

## New tools for designing flight vehicle structures

Jakub Kaczkowski, Institute of Aviation, Al. Krakowska 110/114, 02-256 Warsaw,  
e-mail kuba@sc.ilot.edu.pl



### 1. Introduction

Weight optimization of metal structures is very time consuming process. Unfortunately in composite structures this process is much more longer. due to big amount of potential solutions generated by system layout-material. That's why all efforts to automation this process should be honored. Recently in the market has appeared new program of American firm Collier-Research. Name of this program is HyperSizer and is intended for structure sizing both metal and composite. What is very important HyperSizer is using formulas prepared in Langley Research Center during many years of testing. In this presentation will be shown verification of HyperSizer based on weight optimization of horizontal tail of PZL I-23 all-composite aircraft. PZL I-23 Manager is new product of Institute of Aviation in Warsaw.



Fig.1 PZL I-23 Manager



Fig.2 Static test of horizontal tail  
Load case A MAN Upd - 100% of Limit Loads

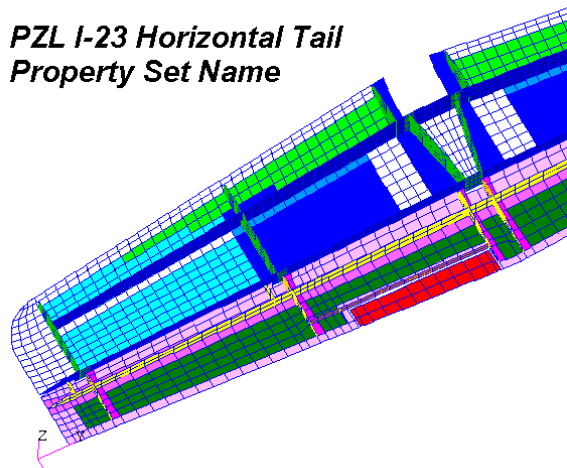
### 2. History of project of horizontal tail

All-composite structure of horizontal tail was sizing using Msc.Nastran and final certificate of the strength was obtained during 10 static tests. As a horizontal tail was designing as first designers wanted to test some of new concepts. In this way experimental tail was created. Results of static tests of experimental structure allow to design new final version of horizontal tail - serial one. The main differences between experimental and serial structure are in used materials. In the beginning, tail was build using wet technology from glass composites. Skin was designed as sandwich structure with foam core. In serial one, sandwich skin was build from glass and carbon prepregs with honeycomb core. In the next part of presentation, is presented comparison of static tests (see tab.1) and analysis.

Tab. 1 History of static tests

No	Load Case	Level of Loads	Remarks
Experimental			
1	A MAN UPd 950 30 091	150%	Stopped due to buckling of central area of the lower skin, between ribs Z1L and Z1P. Stiffness of the structure was increased using sandwich structure.
2	Hasym091 950 30 099L	286%	Done successfully
3	Hasym020 790 16 074L test to the destroying	343%	Destroying due to exceeding ultimate stresses in lower flange of main spar.
Serial			
4	A MAN UPd 950 30 091M	211	Done successfully
5	Hasym091 950 30 099L	155%	Stopped due to failure of main (metal) fittings.

Stress analysis was performed using following model [2].

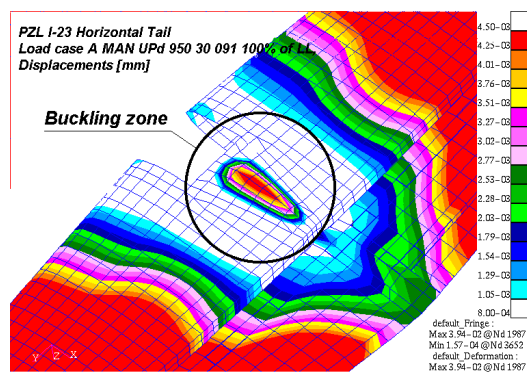


Nastran model of horizontal tail after removing upper skin. Colors shows distribution of properties. Model was built from 4872 QUAD4 and TRIA3 elements. Size of the model (27,425 DOF) is the „social limit“ for FEM models computed on the workstations. Nonlinear static analysis (sol 106) took more than 11 hours. During this job 63 load steps was analyzed, max. disc space requirement was 573 MB, transfer of the data 172 GB. Size of results file (xdb) was 185 MB.

