OPTIMIZATION OF STIFFENED PANEL WITH THE HELP OF MATHEMATICAL PROGRAMMING EXPERIMENTAL VERIFICATION

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Abstract

In the modern aircraft structural design, the high accuracy calculation to obtain the highest efficiency of the structure is possible through the utilization of computer optimization analysis. A system of structural optimization programs based on mathematical programming is being developed at the Institute of aerospace engineering, FME, BUT now. These programs are intended especially for solving the optimal design of the flat stiffened (skin - stringer) panel forced by compression loading. The calculated results were confronted with Finite Element Method analysis (MSC Software- Patran, Nastran) and were also experimentally verified.

1 Introduction

The stiffened panels are the basic structural elements of most of thin wall structures especially aircraft structures (fuselage, wing, empennage structure) since half of twentieth century. This form of the structure is a logical development of the necessity of providing a continuous surface for an airplane, combined with the requirement of the total structure weight. This is also the main reason for stiffened panels are still the most used form of the airplane structure even for the design of modern (just recently designed) aircraft with intermediate and higher loading intensity. Although utilization of the stiffened panel for the airplane structure is known for a relatively long time it is still very difficult to do precise prediction of the stiffened panel behavior during the loading. In despite of the airplane structure is forced by an amount of the loading, the predominant one appears static loading. For thin walls structures (stiffened panels) the most complications are connected with buckling and post-buckling behavior during the compression.

Utilization of the stiffened panels for airframe structures is in so far that even small weight reduction of each of them can significantly affect (in optimal case – reduce) the total empty weight of the structure. On the other side inappropriate design of the stiffened panels can absolutely uselessly increase the total structure weight. And just here is the free space for the utilization of the optimization methods.

The optimum design problem is one of the inverse tasks. It means that the structure parameters are calculated according to a known criteria of the selection, mathematically described as a cost function and the constraint functions. The cost function mostly in aerospace construction represents a weight of the structure. The requirements of the design: strength, buckling, technological, manufacturing, etc. are usually represented by the constraint functions. Nonlinear programming methods are used for the optimal design of the stiffened panels. Optimal design, in our case, means such stiffened panel that satisfies requirements for the load capacity and all specified constraint functions and its total weight is minimal. The precise determination of the load capacity of the stiffened panel with the help of analytical methods is quite complicated. These reasons led to three basic approaches to solve and comparison buckling, post-buckling behavior and total loading capacity during compression of the stiffened panels.

Analytical methods are based on determination of the critical stresses (of the skin and stringers) and their distribution along the cross section area of the stiffened panel.

Utilization of the Finite Element Methods seems like a very effective tool for determination of the load capacity during skin-stringer structure design. With the help of FEM are able to employ non linear material and geometric analysis procedures. It is possible to create the model of buckling and post-buckling behavior of the stiffened panel without consideration of the necessary simplifications usually used in analytical methods.

Although mathematical methods and the methods based on FEM are today on the high level and the results from these analyses are relatively accurate, it is still a very important to use experimental verification of the theoretical calculation during the design stage of aircraft structure. We are also able to make small modifications of the coefficient used in the theoretical methods with the help of experimental verification.

2 Stiffened panel

The stiffened panel is the elementary part of most of the airframe structures with intermediate and higher loading intensity. Stiffened panel is composed of two basic structural parts: Longitudinal reinforcing members (stringers) and the skin.

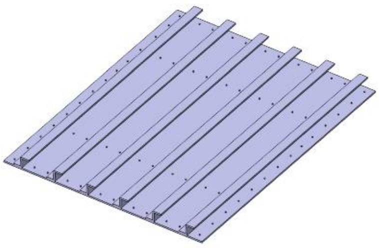


Fig.1 Stiffened panel

2. 1 Longitudinal reinforcing member 1

This is represented by stringers and longerons of fuselage shells and the spar flanges of wings. They are able to carry appreciable tensile loads and, when supported, compressive loads as well. They can carry small secondary bending loads, but their bending rigidity is negligible. So it is customary to describe them as direct load carrying members.

2.2 Skin

Like all thin shells, this is best suited to carrying load in its own surface as membrane stresses. Tensile, compressive and shear loads can be carried, but reinforcement (lateral support) is required for all but the first. The thin skins used in aircraft can only sustain and transmit normal pressure over very short distances by bending. Pressurization loads in a circular section fuselage can, however, be taken by hoop tension stresses.

2.3 Join technique

The stringers are attached to the skins by lines of the rivets, spot welds or perhaps bonding. These joints will be called upon to transmit forces mainly along their length. Forces parallel to the skin and directed at right angles to the stringers or rings or ribs will be limited by the torsion flexibility of these members. Forces normal to the skin will be limited in magnitude by the small bending strength of the skin and stringers. The primary function of these joints is thus the transmission, by shear forces, of direct loads in the reinforcing members to the skin and vice versa. Their secondary functions are indeed essential to the working of the structure but do not give rise to such large loads.

3 Structural optimization - stiffened panel

In the most general terms, optimization theory is a body of mathematical results and numerical methods for finding and identifying the best candidate from a collection of alternatives. The process of optimization lies in the root of engineering, since the classical function of the engineer is to design new, better, more efficiency, and less expensive systems as well as to devise plans and procedures for the improved operation of existing systems.

The power of optimization methods to determine the best case without actually testing all possible cases comes through the use of a modest level of mathematics and at the cost of performing iterative numerical calculations using clearly defined logical procedures or algorithms implemented on computing machines.

