PROPOSAL FOR THE METHOD OF DETERMINING THE MOST INTENSIVE FRAGMENTS RIVET JOINS APPEARING THE SHELL AIR PANELS WORKING UNDER THE INFLUENCE OF TENSION FIELD

Jarosław MAŃKOWSKI, Jerzy OSIŃSKI, Przemysław RUMIANEK

Instytut Podstaw Budowy Maszyn, Politechnika Warszawska
ul. Narbutta 84, 02-524 Warszawa, fax: (+48 22) 234 86 22, email: jarosław.mankowski@simr.pw.edu.pl

Jerzy JACHIMOWICZ

Katedra Mechaniki i Informatyki Stosowanej, Wojskowa Akademia Techniczna

Summary

This article presents the methodology for determining seam rivet fragments most exposed to fatigue damage caused by buckling cover sheet occurring in the semi-monocoque structures. The present study is focused on determining the impact of the tension field, which is one of the cases of buckling, the state of the burden and strain of riveted joints occurring in shell structures. The conditions in which tension field arise for example two-flange girder were also examined. Analysis was also performed to explore micro-slides between the rivet and the hole in the conditions of normal and torsional loads of combined sheets.

The presented method allows both the determination of dangerous places, susceptible to the tension field for the whole structure, as well as a detailed analysis of selected parts of the structure - which can be useful, especially in the design of structures on the basis of supervising durability.

Keywords: shell structures, semi-monocoque structures, riveted joints, tension field, FEM.

PROPOZYCJA METODY WYZNACZANIA NAJBARDZIEJ WYTĘŻONYCH FRAGMENTÓW SZWÓW NITOWYCH WYSTĘPUJĄCYCH W CIENKOŚCIENNYCH PANELACH LOTNICZYCH PRACUJĄCYCH POD WPŁYWEM POLA CIĄGNIEŃ

Streszczenie

Celem artykułu jest przedstawienie metodyki określania najbardziej narażonych na zniszczenie zmęczeniowe, spowodowane wybaczaniem blach pokrycia, fragmentów szwów nitowych występujących w konstrukcjach półskorupowych. W niniejszej pracy skupiono się na określeniu wpływu pola ciągnień, które jest jednym z przypadków wyboczenia, na stan obciążeń i odkształceń połączeń nitowych występujących w konstrukcjach cienkościennych. Zbadano warunki powstawania pola ciągnień na przykładzie dźwigara dwupasowego. Wykonano również analizy mające na celu zbadanie mikropoślizgów pomiędzy nitem a otworem w warunkach obciążeń normalnych i skrętnych łączonych blach.

Przedstawiona w pracy metoda, pozwala zarówno na określenie miejsc niebezpiecznych, podatnych na działanie pola ciągnień, dla całej konstrukcji; jak i przeprowadzenie szczegółowej analizy wybranych fragmentów konstrukcji - co może być przydatne, zwłaszcza przy projektowaniu konstrukcji na trwałość dozorowaną.

Słowa kluczowe: konstrukcje cienkościenne, półskorupowe, połączenia nitowe, pole ciągnień, MES.

1. INTRODUCTION

Riveted joints are classified as persistent connections, in which parts do not change their positions relative to each other. Therefore, design of riveted joints usually comes down to check the basic conditions, such as strength of shear and pressure. This is a simplification in which the residual stresses resulting from the technological process are not taken into account, in which there is rivet clenching [1-3]. The fact that the riveted joints occurring in aircraft structures are overlooked, but in reality are at least partly rubbing joints [4, 5]. In this case, it appears that the basic conditions for checking the strength may be insufficient or may be in significant degree to limit the possibility of the development of a structure due to the need for additional factors of safety. In some special cases it can prove disastrous - as in the case of Boeing 737 Aloha Airlines in-flight No. 243 [6], in which the main cause of the accident[1] was multi-focal coverage cracks along the riveted joint and destruction of a big part of the hull. Examples of multi-focal fatigue cracks of air structures can be found for example in [7], where the authors present the results of shell structures made of natural scale.

Currently, in order to avoid accidents, properly designed shell construction is built with an appropriate[2] supply of safety in relation to the service loads and do not really have concerns that it will be destroyed suddenly during normal exploitation. Today, the struggle leads to an extension of overhaul life through: firstly - increasing the fatigue life, secondly - to increase safety by monitoring the damage - which allows the replacement of worn components and non-threatened exploitation of the whole object.

