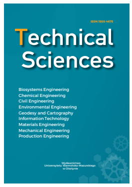
Technical Sciences, 2025, 28, 173–186

UNIWERSYTET WARMIŃSKO-MAZURSKI W OLSZTYNIE

Yearbook peer-reviewed scientific journal
ISSN 1505-4675
e-ISSN 2083-4527
TECHNICAL SCIENCES
Homepage: https://czasopisma.uwm.edu.pl/index.php/ts/



DOI: https://doi.org/10.31648/ts.11257

SELECTED ASPECTS OF RESEARCH ON ADVANCED STATES DEFORMATION OF THIN-WALL AIRCRAFT COMPOSITE STRUCTURES

Tomasz Lis

ORCID: 0000-0003-4220-0679
Faculty of Mechanical Engineering and Aeronautics
Rzeszów University of Technology

Received 08 April 2025, accepted 13 September 2025, available online 17 September 2025.

Keywords: aircraft thin-wall structures, composites, stability, post-critical states.

Abstract

The paper concerns the most significant and characteristic stages of manufacturing and testing the properties of aircraft thin-wall composite structures. Structures of this kind, due to the high requirements in terms of safety, durability and economy of aircraft operation, force the emergence of a number of often mutually contradictory design assumptions. The basic problem is to ensure the necessary strength and stiffness of the structure at the lowest possible weight. In a typical thin-wall structure, due to the small thickness of the skin, it is the covering that buckles, while the frame elements do not lose stability. Therefore, when testing thin-wall structures, it is extremely important to properly prepare the model so that the loss of stability is only local. The choice of stiffness of individual elements and the adopted technological process, which directly determines the properties of the system, are of fundamental importance.

The text presents an exemplary solution of this problem, concerning the concept of research model with the given technological process. The model underwent the loading condition, which corresponds to the real conditions occurring during the flight. In the next stage, the characteristic properties of the composite thin-wall structure, which is a representative part of the aircraft, were recorded. The obtained results make it possible to determine the influence of the adopted solution on the character of the skin deformation and provide a basis for modifications and comparative analyses.

Correspondence: Tomasz Lis, Katedra Inżynierii Lotniczej i Kosmicznej, Wydział Budowy Maszyn i Lotnictwa, Politechnika Rzeszowska, al. Powstańców Warszawy 8, 35-959 Rzeszów, phone: (48) 17 7432350, e-mail: list@prz.edu.pl

Introduction

One of the most commonly used solutions, concerning metal structures still commonly found in aviation, are semi-monocoque structures. They are characterised by high strength and stiffness in relation to weight. These structures consist of a relatively thin skin and a frame consisting of longitudinal (stringers, spars) and transverse elements (frames, ribs). Small thickness of the skin makes it possible to lose stability in the range of loads occurring during the aircraft operation (BRZOSKA 1961). However, loss of stability is allowed only under certain conditions. First of all, it must be of elastic nature and occur locally – in the area of the covering segments limited by the frame elements (KOPECKI et al. 2016).

Problems related to the loss of skin stability started to occur already at the end of the First World War. At that time, the first metal structures appeared. In the initial period, constructors tried to completely eliminate the phenomenon of stability loss of the skin by increasing its thickness. However, this path led to a significant increase in the weight of the aircraft, which significantly impaired their performance. Another solution was to use corrugated sheet metal covering. This type of treatment resulted in a significant increase in the aircraft drag and therefore significantly reduced their performance (HERTEL 1960). As a result of intensive research work, the principle of allowing some forms of critical deformation of thin-wall structure coverings in the range of operational loads was widely accepted. Limiting the area of occurrence of this phenomenon was realised by increasing the elements of the frame or by using stiffeners being an integral part of the frame covering (KOPECKI et al. 2019).

Another direction of research aimed at minimising the aircraft weight is reaching for modern structural materials. In recent decades, the attention of designers is focused on the problem of using various types of composites (ESWARDA et al. 2017, SKOCZYLAS et al. 2019, TIWARY et al. 2022). In the construction of airframes layered composites are used, so-called laminates, produced on the basis of reinforcement in the form of glass, carbon and aramid fibres and polymer resin matrices. Despite the very favourable properties of composites, the only structures made entirely of these reinforced materials are gliders and light aeroplanes. This is due to insufficient understanding of many aspects related to their use (GALIŃSKI 2020). In the first place, we should mention the issues of overall changes of structure properties in time or the problem of introduction of concentrated forces (GALIŃSKA 2020). An important role is also played by the fact that the resultant properties of the composite, and thus of the whole structure, depend to a large extent on the laminate manufacturing process (GERMAN 2001). In extreme cases, the dispersion of properties may reach several dozen percent. Hence, the adopted technological process is one of the fundamental issues of manufacturing aircraft composite structures (BREUER 2016).

