Applications of Structural Optimization Software in the Design Process

Torsten Bråmå* and Ragnar Rosengren*
Saab-Scania AB, S-581 88 Linköping, Sweden

Software tools for structural optimization are now gradually being introduced in the design process. The OPTSYS system is developed primarily for applications on aircraft, space, and automotive structures. OPTSYS is a modular system combining finite element analysis with mathematical programming methods. To illustrate the role of OPTSYS in recent projects, three real life applications are presented: a small-shape optimization example in a separation system for satellites, a case of mixed-shape and sizing optimization in the design of a car suspension, and a large optimization study on a composite wing of a fighter aircraft. The experience of using OPTSYS and the directions of current development are also commented on.

I. Introduction

THE structural system OPTSYS was developed by Saab Aircraft Division and the Aeronautical Research Institute of Sweden in 1982. The system originated from an early version of the OASIS system, developed by Esping.[1] A major contribution was also made by Svanberg[2] regarding mathematical programming software.

The system is primarily based on a finite element (FE) model (ASKA, ABAQUS) of the structure, and a mathematical programming approach is adopted where a sequence of convex approximations of the initial problem is solved. The gradients are calculated with a semianalytical approach. OPTSYS is a modular system with well-defined interfaces to FE programs and codes for aeroelasticity. Further information about the methods used in OPTSYS can be found in Esping,[1] Svanberg,[2] and Bråmå.[3]

Currently, OPTSYS will minimize weight or moment of inertia by modifying cross-section dimensions, material directions, node positions, and more general shape descriptions. Constraints can be defined on displacements, stress, eigenfrequency, buckling, flutter, and aileron efficiency. Other important ingredients are connections to a postprocessor for color-graphic presentation of results and the possibility to treat substructured FE models. The most recent development has involved integration of the preprocessor PREFEM[4] for definition of shape variables, the interface to the ABAQUS FE program, and the treatment of discrete variables.

The introduction of computer tools for structural optimization in the design work is now in effect at Saab-Scania. The goal is that all engineers working with structural analysis and design shall have access to structural optimization software and have the skills to use it efficiently. The practical impact of the use of OPTSYS has not been very large yet, but a number of applications have, however, proved that substantial contributions to the optimal design process can be achieved. OPTSYS is now installed at all divisions of Saab-Scania on VAX, CRAY X-MP, and APOLLO computers.

II. Industrial Applications

A. Separation System for Satellites in ARIANE and ATLAS Programs

This two-dimensional shape optimization illustrates how OPTSYS can be applied also to the small everyday design problem. The clamp shown in Fig. 1 is to be redesigned to reduce the stress concentration in the radius. The weight shall be minimized by changing the shape of the cross section. The constraints are set so that the maximum stress shall be 20% lower and the deflection d is not allowed to increase more than 10%. The six design variables are indicated in Fig. 2. In the final design, both constraints have reached their limits and the cross-section area has been reduced.

B. Shape Optimization of a Saab 9000 Suspension Arm

In order to investigate the performance of a proposed new wishbone design (Fig. 3) for the Saab 9000 car, an optimization project was initiated. The new design is of forged aluminum; the one already in production is built from pressed steel parts. Optimization is important here, as a low unsprung weight of the suspension is crucial for a performance car. A simplistic problem formulation suitable for a first shot was

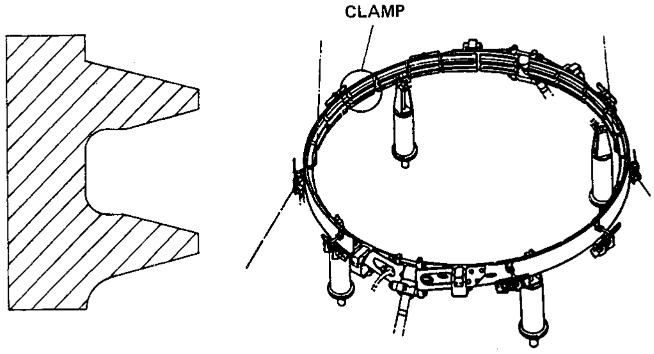

Fig. 1 Satellite separation system.