Air structures are subjected to very high and variable load in time. They are also differentiated with reference to the character of the amplitude and load - a combination of elements of these structures are the most vulnerable to damage as a result they must meet very high demands. Significant values of loads acting on the construction sites, often associated with the occurrence of large displacements parts of the structure, make the riveted seams move very large in value, and complex states of loading [8]. Since the life-time of an aircraft largely depends on the durability of its connections around the world, research on this topic has since intensifed [2, 3, 9-15]. On this basis it can be concluded that the occurrence of local stress concentrations, have a substantial impact relative displacement of joints components, caused by service loads. This applies especially to the semi-monocoque structures[3] where there is a definite change load conditions beyond the critical forces - leading to the formation of an additional burden of large gradients loads in the seam riveted joint length [8]. In such a situation, it becomes necessary to take it into account in the design process because of the relatively large cover deformations in the riveted joint accompanying the buckling of that cover.

2. COVER BUCKLING - PROBLEMS IN CONNECTION WITH ANALYSIS SHELL STRUCTURES WORKING IN OVER-CRITICAL STATE

The necessity to pay special attention to the structural analysis for the over-critical state, is also connected with another important, yet relatively new issue, which is the change in approach to determining the time to damage the structure. Keeping in mind that one of the characteristics features of aircraft structures, which affects the design process, is very long life of 20-30 years or more and taking into account their cost of production, extension of overhaul life and extension of their life this translates into very high costs. Thus, in aviation, is gaining great importance in determining the service life extension than at the time, but according to technical condition, for example by supervising durability using damage tolerance [16-19]. In this case, damage tolerance may be authorized for one or more elements.

A shortcoming of life according to time is a fact that it is not possible to foresee all possible cases of load and working conditions, and therefore assumes the most unfavourable conditions of work and will determine the time overhaul life. Exploitation by supervising durability can significantly prolong the safe operation. This approach to sustainability, however, requires carrying out many detailed research and analysis for determining which charges and what mechanisms cause the destruction. Examples of such activities could be found in [3, 10, 11, 20]. They presented the results of research and analysis of local and micro-local phenomena, occurring in rivet joints, caused by closing the rivet.

In the case of riveted construction, a very important problem is to identify dangerous places - places in the structure, which needs special attention. This implies a need to address many issues affecting the phenomena at the micro level, from which usually begins joints degradation. This is particularly important in the case of semi-monocoque structure, which is allowed to lose the cover stability in elastic range, which further complicates the problem. Structural analysis in the over-critical state, belong to a very complex and require both vast knowledge and experience, the implementation of a series of studies, as well as possession of computer equipment with very high computing power. The scale of the problem, in cases of complex shell structures, is shown clearly by the contents of the document published in 2002 by NASA[4] [23]. In this document, section 6.1.1.7

[1] Described event is called the air accident - Regulation of the Minister of Transport from 18.01.2007 – in case about air accidents and incidents, Dz. U. 27.02.2007.

[2] The overall safety factor currently used in aviation, is 1.5.

[3] Semi-monocoque structure - it is such a shell structure in which elements of the cover is very thin in relation to elements of the framework, and therefore may be a local loss of stability of elastic recovery, while the structure for loads exceeding the maximum operating loads, due to the small thickness - cover elements can work rather than flexion membrane and bending moments and the local bending is taken over by elements of the framework (the bending stress in the elements of cover are very small and usually does not exceed 5%) [21, 22]

[4] NASA - National Aeronautics and Space Administration.

(buckling and destruction) describes the methodology of analysis and loading in cases of shell structures, which should include an analysis of buckling. Also indicates that for the analysis of thin-walled shell appropriate "reduction" factor should be applied that takes into account the differences between classical theory and experimental results of the burden, which causes loss of stability. Mainly due to the fact that the occurrence of tension field (one of the forms of buckling) cannot be ruled out.

3. TENSION FIELD

Tension field – special case buckling covered by the shell structures, formed by the action of tangential forces[5].

In 1928, H. Wagner presented the trial, in which a thin shell of the transverse stiffeners subjected to load, gave rise to a diagonal fold [24]. He demonstrated that uprising buckling of cover doesn't destroy constructions until transverse stiffeners work only on compression (until stability is lost). This had a huge impact on the approach to the design of shell structures.