In recent years, in order to meet increasingly rigorous operational and economic requirements and taking into account the path of development of metallic structures, attempts have been made to produce thin-wall composite structures in which the occurrence of local loss of stability by the skin is allowed (DEGENHARDT et al. 2006).

Such an approach requires the implementation of a number of studies. It starts with the technological process and ends with the registration and documentation of structure properties. Due to the expenditure of both time and resources, the results of such work are usually trade secrets of aircraft manufacturers.

This paper focuses on the problems of manufacturing a thin-walled composite structure using a fragment a wing, tail or a control surfaces as an example. A structure of this kind is loaded in an unfavourable way because the highest load values (normal bending moment and normal shear force) act in the direction corresponding to the smallest geometrical characteristics of the cross-section. The important component of the load is also the torsional moment (STAFIEJ et al. 2000). An additional constraint is the necessity to ensure the local character of the skin deformations and the elastic character of the deformations induced by them. All the presented conditions impose an internal structure solutions. Adopted solutions must be subject to experimental verification both in the range of subcritical and postcritical states deformations, due to the fundamentally different character of the system operation in these two states (KOPECKI 2010). The aim of this paper is to present an example of the manufacturing process of an aircraft composite thin-wall structure as well as a method of recording the so-called representative equilibrium path and documenting the field of post-critical deformations. An important element of the study is also the assessment of the influence of the adopted solution on the character of deformations of the structure carried out by means of the obtained results.

Materials and methods

The subject of the research in this paper is a structure being a representative of a typical aviation semi-monocoque structure being a fragment of a wing or a tailplane. Due to its purpose (lift force generation), the structure must reproduce the airfoil.

In the simplest variant, a structure of this type consists of: leading edge, spar, trailing edge, ribs and the skin (CUTLER 1999). The fundamental idea was to make the skin from a composite so as to observe the postcritical states of this element. The material requirements for the other elements of the model were not imposed, because by assumption they must not lose stability. The geometry of the model and the adopted scheme of the internal structure are shown in Figure 1.

In the course of the work, the contact method of composite fabrication (hand lay-up) was adopted due to its simplicity and the possibility of implementation practically in any workshop (BOCZKOWSKA, KRZESIŃSKI 2016). This method, due to the presented advantages, is also widely used in the light aircraft industry.

Taking into account the complex structure of the model, the necessity of mapping the airfoil (NACA 2418 was used) and the requirement of shape

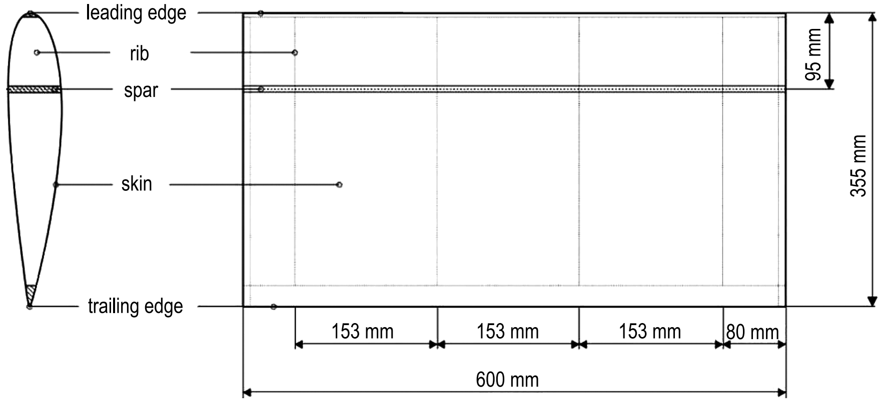


Fig. 1. Model scheme and geometry

stability, negative moulds were used in the manufacturing process. The laminating process of the structure coverings, the assembly of the frame and the closing (gluing) of the model were carried out in a split mould. The preparation of negative moulds reproducing the airfoil is a complex process, the description of which is beyond the scope of this paper. The figure below (Fig. 2) shows a photograph of the moulds used in this work.

