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Experimental – Numerical Analysis of Deformation of Post–Critical States of Thin–Walled Elements of Bearing Airframe Structures

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The study presents the results of studies of thin–walled systems subjected to shear, constituting the forming models of parts of air cover bearing structures. It presents the results of experimental and non–linear numerical analysis in terms of the finite elements method of a number of variants of superstructures. The methods of verifying the results of numerical calculations have been developed, as well as a set of efficient numerical procedures, allowing to obtain reliable results of calculations, has been set.

Keywords: Buckling, thin–walled structures, non–linear analysis, equilibrium path, post–critical deformations.

1. Introduction

Loss of stability of thin shells, subjected to various types of loads, is a phenomenon commonly found in construction of semi–monocoque airplane structures. Fragments of the coverings of the aircraft often lose stability during exploitation. This phenomenon in case of metal structures is permitted, as long as it has a resilient nature and occurs locally in the area of the shell, restricted by elements of the skeleton.

Constant phases of the design process of aircraft structures, therefore, should be the analysis, allowing for the determination of the distribution of stress in advanced post–buckling states of deformation which, in case of the semi-monocoque structure, due to impact forces, are of cyclical character. This causes the appearance in the material of the coating of fatigue effects, and therefore knowledge of the stress field is necessary not only because of the identification of areas of concentration, but also provides the basis for determining the fatigue life of the structures analyzed.

Additional problems can be brought by all kinds of patterns, i.e. service cut-outs and inspection openings, which cause local reduction of construction stiffness. They cause changes in the nature of loss of stability, in comparison to areas without this kind of singularity, as well as the emergence of strong local stress concentration.

In case of composite structures used in aviation, in accordance with the applicable standards, the loss of stability of shells is generally not acceptable. This follows from the fear, that during the number of load cycles and related advanced states of deformation, the damage may occur to the structure of the material, manifested by the delamination of the composite components.

The presented studies are part of a comprehensive program, under which the analysis of the impact of cyclical post–buckling states of deformation on the fatigue life of coatings, which are made of isotropic materials, and the condition of the internal structure of composite materials, are expected.

The basic numerical tools, widely used in the design processes, are programs based on finite elements method. But while in case of linear analysis, the present state of advancement of commercial software, most of the results can be regarded as credible, the more nonlinear procedure used for determining the deformation of advanced post–critical states, still bring many problems. These problems arise from the limited reliability of numerical procedures defining the equilibrium states of the structures, corresponding to the successive points of equilibrium path. As a result, despite the apparently correct mapping of the structure stiffness, it often comes to obtaining the results burdened by significant errors.

To confirm the reliability of the results of nonlinear numerical FEM analysis it is necessary to carry out experimental verifications. In particular, it seems to be reasonable to use a relatively inexpensive experiment which uses a model material.

The convergence of a deformation obtained by the numerical results and the experiment allows the recognition of the reliability of the results of calculations. Based on the principle of uniqueness of solutions, according to which a particular form of deformation corresponds to the one and only one form of distribution of stresses, the effective stress distributions in the deformed shell may also be found reliable.

In order to achieve these comparisons, it is necessary to make possible the precise measurements of the geometry of the deformed body. During the presented studies a scanner Atos of German company GOM Optical Measuring Techniques has been used, the principle of which uses the method of moiré projection

2. Scope and field of study

The presented studies have been aimed to develop an effective methodology for determining the distribution of stresses in the shells experiencing post–critical deformation, including the selection of appropriate numerical methods and parameters controlling the courses of algorithms in nonlinear finite elements method analyses.

The subject of the research presented in this study were thin regimes of shape and dimensions shown in Fig. 1, subjected to shear, which constitute mapping parts of semi–monocoque cover designs. The regimes of different diameter wheel patterns, imitating the service cut–outs have also been analyzed.

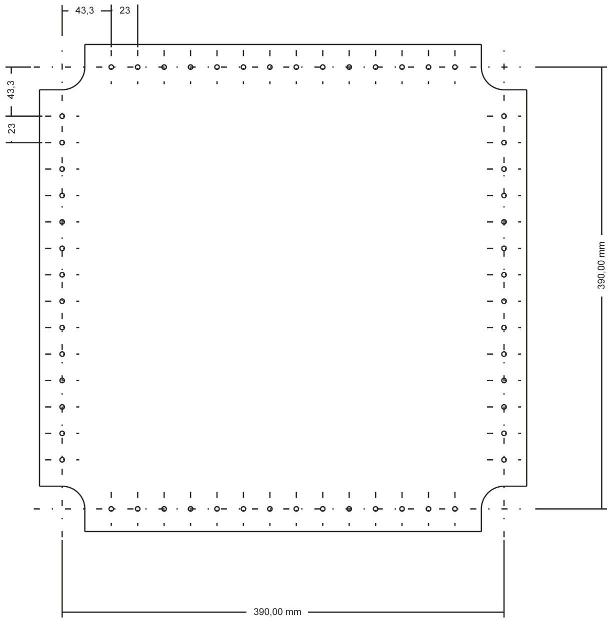


Figure 1 Geometry of the test system

3. Experimental research

According to the assumptions, the predicted test cycle includes several stages, which require the use of appropriate research devices.

