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Mechanical joining of thermoplastic composites - bearing behaviour simulation and validation

ZDĚNEK Pavel[1,a], RŮŽEK Roman[1,b], KUCHARSKÝ Pavel[1,c] and KŘENA Josef[2,d]

[1]VZLU Czech Aerospace Research Centre, Beranových 130, 199 05 Prague 9 – Letňany, Czech Republic

[2]Latecoere LATECOERE Czech Republic s.r.o., Beranových 65, 199 02 Prague 9 – Letňany, Czech Republic

[a]pavel.zdenek@vzlu.cz, [b]ruzek@vzlu.cz, [c]kucharsky@vzlu.cz, [d]Josef.Krena@latecoere.aero

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Abstract. The paper discusses issues associated with failure mechanism of the mechanical fastened joint – bearing strength and clamp-up conditions. Work is focused on carbon fibres with polyphenylenesulfide thermoplastic resin composite material. The bearing strength behaviour of the two different layup alternatives, hole positions, plate thicknesses and tightening conditions are investigated. Numerical simulations were checked with experimental measurements. Propositions to improve simulation results has been made.

Introduction

Linear polyphenylenesulfide (PPS) thermoplastic is widely used in carbon fiber reinforced composite structures in aerospace parts and structures. Increasing interest in carbon fiber/PPS thermoplastic composite materials (C/PPS) is driven by its excellent mechanical properties. It means mainly resistance to impact damage or better formability, especially in comparison with conventional epoxy-based laminates. Widespread application of C/PPS thermoplastic composites is dependent on the manufacturing costs, ability to utilize all the advantages of thermoforming process and optimization of the lay-up. Different studies relating to mechanical behaviour and damage tolerance evaluation of C/PPS thermoplastics were published in the past, for example experimental investigation of factors considered for the strength evaluation [1], investigation of fatigue loading rate to lifetime of the composite with variable thickness [2,3], bearing strength [4] and in-plane shear behaviour [5] etc.

Different methods can be used for thermoplastics joining like bonding [6,7], welding [8] and mechanical fastening. Joining by using of mechanical fasteners is still one of the most effective, widespread and reliable methods. This is caused by the fact that bonding and/or welding methods are not yet fully certificated for airspace applications in primary structures. There are several issues which must be solved in joints with fasteners: bearing strength, preparation of fasteners hole, fastener installation, corrosion, fastener interaction (pull-through, bending), clamp-up, stress concentrations, multiple row limitations, ply configuration effects and off-axis loading.

The paper discusses two main issues associated with failure mechanism of the joint – bearing strength and clamp-up. Typically, the bearing strength of composite materials is relatively lower compared with metals, and additionally the bearing strength is a function of the ply orientation and composition. At the same time tightening of joint could increase the bearing strength of a composite structure. This problem associates with the composite through the thickness feature. Despite several numerical approaches published in the past, widespread applications of carbon/PPS require huge experimental program for fastened joint behaviour verification.

The paper is focused on the numerical simulation and experimental verification of the bearing strength behaviour of two alternatives of the lay-up, positions of the hole, plate thicknesses and tightening conditions. Presented work associates with the design, simulation and optimization [9] of the thermoplastic rib [10], and possibilities to take into account correctly the boundary conditions of the real rib joining into the door structure.

Theory

Major failure modes of single-hole bolted composite joints [11] are shown on Fig. 1. The occurrence of a particular failure mode depends on joint geometry (bolt diameter, laminate width, edge distance and thickness) and laminate lay-up. Tension failure (see a) in Fig. 1) typically occurs, when the ratio of bolt diameter to strip width is sufficiently high. Cleavage failure is prone to occur if the bolt is in the proximity of end of specimen. However, for any given geometry may failure mode vary as a function of lay-up, stacking sequence, geometry or clamping boundary conditions.