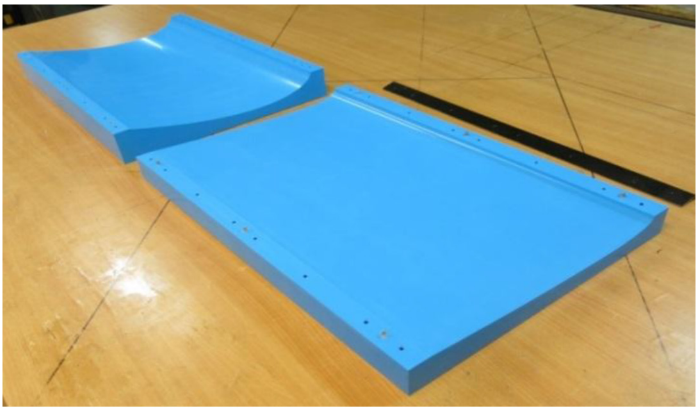


Fig. 2. Moulds used in this work

The first stage of model fabrication consisted in covering the moulds with Frecote NC 770 separator. On the so prepared surfaces, the coating laminating process was carried out. To reinforce the laminate, symmetrical glass fabrics Interglass 02037 and 92110 with weights of respectively: 47.5 g/m^2 and 163 g/m^2 were used. The epoxy resin used is MGS L285 and MGS H286 hardener. An important element is the extension on the bottom coating, which is used to bond the two coatings together at a later stage. In practice, the locally increased thickness of the coating also serves as a leading edge. In order to determine the geometry of the extension, it became necessary to use an additional device mapping the shape of this part of the profile (Fig. 3).

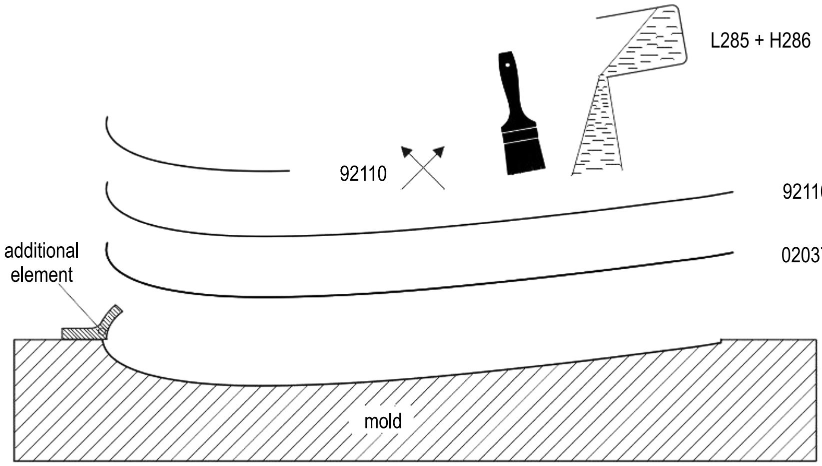


Fig. 3. Skin reinforcement scheme – additional composite layer in the torsion box area

In the lamination process, the orientation of the reinforcement direction at an angle of 45° with respect to the spar was used. This arrangement of composite layers ensures the best torque transfer properties of the coating, because for orthotropic materials, the G modulus responsible for torsional stiffness takes on a maximum value (CHUN-YOUNG NIU 1992). A varied number of fabric layers was used along the chord of the profile, with an additional layer in the torsion box area (Fig. 4). In this way the torsion box skin was protected against loss of stability and favourable conditions were created for the occurrence of critical deformations in the part of the skin between the spar and the trailing edge.

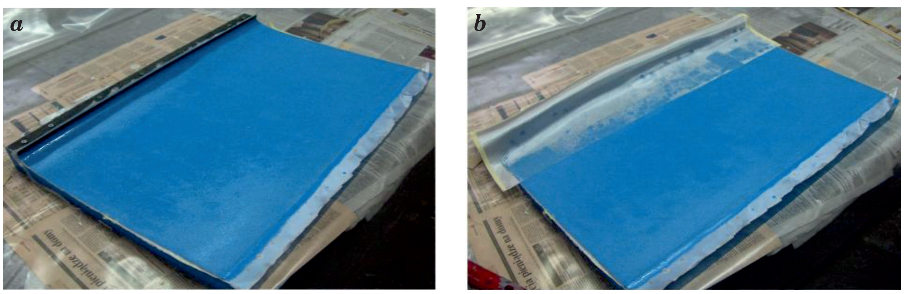


Fig. 4. Laminating process: *a* – visible black additional element responsible for extending the skin for subsequent gluing, *b* – additional reinforcement layer in the torsion box area

This is because the loss of stability of the skin in the torsion box zone is undesirable for aerodynamic reasons (GALIŃSKI 2017). The entire structure was completed with a layer of delamination fabric (peel ply). After the resin had hardened, the delamination fabric was removed and the excess laminate was cut off, preparing the skins for the assembly of the frame elements.

