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COMPOSITES THEORY AND PRACTICE

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NUMERICAL MODELLING AND SIMULATION OF RN-B COMPOSITE JOINT TENSILE TEST AND EXPERIMENTAL VALIDATION

The study develops the numerical modelling of a single rivetnut-bolt single-lap joint (RN-B) with in-plane and out-of-plane technological clearances, applied to joining longitudinal flanges of glass-polyester composite segments of tank covers. 3D modelling has been developed to simulate the RN-B joint tensile test aimed at determining the translational stiffness coefficients of the joint. Next, approximate 2D modelling of the RN-B joint tensile test has been developed using the translational stiffness coefficients (from 3D modelling and simulation), selected shell elements and the bushing-type bar element. The experimental validation test related to the RN-B joint tensile test has been examined up to full loss of load capacity. It has been proved that the translational stiffness coefficients in the elastic range (before joint failure) can be predicted correctly for a 3D joint model. The predicted stiffness coefficients can be applied in 2D modelling for the connections of shell segment flanges having the same stacking sequence of laminas. This approach is useful in engineering calculations and the design of glass-polyester laminate tank covers.

Keywords: **polymer-matrix composite cover, rivetnut-bolt single-lap joint, technological clearances, tensile test, translational stiffness coefficients, 3D modelling, 2D modelling, simulation, experimental validation, MSC.Marc system**

MODELOWANIE NUMERYCZNE I SYMULACJA PRÓBY ROZCIĄGANIA ZŁĄCZA KOMPOZYTOWEGO NN-S ORAZ WALIDACJA EKSPERYMENTALNA

W pracy rozwinięto modelowanie numeryczne pojedynczego złącza jednozakładkowego nitonakrętka - śruba (NN-S) z luzami technologicznymi w płaszczyźnie złącza i prostopadle do płaszczyzny złącza, stosowanego do łączenia wzdłużnych kolnierzy segmentów kompozytowych poliestrowo-szklanych przekryć zbiorników. Opracowano modelowanie 3D do symulacji próby rozciągania złącza NN-S w celu określenia sztywności translacyjnych złącza. Następnie opracowano modelowanie uproszczone 2D złącza NN-S z wykorzystaniem wymienionych sztywności, elementów powłokowych i elementu prętowego typu bushing. Przeprowadzono test eksperymentalny walidacyjny rozciągania badanego złącza aż do całkowitej utraty nośności. Wykazano, że sztywności translacyjne złącza NN-S w zakresie sprężystym (przed zniszczeniem złącza) można poprawnie prognozować z modelu 3D, a następnie stosować je w modelowaniu 2D połączeń kołnierzy o analogicznej sekwencji warstw 2D powłokowych modeli segmentów przekryć kompozytowych poliestrowo-szklanych.

Słowa kluczowe: **przekrycie kompozytowe, złącze jednozakładkowe nitonakrętka-śruba, luzy technologiczne, test rozciągania, sztywności translacyjne, modelowanie 3D, modelowanie 2D, symulacja, walidacja eksperymentalna, system MSC.Marc**

INTRODUCTION

Polymer-matrix composite covers of tanks and canals are built using single-wave/multi-wave shell segments with flanges overlapping one another. To join segments, engineers commonly apply rivetnut-bolt joints (in this study denoted as RN-B) with technological in-plane and out-of-plane clearances. In order to maintain air-tight sealing of the tank/canal, longitudinal sheet rubber gaskets are used on both sides of the RN-B joint line. The literature review has revealed that the RN-B joint had not been examined, either numerically or experimentally.

In reference to the problem being studied, there are some publications on experimental and numerical investigations of classical bolted joints also applied to join laminates, e.g. aircraft structures. McCarthy et al. [1] developed 3D models of single-bolt, single-lap bolted composite (graphite/epoxy) joints. The model was constructed in the non-linear finite element code MSC.Marc. The results are compared to the experimental validation test (surface strains and joint stiffness) performed in the elastic range. The bolt pre-load due to the applied torque was simulated via longitudinal thermal expansion of one of the washers. Element_149 (3D 8-node Composite Brick Element) or global homogeneous orthotropic material derived by performing a series of tensile and shear numerical experiments (20-noded isoparametric hexahedral element) were applied alternatively. The authors presented a parameter study focussed on reduced integration, geometrical non-linearity, modelling of clamped areas of the joint etc. Failure of the joint is not discussed in the study.

The validated model developed in [1] was used in Ref. [2] to investigate the effects of clearance for a nominal 8 mm hole diameter on the strain/stress distribution, joint stiffness and failure initiation.

A global bolted composite joint model was developed and validated by Gray and McCarthy [3]. The laminates are modelled by S4R reduced integration shell elements, whereas the bolt is represented by a combination of two B31 beam elements coupled to two rigid contact surfaces. The finite element code ABAQUS was used in numerical modelling and simulation. The model, validated both experimentally and numerically, can capture the effects of bolt-hole clearance (up to 240 μm), bolt-torque, friction between laminates, bending of the laminates as well as load distribution in multi-bolt joints. The experiments and simulations were performed in the elastic range (before failure).

