ZBORTENIE VALCOVEJ ŠKRUPINY S OTVORENÝM PRIEREZOM ZAŤAŽENEJ NA KRÚTENIE. EXPERIMENTÁLNE SKÚMANIE

POST BUCKLING STATE OF OPEN SECTION CYLINDRICAL SHELL LOADED IN TORSION. EXPERIMENTAL INVESTIGATION

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Abstrakt

Článok sa zaoberá experimentálnou štúdiou stavu po zbortení valcových škrupín s otvoreným tenkostenným prierezom a zaťažených núteným krútením. Boli skúmané tri prípady líšiace sa geometriou: valcové škrupiny s otvoreným prierezom vystužené tromi, piatimi a siedmimi rozperami. Cieľom článku je vykonať analýzu správania sa konštrukcie po jej zbortení s ohľadom na charakter rozloženia deformácie a napätia. Boli vykonané hlavne štúdie vplyvu, dôležitosti a užitočnosti skúmania experimentálneho modelu vo vybraných kritických zónach navrhnutej nosnej konštrukcie. Bolo poukázané na účelnosť experimentovania pre vybrané prípady podobných riešení tvoriacich základ pre odhad numerických MKP modelov a algoritmov.

Kľúčové slová: škrupina, nútené krútenie, otvorený prierez, stav po zbortení, experimenty, analýza MKP.

Abstract

The paper concerns experimental studies post buckling of thin-walled open section cylindrical shells subjected to constrained torsion. Three structure solutions, differential in respect to geometrical: open section cylindrical shells reinforced by three, five and seven stringers are considered. The purpose of the paper constitutes the carrying out of the structure behavior analysis in the range of post-buckling state, as regards of the character of deformation and stress distribution. In particular, studying of influence, importance and usefulness of experimental model investigations of chosen neuralgic zones of designed load-carrying structure, for their rational form were executed. It was shown on the purposefulness of experimentation for the chosen cases of similar solutions, establishing the base to estimation of the numerical FEM models and assumed algorithms.

Key words: Shell, Constrained torsion, Open cross section, Post-buckling state, Experiments, FEM analysis.

INTRODUCTION

Tendencies of designing high-strength, durability and reliability of load carrying structures, in assumption of the rational relation between pay load and dead weight, are leading for designing the search of more and more operative methodologies. It refers to the majority areas of technology, in particular to the thin-walled aerospace structures. Durability and reliability of this kind of structures is being determined with presence of neuralgic zones, of whom presence is resulting from application functions.

These zones usually contain every kind local of cuts-out or reinforcement, introducing sudden changes of geometric parameters.

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With reference to the aerospace thin-walled structures, preservation of the flexural and torsional suitable rigidities constitute the rigorous requirements in the first order.
Ensuring of the required torsional rigidity in closed section shells isn't creating the difficulties, fulfilling this requirement in regard to zones about the open section is the significantly more difficult issue [9,10,[12,13].
Peculiarly disadvantageous to the life of the structure are zones of big cuts-out, where the closed shell structure is evolving to the open profile suddenly.
Example of the solution containing neuralgic cut-out in the zone of the cockpit of the aircraft about the “duck” set up is presented on the Fig. 1.

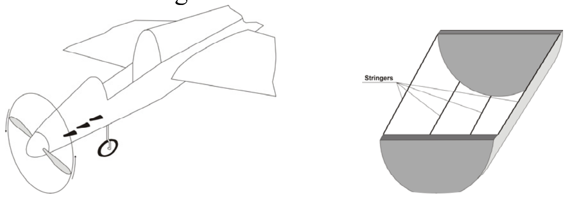


Fig.1 Example of cut-out zone of the aircraft

In such cases with one of the method applied extensively of preservation of the required torsional rigidity is a restricting free warping at least of the one boundary cross-sections, because of which, in conditions of torsion apart from shear stress, normal one are also appearing. Such state of the loading, determined as a constrained torsion disguises existence of high level stress gradients, in particular in the free lengthwise borders of shell. As the result, it can lead to reduction of fatigue life and structure load capacity.

Determination of fatigue life on numerical way becomes possible on the projecting stage of construction already, but it is conditioned of stress distribution knowledge, in all spectrum of permissible load. Relative to aerospace structures it means, in stress analysis local post buckling states of cover elements can’t be neglected, since these forms of deformation are acceptable in operating [13,6]. A typical load ratio of a local skin buckling load to ultimate failure load is common for commercial aircrafts [7]. The above ascertainment leads to conclusion, stress analysis of aerospace structures, ought to be considered in the range of pre buckling, and post buckling state. The search after operative, rapid as well not expensive methods of numerical stress analysis verification, which can be used during designing process of load-carrying structure, when essential variations of conFiguration can be achieved before labor-consuming and expensive executing process of prototype solution, gives attention on comparatively fast to execution in parallel with numerical calculations, selected model experimental investigation of structure, in particular of neuralgic zones.