Fig. 3 FEM model of horizontal tail

**Buckling of the skin during the first static test**

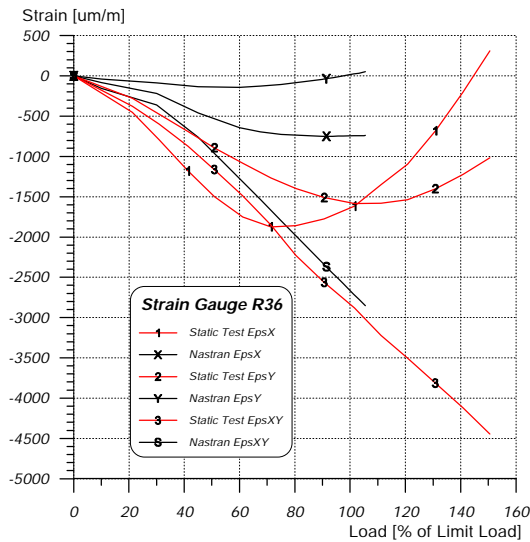
First version of the experimental horizontal tail has no sandwich skin in the central part, because preliminary analysis done „on the paper“ excluded possibility of the buckling. However Nastran showed that possibility of buckling is real. Designers decided to perform static test to resolve this problem.



**Results of nonlinear analysis**

Enlarged central part of the structure, deformations clearly shows buckling zone between ribs 1R and 1L. Remark, color range was changed to better show results.

Fig. 4 Buckling of central part of the skin.

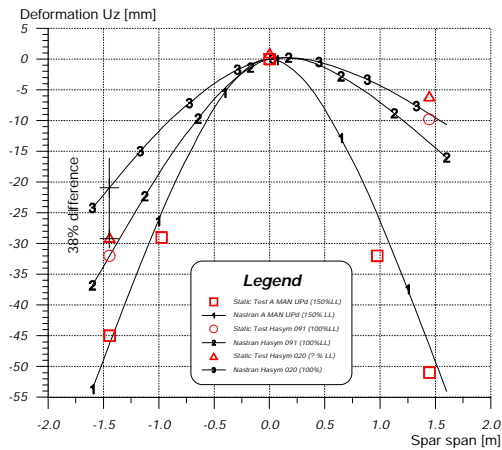


**Results of static test**

Measured during static test strains (solid lines 1,2,3) clearly shows buckling of the skin. The same buckling behavior show Nastran (lines X,Y,S) but there are differences in values of the measured and computed strains. This differences could be caused by coarse model (there was only 6x8 elements on panel) or not coincident position of the strain gauge and center of the FEM element.

Fig. 5 Behavior of central part of the skin

**Deformation of the structure**



On the graph was shown deformation of the structure measured in the plane of the aft spar. solid lines - results of computation symbols - values measured in static tests

In most cases differences were below 20% except static test #3 (triangles), because during this test deflection indicators were wrong calibrated.

Remark. Results for load case A MAN UPd were multiplied by 1.5

Fig. 6 Comparison of the deformation

**Failure mode in third static test**



Structure was destroyed during third test (load case Hasym020) on the level of 343% of limit loads, due to exceeding ultimate strains in lower flange of front spar.

Fig. 7 Zone of initiation of failure - lower skin



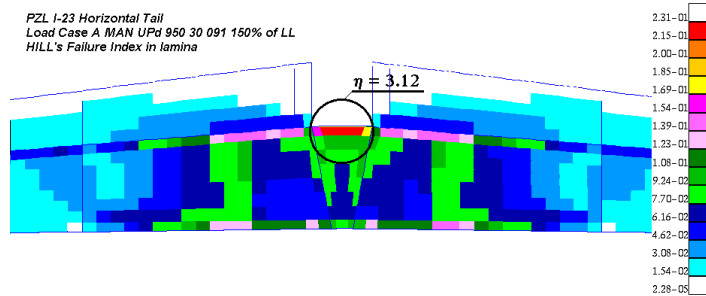
Fig. 8 View of the interior of the structure, after removing part of the skin.



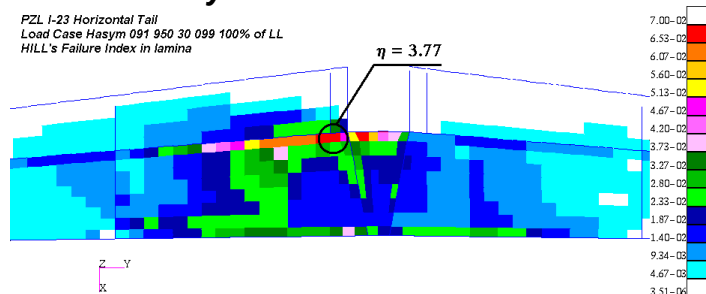
Fig. 9 Enlarged failure zone nearby rib 1R. In center is showed self-locking nut of the fitting.

In estimation of the structure strength TSAI HILL failure indexes and First Ply Failure theory was used. Below were shown distribution of the max. failure indexes in lamina and minimum strength safety factor ( $\eta$ ). Results for all performed tests were presented because small damages generated in previous test could have influence on failure mode in last test.

