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RECENT EXPERIENCES USING FINITE-ELEMENT-BASED STRUCTURAL OPTIMIZATION

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OUTLINE

Structural optimization has been available to the structural analysis community as a tool for many years. The popular use of displacement method finite-element techniques to analyze linearly elastic structures has resulted in an ability to calculate the weight and constraint gradients inexpensively for numerical optimization of structures.

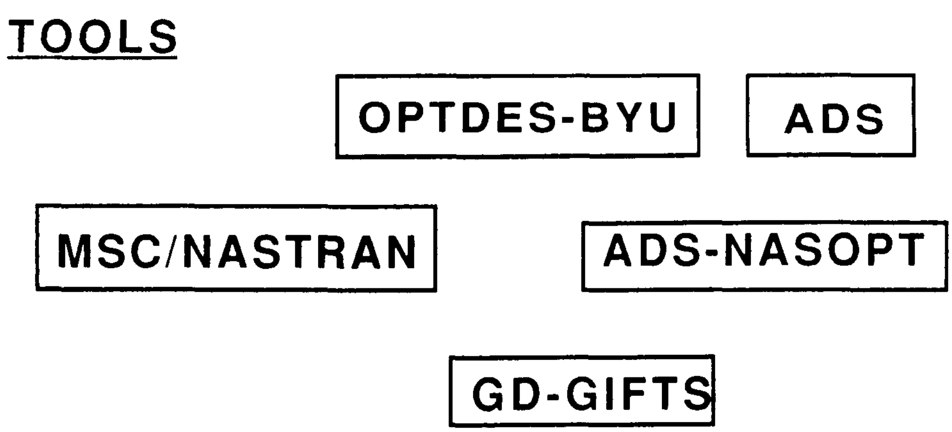
In this presentation, recent experiences in the investigation and use of structural optimization will be discussed. In particular, experience with the commercially available ADS/NASOPT (Reference 1) code is addressed. An overview of the ADS/NASOPT procedure and how it was implemented will be shown. Two example problems will also be discussed.

- BACKGROUND
- PROGRAM FORMAT
- TYPICAL INPUTS
- BUCKLING EXAMPLE
- CANOPY PROBLEM

SOFTWARE GOAL

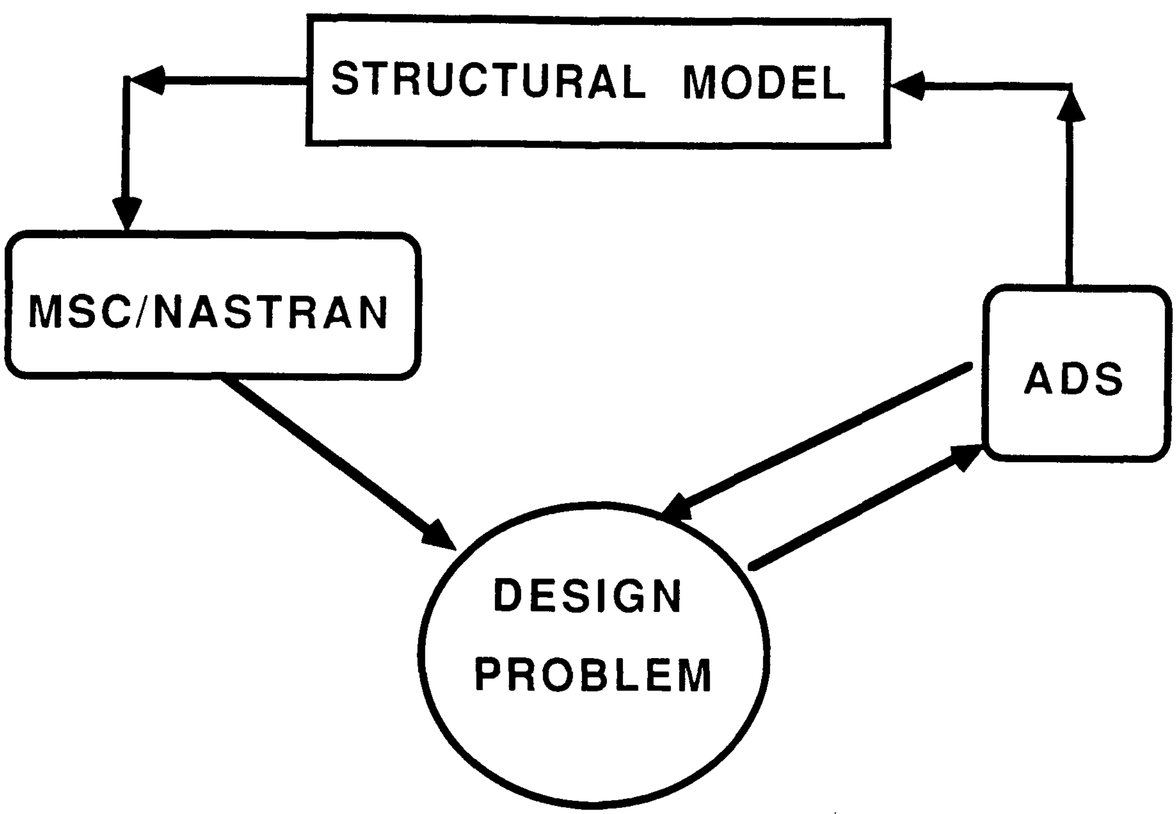
The goal of our structural optimization software investigation was to develop a production level finite-element-based system for aircraft design and resizing. The tools available from vendors are diverse. Optimization methods range in mathematical programming techniques and optimality criteria with various types of sensitivity analyses, design variable linking options, materials capabilities and disciplines. The use of existing finite-element models was also an important consideration. The OPTDES-BYU (Reference 2) and GD-GIFTS, an in-house finite-element program, were combined into an application specific finite-element optimization package using the combined databases from each program. Difficulty arose in making this program generic enough in terms of sensitivity analysis and structural geometry. The ADS/NASOPT program was selected and used in the following applications with favorable results. Since our in-house pre and post finite-element processors communicate with MSC/NASTRAN (Reference 3), ADS/NASOPT minimizes changes to existing finite-element models. In addition, we had prior knowledge of ADS (reference 4).