At bases of those methods an assumption is laying, that being based on the theory of the model similarity it is possible to move, in broad understanding, quantitative conclusions from the observation of physical phenomena in the reliable mechanical setup for other system about the other scale.

With common feature every theoretical formulations of thin-walled structures is assumed, in the smaller or bigger range, idealization of them. A question is occurring, in which range accepted computing model is conforming with real physical condition arising as a result of external load operating. The answer is appearing obvious. It is possible to make this kind of the verification only experimentally, no matter how range of the experiment is able only to embrace selected zone of the load-carrying structure.

SUBJECT AND RANGE OF STUDY

Considered structure represents the open cross-section, thin-walled cylindrical shell. It is accepted, that dominating form of the loading constitutes the torsion. In order ensuring the sufficient flexural rigidity, the structure was strengthened with stringers, and, in order avoiding the local instability of stringers they assumed, that cross-sections were pressed together square. Scheme of structure geometry is presented on the Fig. 2.

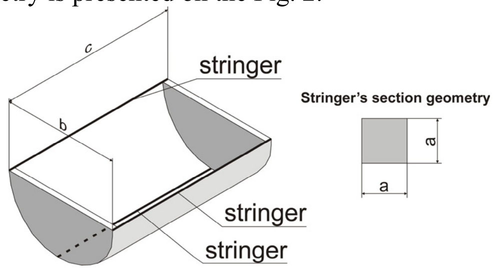


Fig.2 Scheme of structure geometry

The purpose of the paper constitutes the carrying out of the structure behavior analysis in the range of buckling and post buckling state, as regards of the character of deformation and stress distribution, in particular, studying of influence, importance and usefulness of experimental model investigations of chosen neuralgic zones of designed load-carrying structure, for their rational form. It made the analysis, on how many this kind of testing, being able to be ahead of numerical calculations, are able to influence, in the meaning mark, on the range of numerical model simplifications, accepted while design.

EXPERIMENTAL RESEARCH

For three variants of the structure experimental examination were done. They were differing with stringers' number. In the first case the structure was strengthened with three stringers, in the second one - five, the third variation referred to the design with seven stringers. Torsional rigidity were assured assuming, that the structure is fixed on both borders to very stiff plates, thickness of which were 20mm. It was complying with conditions of constrained torsion. Experimental examinations were carried out in the special station, making the realization of assumptions referring to the external loading possible and of accepted boundary conditions. Schematic diagram of the loading and drawing of station present Fig.3.

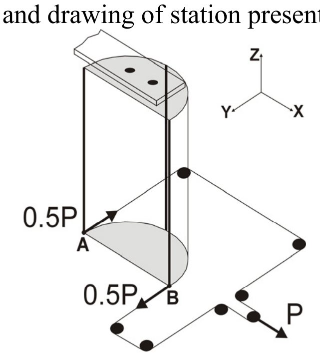


Fig.3 Schematic diagram of structure loading

The structure were executed from polycarbonate material, for which Young modulus is accepting the value E≈3000 MPa, and Poisson ratio $\nu \approx 0.36$. Fig.4 presents instantaneous characteristics of the polycarbonate received as a result of one-dimensional tension test.

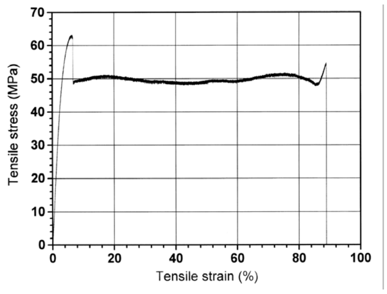


Fig 4. Instantaneous characteristic of polycarbonate

Moreover, this kind of the materials are marked by high optical sensitivity, what is making isochromatics field registration of loaded structure. As the photo-elastic method of examination, the photo-stress method was accepted. In the purpose the skin of structure was rendered with reflective varnish from the inside.
The connection of stringers with skin, by means of mechanisms screw and nut were made. The scale for the distance between of screws t = 20mm was assumed. In order ensuring fixed pressure in places of the connection with stringers of skin and frames, a field of isochromatics was being watched during tightening nuts in the zones of heads of screws, leading to alike value of orders of isochromatics in all places of the connection. The structure prepared for examination fixed in the station presents Fig. 5.