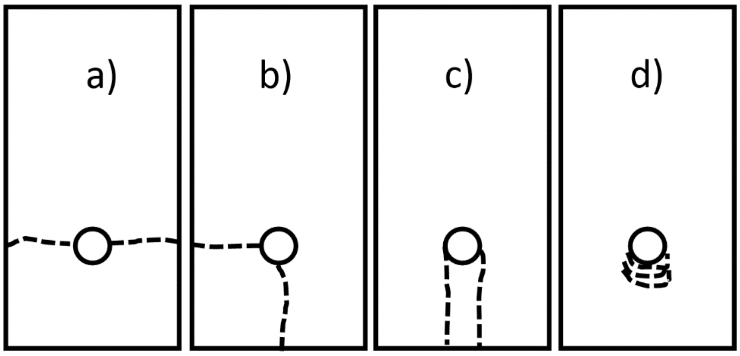


Fig. 1: Failure modes of composite bolted joint. a) Tension failure, b) Cleavage failure, c) Shear-out failure, d) Bearing failure.

Mechanical fastened joint in fibrous composite structures at first behaves like one-phase homogenous engineering material on which it is usually modelled. Together with increasing load the nonlinear behaviour prevails, and final failure occurs long after the nonlinearities appeared. Both fibers and matrix are essentially linear until failure; however, microcracks and delamination appear around bolt hole and cause the internal load redistributions, not accounted for in common mathematical models. More realistic simulation can be achieved, when each lamina is modelled separately.

Woven composites [12] present an interesting alternative to fiber-reinforced composites. In comparison to unidirectional (UD) lamina composites, woven composites have lower in-plane stiffness and strength due to the tow waviness. On the contrary, woven composites are more resistant to delamination and have superior impact response.

Continuum damage models are mostly developed for UD lamina composites. Typical models are Hashin's Failure Criteria [13], LaRC03, LaRC04, Maximum Stress, Tsai Wu or Puck Criteria for initiation of failure and Matzenmiller model [14] for constitutive material with accounted damage progression. These models, however, cannot be directly extrapolated to woven composites, due to the differences resulting from their dissimilar morphologies.

Materials and Methods

Paper is focused on AIMS05-09-002 [15] carbon fibre reinforced thermoplastic material with satin weave and PPS matrix. The two nominal thicknesses of 4 mm and 5.6 mm were investigated. Two variations of layups were used for specimen production. Two boundary conditions of the joint were considered - material clamped with clearance of 0.5 mm and tightened joint with torque of 20 Nm. The bearing strength was experimentally investigated based on the procedures defined in ASTM D5961 standard [16]. Basic test configuration is shown in Fig. 2.

Ultimate bearing strength σ_u and bearing strain were evaluated using following equations:

$$\sigma_u = \frac{P_u}{dt_n}, \tag{2}$$

$$\varepsilon_{br} = \frac{\delta}{d}, \tag{3}$$

where P_u is the maximum load sustained by specimen during the test, d is the nominal bolt diameter, t_n is the laminate thickness and δ is the extensometer displacement.