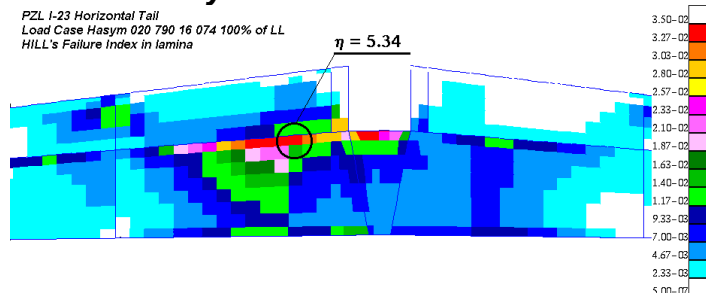
**Load Case A MAN UPd 950 30 091**



**Load Case Hasym091 950 30 099**



**Load Case Hasym020 790 16 074**



**Remark**  
Structure was destroyed on 343% of Limit Load, this means that differences between computed and measured strength is:  
 $5.34/3.43 = 1.55$

Fig. 10 Distribution of the max. Tsai-Hill failure indexes in lamina in all performed tests.

Computed and observed in test failure zone differ from each other. Destroying of the structure nearby rib 1R could be generated by small defects in previous test. Computed difference in strength factors (55%) are evidence of big unforeseeability of composite structures manufactured in classical „wet” technology. That’s why material for new tail was changed to the glass and carbon prepregs.

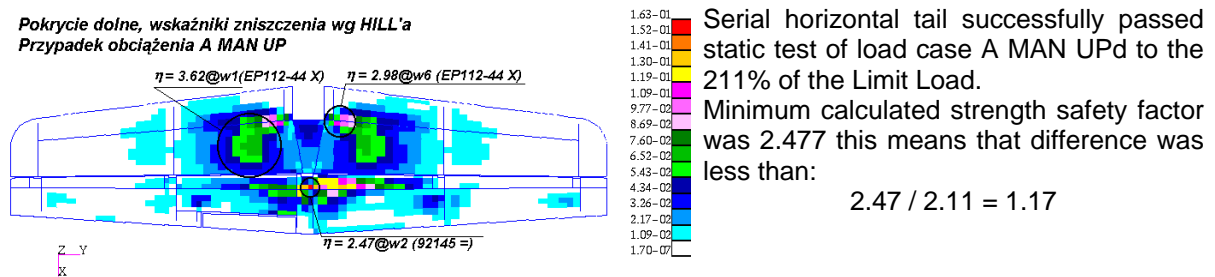


Fig. 11 Distribution of the max. Tsai-Hill failure indexes in serial horizontal tail.

### 3. Optimization of horizontal tail using HyperSizer

#### 3.1 How to HiperSize

Program HyperSizer® was worked out by Collier-Research for sizing structural components [4] Detailed description of HyperSizer and interesting test examples could be found at internet page: [collier-research.com](http://collier-research.com).

The process of „HyperSizing” structure can be broken into following steps:

#### 1) Develop a coarse, planar FEM Model

Unique feature of HS is the ability to model complex structural interaction of a general panel using a relatively coarse two-dimensional elements.

#### 2) Identification of Structural components

Structural components are used as optimization zones. These regions represent the smallest, practically manufacturable sections of structure. Structural components may be composed by as few as one element, but are generally comprised of several elements.

#### 3) Apply external loads to the FEM

For aerospace applications, external loads are surface flight pressures and assignments of masses for internal acceleration loads which integrate together to form balanced load cases.

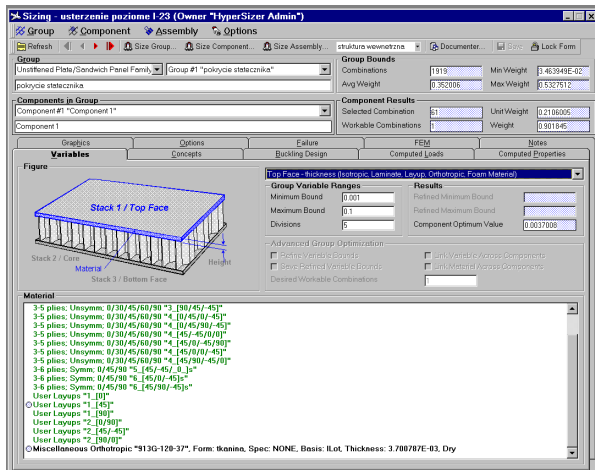
#### 4) Solve for internal loads paths of the current design using FEM

This step is the first step that is executed per each design iteration. For each iteration of this step, the elemental stiffness will be re-calculated for a new, optimized design using HS unique panel formulations.