3. 1 Define the system boundaries

In order to apply the mathematical results and numerical techniques of optimization theory to concrete engineering problems it is necessary to clearly define the boundaries. The system boundaries are simply the limits that separate the system from the remainder of the universe.

3. 2 The performance criterion

Given that we have selected the system of interest and have defined its boundaries, next we need to select a criterion on the basis of which the performance or design of the system can be evaluated so that the best design or set of operating conditions can be identified.

3. 3 The independent variables

The third key element in formulating a problem for optimization is the selection of the independent variables that are adequate to characterize the possible candidate designs or operating condition of the system. There are several factors to be considered in selecting the independent variables. First, it is necessary to distinguish between variables whose values are amenable to change and variables whose values are fixed by external factors lying outside the boundaries selected for the system in question. Furthermore, it is important to differentiate between system parameters that can be treated as fixed and those that are subjected to fluctuations influenced by external and uncontrollable factors. Second, it is important to include in the formulation all the important variables that influence the operation of the system or affect the design definition. Finally, another consideration in the selection of variables is the level of detail to which the system is considered. While it is important to treat all key independent variables, it is equally important not to obscure the problem by the inclusion of a large number of fine details of subordinate importance.

3. 4 The system model

Once performance criterion and the independent variables have been selected, the next step in problem formulation is to assemble the model that describes the manner where the problem variables are related and the way in which the performance criterion is influenced by the independent variables. In general, the model will be composed of the basic material and energy balance equations, engineering design relations, and physical property equations that describe the physical phenomena taking place in the system.

3. 5 Objective and constraint functions

Design of optimally stiffened panel is mainly focused on selection of design parameters so that entire panel's weight will be minimal and all boundary conditions and requirements will be satisfied.

3. 5.1 Objective and constraint functions

Objective function is expressed by design parameters.

$$W_{(\vec{x})} = \rho \cdot \left(A \cdot B \cdot t + K_{FV} \cdot n_V \cdot t_V \cdot h_V \cdot A\right) \qquad (1)$$

where : W - panel weigh

ρ - material density

A,B - external panel dimensions

t - skin thickness

K_{FV} - stringer cross-section coefficient

n_V - number of stringers

t_V - characteristic stringers thickness

h_V - characteristic stringers high

The following functions define the problem of the optimum design for a stiffened panel:

We can find two basic types of constraints. The first one is in the form of equality, these constraints are not often used in structural optimization application. The second one much more common it include inequality constraints, which are listed below and you can find them in their final form:

The skin- stringer construction can develop several separate types of instability, which may be coupled to a greater or less degree.

3. 5.1 Local skin buckling

Local skin buckling between two stringers is given by: $g_1(X)$ Initial buckling (skin buckling) generally involves waving of the skin between stringers in half-wavelength comparable with the stringer pitch. There will also be a certain amount of waving of the stringer web and lateral displacement of the free flange. For some proportions these may become larger than the skin displacements, and the mode becomes more torsion or local in nature.

$$g_1(X) = 1 - \frac{N_x}{A_2 \cdot k_x{}^m} - \frac{N_y}{A_2 \cdot k_y{}^m} \cdot \left(\frac{N_{xy}}{A_2 \cdot k_{xy}{}^m}\right)^2 \qquad (2)$$

Where: $A_2 = A_1 \cdot (X_2 + 1) \cdot X_1{}^3$

$$A_1 = \frac{\pi^2 \cdot E}{12 \cdot (1 - \mu^2)} \cdot \frac{1}{B^2}$$

3. 5.2 Local stringer buckling

Local stringer buckling is given by: $g_2(X)$ Local instability: A secondary short wave length buckling may take place where the stringer web and flange are displaced out of their planes in a half-wavelength comparable with the stringer depth. There will be smaller associated movements of the skin and lateral displacements of the stringer free flange.

$$g_2(X) = \frac{N_y \cdot \mu}{X_1} - \frac{N_x}{X_1} + A_v \cdot \left(\frac{X_3}{X_4}\right)^2 \qquad (3)$$

Where: $A_v = \dfrac{\pi^2 \cdot E \cdot k_v}{12 \cdot (1 - \mu^2)}$

3. 5.3 Global panel buckling

The global panel buckling is given by $g_3(X)$. Flexural instability: simple strut instability of the skin-stringer construction in a direction normal to the plane of the skin. There may be small associated twisting of the stringers. The half-wavelength is generally equal to the rib or frame spacing.

Torsion instability: The stringer rotates as a solid body about a longitudinal axis in the plane of the skin, with associated smaller displacements of the skin normal to its plane and distortion of the stringer cross section. The half-wavelength is usually in the order of three times the stringer pitch.

$$g_3(\vec{x}) = 1 - \frac{N_x}{S_x} - \frac{N_y}{S_y} - \left(\frac{N_{xy}}{S_{xy}}\right)^2 \qquad (4)$$