Basic research device, used in case of a static experiments, consisted of a frame of a large margin stiffness, inclusive of the mounting and loading system (Fig. 2).

Figure 2 Research device for experiments with static 3D scanner ATOS

The tested system was mounted in a special frame, made of rigid steel beams, which were pivotally connected at the corners. The load in the form of forces carried out using the gravity method, using the links passed through the roller system (Fig. 3). In the various phases of the experiment strain, using an optical scanner, was measured.

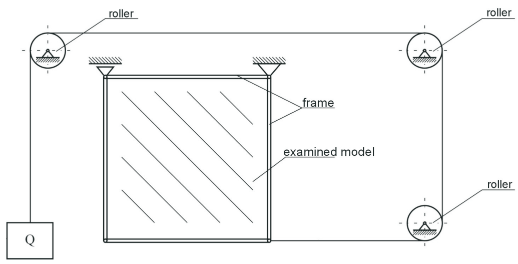
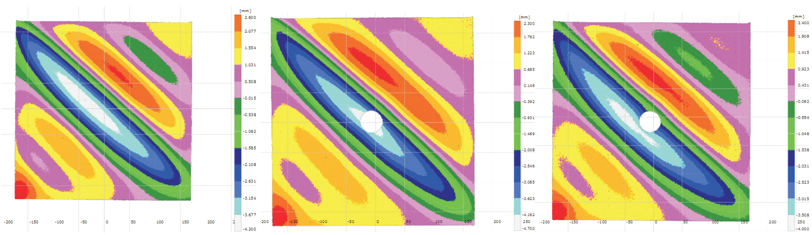


Figure 3 Scheme of fixing and application of the load

The experiment was carried out by using three variants of the model: the system devoid of holes, the system with a central circular hole with a diameter of 35 mm and the system equipped with a hole reinforcing ring with a width of 5 mm and thickness of 4 mm. In all cases investigated bodies have been forcibly charged to a peak of 900 N. Models are made of polycarbonate, of a trade name Macrolon, which is an isotropic material: E = 2150 MPa, ν = 0,4. The loss of stability occurred in relatively low load values, due to the nature of the distribution of stress field forming the tension field. Figure 4 presents the experimentally obtained distributions of displacements in the form of color contours, generated using GOM Inspect Software cooperating with the Scanner 3D ATOS.



a) b) c)

Figure 4 Distributions of displacement normal to the surface of the element, obtained from the experiment: a: a basic model, b: a model with a hole without amplification, c: a model with the ring reinforcing hole

In all cases advanced post–critical deformations had a similar nature, with the main fold extending along the diagonal model. In case of the model with the strengthening of the opening folds a shift toward to the corner has been seen, which resulted from the local rigidity. For all cases, the representative equilibrium paths have been made, which were adopted by the relationship between the maximum displacement in the perpendicular direction to the plane of non–deformed model and the value of loading force (Fig. 9).

In further phases of research, taking into account the determination of the fatigue life of thin shells experiencing post–critical cyclic deformation, the device shall be equipped with numerically controlled actuator of the Zwick Company (Fig. 5).

Figure 5 Research device of the fatigue test

4. Nonlinear numerical analysis

Numerical calculations were performed using the software MSC Patran - MSC MARC. The tested bodies were mapped using about approx. 5,000 thin–shell elements. In case of the model system around 2000 fixing thick–shell elements were used. A combination of a continuous attachment between the system and the model test system was applied. This simplification resulted from the pursuit of achieving the small size of the task and the fact that in case of use of the type of MPC bonds, used to map of the discrete wiring, in the nonlinear numerical procedures numerous errors occur, which lead to distorted results or even making it impossible to obtain a solution. After a series of numerical tests it was found, that the best qualitative and quantitative results of the calculation allows for a combination of secant prediction method and hyperspheric Crisfield correction strategy. The appropriate values of parameters ??for nonlinear process control have been selected. The Figure 6 shows the numerical models of examined systems with visualized mesh.

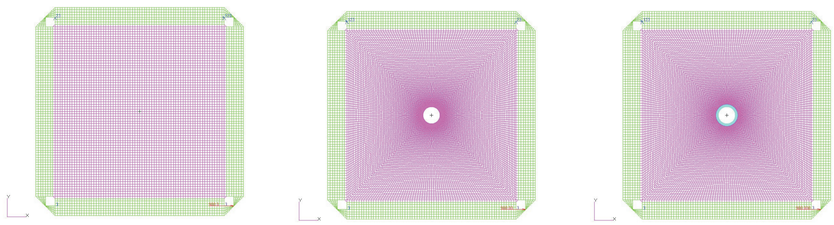


Figure 6 Numerical models of systems analyzed

Fig. 7 shows the numerically obtained distributions of deformation, and Fig. 8 shows effective stress distributions by the Huber-Mises-Hencky hypothesis in the analyzed models.