#### 5) Specify or modify optimization parameters

In building optimization model main role plays correctly definition of variables and limits

Design variables



In HyperSizer there are two kinds of design variables:

- dimensions of cross-section of selected design concept
- materials

Fig. 12 Definition of design variables

HyperSizer has possibility to define several families of beams which have similar or common characteristic. The presently defined families in HS are:

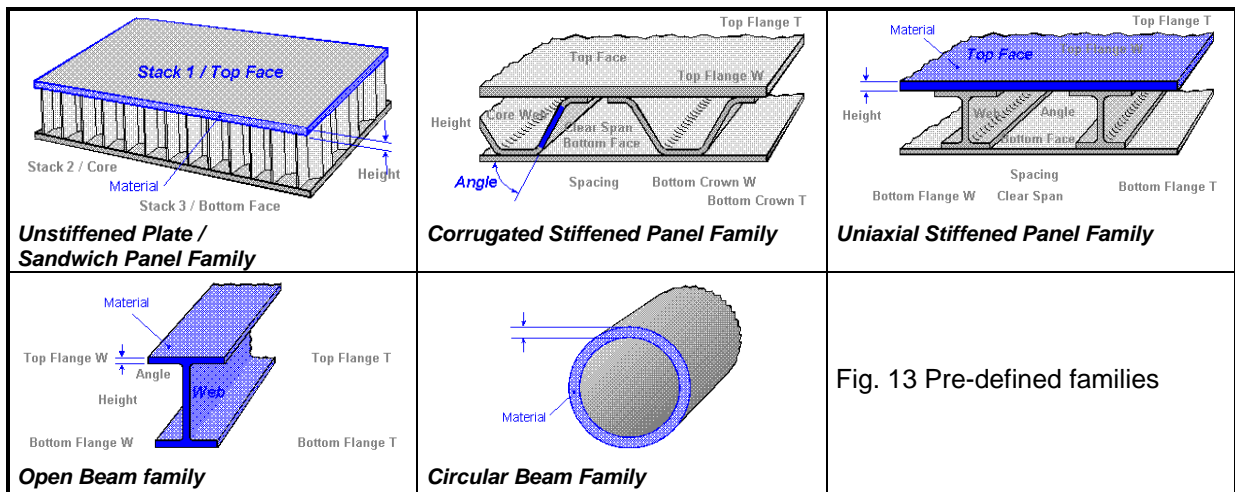
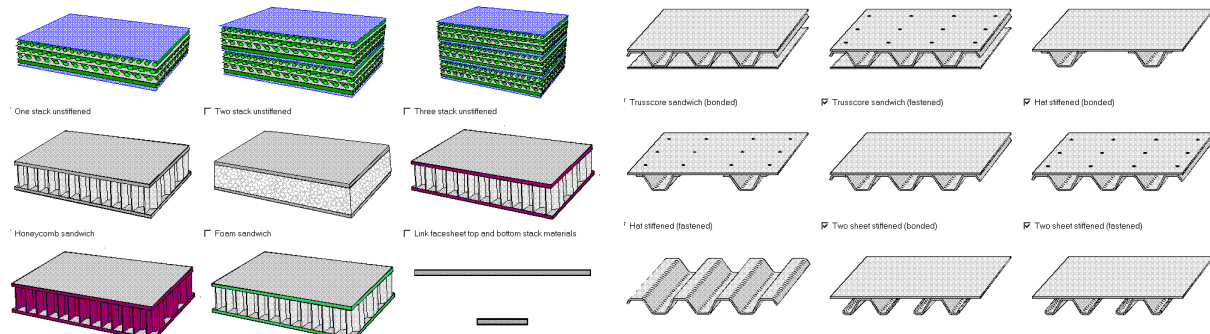


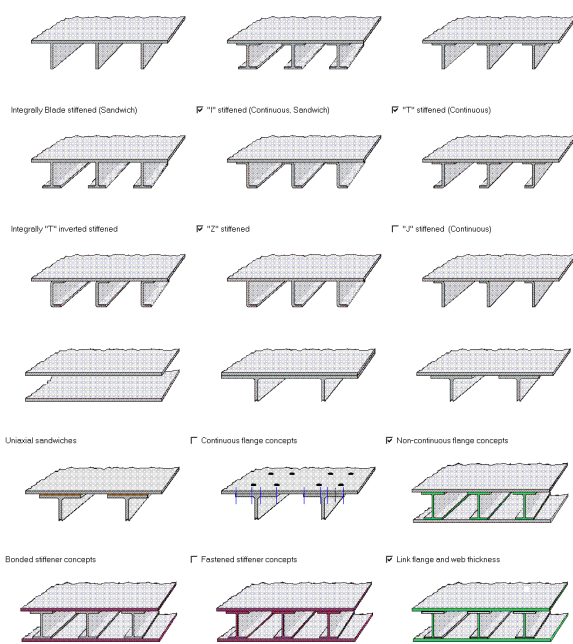
Fig. 13 Pre-defined families

Structural systems are made of various types of panel and beam concepts. HyperSizer includes over 40 different panel and beam concepts.