An enhanced analytical approach for modelling the load distribution in multi-bolt composite joints was developed in [4]. The model is a closed-form extension of the spring-based method, where bolts and laminates are represented by a series of springs and masses. A three-bolt, single-lap joint is investigated and positively validated both experimentally and numerically.

A 3D FE model of bolted single-lap composite-aluminium joints was developed by Ireman [5]. The laminate was modelled using the layered solid element available in the ABAQUS system (one layer of finite elements reflects four plies of laminate). The bolt, washer and nut were modelled as one unit using C3D6 wedge elements and C3D8 brick elements. The author examined experimentally the laminate layup and thickness, bolt diameter and type, clamping force etc. The numerical model was validated experimentally via measuring deformations, strains, and bolt load. The experiments and simulations were performed in the elastic range (before failure).

The study develops numerical modelling of a single rivetnut-bolt single-lap joint (RN-B) with in-plane and out-of-plane technological clearances, applied to the joining of longitudinal flanges of glass-polyester composite segments of e.g. sewage-treatment plant tank covers. The in-plane technological radial clearance of 6 mm is commonly applied in composite covers. This solution was designed by C.F. Maier Europlast GmbH & Co KG, Königsbronn, Germany before 2006. The in-plane clearance makes the site assembly of flexible composite covers of span lengths 10÷35 m possible. The distance between the connected composite plates, i.e. out-of-plane technological clearance, is protected by additional vertical boundary elements which enlarge the spatial stiffness of the flanges and protect the out-of-plane technological clearance for air-tight sealing with longitudinal sheet rubber gaskets (EPDM).

The authors consider a single rivetnut-bolt single-lap joint in order to determine the in-plane stiffness of the connection both numerically and experimentally. Longitudinal flanges of glass-polyester composite segments of tank covers are connected by a series of RN-B joints distanced by 300÷350 mm. The geometrical dimensions of the RN-B joint have been taken from a selected engineering project of a rectangular composite cover, made accessible by ROMA Co, Grabowiec, Poland. The parameter study focussed on the selection of options/values of numerical modelling and simulation of composite joints has also been performed by the authors' team and is planned for publication in another journal (the manuscript is currently being reviewed).

3D modelling has been developed in order to simulate the RN-B joint tensile test aimed at determining the translational stiffness coefficients of the joint. Approximate 2D modelling of the RN-B joint tensile test has been developed using the translational stiffness coefficients (from 3D modelling and simulation), selected shell elements and the bushing-type bar element. The experimental validation test related to the RN-B joint tensile test has been examined on an exemplary RN-B composite joint taken from real composite segments of the selected rectangular cover.

DESCRIPTION OF RN-B JOINT AND EXPERIMENTAL TENSILE TEST

The RN-B single-lap joint is composed of the following components (Fig. 1): M10 rivetnut with cylindrical flange, M10x40 steel bolt, M10 steel washer, SR1986 rubber washer, EPDM sheet rubber gaskets between two composite plates elements (marked with black rectangles). The joint connects two tested plates of 6.1 mm thickness each, distanced by EPDM gaskets (out-of-plane clearance), made of a polymer-matrix mixed laminate with a symmetric stacking sequence M/T/M/T/M/T/M, where M is an E-glass EM 1002/600/125 mat reinforced layer of 1.00 mm average thickness, whereas T is an E-glass STR 027-600-125 1/1 plane weave fabric of 0.70 mm average thickness. The ply angles related to the weft/warp fibres are [0/90] with respect to the longitudinal axis of the joint. Both E-glass products are manufactured by KROSGLASS Co., Krosno, Poland. Polimal 104 polyester resin, produced by Organika-Sarzyna Co, Sarzyna, Poland, is used as the matrix. The laminate plates were manufactured using contact technology. A cylindrical hole of 22 mm in diameter is cut in the upper laminate plate in order to maintain the in-plane radial clearance.

A rivetnut fastener made of A2-70 steel is riveted in the lower laminate plate and joined with a bolt to the upper plate. The rivetnut fasteners are produced by WASI Co. funded by E. Wagner and W. Simon [5].

The authors' team has examined two RN-B joint tensile tests on specimens of the dimensions shown in Figure 1, which are close to the specimen dimensions in [1-5]. The joint dimensions reflect the real RN-B joint designed by ROMA Co. for longitudinal flange connections of the selected sewage-treatment plant tank cover. The tests have been performed on an INSTRON 8802 testing machine at the traverse velocity of 30 mm/min (kinematic excitation).