TO DEVELOP A PRODUCTION LEVEL FINITE ELEMENT BASED STRUCTURAL OPTIMIZATION SYSTEM FOR AIRCRAFT DESIGN AND RESIZING



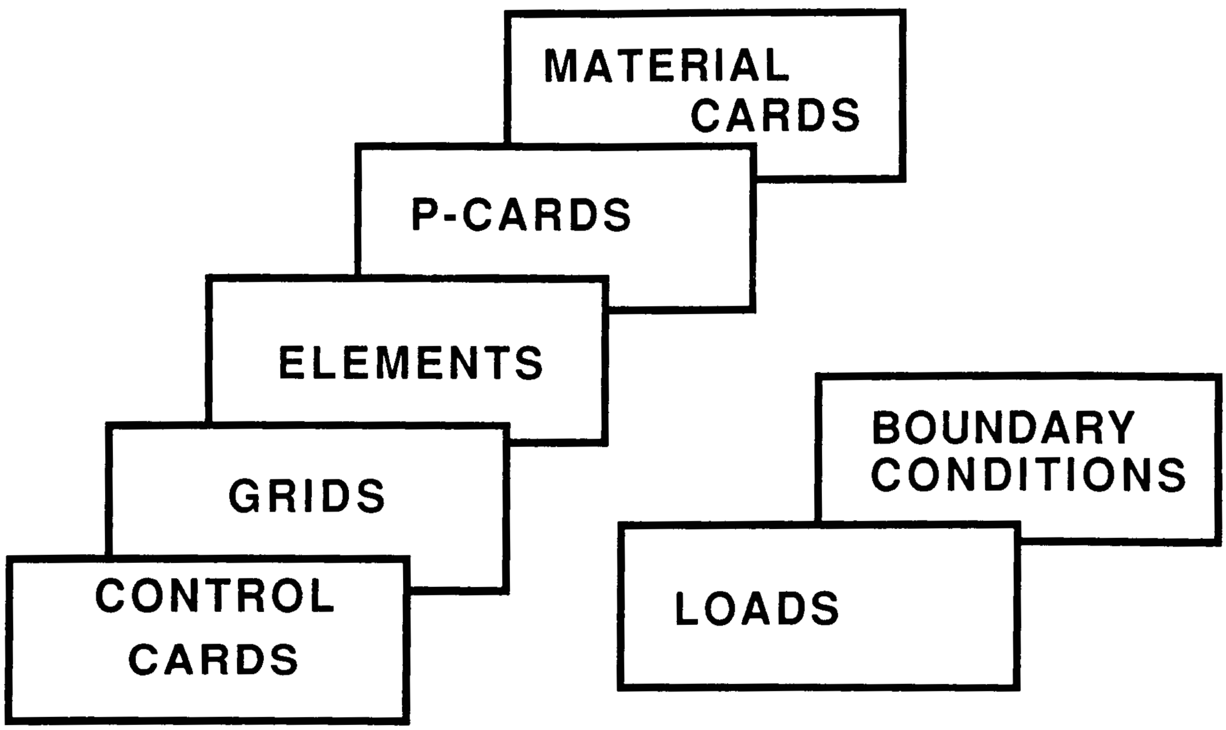
OUTLINE OF ADS/NASOPT

The ADS/NASOPT procedure uses a structural finite-element model as the starting point in an analysis cycle; then it translates this into a design model through NASOPT. The program then optimizes using the ADS optimization program and returns to the structural model to update the data if so chosen by the user. A combination of approximation techniques, sensitivity analysis and optimization algorithms allows the user to minimize his objective function (such as weight) subject to constraints (such as stress allowables, buckling load factors, or displacements).



TYPICAL MODEL REQUIREMENTS

The structural finite-element model includes the MSC/NASTRAN bulk data information such as control cards, grid points, elements, materials, properties, loads, and boundary conditions. ADS/NASOPT is limited in the variety of elements that can be resized as design variables; however, the finite-element model may contain unlimited types of elements available in the MSC/NASTRAN element library.