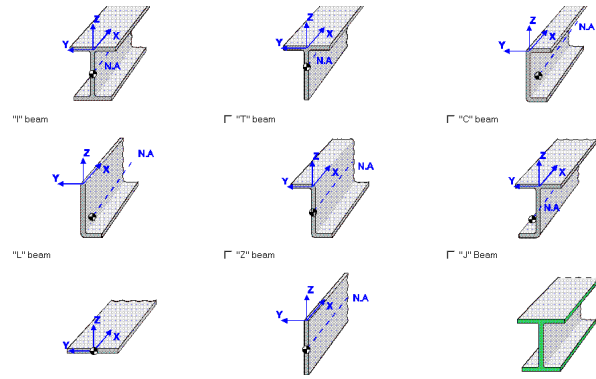


10 Sandwich /Unstiffened panel concepts

9 Corrugated panel concepts



21 Stiffened panel concepts



8 Open section beam concepts

Fig. 14 A library of Panel and Beam concepts

Material Form

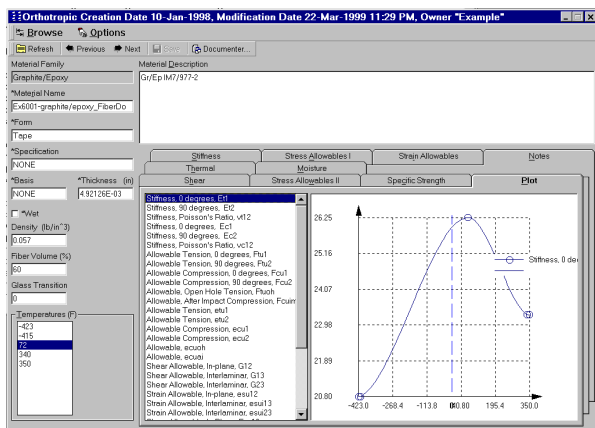


Fig. 15 Material Database

One of the strengths of the HyperSizer lies not only in the materials it provides, but also in the ability of user to create and modify their own material properties. The materials are broken into six basic categories:

- isotropic materials
- orthotropic materials
- honeycomb materials
- foam materials
- laminate definitions (composite material)
- layup definition (composite material)

Optimization using composite materials should be pointed out.

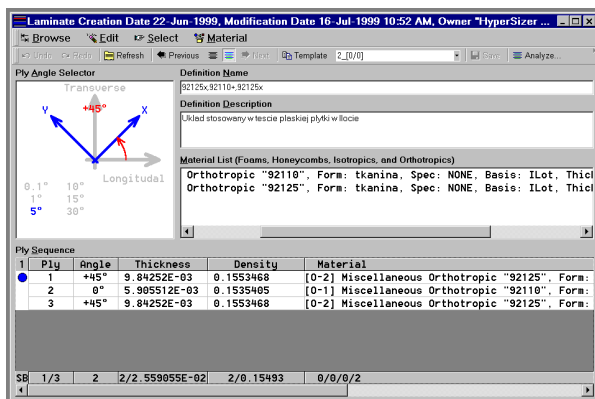


Fig. 16 Laminate definition form

User could optimize structure using 3 concepts.

- equivalent orthotropic material
- laminates
- layups

## Optimization using equivalent orthotropic material (Quick Composite)

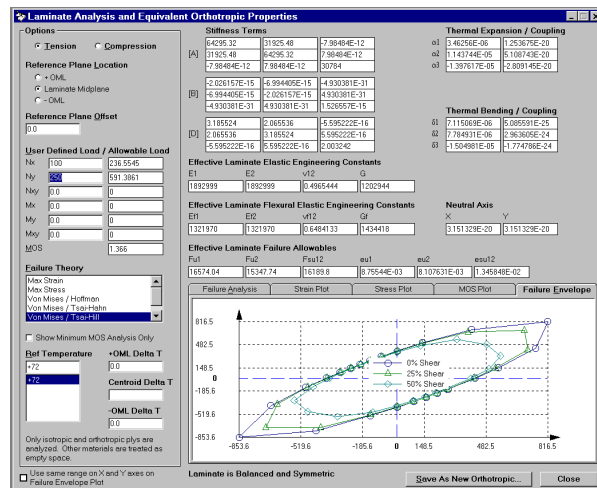


Fig. 17 Laminate analysis form

Allowing the user to treat laminates as equivalent, homogenous orthotropic materials and optimize by varying their thickness in a continuous isotropic sheet metal manner. This allows quick computation of laminate thickness and best ply direction percentages.

## Optimization using laminate

A laminate is a material composed of two or more layers of similar or dissimilar materials bonded together. One of the differences between a laminate and the other materials is that the thickness of each ply of a laminate and so the thickness of the laminate itself is fixed when a laminate is specified, but HS could choose on of the selected for analysis laminates.

## Optimization using layup

A layup is similar to a laminate, in that is a specification for a multi layered material, but there are two important differences. First, each ply of layup must be composed of the same composite material. Second, while the fiber angle of each layer is specified as a part of layup definition, the ply material is not. This means that for layup HyperSizer can choose the optimum orthotropic material.