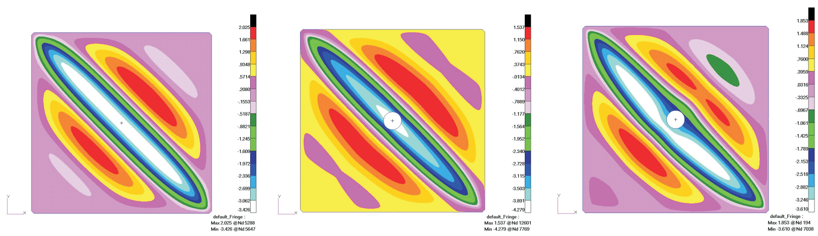


Figure 7 Distributions of displacement in the direction normal to the plane of the non–deformed model

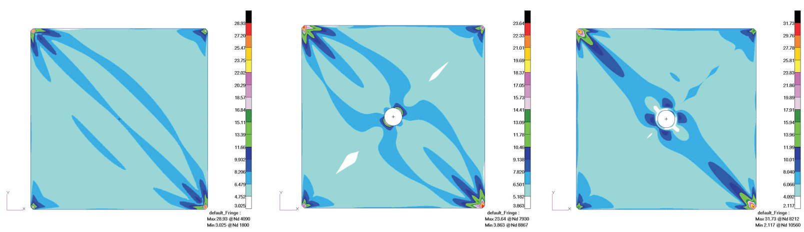


Figure 8 Distributions of effective stress, according to Huber–Mises–Hencky hypothesis

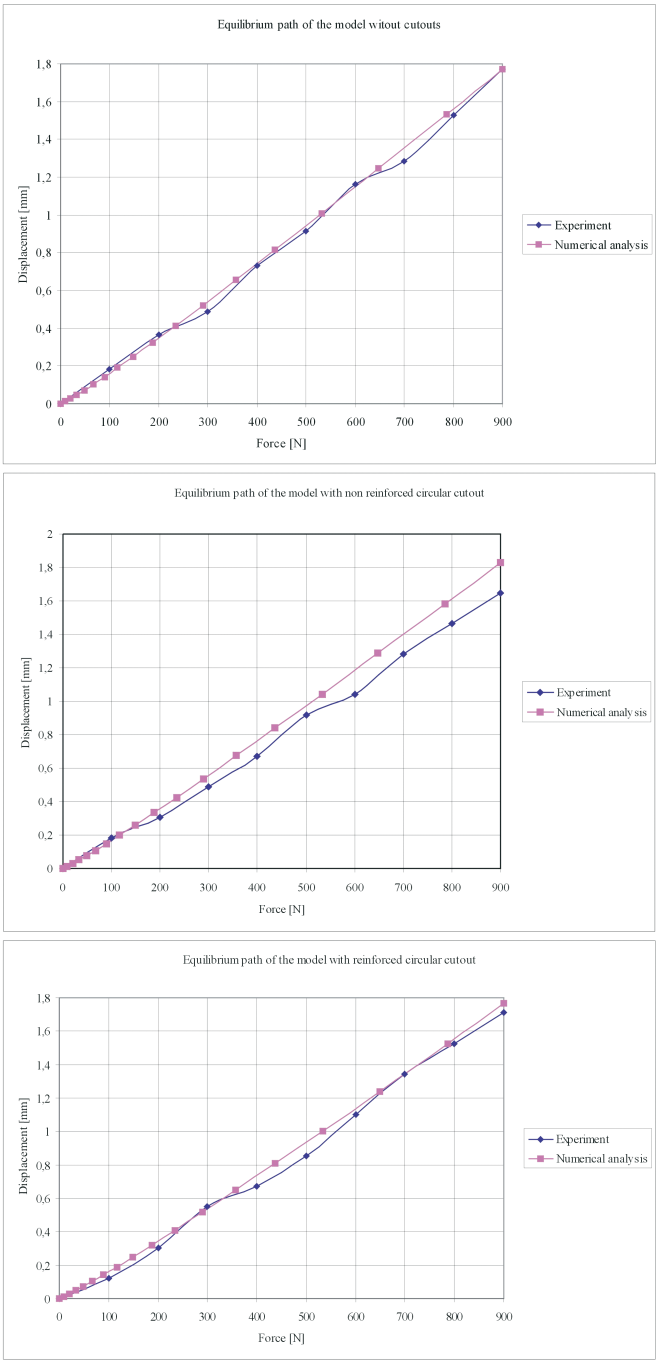


Figure 9 Comparisons of representative equilibrium paths

Fig. 9 presents a summary of representative equilibrium paths obtained from experimental research and non–linear numerical analysis.