TYPICAL ADS/NASOPT INPUT

The ADS/NASOPT program requires some additional input in the form of NASTRAN data card images. These data include design variable, and constraint definitions, design variable upper, lower bounds, move limits, and method of optimization. A typical input sequence also requires NASOPT instructions or job control language. ADS/NASOPT is run in phases each performing a specific function in the optimization task. Phase 1 sets up the database by reading the NASTRAN and design data. Phase 2 prepares the NASTRAN sensitivity analysis data after screening the analysis results. Phase 3 reads sensitivity results, prepares the appropriate model and calls ADS to perform the optimization. Phases S and A call MSC/NASTRAN to execute the desired solution sensitivity solution sequences 51,53,55 (for phase S) and analysis solutions 24,61,63,65 (for phase A).

Generation of the extra data cards to convert a MSC/NASTRAN finite-element model to an ADS/NASOPT design model can be tedious for large models. Work station procedures included as a part of the finite-element pre-processors facilitate routine use of programs such as ADS/NASOPT.

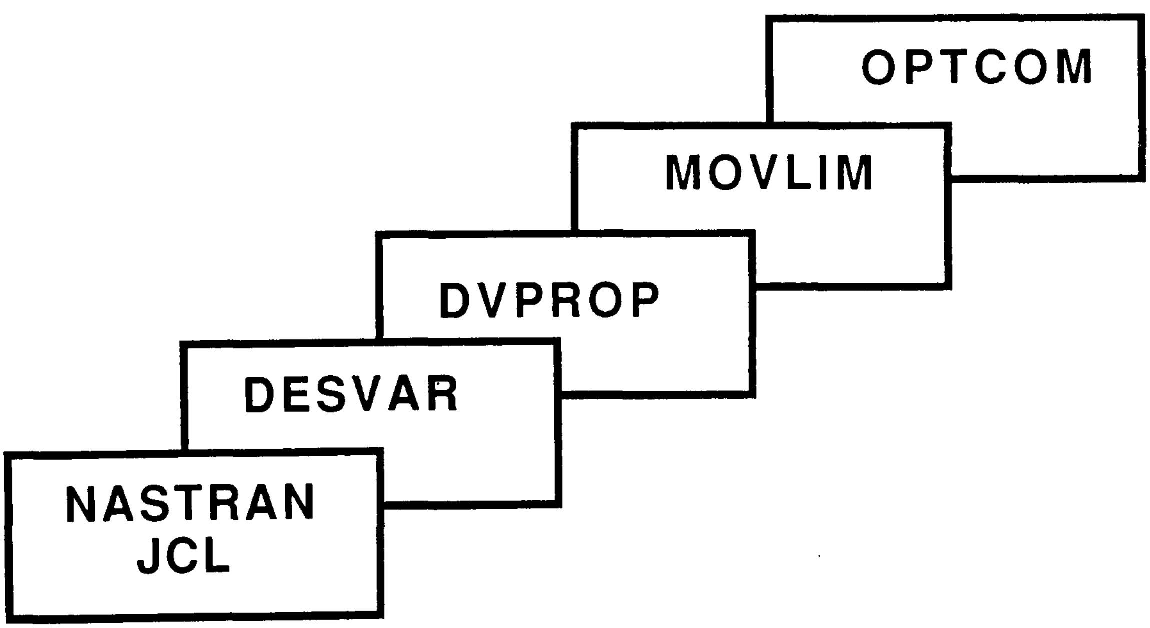


PLATE BUCKLING EXAMPLE - NASTRAN MODEL

The first example represents a typical section from an aircraft structure. This particular section was extracted from a fuselage keel beam and loaded with combined shear/biaxial displacements. The hole typifies routing requirements of plumbing, electrical, and fuel considerations.

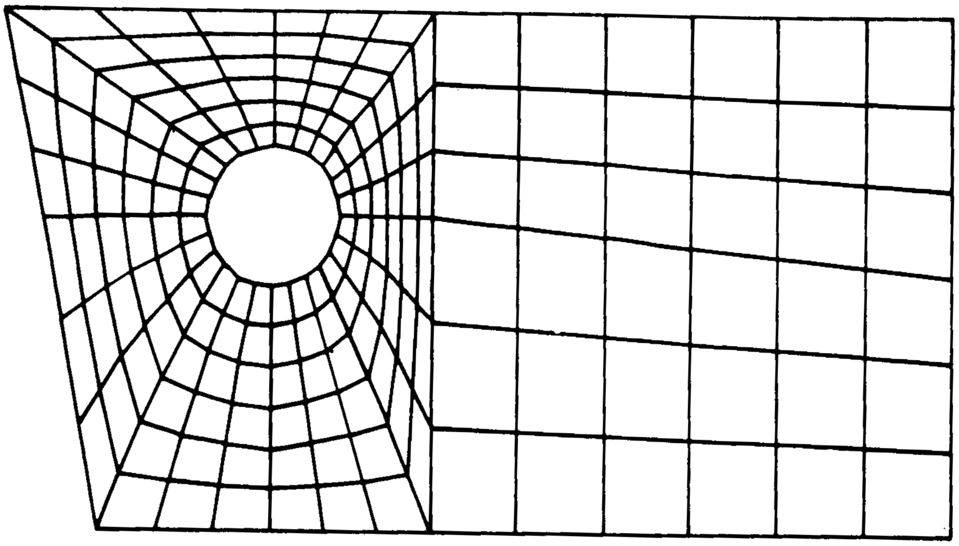


PLATE BUCKLING EXAMPLE - PROBLEM INPUTS

Material properties were selected for a typical aluminum alloy. In the case of this illustration, only two design variables were selected. Physical linking of the finite-element thicknesses was incorporated as shown in the figure. Although two design variables may be a crude definition of the design space, for manufacturing reasons, the design of such structure may often require this definition. And, the problem illustrates interesting results.