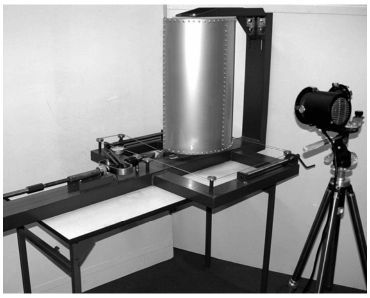


Fig.5 The structure fixed in the station prepared for examination

RESULT OF EXPERIMENT

The structure reinforced with three stringers

They submitted to an examination in the first order the structure with three stringers. Making the measurements of the angle of torsion versus the torsional moment presented plot was made on the Fig.6. A control of the loading was being realized during measurements.

It stated during examinations that the loss of stability of the structure was beginning from local buckling of the skin watched in boundary stringers' proximity, when the torsional moment accepted the value $M_t \approx 20$ Nm, but the angle of torsion reached: $\Theta \approx 2^0$ (see Fig. 6).

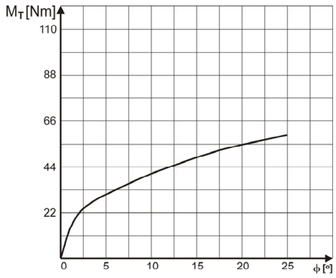


Fig.6 Torsional moment versus angle of torsion

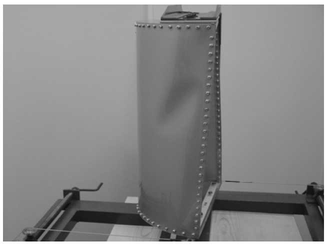


Fig.7 Beginning of local buckling. M_t=25 Nm

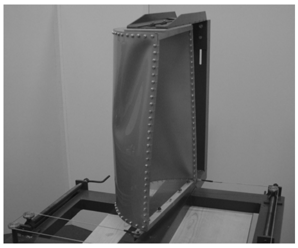
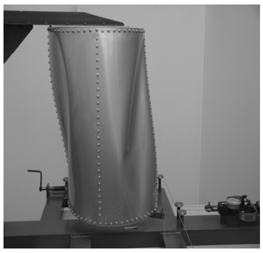


Fig.8 The next phase of post-buckling state. M_t=35 Nm

They were making measurements repeatedly, receiving negligible dispersion of the results. To the measure of the increase in the load it was occurring increasing of post-critical deformation, which spread out the bigger and bigger zone of structure.

The snap through phenomena weren't watched it, what its reflection found in the shape of the curve $M_t = M_t(\phi)$ presented on the Fig.6.



a) b)

Fig.9 Advanced phase of post-buckling elastic deformation. M_t=60 Nm. The structure reinforced with three stringers, a) The sight from the inside, b) The sight from the outside.

On the Fig.9 advanced phases of elastic post-buckling deformations are presented. In accordance to expectations structure deformation is showing the antisymmetric form in all phases of loading. It is finding this reflection of stringers' deformation. In particular it is bringing forward strong of bending boundary stringers, while the central stringer shape isn't suggesting bending state. Received of examinations large deflections of the shell making reducing of the torsional rigidity, in practice is eliminating the application of similar solutions containing the small number of stringers, despite of purely elastic material deformations. In particular it refers to the situations when, from functional consideration, a possibility to reinforce the structure by means transverse frame isn't existing, while increase of stringers' number isn't limiting the function of the structure.

THE STRUCTURE REINFORCED WITH FIVE STRINGERS

We will consider the case currently, when in the structure stringers' number increased for five, arranged uniformly. The modification was purposing determination increase of the torsional structure rigidity. In order determining of this increase, as similarly as in the previous case of three stringers, defining of the load – displacement-path in the range of post-buckling deformations were made, assigning dependence of the torsional angle from the torque moment presented on the Fig. 10. Also in this case during the measurements control of the loading were made.