The essence of tension field is that in spite of charging to cover only the tangential forces in coverage after exceeding the critical load, there is a complex state of stress in Fig. 1.

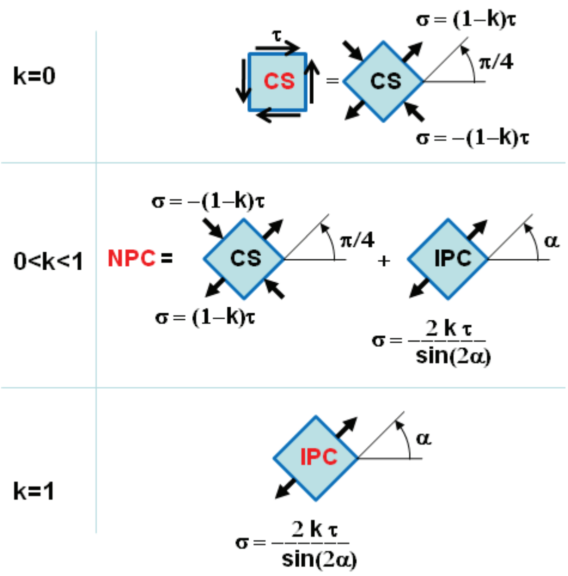


Fig. 1. State of stress in tension field

In the case of the tension field it should be divided into three phases depending on the value of the load:

- first phase, in which the load does not exceed the critical load, therefore, the coverage is only pure shear CS (1), in principle, should not even talk about the tension field:

$$\sigma_{PC} = \sigma_{CS} = \tau \quad (1)$$

- second phase, in which the load exceeds the critical force in this case the state of stress in the coating is a superposition of pure shear CS and tensile stress resulting from folding the cover, so the tension field IPC (2), the second phase is called the incomplete tension field and identified NPC[6];

$$\sigma_{PC} = \sigma_{CS} + \sigma_{IPC} \quad (2)$$

$$\sigma_{CS} = (1-k)\tau\,; \quad \sigma_{IPC} = \frac{2k\tau}{\sin(2\alpha)}\,;$$

- third phase, in which the load is so large that there is no longer just a clean cutting stress stretching IPC (3); of course this is a purely theoretical case, but may be taken into account for very thin covers.

$$\sigma_{PC} = \sigma_{IPC_{(k=1)}} = \frac{2\tau}{\sin(2\alpha)} \quad (3)$$

Structural damage as a result of the tension field may occur when:

- the strength of the material covering the tension is exceeded - will tear the substance;
- the critical force for the elements of the skeleton is reached, due to the increasing normal force and the emergence of the load perpendicular to the axis of rods of the framework.

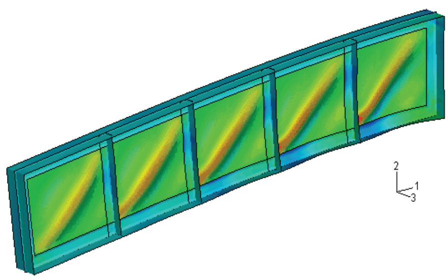


Fig. 2. Deformation of the cover was created in bended thin-walled girder

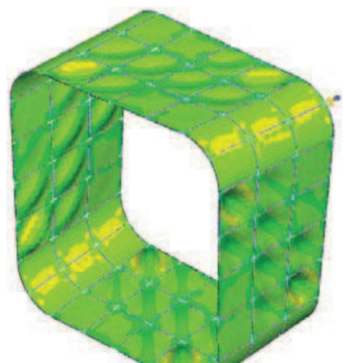


Fig. 3. Deformation of a cover in the simplified model of an aircraft fuselage section, which is subject to torsion

[5] Definition based on [28].

[6] NPC - incomplete tension field, the term introduced by Professor Zbigniew Brzoska [28].

In real structures, the problem of the tension field most often occurs in thin-walled girders (Fig. 2) and the external covering of aircraft, especially in covering the fuselage, which include subjection to torsion (Fig. 3).