MATERIAL PROPERTIES

E = 10. 0 E7 POISSON'S RATIO = 0.3

DENSITY = 0.1 LB/CU INCH

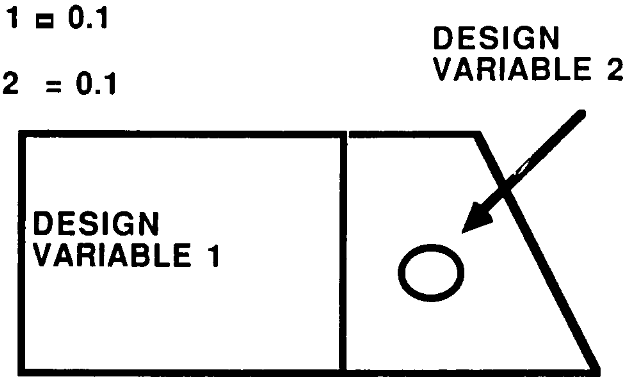
DESIGN CONSTRAINTS

BUCKLING EIGENVALUE => 1.5

INITIAL DESIGN

THICKNESS VARIABLE 1 = 0.1

THICKNESS VARIABLE 2 = 0.1



OBJECTIVE FUNCTION

MINIMUM WEIGHT

DESIGN HISTORY OF PLATE BUCKLING EXAMPLE

The pertinent results from the ADS/NASOPT run are shown in both tabular form and graphically. The table displays weight, thickness (the two design variables), and the buckling load factor. The procedure was run for eight optimization iterations. The weight and buckling load factor are both displayed with respect to the vertical axis of the graph.

The first observation of note is that after eight iterations, the process failed to satisfy the buckling load factor constraint. The second observation is that the buckling load factor steadily increased along with the design thickness through iteration 3. At iteration 4, the thicknesses began to separate, and the buckling constraint attained its highest point. During the remaining iterations, the thicknesses flip/flop and the buckling constraint actually decreased.

As best as we could determine, the design process seemed to be confused. ADS/NASOPT incorporates linear approximations, and between the few number of design variables, nonlinearity of buckling, and the choice of move limits, satisfactory results were obtainable.

We attribute our lack of success in this example to problem complexity and user inexperience.