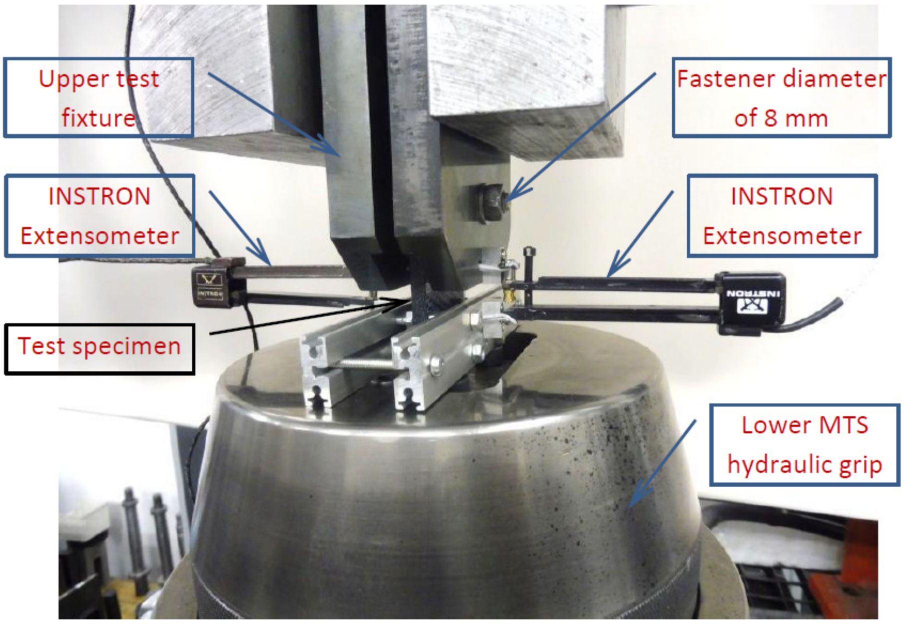


Fig. 2: Bearing test configuration

The ABAQUS software [17] for numerical simulation was used. Finite element model consists of the three parts – specimen, cylindrical fastener and clamping rigs. The fastener and clamping rigs were considered as rigid, undeformable parts. This assumption was made for the purpose of contact convergence; however, real stiffness of deformable part (composite specimen) is only about four times lower then real stiffness of presumably rigid parts (steel bolt and clamping rigs). For this reason, contact stresses cannot be assumed as strictly realistic. Idealization of bearing test in FEM is shown in Fig. 4.

Each composite ply was represented by a separate shell layer meshed with continuum shell elements SC8R [17]. Layers were connected by the cohesive contact with interlaminar stiffness characterization. Initiation of delamination damage was controlled by the Quadratic traction criterion; damage propagation was based on the mixed-mode Benzeggagh-Kenane law [18]. Hashin’s Failure criteria for carbon fibre-reinforced polymer [13] were applied to account criterion for damage of matrix and fibres. Degradation process was estimated as quasistatic, hence the Abaqus implicit solver was used.

Simulations were made for each alternative of the joint configuration and boundary condition. Results obtained experimentally and numerically were compared in terms of bearing stress – bearing strain curves and failure modes.

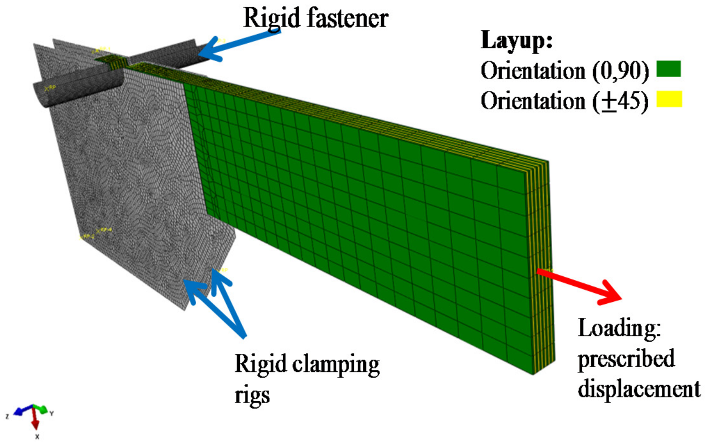


Fig 3: Idealization of bearing test facility in finite element model

Results

Influence of clamping boundary conditions and hole distances from the edge of specimen in the load direction on the ultimate bearing strength is shown in Fig. 4.