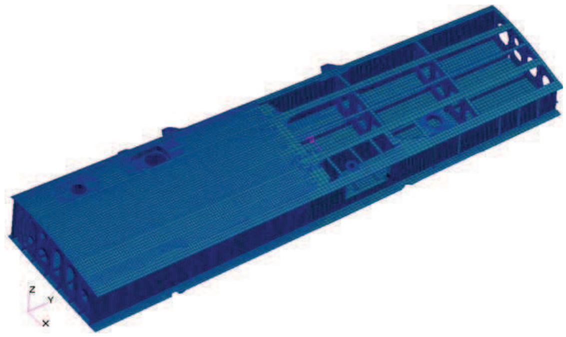
A detailed summary of the phenomenon presented by Paul Kuhn of the National Advisory Committee for Aeronautics in 1952[7], and then fully structured description of this phenomenon, posted a comprehensive monograph on the analysis of shell structures [25], published in 1956. Other important items, which contain a number of details about the tension field, are: [24] published in 1960[8], [26] published in 1961[9] and [27] published in 1965[10]. In 1965 he appeared in revised and enlarged edition of the book, "Statics and stability of structures" [28]. The next thesis, which concerns the subject of tension field were based on the work of J. P. Timoshenko, P. Kuhn, and Z. Brzoska.

4. METHODOLOGY OF RESEARCH AND ANALYSIS

As already noted, the tension field is a phenomenon whose occurrence is closely associated with shell structures. It occurs both in the outer covering of shell structures and in shell girders covering. Therefore, in order to assess the impact of this specific type of buckling load on the state of riveted joints, a series of analysis or test of the proposed structure was performed.

Analysis can be divided into three groups depending on the scale of the model. The proposed models are:

- global model (entire structure or a sufficiently large part of it) - the analysis of such a model is to answer charges relating to merger riveted joint and the location of vulnerable parts of the structure [29, 30] (an example of a global model is shown on Fig. 4);
- local model (selected portion of the structure) - the analysis of this model is used in determining the movements of dangerous places (such as a local model is shown in Fig. 5);
- micro-local model - (appropriately sized fragment containing one or two rivets) - used to perform two studies:
  - analysis of closing the rivet, in order to determine the initial stresses and strains introduced into the model;
  - riveted joint call for an analysis of stresses and deformations introduced and applied displacements obtained from the analysis of local model - in order to obtain answers about the stress concentrations and the size of the relative displacements of individual elements of the connection.



Rys. 4. FEM model of the fragment of the wing (the main torque box) PZL M28 Skytruck - for selected treated as a global analysis (to show the hidden internal structure to cover the upper part of torque box)

Most of the analysis of tension field of impact assessment on the state of riveted joints is carried out using FEM. FEM systems have many features in common - especially the basic elements and models of library materials and computational methods [31-33]. Results obtained from different FEM systems, using the same model (the number of elements, type of elements, the calculation method and material models), should be the same. This statement is purely theoretical. In practice, there is another very important factor: namely, the FEM is not the scientific method but approximate method - in conjunction with the accuracy of the results still depends on "numeric" - the applied methods of solving equations and methods for their software. Moreover, due to the sensitivity of this method for numerical errors, the impact on the outcome is also a class of computer equipment used for analysis. Thus, in addition to the need to adapt to the analysis of the available computer hardware and to resolve the problem selection of an appropriate methodology for modelling of riveted joints, it depends on: first, the scale model, and secondly on the requirements associated with the introduction of charges. Until that time, some interesting theses in which, special emphasis on the above issues.

The problem of modelling methods of riveted joints to the environment of one or more rivets were raised in [34, 35]. These theses contain examples of different ways of modelling riveted joints and guidance on the scope of applicability of the methods discussed in them. The problem of modelling global structures, which are riveted joints, has been addressed in [29, 36]. Particularly important is the thesis of [29], which has been shown that the influence of internal stresses caused by clenching a rivet is local and does not exceed 8-10 rivet diameters. Above this limit, the modelling process of the rivet does not matter. Based on the

---

[7] *A SUMMARY OF DIAGONAL TENSION*, Kuhn Paul (information is posted on the basis of [23] First Edition)

[8] Autor: Hertel Heinrich, Dr. Ing. O. Professor an der Technischen Universitët Berli

[9] Autor: Zbigniew Brzoska Dr Inż. Profesor IPPT PAN, PW.