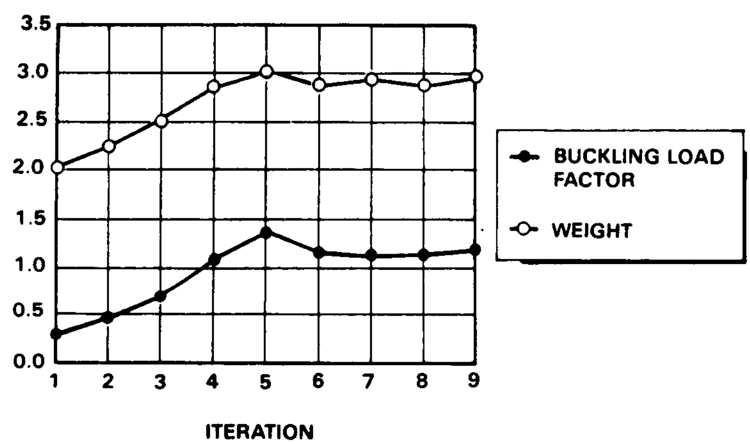


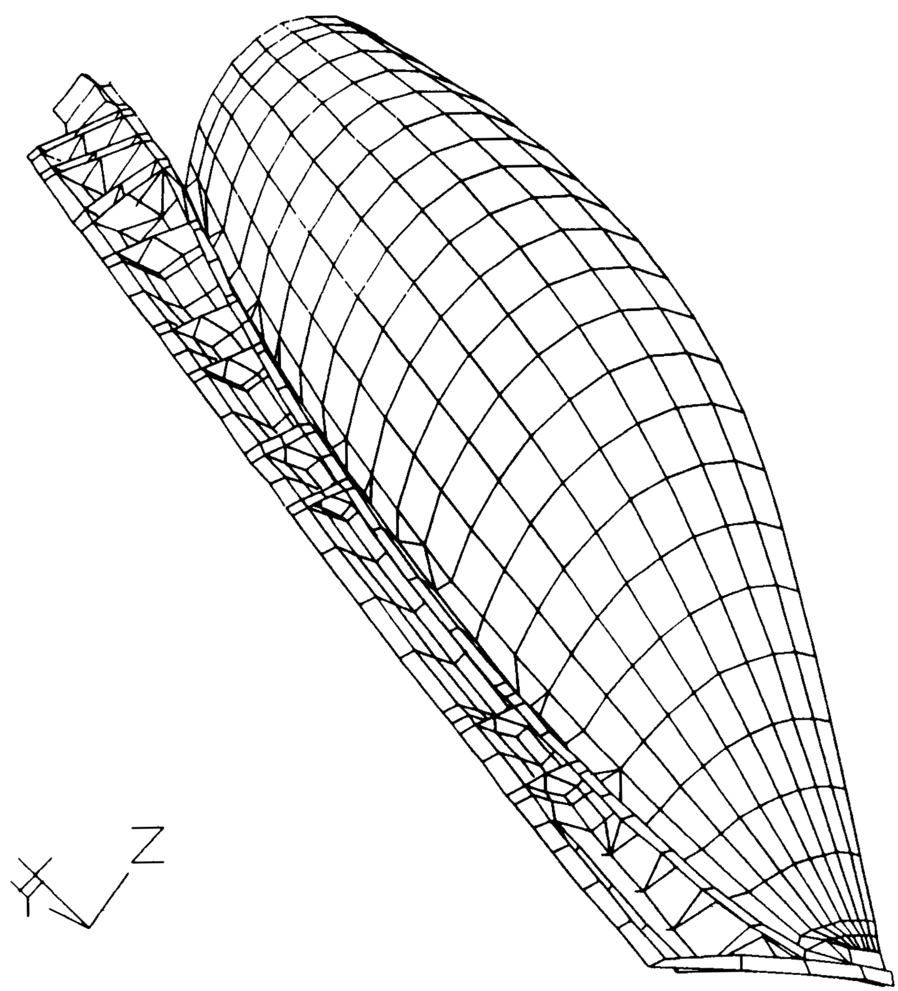
PLATE BUCKLING PROBLEM DESIGN VARIABLE VALUES

	INITIAL	1	2	3	4	5	6	7	8
WEIGHT	2.03000	2.24460	2.51270	2.84790	3.02580	2.86680	2.94650	2.87480	2.97200
THICKNESS UPPER	0.10000	0.12500	0.15625	0.19531	0.17494	0.18883	0.15736	0.19544	0.15287
THICKNESS LOWER	0.10000	0.12500	0.15625	0.19531	0.24414	0.20345	0.24061	0.20051	0.24185
BUCKLING LOAD FACTOR	0.28290	0.44200	0.69060	1.07910	1.37640	1.16440	1.12280	1.13580	1.20000

SINGLE PIECE CAST CANOPY FRAME - NASTRAN MODEL

A canopy bow frame model was optimized to test the functionality of the ADS/NASOPT software. A modern fighter aircraft canopy is primarily constructed of a polycarbonate transparency mounted in an aluminum frame. The frame is typically fabricated from various castings, extrusions, plate and sheet stock. This design is a labor intensive subcomponent to the canopy assembly. To replace the design with a single piece casting would represent a cost savings provided the additional tooling costs could be offset by the reduced labor costs.

The finite-element model of 1140 grid points and 588 bending elements was developed to represent the behavior of the structure. The NASTRAN model was adapted from the production finite-element model of the F-16 canopy frame with changes minimized to guarantee accurate comparisons in results.



DESIGN AND ANALYSIS MODELS - INITIAL SIZING

Eighty-eight design variables representing the canopy frame were selected from the bending elements available with 84 given initial thickness of 0.2 gauge size. The remaining 4 design variables representing the bow hoops, external covers, transparency, and tension ties were given "fixed sizes" to maintain their assembly requirements. These design variables were used mainly to allow stress constraints related to these elements to be applied and influence the design process. It seemed that ADS/NASOPT allows the user to constrain element behavior only if the element is labeled as a design variable. Regardless, this incident highlighted the need to consider neighboring structure in an optimization design setting.

88 VARIABLES REPRESENTING GAUGE THICKNESS FOR VARIOUS PARTS OF THE CANOPY FRAME

SIZE CONSTRAINTS

COMPONENT	SIZE CONSTRAINTS
CANOPY FRAME	$0.080 < t < 0.500$ inch
EXTERNAL COVERS	$0.100 < t < 0.100$ inch
BOW HOOPS	$0.250 < t < 0.250$ inch
TRANSPARENCY	$0.700 < t < 0.700$ inch
TENSION TIE	$0.150 < t < 0.150$ inch

2

DESIGN AND ANALYSIS MODEL - LOADING CASES

Two symmetric loading cases were selected representing ultimate cabin pressure and a balanced ejection condition. The ejection condition was balanced by inertia loads at the latching mechanism location along the length of the frame. Boundary conditions of a plane of symmetry along the aircraft were accounted for with reaction points at the tension tie locations. These loading cases represent typical production loading configurations.

The candidate materials used were A357 alloy for the frame which is a high strength heat treatable Al-Si-Mg alloy that is relatively inexpensive to manufacture. Other materials were kept as the current design exists.