Where: $S_x = \dfrac{A_1 \cdot x_1{}^3 \cdot \left[(1 + \alpha^2)^2 + G\right]}{\alpha^2 \cdot (1 + \tilde{t})}$

$$S_y = \frac{A_1 \cdot x_1{}^3 \cdot 2 \cdot \left[1 + \sqrt{(1 + G)}\right]}{\alpha^2}$$

$$S_{xy} = \frac{A_1 \cdot x_1{}^3 \cdot 2 \cdot \sqrt[4]{(1+G)} \cdot \sqrt{4 \cdot \sqrt{(1+G)} + 3 \cdot (1+G) + 1}}{\alpha^2}$$

$$G = \frac{x_2 \cdot K_I \cdot x_3 \cdot x_4{}^3 \cdot (1 - \mu^2) \cdot \kappa}{B \cdot x_1{}^3}$$

$$\tilde{t} = \frac{K_F \cdot x_2 \cdot x_3 \cdot x_4}{B \cdot x_1}$$

3. 5.4 Strength constraint

The strength is included in constraint: $g_4(X)$

$$g_4(X) = R_m - \frac{1}{X_1} \cdot \sqrt{N_x{}^2 + N_y{}^2 - N_x \cdot N_y + 3 \cdot N_{xy}{}^2} \qquad (5)$$

3. 5.5 Number of stringer limitation

The limitation of the number of stringers is one of the design-technological limitations and it is given by: $g_5(X)$

$$g_5(X) = n_{v\max} - X_2 \qquad (6)$$

Where: $n_{v\max}$ -max. required number of stringers

3. 5.6 Minimum skin thickness limitation

The limitation of the minimum skin thickness is given by : $g_6(X)$

$$g_6(X) = X_1 - t_{\min} \tag{7}$$

3. 5.7 Maximum skin thickness limitation

Analogous to minimum skin thickness is determined the maximum skin thickness : $g_7(X)$

$$g_7(X) = t_{\max} - X_1 \tag{8}$$

Where: The thickness $t_{\max}, t_{\min}$ are prescribed data.

3. 5.8 Stringer height limitation

The stringer height is defined as follows : $g_8(X)$

$$g_8(X) = h_{v\max} - X_4 \tag{9}$$

3. 5.9 Regularity of asymptotic values

Regularity of asymptotic values of coefficient $k_x{}^m$ is given by: $g_9(X)$

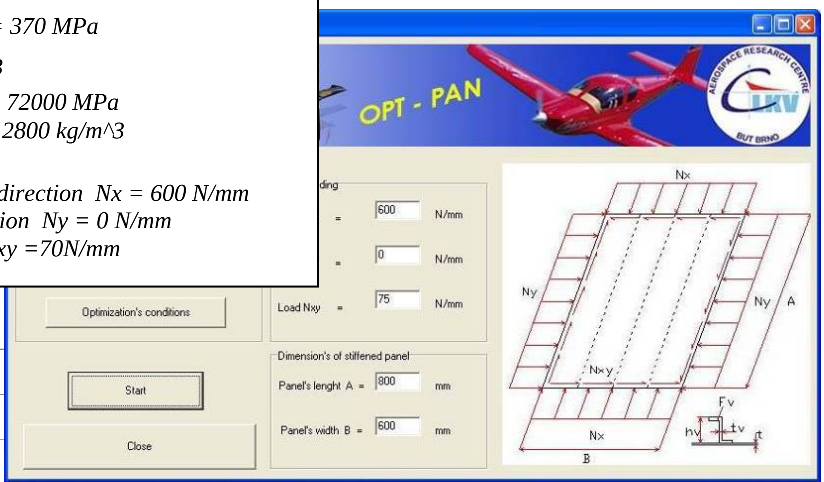
$$g_9(X) = X_3 - X_1 \tag{10}$$

Non linear optimization method based on Himmelblau algorithm was used for the optimal stiffened panel design. Algorithms describing objective and constraint functions described in chap.3.5. were implemented into Himmelblau based algorithms.

4 Structural optimization OPTPAN software

Software application OPTPAN was created in Borland Delphi version 7.0. Illustrative picture of practical example of OPTPAN utilization is in Fig.2

Input values	*Panel's length A=800mm* *Panel's width B =600mm*
Material characteristics	*Ultimate strength σ_{pt} = 370 MPa* *Poisson. const. μ =0,33* *Modulus of elasticity E= 72000 MPa* *Density of material ρ =2800 kg/m^3*
Panel's loading	*Loading in longitudinal direction Nx = 600 N/mm* *Loading in lateral direction Ny = 0 N/mm* *Loading by shear flux Nxy =70N/mm*



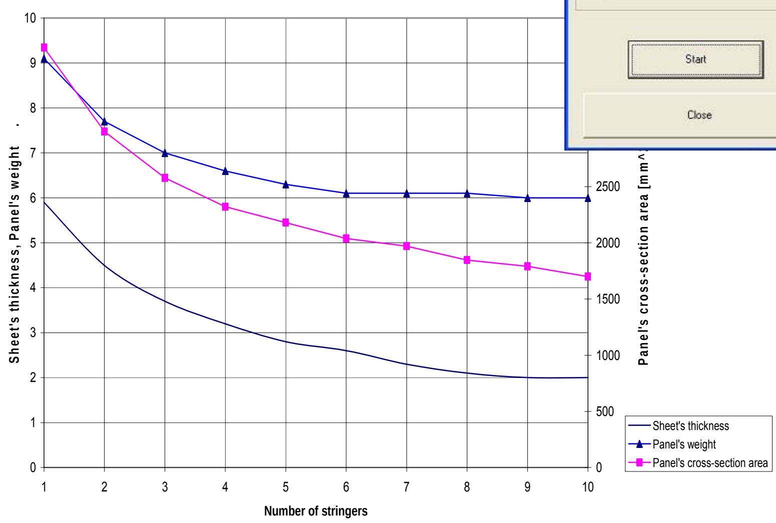


Fig.2 Software OPTPAN developed on Brno University of Technology for stiffened panels optimization. Graph includes OPTPAN's results for optimization for the above mentioned example of input data. From the graph it is quite clear that for the same panel external dimensions and the same loading, it is more preferable to use structure with more stringers especially with regard to the total panel's weight.