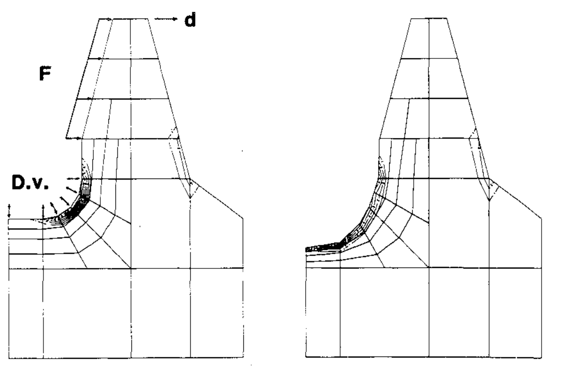

Fig. 2 Initial and final design.

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*Research and Development Engineer, Saab Aircraft Division, Stress Department.

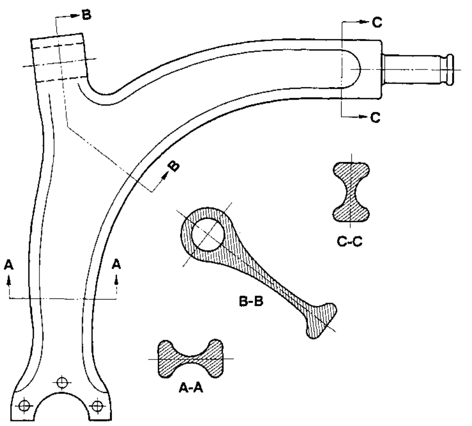

Fig. 3 Wishbone layout.

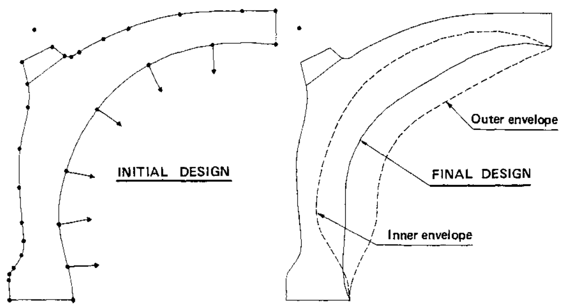

Fig. 4 Geometry of initial and final design.

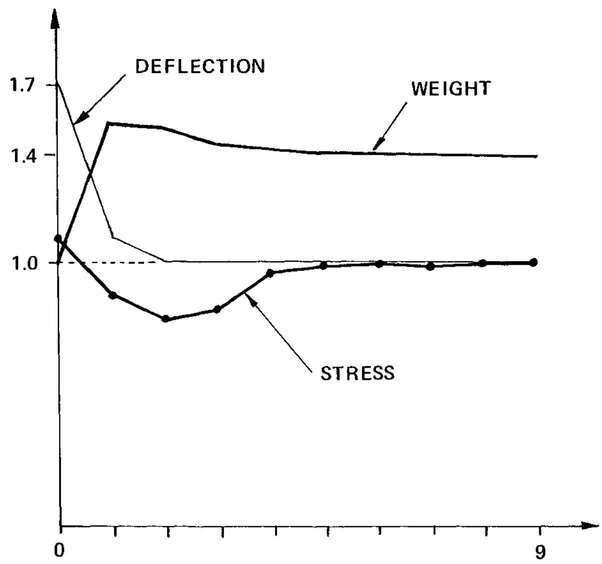

Fig. 5 Iteration histories.

sought. An FE model consisting of 230 shell elements was applied with three loading cases: maximum straightline braking, maximum lateral acceleration (cornering), and maximum combined braking/lateral acceleration.

The cross-sectional properties along the wishbone are varied by having the thickness of the elements as variables in the optimization problem. The inner boundary is described by B-splines in the geometry description of the preprocessor PREFEM. The control points of these splines are connected to design variables, as seen in Fig. 4 (indicated by arrows). Upper and lower limits on the values of the design variables account for various geometrical limitations.

Stress constraints were defined to keep the maximum von Mises stress below the yield stress. The basic stiffness requirement was that the stiffness of the new wishbone should equal the stiffness of the original (steel). This requirement, handled through deflection constraints, is disputable design-wise but is a fair starting point for an optimization study.