The frame of the model was made of spruce strips constituting the spar chords, while the spar wall and ribs were made of aircraft plywood. The adopted solution of the frame is a classic example of the internal structure of a semi-monocoque wing. In the rear part of the model a vertical plywood wall was glued, which together with the gluing compound forms the trailing edge. Composite sleeves were glued into the adjacent wing ribs in order to fix the model on the test stand (Fig. 5).

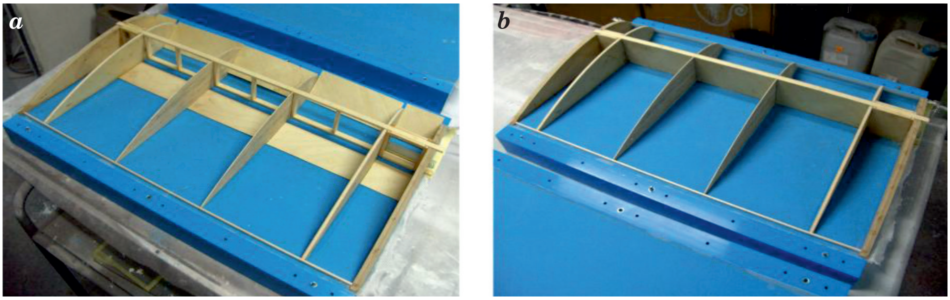


Fig. 5. Internal structure: *a* – elements of the frame, *b* – complete frame

The final stage of the wing production was to glue the lower covering, on which the frame elements were assembled, and the upper covering (Fig. 6). Both skins were glued in the moulds. The adhesive mixture consisted of the resin used for lamination (50% volume ratio) with fillers in the form of aerosil (40% volume ratio) and microballoon (10% volume ratio). This adhesive mixture is often used in the manufacturing process of composite components for light aircraft. The lamination and gluing processes took place at room temperature, at around 22°C and 60% humidity. The laminate shells and the adhesive mixture used to bond them, thanks to their transparency, significantly facilitated the control of the amount

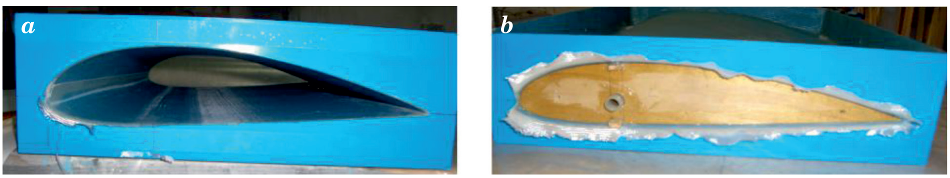


Fig. 6. Joining the shells: *a* – joining method on the leading edge, *b* – closed mould, the view of the root rib with a glued composite sleeve

of adhesive dispensed and the quality control of the bonding. After the adhesive had hardened and the mould was opened, the model was ready for testing (Fig. 7).

The model was subjected to experimental tests. For this purpose a test stand was prepared (Fig. 8), which imitated the wing loading condition occurring during the flight.

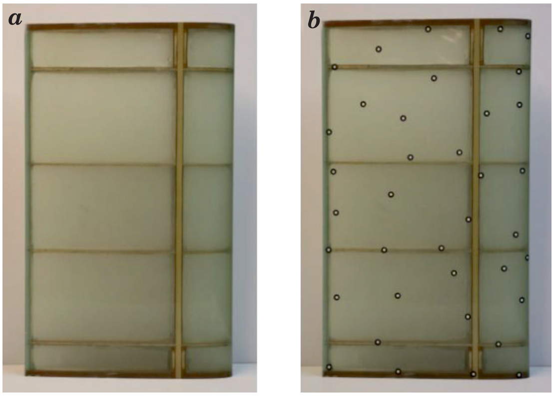


Fig. 7. Ready-to-test model: *a* – after removal from the mould and cutting off the excess material, *b* – after wrapping with paper reference points

Fig. 8. Test stand

The design of the test stand ensured the necessity to take into account the three components of the load condition: the shear force, bending moment in the direction perpendicular to the chord, and the torsional moment which plays a decisive role in the loss of stability of the skin (HOWE 2004). The required loading condition was realised by means of appropriate fixing of the model and gravitational method of force application (Fig. 9).