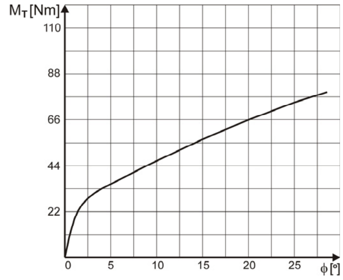


Fig.10 Torsional moment versus angle of torsion

Fig.11 The structure reinforced with five stringers. Early phase of post-buckling elastic deformation. M_t=35 Nm

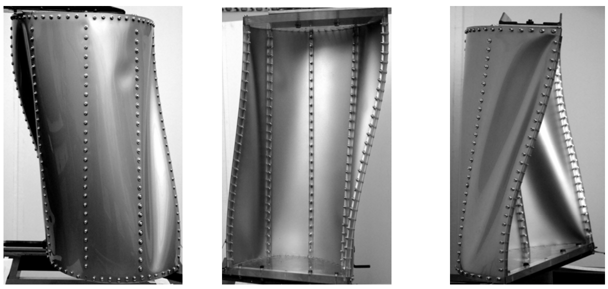


Fig.12 The structure reinforced with five stringers. Advanced phase of post-buckling elastic deformation. M_t=75 Nm

The plot presented on the Fig.10 confirms the identical character of the loss of the stability, which was watched during examinations of the structure reinforced with three stringers. It is perceptible no matter how obviously an increase of the constrained torsional rigidity of modified structure (five stringers) it isn't appearing not less than so meaningful it would be able to pose the satisfying solution. It is bringing forward when he is appearing, significant dissimilarity of the form of deformation of the structure stressed skin with five stringers. Basic deformation, making reducing of stiffening is located in segments of skin of boundary stringers put in proximity. while in central zones of skin we can observe only local buckling. Provided that two boundary stringers are subjected to strong bending, three remaining stringers are located in notdeformed condition. It is the matter of course, that watched deformation are translating themselves for level and distribution of the stress. The problem will be considered in more farther considerations.

THE STRUCTURE REINFORCED WITH SEVEN STRINGERS

With the next solution which was subjected to the analysis constituted the structure containing seven stringers put symmetrically. As similarly as in the previous cases also in the considered case identical boundary conditions and the same experiment methodology were kept.

The inserting of two next stringers changed the torsional rigidity in the meaning way. It also changed quite indeed character of post buckling deformation. It is proving it both the relation: torsional moment - angle of rotation of the boundary section of the structure presented on the Fig.13, as well as the form of post-buckling deformation shown on the Figs.14 and 15. Process of post critical deformation was initiated in the form of local buckling of skin in zones neighbouring on boundary stringers, when the loading with the torsional moment accepted value M_t=33Nm. The increase of the loading made increasing of deformation. She was taking place in the gentle way without of the snap through phenomena. The range of the loading was limited to the value of the M_t=110Nm torsional moment. The clearly elastic character of the structure deformation: an earlier stage - M_t=55Nm, and advanced phase - M_t=110Nm, are presented on the Figs. 14 and 15 respectively.

A fact is bringing forward, that in spite of the increase in the torsional rigidity of design in whole its area, in practice, post buckling deformation comprises only zones neighbouring on boundary stringers. To notice easily (see Figs 14 and 15) that the central stringers are keeping rectilinearity during testing in the whole range. It is letting suppose that mentioned stringers are subjected to bending within a small range.

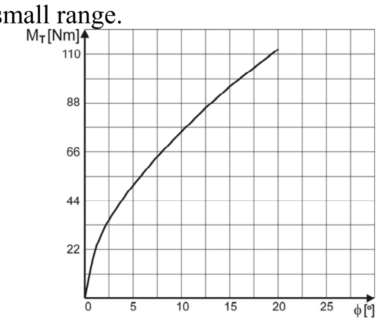


Fig.13 Torsional moment versus angle of torsion. Structure with seven stringers

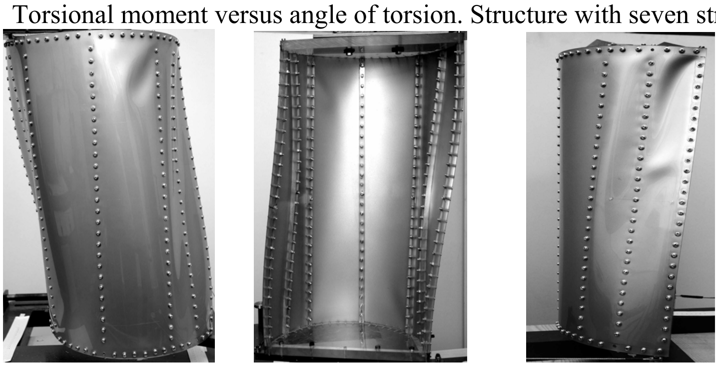


Fig.14 The structure reinforced with seven stringers. Early phase of post-buckling elastic deformation. M_t=55 Nm