5 Determination of the stiffened panel load capacity

The precise determination of the stiffened panel load capacity is the essential key for the proper optimally design of the stiffened panels. Three main methods are considered. The utilization of the particular method depends especially on the level of the design (The preliminary design gives priority to velocity of the calculation on the other side the FEM are especially focused for the final design and gives the priority to the maximal accuracy. The utilization of analytical methods as well as methods based on FE is still necessary to complete by any of experimental methods.

5. 1 Analytical method

Analytical methods can be very useful tool in the area of the preliminary analysis because of the simplicity and high speed finding of the sufficiently good results. The analytical methods estimation of the load capacity is usually based on the determination of critical stress of individual components. (This part of design is critical for the accuracy of the calculation). Very effective tool seems to be the method with designation: ***The Gradually Increased Loading Method (GILM)*** published by [3]. This method allows as well as other analytical methods to find the total load capacity of the stiffened panel but in addition it allows us a relatively precise description of the loading history.

The GILM basic simplified algorithm is shown below on fig.3:

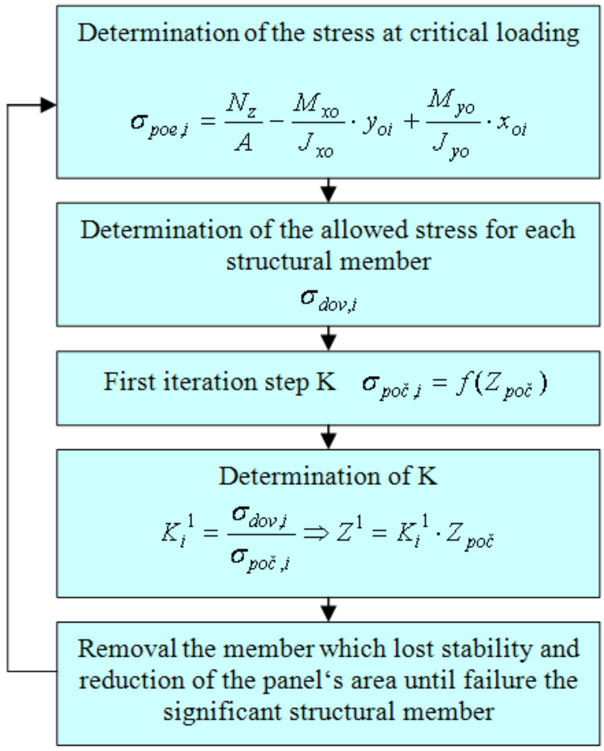


Fig.3 The algorithm of the GILM (An Example of the practical utilization of the MGIL is described in task 5.4.

5.2 Finite element method FEM

FE method is a very popular tool for structural analysis today. It is a very effective variation method for the design of even a very complex structural parts or assemblies. In comparison with Analytical methods (in our case represented by GILM) are the FE methods more accurate but the speed of calculation is significantly slower. All FME analyses involved in this paper were made in MSC software (Patran, Nastran).

FEM design process (stiffened panel load capacity estimation) consists of several basic parts [8].

5.2.1 Model idealization

For most of computational analyses the real structure has to be idealized, because of impossibility to include all details to the model. This part of FEM analysis is very important. Wrong model proposal may significantly affect results. The first extreme is too simplified model which usually gives nonrealistic results.

The second extreme is too detailed model which leads to unreasonable computation time.

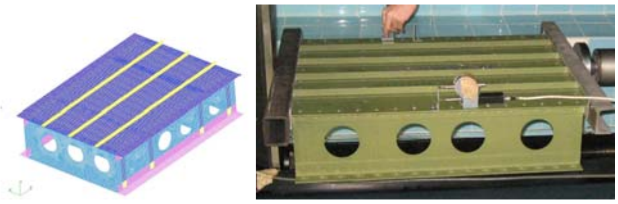


Fig.4 Testing box including stiffened panel (Modeled vs. Real)

5.2.2 Element selection

For most of FEM it is typical of utilization of the elements which represents a structural part. It is necessary to consider two basic goals. Primarily, the element type determination. For thin walled structure, especially for stiffened panel, it is typical to use quadratic shell elements. A very important role also plays the element density estimation. Especially for thin walled structures were the buckling is the most common form of the failure it is recommended [8] to use at least four elements per buckle half-wavelength (to obtain a high degree of accuracy).

5.2.3 Boundary condition

Boundary condition estimation is usually a very complicated step of FEM analysis. The utilization of the testing box described in chap. 5.3.2 this step is significantly simplified. Only two necessary types of boundary conditions are used for FEM analysis of stiffened panel in this paper.

a) All three degrees of freedom in translation are removed. See fig. 5 (left)
b) Loading is represented by displacement of boundary nods. See fig. 5 (right)

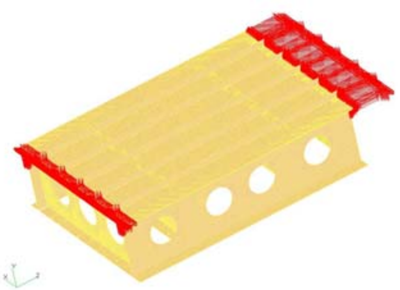


Fig.5 Boundary condition of stiffened panel and testing box

5.2.4 Material modeling

Material behavior for the skin, stringer and frames must be appropriately represented. It is quite complicated to estimate a material behavior especially in non linear area. Coupon tests of used material which provide real material properties and characteristics are highly recommended.