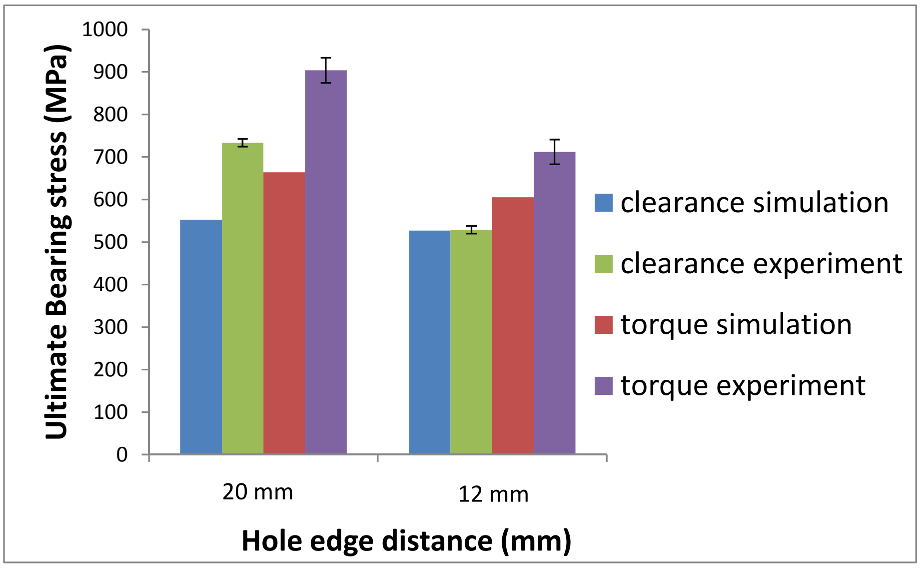


Fig. 4: The influence of boundary conditions of clamping with torque or with clearance and hole edge distance on Ultimate bearing stress determined numerically and experimentally.

Comparisons of bearing stress – bearing strain curves for different boundary conditions are shown in Fig. 5-6. Damage progression is illustrated on the example of Hashin Matrix Failure Initiation Criterion shown in Fig. 7. Results in Fig. 7 correspond to 4 mm thick specimen clamped with clearance and to the hole distance of 12 mm from the edge of the specimen (ED). Specimen is loaded in tension in horizontal direction. Results are shown for two representative plies with orientation (±45) and (0,90) and for three stages of damage progression. Scale value of 1 in Fig. 7 indicates the state in which the failure initiation criterion has been met and element undergoes stiffness degradation according to the associated evolution law.

Experimentally, significant increase of bearing strength was observed for clamping with torque in comparison to clamping with clearance. Similarly, bearing strength depends on the hole distance from the edge. Larger hole distance from the edge of the material led to higher bearing strength. Influence of used composite thickness, resp. layup variations, was unneglectable. Numerical simulations showed similar trends; however, positive effect of boundary conditions was significantly smaller in comparison with experimental data. It could be caused by using of continuum shell elements SC8R instead of solid elements for ply by ply calculation. Solid elements should ensure more precise distribution of contact and through-the-thickness stresses in comparison to continuum shell elements.

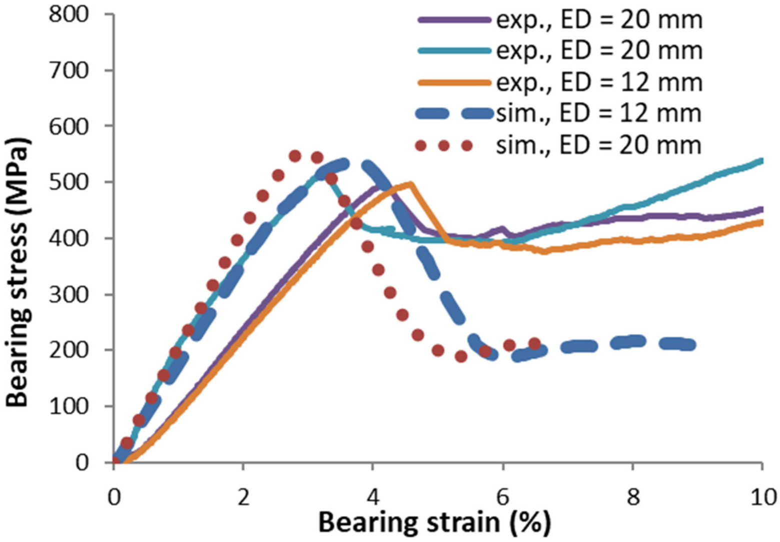


Fig. 5: Comparison of bearing stress – bearing strain curves obtained experimentally (exp.) and from numerical simulations (sim.) for specimens 5.6 mm thick clamped with clearance. ED stands for distance from the hole to the edge of the specimen.