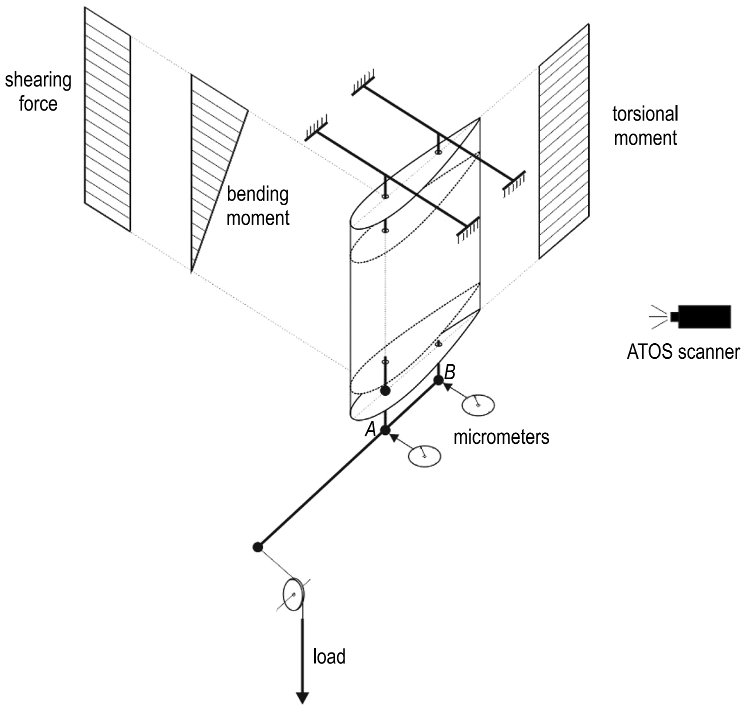


Fig. 9. Scheme of the test stand and the load implemented

A separate issue is the measurement of displacements of characteristic points and the method of recording the form of post-critical deformation. For this purpose, the test stand was equipped with a system of displacement sensors of characteristic points (point *A* and *B*), and an ATOS optical scanner. HAZ 2155-65 dial gauges were used as displacement sensors. Thanks to their magnetic base and articulated connections, they were a convenient addition to the test stand. Before the main measurements were taken, the system was preloaded. After the load was removed, they indicated the initial value.

During the experimental research, for successive predetermined equilibrium states of the structure corresponding to the applied load value, the displacement of characteristic points was recorded. A system of displacement sensors was used for the measurement (Fig. 10).

Displacements, with known geometry of the system and assuming small values of the torsion angle (below 1°), allowed to determine the total torsional angle of the structure:

$$\mathrm{tg} \propto = \frac{u_A - u_B}{l_{AB}} \tag{1}$$

$$\propto = \tan^{-1}\frac{u_A - u_B}{l_{AB}} \qquad (2)$$

where:

u_A – displacement of point A,

u_B – displacement of point B,

u_{AB} – distance between points A and B.

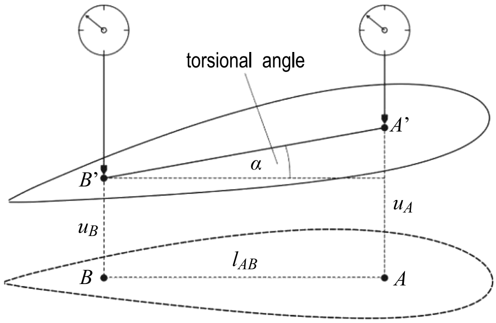


Fig. 10. Measurement of the torsional angle

The representative equilibrium path is a fundamental relation in a nonlinear problem (DOYLE 2001). In the case described, geometric nonlinearity is present. The relationship between the state of the structure and the load is determined by a selected parameter characterising the deformation of the system, and an appropriate control parameter related to the load. A representative equilibrium path can be used to determine both linear and non-linear behaviour after the loss of stability.