The resulting optimization problem consisted of 122 thickness variables, 6 shape variables, 1300 stress, and 6 deflection constraints. The problem was solved in nine iterations. For a weight increase of 40%, OPTSYS found an optimal solution with high enough stiffness (63% increase). The final design is determined, for this problem statement, completely by the stiffness requirements, two of which are at the critical limit. The stress constraints have no impact on the solution as they all are noncritical (albeit very close). Results are shown in Figs. 4, 5, and 6.

The final design is thickness-wise dominated by the defined lower limit. The exception being the far left part, which is built up probably to create high enough stiffness for the lateral load.

The average CPU time per iteration, on a VAX 8800, was roughly 550 s; the FE analysis part, thereof, was about 100 s.

C. Composite Wing of the Gripen Aircraft

The main purpose of this very large application was to investigate the possible weight savings for redesign of the wing skins with two different choices of new composite materials (Fig. 7).

A substructured FE model of the complete aircraft was used (Fig. 8). By including the optimization-wise active parts of the wing structure in a separate substructure, the amount of calculations needed in each iteration was reduced to a reasonable size. The active substructure contained about 5000 degrees of freedom compared to the 125,000 in the complete aircraft model. Eight loading cases were selected for this study.

The design variables were associated to layers in 254 different composite stacks. The layout in each stack was defined by three independent variables controlling the number of 0-, 90-, and +/−45-deg layers, making a total of 762 design variables. One of several finite elements in the wing panels was then linked to each stack. To limit the total thickness of the wing panel, explicit constraints were defined on the sum of variables connected to the same stack. Constraints were also imposed on fiber strain and buckling in the composite panels where a fairly simple handbook method for analysis of panel

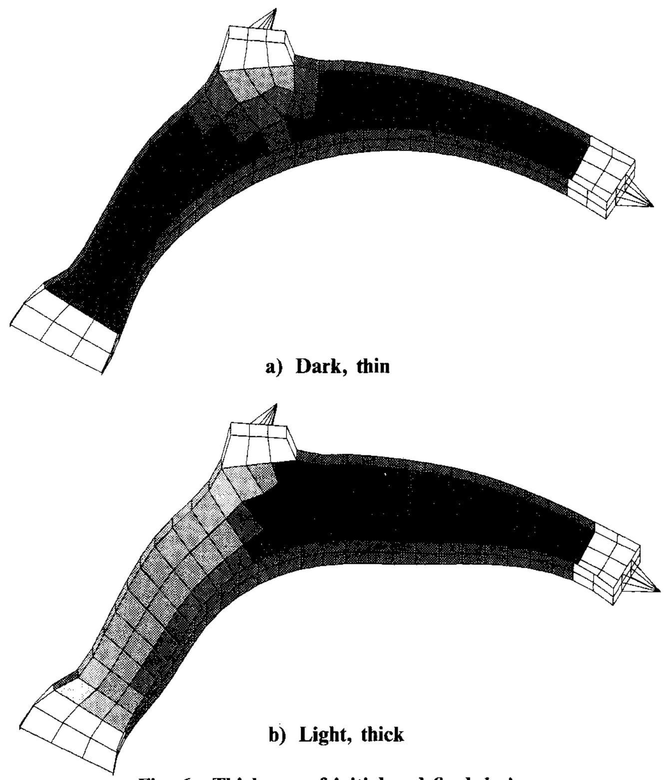

Fig. 6 Thickness of initial and final design.

buckling was used. Constraints on the aircraft performance, such as aileron efficiency, ideally should also have been included. Because criteria were to maintain current performance, it was considered to be sufficient in formulating the aeroelastic requirements as a number of constraints on the wing torsion. A total of about 20,000 potential constraints was defined of which a few hundred were active in the final design.

Six global iterations were enough to solve this problem for each of the two alternative materials (see Fig. 9). One iteration needed approximately 2000 CPU seconds in the CRAY-1A; 130 s for the reanalysis, 1000 s for the gradient calculation, and 800 s for the solution of the approximate subproblem. The portion of the iteration time consumed by the subproblem solution was much larger here than in smaller problems. One way to reduce this portion was to lower the demand on accuracy in the solution of the subproblem.

The layups produced by OPTSYS have to be adjusted to production requirements that are impossible to account for in the original problem statement. This manual work leads, of course, to increased weight and can be very tedious. Good postprocessing aids are absolutely vital when dealing with the huge amount of information created in large applications like this.