## Constraints

During optimization process user can define several kind of constraints, broken into following groups:

- strength properties - for each chosen concepts many different types of strength checks (over 100) are included. The user can toggle as many on and off as desired. Most of the criteria's are commonly used and established methods.
- stiffness properties - as a constraint could be used stiffness of the plate or beam, defined as a stiffness matrix coefficients.
- functional properties - as a constraint could be used also modal frequency, deformation and midspan deflection.

## 6) Allow HyperSizer to optimize the structure

The most important step in sizing and the one in which the capabilities of HyperSizer really take over is the actual optimization of the structure. Most of the analytical work of HyperSizer is performed during this step. HyperSizer first generates all possible permutations of the user-specified optimization bounds. Internal logic is able to filter out impossible design and the remaining design concepts are evaluated for structural integrity using an extensive list of analytical physics based structural analysis.

## 7) Control of solution

Each of solutions need to be controlled. Two things should be checked:

- Does solution change internal forces?
- Is the solution optimal (has minimum weight)



### 3.2 HyperSizer's modell of horizontal tail

Optimization model for HyperSizer was build, based on serials horizontal tail structure [3]

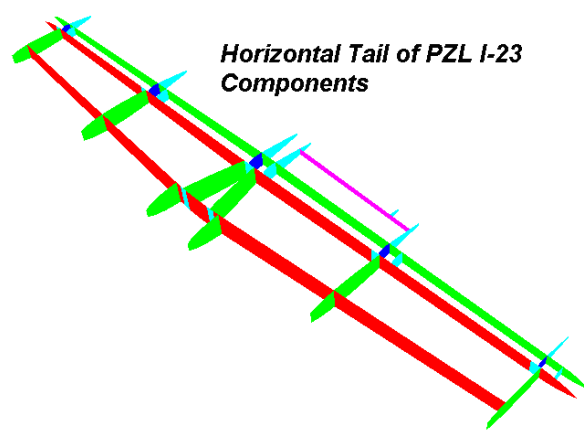
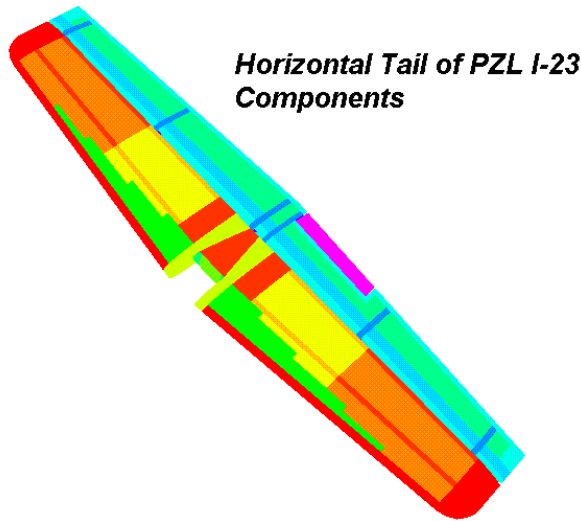


Fig. 18 Skin - components scheme

Fig. 19 Internal structure - components scheme

Below is presented example definition of optimization variables for firs group

#### Group 1 Skin of the stabilizer

Family	unstiffened / sandwich panel
Active concepts	Single stack, honeycomb, unsymmetrical
Components	
Permitted layouts for top face	<ol style="list-style-type: none"> <li>1 [0], [45], [90]</li> <li>2 [0/90], [45/-45], [90/0]</li> <li>3 [0/0/0], [0/45/-45], [45,-45/90], [90/45/-45], [45/-45/0], [45/0/-45], [45/90/-45]</li> <li>4 [0/45/-45/90], [0/45/0/-45], [0/45/90/-45], [45/-45/0/0], [45/0/-45/90], [45/0/0/-45], [45/90/-45/0]</li> <li>5 [45/-45/_0_]s</li> <li>6 [45/0/45]s, [45/90/-45]s</li> </ol>
Materials for top face	913G-120-37
Materials for core	Nomex48 thickness 4, 5, 6, 7, 8 mm
Permitted layouts for bottom face	<ol style="list-style-type: none"> <li>1 [0], [45], [90]</li> <li>2 [0/90], [45/-45], [90/0]</li> <li>3 [0/0/0], [0/45/-45], [45,-45/90], [90/45/-45], [45/-45/0], [45/0/-45], [45/90/-45]</li> <li>4 [0/45/-45/90], [0/45/0/-45], [0/45/90/-45], [45/-45/0/0], [45/0/-45/90], [45/0/0/-45], [45/90/-45/0]</li> <li>5 [45/-45/_0_]s</li> <li>6 [45/0/45]s, [45/90/-45]s</li> </ol>
Materials for bottom face	913G-120-37

### 3.3 Results

Tab. 2 Results of MSC.Nastran optimization

Total weight of experimental tail	8.48 kg
Total weight of serial tail	6.45 kg
profit	31%