5.2.5 Solution procedure

For complete stiffened panel buckling and post buckling behavior prediction, the most suitable method appears the nonlinear analysis. (MSC Software Patran/Nastran – SOL 106).

5.2.6 Effect of initial imperfections

The modeling of initial imperfections plays a very important role in simulation of buckling and post buckling behavior of thin walled structures. Without imperfections implementation in to model the results by FEM are significantly different. (Model structure is able to force much more loading than real structure). The correct imperfections estimation is key factor to accurate load capacity of stiffened panel prediction. In the case of stiffened panel it is usually adequate to make a geometrical translation of several nodes in the distance 1xskin thickness. Next form of imperfections is sometimes considered eg. Stress imperfections [MKP imperfect2].

The results of FEM analyses are summarized and confronted with other approaches (analytical, experimental) in chap.5.4. The example of some results is shown on fig.6

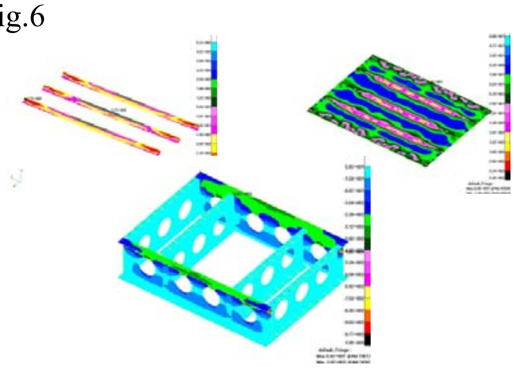


Fig.6 FEM analysis results

5.3 Experimental methods

Experimental verification of the results by analytical and FE methods still belongs to necessary part of aircraft design. Experimental verification is a very important part also for this research.

Stiffened panels are mostly used in the aircraft structure with higher loading intensity. Stiffened panels with common dimensions (for such aircraft structures) were selected for optimization and testing. The dimensions were also determined with regard to the size and performance of available testing machine (available space and the maximal compressive force).

External panel's dimensions and loading direction is shown in fig.7

$A = 800mm$

$B = 600mm$

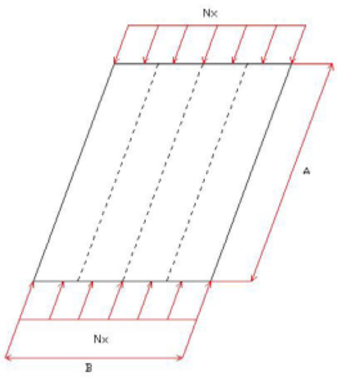


Fig.7 External panel's dimensions and loading type

The testing equipment is composed of several basic parts:

5.3.1 Testing machine

Technical parameters of testing machine:

Max. force 500 000N
Available testing space (height) 900 mm

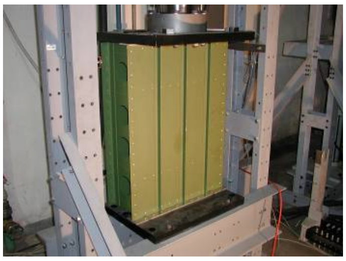


Fig.8 shows the view on testing machine.

The testing machine is composed of a heavy stand and the hydraulic actuator. It includes the dynamometer. These components are connected to the central computer recording the data from the measurement. Fast evaluation of measurement is possible see fig.9.

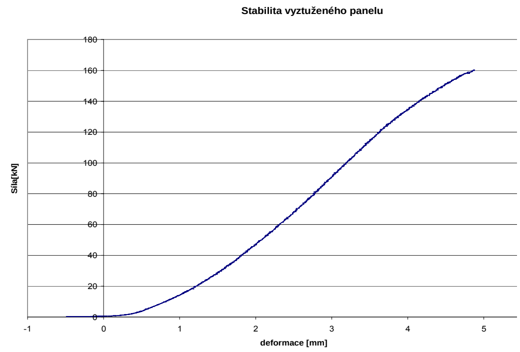


Fig.9 Relation between the force and the hydraulic actuator translation

5.3.2 Testing box

The testing box belongs to the fundamental parts of the testing equipment. Catia model vs. the real box is shown on the figure 10. This special box enables a realistic simulation of the boundary conditions during the testing of the buckling and post buckling behaviour of the stiffened panel. Riveting nuts for easier panel's exchange are attached in the flanges of the ribs and flanges of the spar. It is also possible to fasten two stiffened panels on one box (both sides are ready for panel´s clamping) at one moment by threads. It allows faster change of stiffened panels for next measurement. Dimensions of the box correspond to dimension A resp. B of stiffened panel see fig.7.