A summary of weight savings and the relative data for the composite materials can be found in Table 1. The results in terms of optimal layups will be valuable in a possible redesign of the wing.

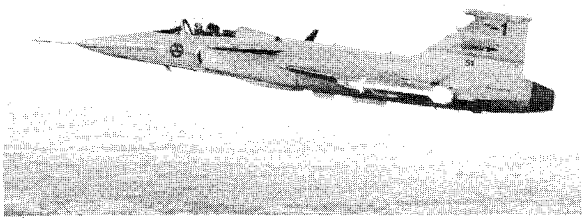

Fig. 7 Gripen.

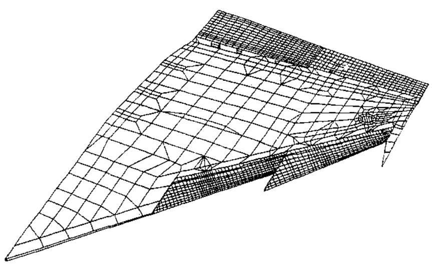

Fig. 8 FE model of the wing.

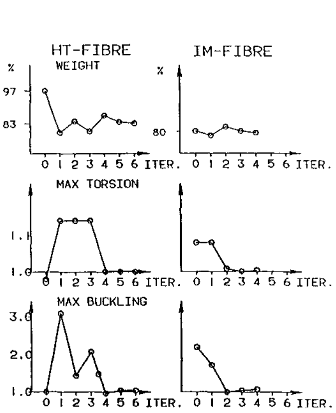

Fig. 9 Iteration history.

Table 1 Summary of results and material data

Matrix:	Initial wing design 914-T300 Brittle epoxy	"HT" 6367C-HTA7 Toughened epoxy	"IM" 6376C-IM500 Toughened epoxy
Elastic Modulus			
E11	0.97	1.0	1.2
Allowables			
ϵ_t	0.8	1.0	1.0
ϵ_c	0.92	1.0	0.86
Price	0.9	1.0	1.5
Weight saving, %	(Not optimized)	14	20

III. Comments on the Experience of Using OPTSYS

The formulation of the optimization problem is vital. We have experienced that the designer often ends up with a sequence of redefined problem formulations as the solution of one problem tends to generate more knowledge about the behavior of the structure.

When there is a layout problem, as in the wing example, one solution strategy is to begin with a formulation with many independent design variables. Based on the material distribution given by this solution, additional variable linking can be introduced. This refined problem definition, containing fewer variables, can then give a solution more attractive from the manufacturing point of view.

Sometimes it is not possible to exactly specify the performance criteria, as a structural optimization problem often is only one part of a global design optimization. What the designer really wants to know is how much weight penalty he has to pay for additional performance.

The optimization has implications on how to build the FE model. The immediate concern is to assure that the model is accurate enough for all combinations of design variable values. The most obvious case is the mesh disturbance caused by shape variables. The use of substructures is also affected, as the computational cost can be significantly reduced if the optimization-wise active parts of the structure are isolated from the passive parts.

IV. Directions of Current Development

OPTSYS is becoming more and more integrated in the computer aided engineering environment. Interfaces to pre/postprocessors and computer aided design systems will be improved. The classes of problems that can be addressed will be extended by refining the definition of design variables and introducing new constraint functions. For instance, a possibility to treat acoustic constraints is a highly desired feature in the context of aircraft and automotive structures. The potential use of knowledge-based techniques in connection with OPTSYS is also being investigated.

References

[1]Esping, B. J. D., *Structural Optimization Using Numerical Techniques*, The Royal Institute of Technology, Stockholm, 1985.

[2]Svanberg, K., "The Method of Moving Asymptotes—A New Method for Structural Optimization," *International Journal for Numerical Methods in Engineering*, Vol. 24, 1987, pp. 359–373.

[3]Bråmå, T., "Weight Optimization of Aircraft Structures," *Computer Aided Optimal Design: Structural and Mechanical Systems*, edited by M. Soares, Springer-Verlag, Berlin, Heidelberg, 1987, pp. 971–985.

[4]*PREFEM, User Manual, Version 5.4*, Veritas Sesam Systems A.S.