LOADING CONDITIONS

CASE 1 10.2 PSI CABIN PRESSURE

CASE 2 PILOT EJECTION

BOUNDARY CONDITIONS

3 HOOK LATCHES

1 PIVOT

CENTERLINE SYMMETRY

MATERIALS

FRAME, CAST A357

EXTERNAL COVERS, BOW HOOPS, Al 2024

TRANSPARENCY, POLYCARBONATE

PIVOT FITTING TENSION TIE, PH13-8 STAINLESS STEEL

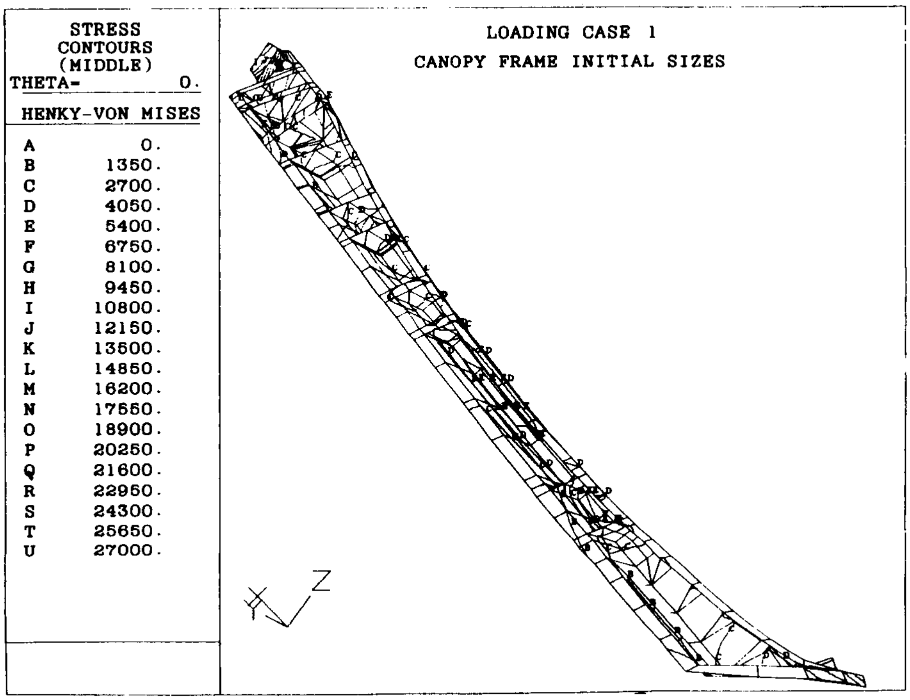
SINGLE PIECE CAST CANOPY FRAME - STRESS CONSTRAINTS

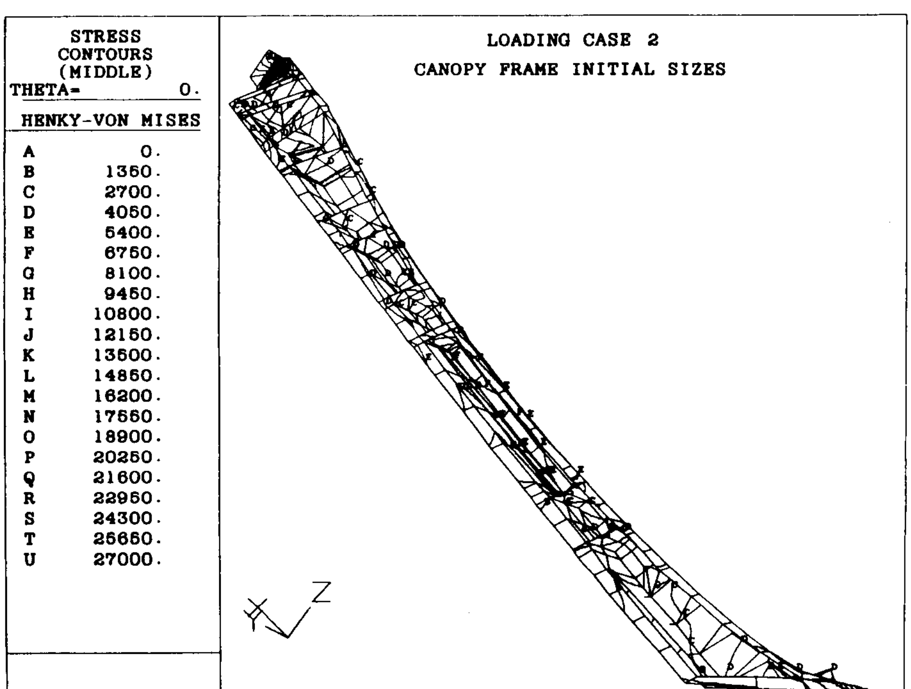
The canopy frame consists of bending elements representing flanges and webs. These elements were sized using a 26250 psi von Mises maximum stress. The bow hoops and external covers are loaded in tension with a required stress level between 40000 psi and 50000 psi for principal stresses. The polycarbonate transparency was held to a maximum 2000 psi von Mises stress. Finally the tension ties are loaded in tension, and the members were sized using 75000 psi as a maximum axial stress.

COMPONENT	STRESS CONSTRAINTS
CANOPY FRAME	VON MISES < 26250 PSI
BOW HOOPS, EXTERNAL COVERS	40000 < PRINCIPAL < 50000 PSI
TRANSPARENCY	VON MISES < 2000 PSI
TENSION TIE	AXIAL < 75000 PSI

SINGLE PIECE CAST CANOPY FRAME - INITIAL SIZING

The finite-element results for the initial sizing show large regions of low stress as expected.