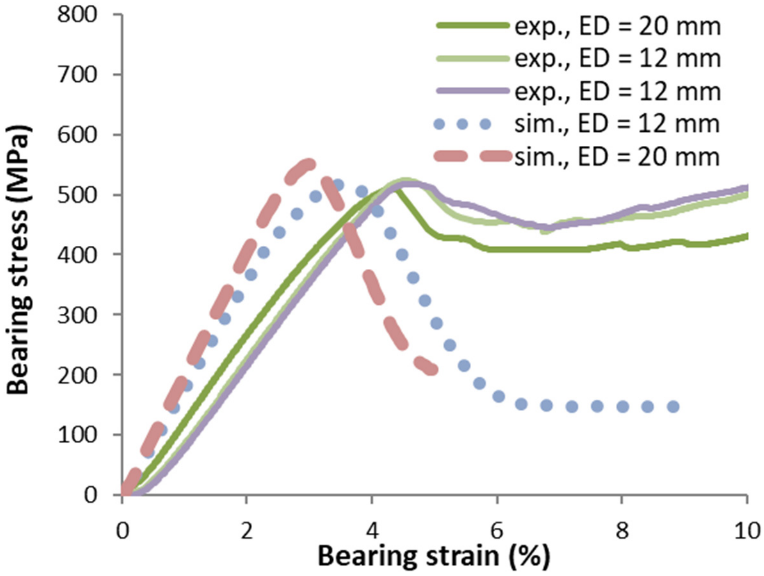


Fig. 6: Comparison of bearing stress – bearing strain curves obtained experimentally (exp.) and from numerical simulations (sim.) for specimens 5.6 mm thick clamped with clearance. ED stands for distance from the hole to the edge of the specimen.

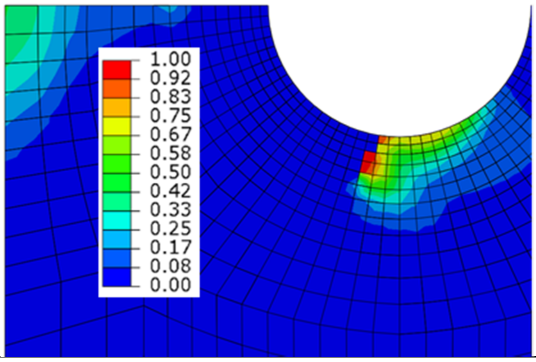
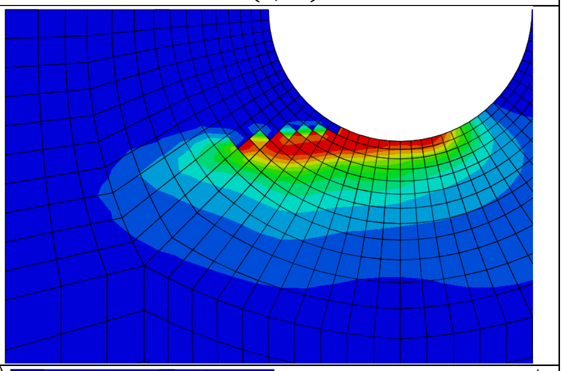
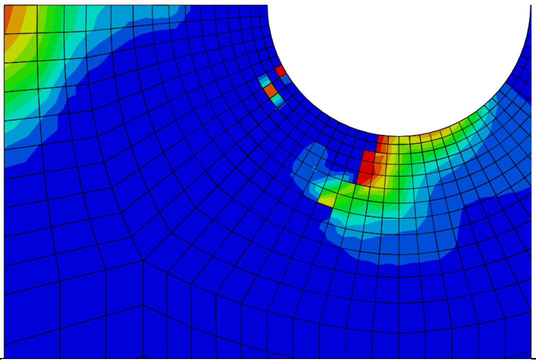
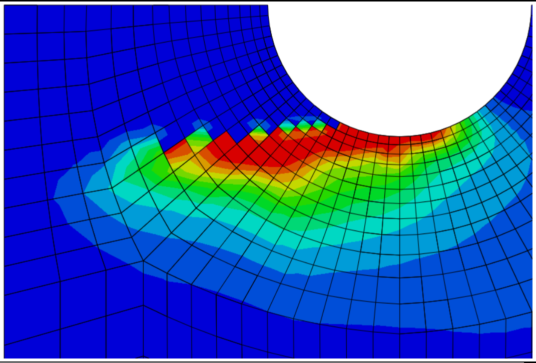
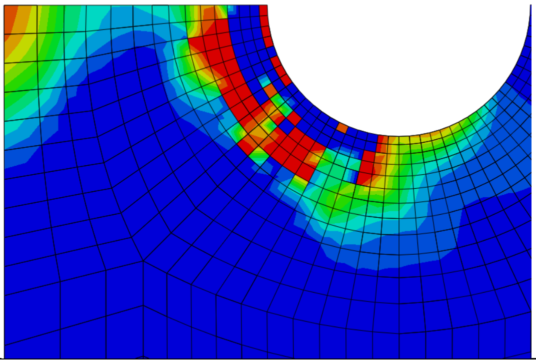
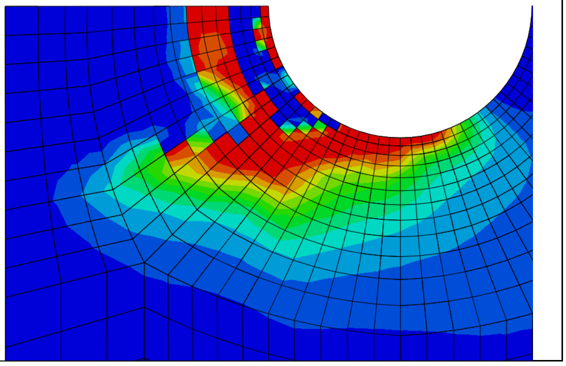
	Hashin Matrix tension failure index, Lamina orientation (±45)	Hashin Matrix tension failure index, Lamina orientation (0,90)
90 % Peak load		
Peak load		
Post peak load		