Tab. 3 Results of HyperSizer optimization

Total weight of serial tail	6.45 kg
Total weight of tail optimized by HyperSizer	4.92 kg
profit	31%

Tab. 4 Weights of groups

NG	Group	weight	% of total
1	Stabilizer skin	2.506 kg	52
2	Stabilizer spar	0.505 kg	9
3	Stabilizer ribs	0.144 kg	3
4	Elevator skin	1.469 kg	29
5	Elevator spar	0.165 kg	3
6	Elevator ribs	0.059 kg	2
7	Trimmer	0.071 kg	2

Tab. 5 Controlling load case

Load case	Controlled weight	% of total weight
1) A MAN UP 850 21 009	4.524 kg	90%
2) D GUST DN 1059 35 040	0.393 kg	9%
3) D GUST DN 825 21 020	0.001 kg	1%

Tab. 6 Controlling failure analysis

Strength	0.816 kg
Global buckling	3.597 kg
local buckling	0.0 kg

**Horizontal Tail of PZL I-23  
Unit Weight [kg/m<sup>2</sup>]**

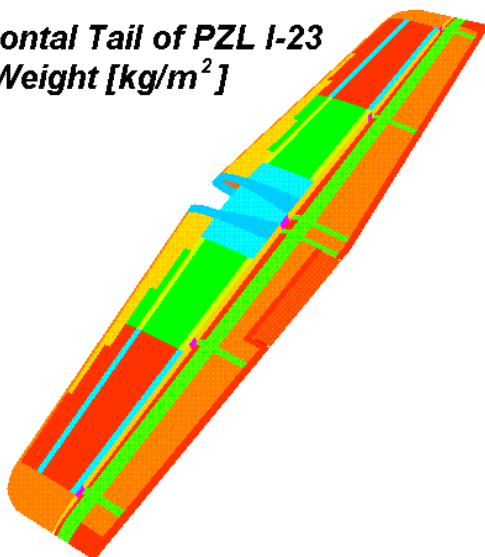
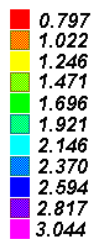


Fig. 20 Unit weight distribution

**Horizontal Tail of PZL I-23  
Core thickness [mm]**

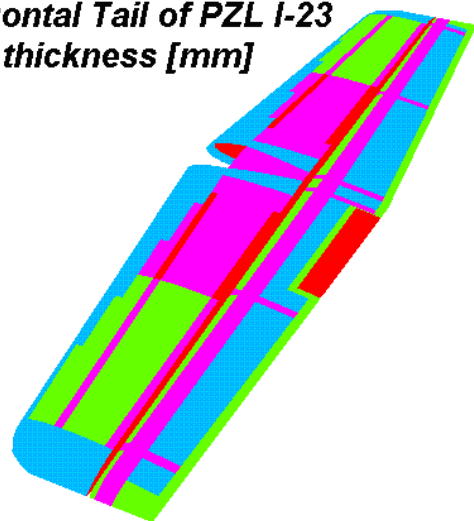
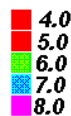


Fig. 21 Core thickness distribution

HyperSizer provides interactive viewing of computed data

- Internet standard VRML graphics allow the user quickly preview candidate designs and review results
- Any component, group, assembly or entire project can be displayed
- All data types shown, such as: panel units weights, minimum Margin of Safety, controlling load case, optimum panel concept and others.