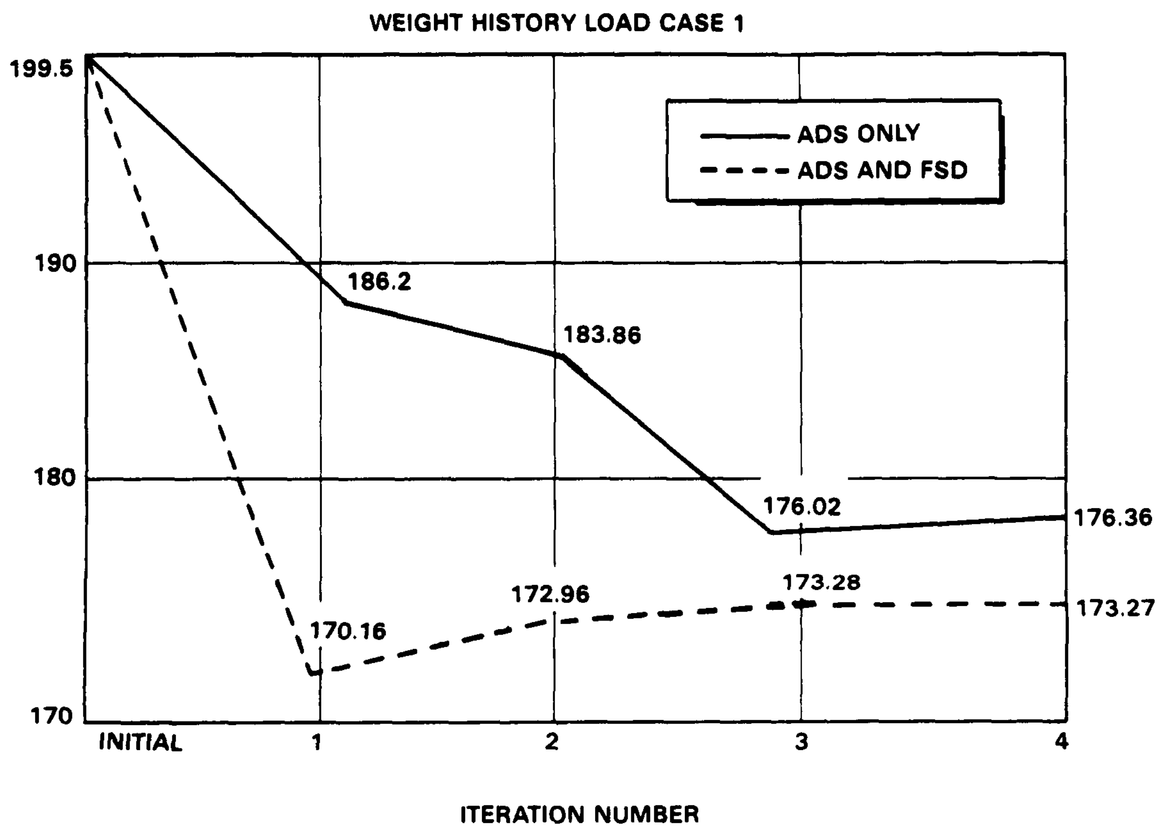




SINGLE PIECE CAST CANOPY FRAME - WEIGHT RESULTS

A comparison of two optimization methods was achieved for designs derived from load case 1, the ultimate cabin pressure case. Path 1 used 4 ADS steps using the Modified Method of Feasible Directions algorithm, while path 2 used 1 fully stressed design analysis and 3 ADS cycles. The FSD path also took less CPU time when run on the CRAY.