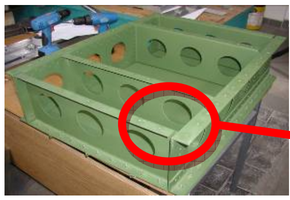


Fig.10a Real testing box

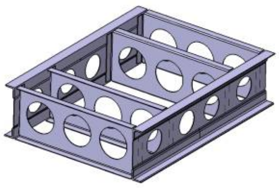


Fig.10b 3D model box

5.3.3 Measuring instruments

Several ways how to measure stability, buckling, post-buckling behaviour and total load capacity of the stiffened panels during compression exist. Measuring instruments in this paper are divided in two basic categories. The first belongs to research of buckling and post-buckling behaviour of skin and stringers of the stiffened panel. Second belongs to research of total load capacity of the stiffened panel with regard to testing equipment.

5.3.3.1 Buckling measurement by digital camera

The principle of this method is to record the stiffened panel by video camera and next evaluate a translation of the selected points (as movement of pixels). For better visualization the panel was divided by grid, see fig.11. Key problem of this method is to harmonize video camera and loading time.

The video camera was situated on the bottom of the stiffened panel. Pictures were done with the help of the system of mirrors. See fig.11. There are evident differences on the unloaded panel vs. loaded panel.

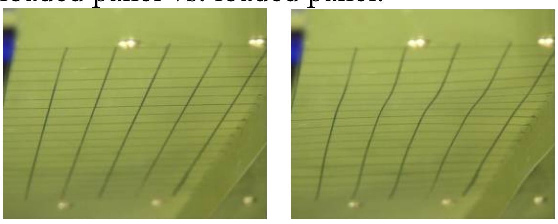


Fig.11 Unbuckled vs. buckled stiffened panel

This method is not very useful for early phases of buckling. Lines in the grid are very thick compared to pixel's magnitude. Recognizing exact time when the skin starts to buckle was difficult. Evaluation of this method is time consuming.

This method is more suitable for evaluation of a dynamic experiment with larger shape deviation.

5.3.3.2 Buckling measurement by drift meters

Also Sylvac drift meters were used to find the critical compression loading of stiffened panel components. The drift meters are very sensitive equipment which is able to record even a very small movement of the skin. From the theory of thin plates buckling it is clear that skins buckles in a sinus waves. Using this theory, it is necessary to find a best drift meter position. It means to situate the drift meter to the top of sinus curve (not to the nod!). Correct position is established using information from fig. 12.

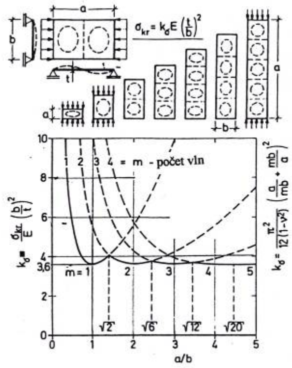


Fig.12 Number of waves on the skin within the compressive loading

The positioning of the drift meters on the skin of stiffened panel is shown on Fig.13 Buckled vs. unbuckled skin.

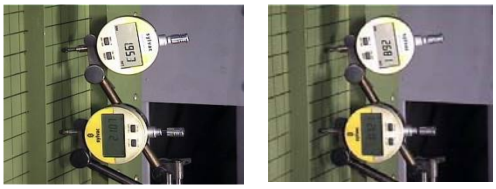


Fig.13 Unbuckled vs. buckled skin

This method for buckling and post buckling behavior measurement of stiffened panels seems very attractive especially for its simplicity and for quite high accuracy. Despite of this fact we reached very valuable results, see. Fig.14. Although, we used only three drift meters on relatively large surface, the time of skin buckling is quite clear from fig.14.

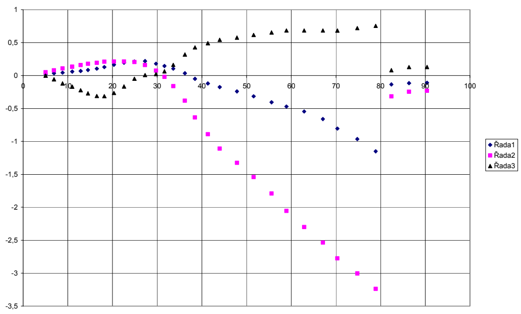


Fig.14 Relation between drift meters deviation and panel's loading

5.3.3.3 Buckling measurement by aripots

Aripots were also used to find critical compression loading of stiffened panel components. This equipment has a similar sensitivity as drift meters described in previous paragraph. Same presumptions as of positioning drift meters are considered for positioning of the aripots. Five aripots were used for better (more precise) description of the skin's behaviour, see Fig. 15

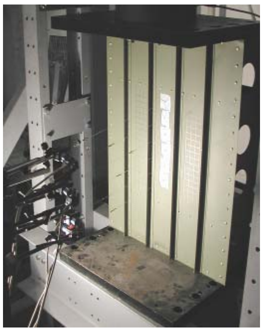


Fig.15 Measurement by aripots

Similar to measurement by drift meters, measurement by aripots seems very attractive and low costs of measurement.

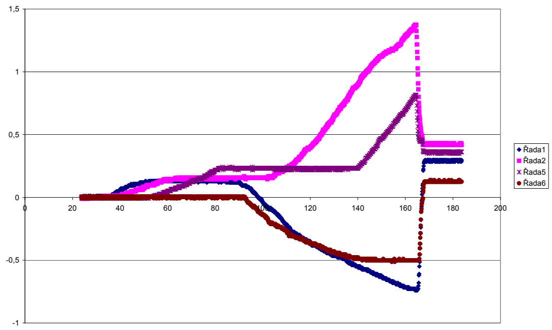


Fig.16 Relation between aripots deviation and panel's loading. The point of buckling start is clear.

