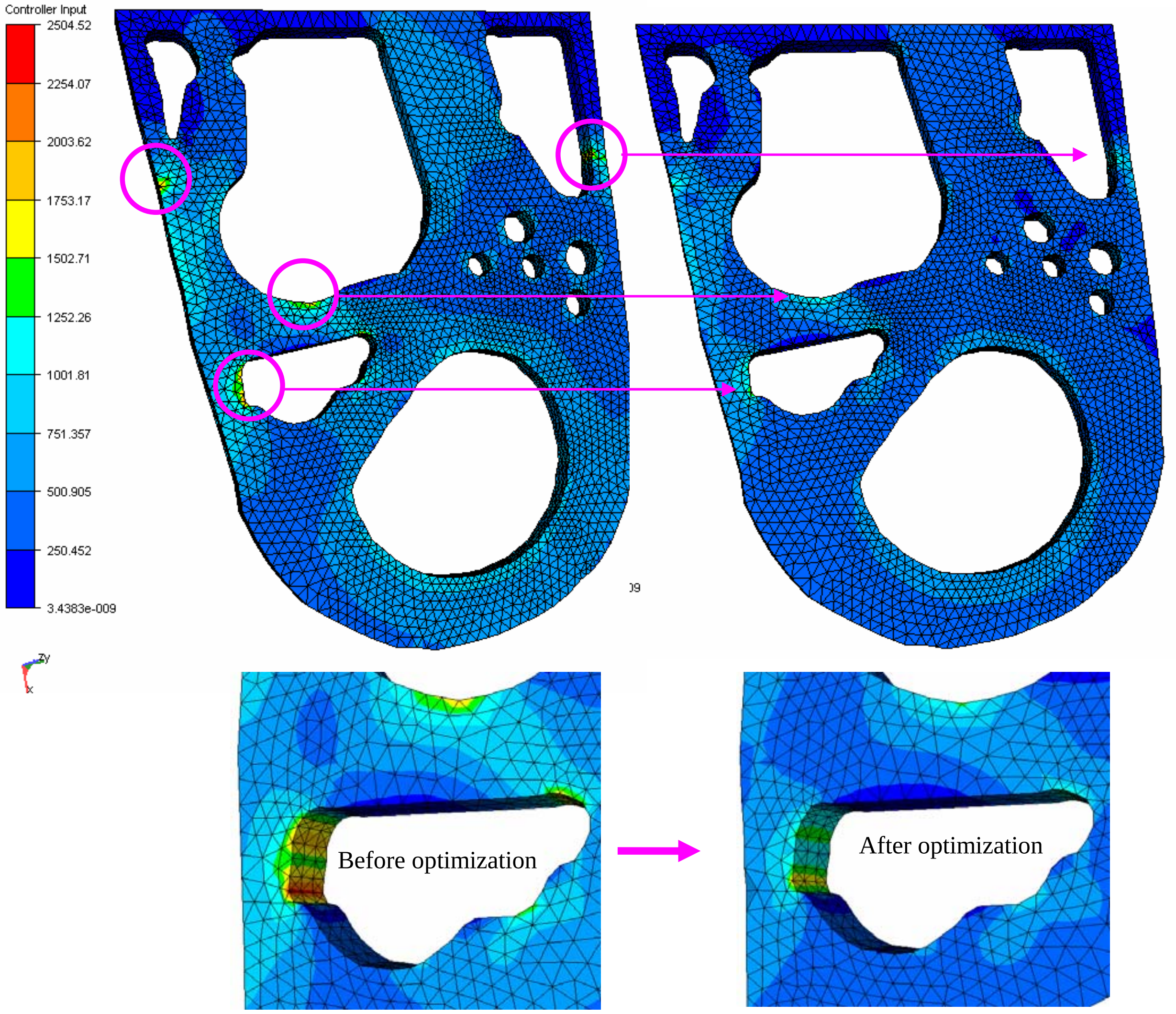

Fig. 10 Shape optimization

Fig. 11 Final Optimized Model

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