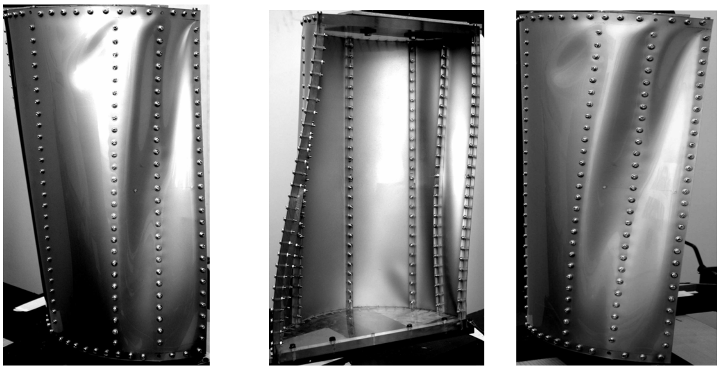


Fig.15 The structure reinforced with seven stringers. Advanced phase of post-buckling elastic deformation. M_t=110 Nm

In comparing to two first versions (three and five stringers) strengthened with seven stringers an essential increase in the torsional rigidity of the structure is perceptible. Plots presented on the Fig.16 illustrate dependence of the torsional moment versus angle of torsion, in all three cases of structure solution at the same time. For example, when the value of the loading M_t=55Nm the torsional angle of structure with three stringers accepts value 20^0, while for the structure with seven stringers, for the same loading, the torsional angle attains 6^0 only.

Basic change of the structure rigidity is influencing essentially for the change of the value and stress distribution, knowledge of which is posing determining the fatigue life of structure.

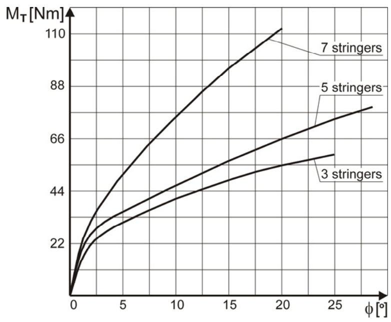


Fig.16 Torsional moment versus torsional angle. Reinforcing with stringers by three variations.

The stress distribution in the range of post-buckling deformation can be obtained on the numerical way. However the credibility of effects of calculation is made dependent on adequacy of the numerical model. In the considered case, good - how is appearing - criterion of the estimation of the accepted model can be able to pose compatibility of the form and the value received on the numeric way of deformation, obtained with deformation during experimental studies. Preliminary computation based on the proposed criterion were executed for the structure with three stringers.

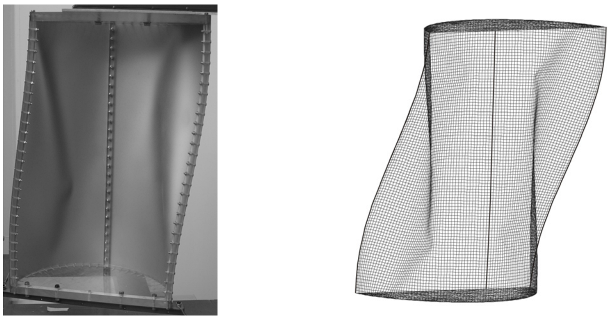


Fig.17 Forms of real and received on the numerical way deformation. Structure reinforced with three stringers, real scale of deformations

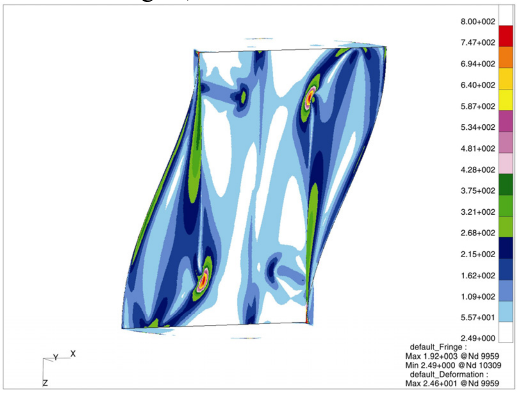


Fig.18 The effective stress distribution in the external surface of structure according to Huber – Mises criterion. M_t=60Nm

CONCLUSION

Realized examinations are making it possible to formulate a number of conclusions about significant importance for designing the practice of similar load carrying structures.

- The results of experimental studies are delivering a number of data of elaborated numerical models being able to pose the base for the estimation adequate for solving of geometrically non-linear problems.
- Compatibility of the value and the character of real and numerical objects deformations is ensuring the credibility of the calculated stress field in the range of post-buckling deformation
- Determining the stress-field on the basis of the specified numerical model is permitting to determine on the numerical way the fatigue life of structure before the expensive and labour-consuming realization of the prototype solution.

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