Fig. 7: Evolution of Hashin matrix tension criterion of failure.

The reasons for the other discrepancies between experiments and simulations may have resulted from multiple model idealizations. Firstly, the assumption of rigid fastener is incorrect and leads to more severe damage of specimen. Secondly, the continuum damage model based on Hashin failure criteria for fiber reinforced polymers, underestimates the influence of fiber reinforcement in transverse direction for woven reinforced composites. Moreover, real pressure distribution for boundary condition of clamping with torque is probably concentrated in the vicinity of the hole, while in simulation, the pressure was assumed uniform on the whole clamping surface.

Chosen modelling method was based on several assumptions and simplifications such as rigid fastener and clamping rigs, continuum shell elements for modelling of composite layer, mesh sizing or implicit integration scheme. The desired outcome consisted of relatively low time consumption of both the computation and evaluation of the analysis, easy accessibility of progressive continuum damage model, sufficient contact convergence and portability of the method to the global model of part of real construction.

Alternative choices are joined with considerable pros and cons. The explicit integration scheme should lead to better contact convergence for the price of higher time consumption of the analysis and higher numeric accumulation of errors. Softer meshing would lead to more precise stress distribution, however, with a significant increase of computation time. Solid elements for ply by ply modelling of composite and deformable bolt and clamping would lead to better contact stress distribution in the exchange for higher time consumption of computation and the necessity of implementation of user defined progressive damage model (e.g. Hashin‘s Failure Criteria for solid elements).

Conclusions

Influence of boundary conditions, such as clamping force and hole distance to the edge of the part, to bearing strength were experimentally verified. Similar trends were qualitatively but not quantitatively observed also numerically. Modelling of composite failure proved to be very complex task. Progressive damage modelling in combination with contact and large deformations suffers with convergence issues in implicit integration scheme. Using of rigid elements for dummy of load introduction system lead to convergence improvement of numerical models, but by contrast the lack of prediction is much higher. Explicit integration together with ply by ply methodology with flexible parts may to be more suitable for simulation.