All measuring methods presented till now are focused on research of buckling and post buckling behaviour of the skin. No special method was used for the research of buckling and post buckling behaviour of the stringers. It is possible to find local stringers instability only by observation Fig.17

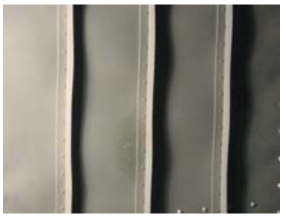


Fig.17 Stringers buckling

Although, above mentioned measuring methods are applicable for observing the buckling and post buckling behavior the big limitation makes a utilization of the special testing box. When the testing box is used we are not able to determine the load distribution between the box and the panel with adequate accuracy.

Several experiments were done to distinguish the panel's loading and the testing box loading.

a) Two measurements were made for the same boundary condition. In the first case only the testing box was loaded. In the second case, testing box including stiffened panel were loaded. Difference in loading for the same deformation can be distinguished by force applied to the panel. See Fig.18

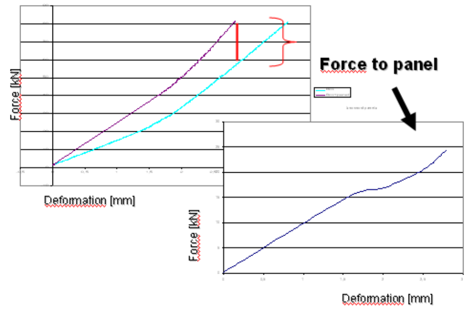


Fig.18 Determination of the loading distribution

b) Two drift meters were attached to flange of the testing box to find the flange deformation and actual flange stress during loading. Force to the testing box was calculated from the flange stress. The difference between the total force measured by dynamometer and calculated value of the force to the testing box is the force to the stiffened panel See fig.19

Fig.19 Determination of loading distribution by drift meters

5.3.3.3 Total load capacity, buckling and post buckling behavior prediction for the stiffened panel using of tensiometers

The inaccuracy was relatively high for all methods used before. Significant progress is connected with utilization of tensiometers. Tensiometers measuriement seem to be very effective tool both for

Fig.20 Tensio-measurement

total load capacity measuring and for buckling and post buckling behavior monitoring.

The tensiometers with designation 10/120LY13 were used for the measurement.

The tensiometers locations are very important for precision measurement. For precise determination of the compressive stress, especially for thin wall structure, it is necessary to attach two tensiometers on both sides (directly opposite) of the measured object for elimination of the bending stress see Fig.21.

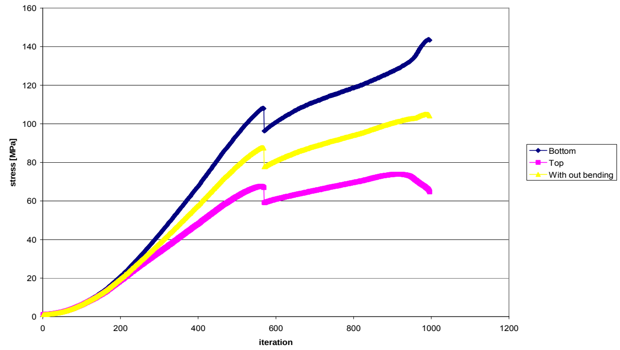


Fig.20 Estimation of the purely compressed stress

All tensiometers were located in the same cross section area (of box-panel) which allowed us to show the compression stress distribution in this region for the stiffened panel and the testing box. Fig. 21 and Fig. 22 clearly show buckling and post buckling behavior of individual panel's component (skin, stringer, box flange) during the increasing loading.

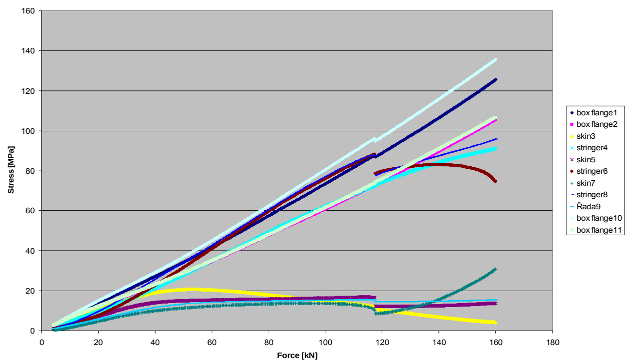


Fig.21 Relation between stress and force during compression

Stress distribution along the cross section area of stiffened panel included testing box flanges

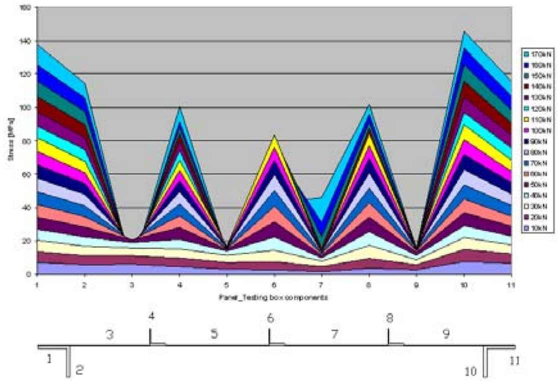


Fig.22 The real stress distribution along the cross section area of the stiffened panel and testing box

The theoretical stress distribution along the cross section area of the stiffened panel is shown on Fig.23. The comparison of theoretical and experimental results shows nearly perfect match.