The assumption of the total torsional angle as the characteristic quantity results from the fact that, in the case of a semi-monocoque structure, torsion is the main cause of the occurrence of critical deformations. This is due to the clear separation of the functions of the individual elements of the semi-monocoque structure, where the spar carries the shear force and the bending moment, while the skin carries the torsional moment.

Results and discussion

Experimental tests were carried out at increasing and then decreasing load values. This made it possible to determine the hysteresis and to check whether any permanent deformation occurs in the tested system. For each value of the applied load, the displacements of the reference points were recorded. On this basis, the total torsional angle of the structure was determined. After removing the load, the angle returned to its initial value, which proves the elastic character of deformations as well as the lack of loose parts in the system that fixes and loads the model. As a result, a representative equilibrium path was obtained, determined as the average of two series of measurements corresponding to increasing and decreasing the load (Fig. 11).

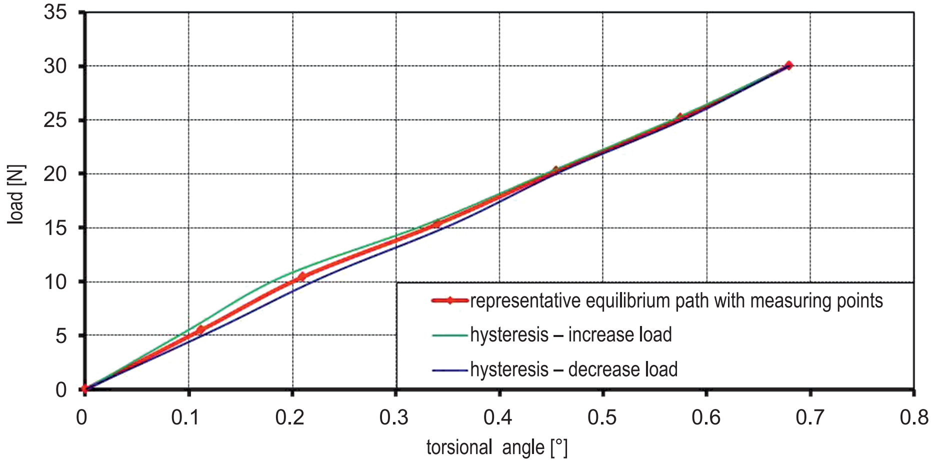


Fig. 11. Representative equilibrium path

Analysing the equilibrium path obtained, it can be stated that it has an almost linear course, devoid of peculiarities. The bifurcation point (intersection of subcritical and postcritical paths) is not marked, which results from the method of load application and displacement measurements for the determined equilibrium states. The structure retains its stiffness even after the loss of stability of the skin, so that it is able to carry loads also in post-critical states. This fulfils a fundamental requirement for any semi-monocoque structure.

In addition to a representative equilibrium path to determine the behaviour of the system in the covering range, it is also necessary to determine the form of deformation of the skin. Such information also allows verification of the fulfilment of the requirement of the local character of the post-critical deformations. Documentation of the character of the deformation of the skin is a problematic issue due to the difficulty of capturing the deformation of the covering in a photographic manner, if only because of small curvatures of the coating and accompanying light reflexes. For these reasons, the surface deformation of the tested model was recorded using the ATOS optical scanner (Fig. 12).

Fig. 12. ATOS scanner

The basic elements of the system consist of two digital cameras cooperating with dedicated computer software to create digital models of real objects. The principle of operation of the device is based on a modified Moiré method. During the projection of projection stripes onto an object, a series of photographs is taken. The images registered by the cameras are related to the shape of the element. These images are the basis for determining the spatial position of each point of the examined surface. The point cloud obtained in this way is subjected to a polygonisation process. After the poligonisation, smoothing and removal of redundant elements, a digital model reflecting the shape of the real object is obtained. The scanner software also enables comparison of the obtained surface with a reference surface. This makes it possible to create a colour map of displacements or geometric deviations.

In the case described here, deformation measurement consisted of two stages. The first one consisted in taking (ATOS scanner) a series of photographs of the model before applying the load. As a result, a digital image of the non-deformed model surface was obtained. The second stage consisted of scanning the deformed surface for the target load value. The reference surface was marked with red colour (Fig. 13*a*), while the surface of the model after the stability loss was marked with grey colour (Fig. 13*b*). The photographs show auxiliary reference points located both on the model and in its environment. These points constitute a reference system enabling the compilation of the whole series of photographs taken (Fig. 13*c*, *d*). Taking the unloaded model surface as a reference, it is possible, taking into account the deformed surface, to create a colour map of the deformation of the system (Fig. 13*e*).