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References

[1] M. Kadlec, L. Nováková, R. Růžek, An Experimental Investigation of Factors Considered for the Short Beam Shear Strength Evaluation of Carbon Fiber–reinforced Thermoplastic Laminates, Journal of Testing and Evaluation, 42(3) (2014) 580-592, http://dx.doi.org/10.1520/JTE20120043.

[2] R. Růžek, M. Kadlec, L. Petrusová, Effect of fatigue loading rate on lifespan and temperature of tailored blank C/PPS thermoplastic composite. International Journal of Fatigue, 113 (2018) 253-263. https://doi.org/10.1016/j.ijfatigue.2018.04.023.

[3] P. Homola, M. Kadlec, R. Růžek, J. Šedek, Fatigue behaviour of tailored blank thermoplastic composites with internal ply-drops, Procedia Struct. Integr. 5 (2017) 1342–1348, https://doi.org/10.1016/j.prostr.2017.07.144.

[4] A. Zeole, Experimental Investigation and Analysis for Bearing Strength Behavior of Composite Laminates, Wichita State University, Dept. of Mech. Engineering, 2006.

[5] Z. Chen, T. Phung, R. Paton, P. de Bruijn, Characterisation of a Reinforced PPS Thermoplastic Laminate For Forming Simulations. Composite Techologies for 2020: Proceedings of the Fourth Asian-Australasian Conference on Composite Materials (Accm 4), Elsevier, 2004, ISBN: 1845690621.

[6] J. Šedek, R. Hron, M. Kadlec, Bond Joint Analysis of Thermoplastic Composite Made from Stacked Tailored Blanks. Applied Mechanics and Materials, 827 (2015) 161-168, ISSN 1662-7482. DOI: 10.4028/www.scientific.net/AMM.827.161.

[7] J. Šedek, R. Hron, M. Kadlec, Evaluation of a bond joint in a carbon weave reinforced thermoplastic manufactured from stacked tailored blanks. In EAN 2015 - 53rd

Conference on Experimental Stress Analysis (EAN2015). Český krumlov (CZ), 1 – 4 June 2015, 399-402.

[8] A. Yousefpour, M., Hojjati, J.P. Immarigeon, Fusion Bonding/Welding of Thermoplastic Composites, Journal of Thermoplastic Composite Materials, 17(4) (2004) 303–341. https://doi.org/10.1177/0892705704045187.

[9] J. Šedek, Optimization of composite airframe rib using tailoring blank technology. In: EAN 2016 - 54th International Conference on Experimental Stress Analysis. Srní (CZ), 30 May – 2 June 2016.

[10] R. Růžek, J. Šedek, M. Kadlec, P. Kucharský, Mechanical behavior of thermoplastic rib under loading representing real structure conditions. In: EAN 2016 - 54th International Conference on Experimental Stress Analysis. Srní (CZ), 30 May – 2 June 2016.

[11] ASM Handbook Volume 21: Composites, ASM International, Editor: D.B. Miracle and S.L. Donaldson, 2001, ISBN: 978-0-87170-703-1.

[12] C.G. Huguet, A continuum damage mechanics model for woven composites. Masters Thesis. Delft University of Technology, 2017, http://resolver.tudelft.nl/uuid:63f1527a-b2f2-4474-9a63-20234a6057ae.

[13] Z. Hashin, A. Rotem, A fatigue criterion for fiber-reinforced materials. Journal of Composite Materials, 7 (1973) 448–464.

[14] Matzenmiller A., Lubliner J., Taylor R.L., „A constitutive model for anisotropic damage in fiber-composites“, Mechanics of Materials, 20 (1995) 125-152.

[15] AIMS Airbus Material Specification, AIMS05-09-002, 2007.

[16] ASTM D5961 Standard Test Method for Bearing Response of Polymer Matrix Composite Laminates. ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States.

[17] Abaqus 2017 Documentation. Dassault Systemes Simulia Corporation; 2017.

[18] M.L. Benzeggagh, M. Kenane, Measurement of Mixed-Mode Delamination Fracture Toughness of Unidirectional Glass/Epoxy Composites with Mixed-Mode Bending Apparatus, Composites Science and Technology, 56 (1996) 439–449.