5. Discussion of results

Using the principle of uniqueness of solutions requires a sufficiently accurate numerical representation of advanced states of deformation of the investigated structures. The basic criterion for assessing the accuracy is the overall similarity obtained through numerical and experimental displacement distributions at the assumed maximum load. Furthermore, it is necessary to obtain a satisfactory convergence of the equilibrium paths. In case of systems with many degrees of freedom, the equilibrium path, which is a relationship between a set of state parameters and the control parameter associated with the load, is a subset of the multi–dimensional state space. For practical reasons, dictated by the limited possibilities of measurement, as well as the desire for the effective visualization of results, the criterion of similarity of the processes of deformation was considered the compatibility of representative equilibrium paths, representing the relationship between the geometric representative value, and the control parameter, constituting the measure of the load.

According to accepted criteria, the basis for assessing the reliability of the results of nonlinear numerical analysis was the similarity of displacements distributions presented in Figs 4 and 7. Given the virtually identical nature of the deformation and the displacement of very similar values in the corresponding areas of both types of models, it is considered that the adopted predictive method and corrective strategy constitute an effective combination for this type of problem. Additional confirmation of the reliability of the results is the satisfactory convergence of representative equilibrium paths obtained experimentally and numerically, for each of the analyzed structures.

Therefore, also effective stress distributions shown in Fig. 8 were considered reliable. As expected, in all cases, the stress concentration zones were located at the corners of systems and it was there that the fatigue damage should occur. It should be emphasized that the strengthening of corners' regions to eliminate stress concentration, seems possible and even relatively easy, from the design point of view. Assuming sufficient strengthening of the structures' corners important is the distribution of stresses in the central regions of models. In all cases, elevated stress values occur along the borders of the folds, which result from the effects of bending in the shell. In addition, the stress concentration zones occur in areas of the holes, but in the case of the hole with reinforcement, gradients, and reduced maximum stress value are much smaller than the hole unfortified.

From these observations, the essential recommendations relating to the construction of such load–bearing structures emerge, according to which it seems appropriate to apply suitable reinforcement both in the corner zones and in cut–out zones. The resulting distributions of stress can be the basis for further analysis of a fatigue crack. These analyzes must include the use of appropriate software, for example, MSC Fatique and adequate model experiments.

The proposed research program is therefore a combination of experiments of a static and fatigue character, as well as various types of numerical analyzes, using modern software based on finite elements method.

References

[1] **Arborcz, J.**: Post–buckling behavior of structures, Numerical techniques for more complicated structures, *Lecture Notes in Physics*, 228, **1985**.

[2] **Bathe, K. J.**: Finite element procedures, *Prentice Hall*, **1996**.

[3] **Doyle, J. F.**: Nonlinear analysis of thin–walled structures, *Springer–Verlag*, Berlin Heidelberg New York, **2001**.

[4] **Crisfield, M. A.**: Non–linear finite element analysis of solid and structures, *J. Wiley & Sons*, New York, **1997**.

[5] **Felippa, C. A., Crivelli, L. A. and Haugen B.**: A survey of the core–congruential formulation for nonlinear finite element, *Arch. of Comput. Meth. In Enging*, 1, **1994**.

[6] **Felippa, C. A.**: Procedures for computer analysis of large nonlinear Structural System in Large Engineering Systems, ed. by A. Wexler, *Pergamon Press*, London, **1976**.

[7] **Kopecki, T.**: Stages of advanced deformity in the design of thin–walled regimes, *Publishing House of the Rzeszow University of Technology*, Rzeszow, **2010**.

[8] **Kopecki, H.**: Problems in the Analysis of load–bearing structures stress states in the light of experimental methods using the mode mechanics methods, in Polish], Rzeszów University of Technology Scientific Papers , No. 78, Rzeszow, **1991**.

[9] **Laerman, K. H.**: The principle of integrated photo–elasticity applied to the experimental analysis of plates with nonlinear deformation, Proc 7 th Conf on experimental stress analysis, Haifa, **1982**.

[10] **Lynch, C.**: A finite element study of the post buckling behavior of a state typical aircraft fuselage panel, PhD. Thesis, *Queen's University Belfast*, **2000**.

[11] **Marcinowski, J.**: Nonlinear stability of elastic shells, in Polish, *Publishing House of Wroclaw University of Technology*, Wroclaw, **1999**.

[12] **Rakowski, G. and Kacprzyk, Z.**: The finite elements method in mechanics of structures, in Polish, *Publishing House of Warsaw University of Technology*, Warsaw, **1993**.