The obtained deformation map allows to conclude that the loss of stability of the skin on both the bottom and top surfaces of the model has a local character, limited by the elements of the skeleton. Additionally, no loss of stability of the torsion box was found, which is an important aerodynamic requirement. For this reason the torsion box was omitted in the presentation of the results (Fig. 14). In the analysed case it can be stated that the examined area, divided by the

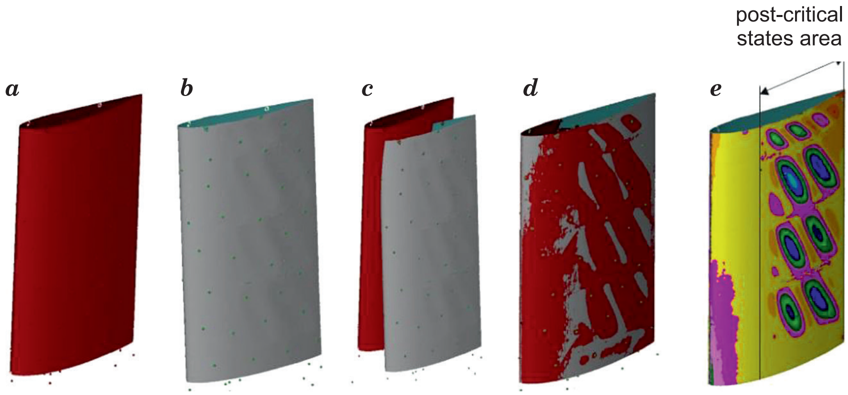


Fig. 13. Stages of creating a deformation map

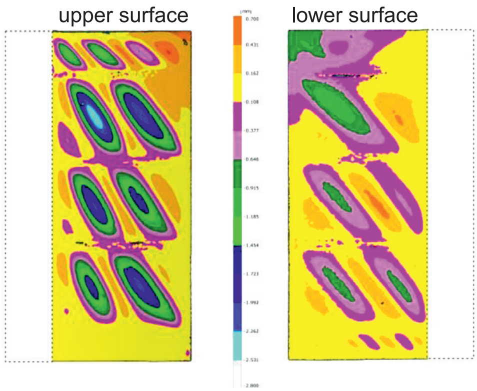


Fig. 14. Deformation maps of the upper and lower shell surfaces.
The location of the torsion box is marked with a dashed line

elements of the frame into smaller segments, has a different form of deformation on the upper and lower surface. In the area of each segment of the upper surface, two distinct folds were observed, the depth of which reaches up to 2.5 mm. On the lower surface, the folds are less distinctive and their depth does not exceed 1.2 mm. The distribution of the deformation of the coating indicates an even distribution of the load on the individual segments of the coating. Similar deformations of individual segments (with similar geometry and stiffness) indicate a similar load level, which indicates an even distribution of the load on the coating. According to the principle of uniqueness, a given state of deformation can correspond to only one state of stress. The observed difference in the depth of the folds on the lower and upper surfaces is due to the different curvature radius, dictated by the geometry of the airfoil used.

Summary

The concept of the research model presented in this paper, using a composite skin and wooden frame elements, taking into account the requirements for thin-wall aircraft structure, was reflected in the applied technological process. The designed test stand allowed to reproduce the actual load condition occurring during the flight. Registration of the load, displacement of reference points, as well as the character of deformation of the structure allowed to obtain both quantitative information (representative equilibrium path) and qualitive information (deformation field map), which are the basis for an unambiguous assessment of the properties of the tested structure.

On the basis of the results obtained, it can be stated that the tested system behaves correctly. The loss of stability has the character of symmetrical stability bifurcation – the structure does not lose its stiffness after exceeding the critical load value. The value of the torsional angle of the structure is small (below 1°), which corresponds to the values required for aerospace structures. The area of deformation of the skin is limited to the segments between the elements of the skeleton. However, it does not extend to the torsion box. On this basis, it can be concluded that the adopted research method allows full verification of the adopted solutions and the applied technological process.

The obtained results may form the basis for further research on the comparison of various solutions of the structure. The aim of this work may be to work out a stiffening scheme ensuring the most uniform distribution of load on the cover taking into account the change of the structure weight.