As a example, are show results for group 1 - stabilizer skin

## Group 1 Stabilizer skin

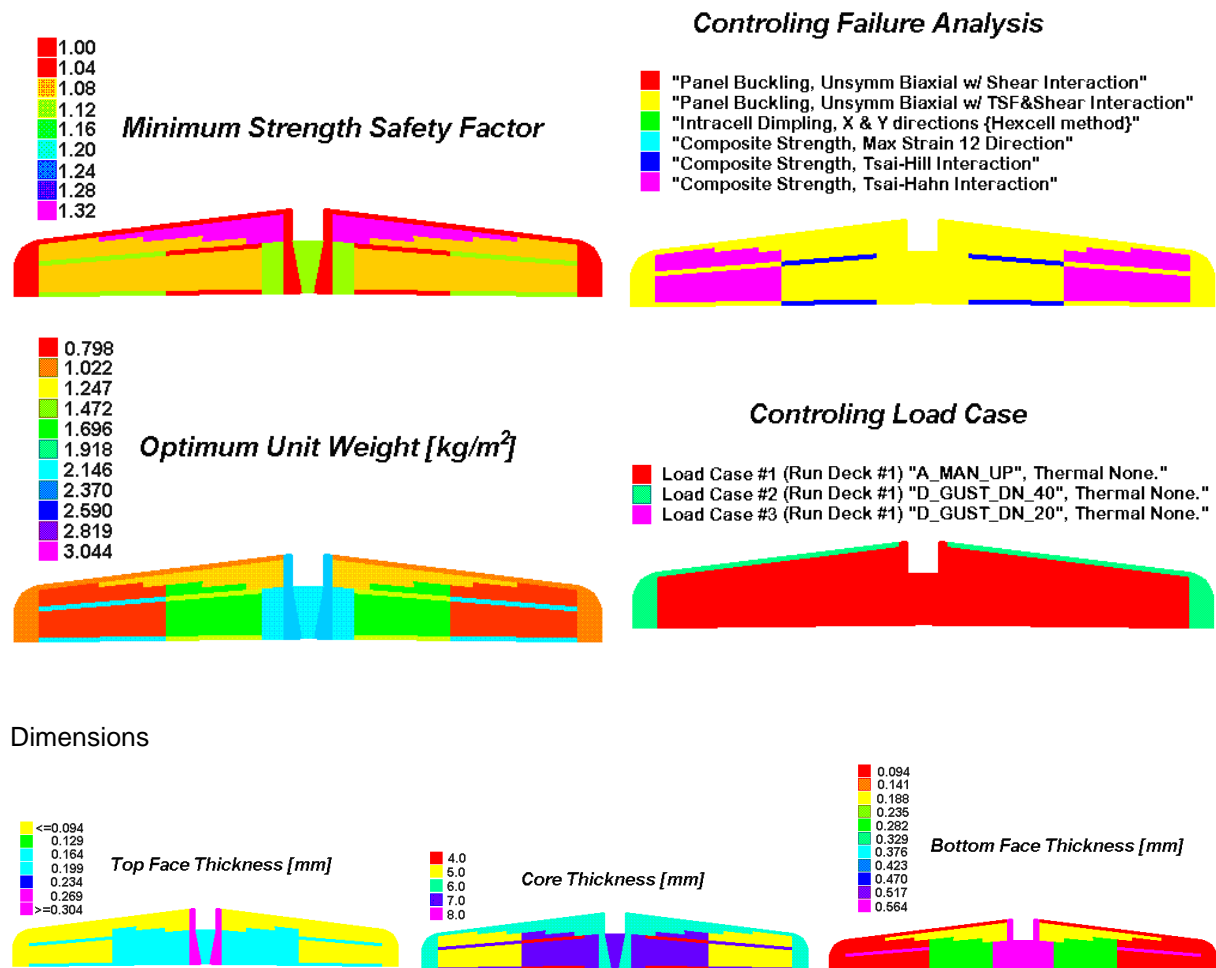


Fig. 22 Results for group 1

## 4. Conclusion

- 1) In most cases Nastran gave correct description of structure behavior. The same buckling mode have obtained, the same deformation form and similar critical areas. Differences appearing in quantities.
- 2) Computed deformations are very close measured, max. differences not exceeded 20%. Considerably worst situation is in stresses (strain) especially in postbuckling behavior. Big differences in stress calculation leading to the big differences in calculation strength of the structure. Increasing reliability of calculations of the composite structures could be reached in several ways:
  - a) increasing „mesh density” in FEM models. This methods needs more powerful computers. Global/Local method in some cases could resolve problem of computer resources.
  - b) introducing additional safety coefficients. This method is often used by many designers. For example in McDonell Douglas company is used rule not to exceeding level of computed major strains equals  $6000 \mu\text{m}/\text{m}$  for ultimate loads with safety factor 1.5. Used material (IM7/977-3) has strength equals  $12000 \mu\text{m}/\text{m}$ , this means that additional safety coefficient equals 2.0 and total safety coeff.  $1.5 \cdot 2.0 = 3.0$
  - c) introducing empirical and semi-empirical methods. Stress based on empirical methods lead to calculate internal forces flow and compare this forces with critical values evaluated in static test. This approach is very reliable and safety, but required large quantity of various tests and is very expensive. For example during design process of new composite wing and tail of F/A18 E/F Super Hornet Boeing company proceed together 12393 tests. They performed 380 tests for material selection, 1800 to select proper technology, 8000 to estimate material properties, 2200 static tests of joints, 10 static tests of isolated structures. This big quantity of tests allow to perform only 3 static tests of whole airplane. What is very important HyperSizer is using semi-empirical approach.
- 3) Presented test showed that HyperSizer is very useful in designing process of shell structures. One of the most important features of this program is speed of analysis. Optimization of horizontal tail using HyperSizer took 2 days, on the contrary the same work done using Nastran took 3 month. In both cases benefits on the structure weight was approx. 30%.



## 5. References

- [1] Reports from static test of PZL I-23 airplane. Internal report of ILot
- [2] Buckling analysis of horizontal tail of PZL I-23 airplane. Internal report of ILot
- [3] Optimization of horizontal tail of PZL I-23 airplane. Internal report of ILot
- [4] HyperSizer reference manual. Collier Research.