[10] Autor: Jerzy Teisseyre Dr Inż. Profesor IPPT PAN, Politechnika Wrocławska.

results cited in the theses, we can conclude that building a local model for analysis, should be elected for more than a dozen area of the rivet diameter, and should be modelled, at least in a simplified manner, the phenomenon of contact. Micro-local model should be extended to cover from one to several rivets, including all contact pairs. However, building a global model construction, the rivet model can be replaced by a single beam element, or may be omitted. Today, despite major simplifications in global models, it puts ever greater demands on such analysis, because they allow for precise determination of risk areas and are the source of the data (stress, displacement) for analysis on a local scale and micro-local.

Therefore, it is necessary to carry out many studies, aimed at optimal finite element models for each stage of the analysis, because the same models will be used during subsequent analysis. The work can be divided into four stages.

4.1. Stage 1 - Preliminary analysis of construction - a global model

In the initial design phase to make a preliminary analysis of the construction to determine the basic dimensions of the carrying structure (cross-sections of skeletal elements, sheet thickness) and between other levels of burden riveted joints. The purpose of this analysis is also the general designation of the displacements and stresses in the structure, which is the starting point for many other detailed analyses. An example of this global analysis can be reduced tensions in the map coverage of the visible portion of the wing buckling coverage zones depicted in Fig. 5, obtained for one of the manoeuvring loads [29].

Fig. 5. Reduced stress (by H-M-H11) [MPa] and the displacement in the model wing. The apparent local loss of stability

In the course of this thesis, actions taken include the implementation of the initial design and analysis of sample designs. After reading a number of structural solutions, in which there are problems with the drawings on the field, three examples were selected: classical two-flange girder, two-belt girder with holes in coverage and the spatial structure of a fragment corresponding to the aircraft fuselage subjected to twisting, and then made their global models and conducted appropriate analysis. The obtained results allow, inter alia, to identify high-risk places in the structure which should be subjected to a thorough analysis. Over these results the analysis global-local models were used to determine charges, (step 2)[12]. The results of the thesis have been published in [37-39].

4.2. Stage 2 - Analysis of a chosen structure - local model

This phase includes analysis of the construction areas especially threatened by the stress concentration and buckling in the action from the tension field Fig. 6 Verification should especially burden the state and deformation of the rivet seams [29, 30].

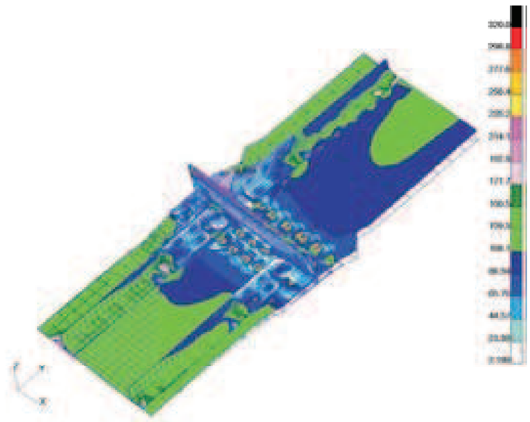


Fig. 6. The combination of riveting, a local model of the wing - reduced stress (by H-M-H) [MPa] - frame and cover on the side of formed rivet heads

The remainder of the paper presents results of calculations of the air panel sample, for which we were a "classic" analysis of the connection and the riveted joint analysis of the FEM, with emphasis on the combination of riveting. Based on the results of the choice of the most loaded rivets for detailed analysis of a single rivet. Obtained at this stage, the results were used to determine the burden for the analysis of micro - local models (stage 4). They will also be used to prepare the test program (stage 3).

[11] H-M-H - reduced stress by hypothesis Huber - Mises - Hencky

[12] The concept of a global model is contractual in nature and smooth, and is understood as a model superior to the other model, which in this case is considered to be local, or subordinate. Otherwise, the global model can be considered as a local example, presented as part of the wing is a local model for the entire model, or an entire wing of the aircraft.

4.3. Stage 3 - Research - Review FEM models

Due to the rapidly growing opportunities and the development of FEM software hardware, computing tools get more powerful. This allows the analysis of increasingly complex cases. At the same time, the field analysis of complex, nonlinear problems is relatively new and therefore there is a small number of publications with real test results. If these facts are combined with the fact that the FEM systems are excellent tools and the "by oneself" do not count, it becomes necessary to perform the test on real objects, to verify the FEM models - in this case, the analysis is used to calls riveted joint. At this stage the preparation of the assumptions and tests connections, whose results will be used to verify the calculation method. Another important factor is to design a test sample in such a way as to be representative and have as many features of a connection that will be present in the actual construction. In particular, attention should be paid to the selection of the load..