A representative equilibrium path and a post-critical deformation map obtained in the experiment may be used to validate the FEM model of the tested structure. The convergence of equilibrium paths and deformation characteristics of the real model and numerical model is the only way to obtain information on stresses in the tested structure.

The presented conclusions allow to work out the most favourable solution from the point of view of the mass and stiffness of the structure. Comparison of the thin-wall structure properties with the corresponding model with inherently stiffened covering (sandwich structure) may determine the load range at which one solution gains advantage. This may be of importance, for example, in the case of a light aircraft tail, which is subjected to relatively low load values and which is required to be as light as possible. The common sandwich covering in this case may be heavier (given the presence of the filler, bonding adhesive and the requirement for a minimum number of composite layers) than the covering variant without such stiffeners. An additional advantage to undertake such work is the simpler and quicker process of producing a structure without a sandwich.

References

BOCZKOWSKA A., KRZESIŃSKI G. 2016. *Kompozyty i techniki ich wytwarzania*. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa.

BREUER P. 2016. *Commercial aircraft composite technology*. Springer, Switzerland.

BRZOSKA Z. 1961. *Statyka i stateczność konstrukcji prętowych i cienkościennych*. PWN, Warszawa.

CHUN-YOUNG NIU M. 1992. *Composites airframe structures*. Conmilit Press, Hong Kong.

CUTLER J. 1999. *Understanding aircraft structures*. Oxword Blackwell Science Ltd.

DEGENHARDT R., ZIMMERMAN R., ROLFES R., ROHWER K. 2006. *COCOMAT – improved material exploitation of composite airframe structures by accurate silmulation of postbuckling and collapse*. Composite Structures, 73(2): 175-178.

DOYLE J.F. 2001. *Nonlinear analysis of thin-walled structures*. Springer, New York.

ESWARDA PRASAD N., WANHILL R.J.H. (Eds.). 2017. *Aerospace materials and material technologies*. Vol. 1. *Aerospace materials*. IIMS. https://doi.org/10.1007/978-981-10-2134-3

GALIŃSKA A. 2020. *Mechanical joining of fibre reinforced polymer composites to metals – a review*. Part I. *Bolted joining*. Polymers, 12(10): 2252; https://doi.org/10.3390/polym12102252

GALIŃSKI C. 2017. *Wybrane zagadnienia projektowania samolotów*. Wydawnictwo Instytutu Lotnictwa, Warszawa.

GALIŃSKI C. 2020. *Wybrane zagadnienia konstrukcji samolotów*. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa.

GERMAN J. 2001. *Podstawy mechaniki kompozytów włóknistych*. Politechnika Krakowska, Kraków.

HERTEL H. 1960. *Leichtbau*. Springer, Berlin.

HOWE D. 2004. *Aircraft loading and structural layout*. American Institute of Aeronautics and Astronautics, Reston.

KOPECKI T. 2010. *Stany zaawansowanych deformacji w projektowaniu cienkościennych ustrojów nośnych*. Oficyna Wydawnicza Politechniki Rzeszowskiej, Rzeszów.

KOPECKI T., BAKUNOWICZ J., LIS T. 2016. *Post-critical deformation states of composite thin-walled aircraft load-bearin structures*. Journal of Theoretical and Applied Mechanics, 54(1).

KOPECKI T., LIS T., MAZUREK P. 2019. *Experimental and numerical analysis of a composite thin-walled cylidrical structures with different variants of stiffeners, sobjected to torsion*. Materials, 12(19): 3230. https://doi.org/10.3390/ma12193230

SKOCZYLAS J., SAMBORSKI S., KŁONICA M. 2019. *The application of composite materials in the aerospace industry*. Journal of Technology and Exploitation in Mechanical Engineering, 5(1). http://dx.doi.org/10.35784/jteme.73

STAFIEJ W., RODZEWICZ M., BORKOWSKI P., HEJDUK H., LATUSZEK M., ROSZAK J., WYMYSŁOWSKI P. 2000. *Obliczenia stosowane przy projektowaniu szybowców*. Politechnika Warszawska, Warszawa.

TIWARY A., KUMAR R., CHOCHAN J.S. 2022. *A review of characteristics of composites and advanced materials used for aerospace applications*. Materialstoday. Proseedings, 51(1): 865-870. https://doi.org/10.1016/j.matpr.2021.06.276