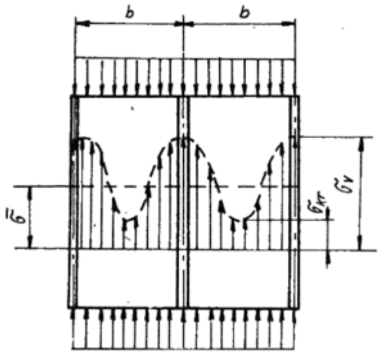


Fig.23 The real stress distribution along the cross section area of the stiffened panel

5. 4 Total load capacity comparison of used methods

Three main approaches were used for prediction of the total load capacity of stiffened panels: Analytical methods, Utilization of FEM, Experimental verification. The results of individual approaches were systematically confronted. On the basis of this verification there were modified the input data for:

Analytical methods: boundary conditions (It is very difficult to exactly determine if riveting or screwed connection creates more pinned or fixed boundary condition).

FEM: The utilization of FEM analyzes for flat thin walled structures bears a several complications which can cause a significant decrease in accuracy. Very important is correct determination of suitable imperfections (material, geometric) which are necessary for correct buckling prediction. The simplification of the model (eg. riveted vs. integrally stiffened panel) also significantly affect the results.

The example of the total load capacity estimation is shown on Fig.24

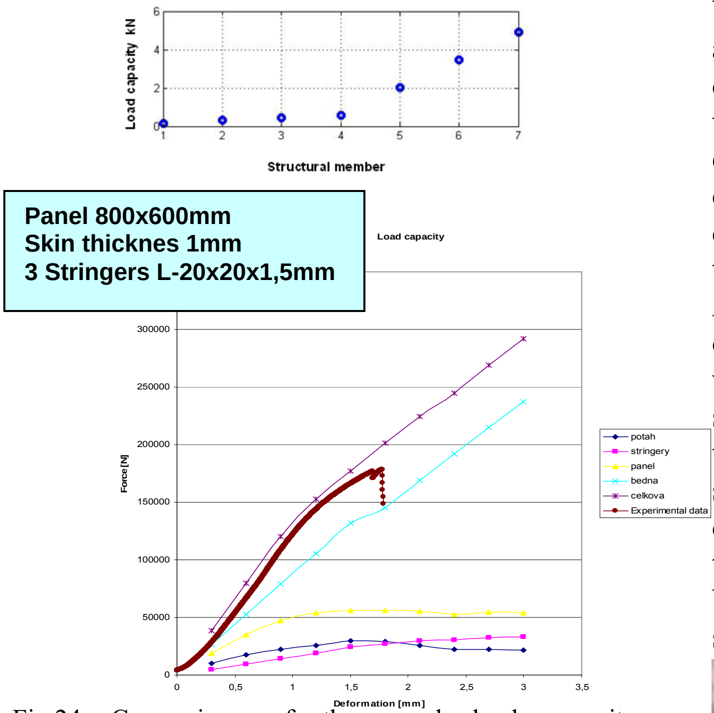
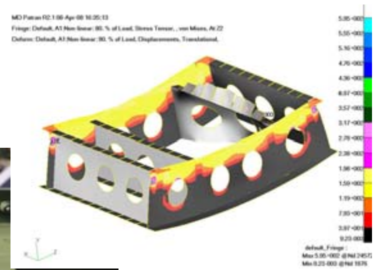


Fig.24 Comparison of the panel load capacity (approximately 50kN) and the total load capacity (180kN) for input data was made. The results from all three methods seem to be very similar.

5 Conclusions

The optimal design of the stiffened (skin-stringer) panel using mathematical programming methods is presented in this paper. The optimization program OPTPAN was made at Institute of Aerospace engineering, BUT. This program includes non linear optimization methods described by Himmelblau and algorithms for description of buckling and post buckling behavior of the stiffened panels presented in [3]. The main focus of OPTPAN software is especially aimed for preliminary design stage. The principle of precise results of OPTPAN software is accurate determination of the total load capacity of stiffened panel using analytical method. The analytical methods give very good results but exact estimation of the boundary conditions, material properties, proper buckling and post buckling algorithms is required.

Therefore analyses based on FEM and experimental verification was done to verify results of analytical methods and to refine the input data. Special testing box was made for testing of stiffened panels load capacity, buckling and post buckling behavior to simulate as much as possible real boundary conditions during the loading. Although the utilization of the testing box during experiments gives excellent results, it was affected by several complications. The biggest one is relatively difficult recognition of the distribution of the total force in to the panel and the testing box. Another complication is that the testing box can only be utilized for the stiffened panels for which skin and stringers have critical stress significantly lower than critical stress of the testing box. If the critical stresses are nearly the same the great forces are needed for testing and damage of the testing box can occur see fig.25



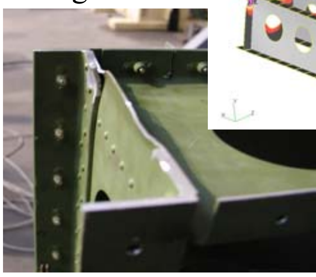


Fig.25 Testing box damage

The results of FEM analyses are in agreement with both analytical and experimental results. It is necessary to follow basic recommendations. The utilization of geometrical imperfections in 3D model is necessary. If the imperfections are not used the significantly higher load capability is predicted. The excessive simplification of the model (using integrally stiffened panel instead of riveted skin stringer panel) can also markedly affect the results.

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