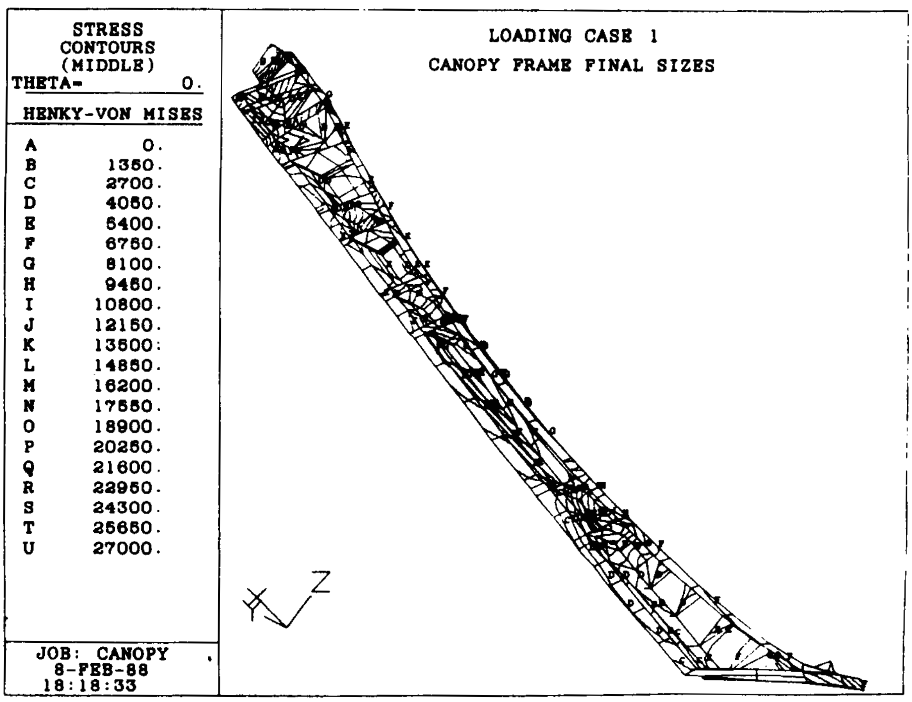
SINGLE-PIECE CANOPY FRAME

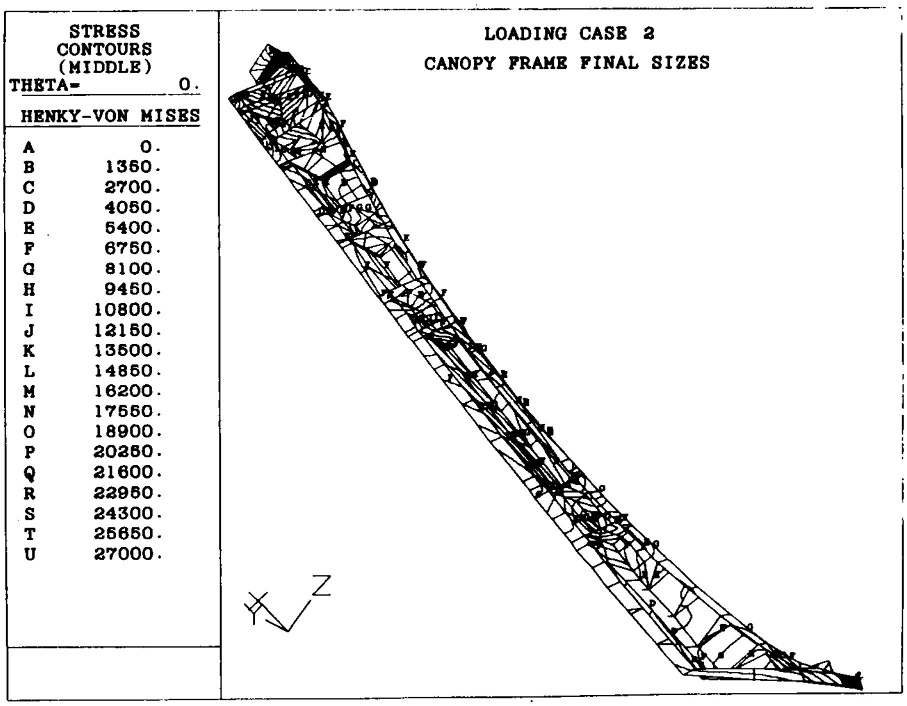


SINGLE PIECE CAST CANOPY FRAME - STRESS RESULTS

The final stress results for load case 1 the ultimate pressure case, show areas of high stress concentration near the tension ties. The optimized structure was sized predominantly to minimum gauge with the exception of the tension tie points and canopy latch hooks.

Although, it seems in hindsight that the problem was trivial as a built-up frame structure, the design was complex. This exercise demonstrated the functionality of ADS/NASOPT as a preliminary design tool because all aspects of the structure were included simultaneously in the structural sizing.




STRESS
CONTOURS
(MIDDLE)
THETA= 0.
HENKY-VON MISES
A 0.
B 1350.
C 2700.
D 4050.
E 5400.
F 6750.
G 8100.
H 9450.
I 10800.
J 12150.
K 13500.
L 14850.
M 16200.
N 17550.
O 18900.
P 20250.
Q 21600.
R 22950.
S 24300.
T 25650.
U 27000.
LOADING CASE 2
CANOPY FRAME FINAL SIZES
X
Y
Z

SUMMARY

In summary, our studies have provided four significant lessons learned. First it is evident that effective use of optimization techniques in design requires a robust-expert preprocessor as part of a basic finite-element preprocessor. Second, as in the example of the buckling problem, the design problem must be well posed both in a practical design sense and a numerical sense. The third observation to be made relates back to the problem definition. In particular, although neighboring elements to a design model may not be subject to resizing, their behavior may impose constraints on the design model. These constraints may be imposed through the use of larger models or formal decomposition methods. ADS/NASOPT provides functional use of MSC/NASTRAN as a preliminary design optimization tool.

- **LARGE DESIGN MODELS REQUIRE PREPROCESSORS**
- **ADS/NASOPT REQUIRES EXPERIENCED USAGE**
  - ✓ **DESIGN MODELS**
  - ✓ **ALGORITHM**
- **SENSITIVITY OF NEIGHBORHOOD STRUCTURE IS ESSENTIAL**
  - ✓ **DECOMPOSITION**
  - ✓ **LARGE MODELS**
- **ADS/NASOPT PROVIDES FUNCTIONAL USE OF MSC/NASTRAN**

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