4.4. Stage 4 - Detailed analysis of the riveted joint calls - the micro-local model

At this stage, using data from the local model (stage 2) and assumptions for the implementation of the FEA model, as evidenced by test results (stage 3), followed by preparation of finite element models for detailed analysis of the riveted joint connection of the test structure. The results of the analysis on the model of micro-local, allow to determine the degree of stress concentration and to assess the intensity of co-movements of the surface - which allows for detailed and very accurate assessment of the test portion of the joint.

5. SUMMARY

Riveted seams occurring in shell structures, especially semi-monocoque structures, are exposed to the difficulty of determining the load caused by buckling of coverage. A special case of this type of load is a tension field.

The proposed method allows the selection of the most heavily loaded portion of rivet seams, and then to isolate a single rivet environment where stress is the greatest. This is particularly important in the design of structures on the stability of the supervised control of damage tolerance. Knowledge of the biggest areas of stress, pressure and relative displacement of elements is essential in determining potential sites for crack initiation, and the knowledge of the stress field can identify the direction and speed of propagation.

In the proposed method of performance analysis, based on the use of FEM. Please note that this method is approximate and, therefore, is required for experimental verification of models and analysis.

6. BIBLIOGRAPHY

[1] Derewońko A., Jachimowicz J., Szymczyk E.: *Analiza połączenia nitowego z uwzględnieniem naprężeń resztkowych i eksploatacyjnych*. VIII Międzynarodowa Konferencja Naukowa Computer Aided Engineering, Polanica, Oficyna Wydawnicza Politechniki Wrocławskiej, 2006.

[2] Derewońko A., Jachimowicz J., Szymczyk E.: *Numeryczna symulacja procesu nitowania*. IX Konferencja Naukowo-Techniczna „Programy MES w Komputerowym Wspomaganiu Analizy Projektowania i Wytwarzania", Giżycko, WAT, 2005. str. 19-22.

[3] Szymczyk E., Derewońko A., Jachimowicz J.: *Analysis of displacement and stress distributions in riveted joint*, III European Conference on Computational Mechanics Solids, Structures and Coupled Problems in Engineering, Lisbon, Portugal, C.A. Mota Soares et.al. (eds.), 2006.

[4] Łaguna J., Łypacewicz K.: *Połączenia śrubowe i nitowe*. Warszawa, Arkady, 1986.

[5] Jachimowicz J., Kaniowski J., Karliński W.: *Zmęczenie cierne w konstrukcjach lotniczych*, XVIII Sympozjum: Zmęczenie Materiałów i Konstrukcji , Bydgoszcz-Pieczyska, 2000.

[6] Hawaiian Steam Engineering: *Aloha Airlines Flight 243 - Aircraft Accident - Maui Hawaii*. [Online] 1997. http://www.aloha.net/~icarus/index.htm.

[7] Boyd D., Howard and Co.: *Corrosion detection devices*, Department of Energy, 2003. Contract No. DE-AC09-96SR18500 U.S.

[8] Mańkowski J.: *Wpływ pola ciągnień na obciążenia połączeń nitowych występujących w konstrukcjach cienkościennych*. Warszawa, Politechnika Warszawska, 2009, rozprawa doktorska.

[9] Müller Richard P. G.: *An experimental and analitical investigation on the fatigue behaviour of fuselage riveted lap joint*. Delft University of Technology, 1995, rozprawa doktorska.

[10] Derewońko A., Jachimowicz J., Szymczyk E.: *Numeryczne szacowanie poziomu naprężeń resztkowych w zakuwanym połączeniu nitowym.* praca zbiorowa pod red. Tadeusza Niezgody „Analizy numeryczne wybranych zagadnień mechaniki" Warszawa, WAT, 2007, str. 329-350.

[11] Kubiak T., Młotkowski A., Niezgodziński T.: *Zastosowanie metody elementów skończonych do badania procesu nitowania*. t. 23 - Analizy numeryczne wybranych zagadnień mechaniki, Warszawa, 2007, str. 445-457.

[12] Jachimowicz J., Kajka R., Kaniowski J., Karliński W.: *Fretting w konstrukcjach lotniczych.* Tribologia: tarcie, zużycie, smarowanie Tom 201, 3/2005, 2005, str. 97–108.

[13] Jachimowicz J., Kajka R., Krysztofik J., Szachnowski W., Szymczyk E.: *Stan odkształceń i naprężeń w pobliżu nitu w konstrukcji lotniczej – analizy MES i badania*, IX Konferencja Naukowo-Techniczna „Programy MES w Komputerowym Wspomaganiu Analizy Projektowania i Wytwarzania", Giżycko, WAT, 2005.

[14] Gołoś K.: *Trwałość zmęczeniowa metali w ujęciu energetycznym*, Warszawa, Wydawnictwo Politechniki Warszawskiej, 1990.

[15] Dębski M. A., Dębski D. K., Gołoś K. M.: *Hypothesis of loads cycle reduction to equivalent fatigue cycle*, Prace Instytutu Lotnictwa, Warszawa, Wydawnictwo Naukowe Instytutu Lotnictwa, 2005. 4/2005 (183). praca zbiorowa. ISSN 0509-6669.

[16] Głowiński S.: *Identyfikacja stanu technicznego oraz podstawy prognozowania pracochłonności napraw urządzeń mechanicznych na przykładzie eksploatacji statków powietrznych*, Koszalin, Politechnika Koszalińska, 2004, rozprawa doktorska.

[17] Chang J. B., Rudd J. L.: *Damage Tolerance of Metallic Structures, Analysis Methods and Applications,* ASTM International, 1984. ISBN-EB: 978-0-8031-4908-3.

[18] Lewitowicz J.: *Podstawy eksploatacji statków powietrznych,* Tom 1. Statek powietrzny i elementy teorii, Warszawa, Wydawnictwo Instytutu Technicznego Wojsk Lotniczych, 2001. ISBN: 83-900817-4-1.

[19] LexTech, Inc.: *DTD Handbook, Handbook for Damage Tolerant Design*. 2008. http://www.afgrow.net/applications/DTDHandbook/default.aspx.

[20] Jachimowicz J.: *Ocena wytrzymałości konstrukcji,* Wewnętrzne materiały szkoleniowe. Warszawa, Instytut Lotnictwa, 1996.

[21] Jachimowicz J., Lamparski J.: *Przegląd materiałów z zakresu obliczeń metodą elementów skończonych cienkościennych konstrukcji lotniczych*. Warszawa: Instytut Lotnictwa, 1976. Sprawozdanie Instytutu Lotnictwa nr 6/BW/WS/76.

[22] Jachimowicz Jerzy i inni: *Opracowanie metody obliczeniowej oraz przykłady obliczeń rzeczywistych konstrukcji lotniczych*. Sprawozdanie Instytutu Lotnictwa. Warszawa: Instytut Lotnictwa, 1980. 21/RW/WO/80.

[23] National Aeronautics and Space Administration, International Space Station Program, Johnson Space Center: *Payload flight equipment requirements and guidelines for safety–critical structures,* Houston, Teras, NASA, 2002. Contract No. NAS9–02099 (PA16).

[24] Hertel H.: *Leichtbau flugzeuge und andere leichtbauwerke*, Springer-Verlag, 1960.

[25] Kuhn P.: *Stresses in aircraft and shell structures*, New York / Toronto / Londyn, McGraw-Hill Book Company Inc., 1956.

[26] Brzoska Z.: *Statyka i stateczność konstrukcji prętowych i cienkościennych*, Warszawa, Państwowe Wydawnictwo Naukowe, 1961.

[27] Teisseyre J.: *Budowa nadwozi, Część I – obliczenia*, Warszawa, Wydawnictwa Komunikacji i Łączności, 1965.

[28] Brzoska Z.: *Statyka i stateczność konstrukcji prętowych i cienkościennych*, Wydanie drugie – zmienione, Warszawa, Państwowe Wydawnictwo Naukowe, 1965.

[29] Jachimowicz J., Wronicz W.: *Wybrane problemy modelowania nitowanych, lotniczych struktur cienkościennych*, Przegląd Mechaniczny, 2008, 5, str. 25-34.

[30] Derewońko A., Jachimowicz J., Sławiński G., Szymczyk E.: *Modele globalne i lokalne MES w analizie struktur lotniczych na przykładzie fragmentu skrzydła samolotu PZL M28 Skytruck*, Warszawa, Biuletyn WAT, 2010. Vol. LIX, 1(657).

[31] ABAQUS: *Abaqus analysis user's manual*, United States of America, ABAQUS, Inc., 2004.

[32] ANSYS Inc., ANSYS: *Documentation Manuals, ANSYS Realase 9.0.* Canonsburg: SAS IP, Inc., 2004.

[33] MSC.Software Corporation: *MSC. Nastran 2007, User's Guides*. Santa Ana, MSC.Software Corporation, 2007.

[34] Jachimowicz J., Kajka R.: *Problemy modelowania połączeń nitowych metodą elementów skończonych*, VIII Konferencja Naukowo-Techniczna Programy MES w Komputerowym Wspomaganiu Analizy, Projektowania I Wytwarzania, Rynia, Institute of Aviation, 2003, str. 12.

[35] Mańkowski J.: *Opracowanie metodyki modelowania połączeń obrotowych metodą elementów skończonych bez użycia zagadnienia kontaktu z wykorzystaniem systemu ABAQUS/Standard*, Warszawa, 2003, praca wykonana na zlecenie FAURECIA Fotele Samochodowe Sp. z O. O..

[36] Mańkowski J., Osiński J., Żabicki A., Żach P.: *Modelowanie połączeń typu sworzeń - otwór za pomocą MES bez użycia analizy kontaktowej*, Systems IX, Wrocław, Oficyna Wydawnicza Politechniki Wrocławskiej, 2004, str. 670-674.

[37] Mańkowski J., Jachimowicz J., Osiński J.: *Selected problems concerning the analysis of thin-walled structures with the use of finite element metod*, Journal Of Kones Powertrain And Transport, 2008, str. 109-118.

[38] Jachimowicz J., Mańkowski J., Osiński J.: *Wybrane problemy analizy konstrukcji cienkościennych z zastosowaniem MES*, X Jubileuszowa Konferencja Naukowo-Techniczna „Programy MES we Wspomaganiu

Analizy, Projektowania i Wytwarzania", Kazimierz Dolny, 2007, str. 63-64.
[39] Mańkowski J., Osiński J., Żach P.: *Pole ciągnień w cienkościennym dźwigarze lotniczym*, XII Sympozjum Stateczności Konstrukcji , Zakopane, 2009, str. 285-288.

Prof. Eng. **Jerzy OSIŃSKI** He currently works at the Warsaw University of Technology - Institute of Mechanical Engineering, where he is Deputy Director for Research.

For many years he deals problems with strength analysis of structures using the Finite Element Method. He has authored a lot of scientific publications, monographs and scholarly books, among which include, inter alia, university script, entitled: *"Strength calculation of machine elements using the Finite Element Method"*.
He is also the editor of the *Dynamics Problems* journal, and CEO of the Association of Automobile Recycling Forum.

PhD Eng. **Jerzy JACHIMOWICZ** The longstanding scienti-fic-research employee of Aviation Institute in Warsaw, and The Institute of Mechanical Engineering at Warsaw University of Technology.

Currently working in the Department of Mechanics and Applied Informatics, Military University of Technology in Warsaw.

Since the beginning of his career, he designed and strength analysis of aircraft structures. For many years, deals with the practical issues associated with the Finite Element Method in the analysis of shell constructions.

He has extensive experience, supported by long-standing practice at the Aviation Institute in Warsaw. He is a lot of scientific works and publications author.

PhD Eng. **Jarosław MAŃKOWSKI** - He is a scientific - educational employee at the Institute of Mechanical Engineering at The Warsaw University of Technology.

Since the beginning of his career dealing with issues related to the design, and especially the Finite Element Method in the analysis of structures, inter alia: analysis of shell structures, nonlinear problems such as buckling, contact, large deformations, elasto-plastic materials.

He is the author of over a dozen scientific works and publications.

MSc Eng. **Przemysław RUMIANEK** - PhD student at the Faculty of Automotive and Construction Machinery Engineering at The Warsaw University of Technology - Institute of Mechanical Engineering. His main interests are related to the strength of materials and structural strength analysis using the Finite Element Method

.