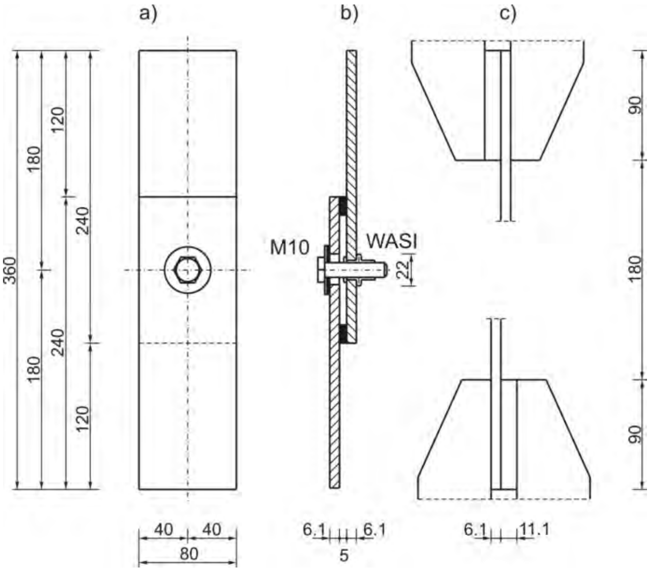

Fig. 1. RN-B joint tensile test: a, b) RN-B single-lap joint, c) fastening joint in grips

Rys. 1. Test rozciągania złącza NN-S: a, b) złącze NN-S dwóch płyt laminatowych, c) mocowanie złącza w uchwytach

Figure 2 presents the *F-s* (tension force - traverse displacement) experimental curves registered for two RN-B joint tensile tests.

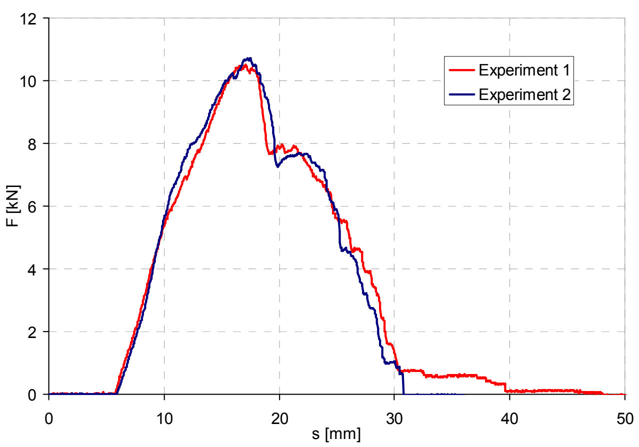

Fig. 2. *F-s* experimental curves obtained for two RN-B joint tensile tests

Rys. 2. Przebiegi *F-s* uzyskane w dwóch testach rozciągania złącza NN-S

The first stage reflects the free motion of the upper composite plate up to contacting the bolt to the hole surface (s = 6 mm). The initial stiffness of the joint in the tensioning direction equals ~1350 N/mm and, after reaching displacement s = 11.5 mm, the translational stiffness decreases to ~920 N/mm. The average maximum value of the tension force equals 10.67 kN at displacement s = 17.4 mm. A further increase in displacement s results in gradual loss of the load capacity of the joint.

3D MODELLING OF RN-B JOINT

The longitudinal mono-symmetry of an RN-B joint enables the construction of a numerical model for half the joint. The model has been constructed using the HyperMesh code. The following simplified assumptions are adopted:

1. the rivetnut is modelled as a deformable cylindrical element neglecting the cylindrical flange and plastic fold resulting from riveting technology
2. residual strains and stresses in the neighbourhood of the rivetnut, resulting from riveting technology are not taken into consideration
3. the bolt head is modelled as a cylinder
4. thread geometry is not modelled, thus the bolt and the rivetnut are connected rigidly.

Two rigid planes, fixed and moving, are incorporated to model machine grips. The third rigid plane reflects the symmetry plane. The laminates have been divided into 7 finite element layers corresponding to subsequent structural laminas. The RN-B joint numerical model is presented in Figure 3.

The tension process of the RN-B joint was simulated using the non-linear FE code MSC.Marc. The laminas and iron components are meshed with Element_7 which is an 8-node isoparametric finite element having three translational DOFs at each node. The right behaviour at shear and bending of this element has been maintained via applying the 'assumed strain' procedure [8]. Rubber washers and sheet gaskets are meshed with Element_84 which is an 8-node isoparametric finite element with an additional pressure node. Each corner node has three translational DOFs, whereas the 9th node has one DOF, i.e. negative hydrostatic pressure.

The RN-B joint FE model contains three material types, i.e. isotropic steel, orthotropic laminas [9] and rubber materials. Laminas reinforced with mat (M) or fabric (T), are modelled as linear elastic-short orthotropic materials. 'Selective Gradual Degradation' progressive failure has been taken into account assuming the 'Max Strain' criterion for mat laminas and 'Hashin Fabric' criterion for fabric laminas. The MSC.Marc system registers 6 failure indices at each Gauss point according to the formulas given in [7, 8].

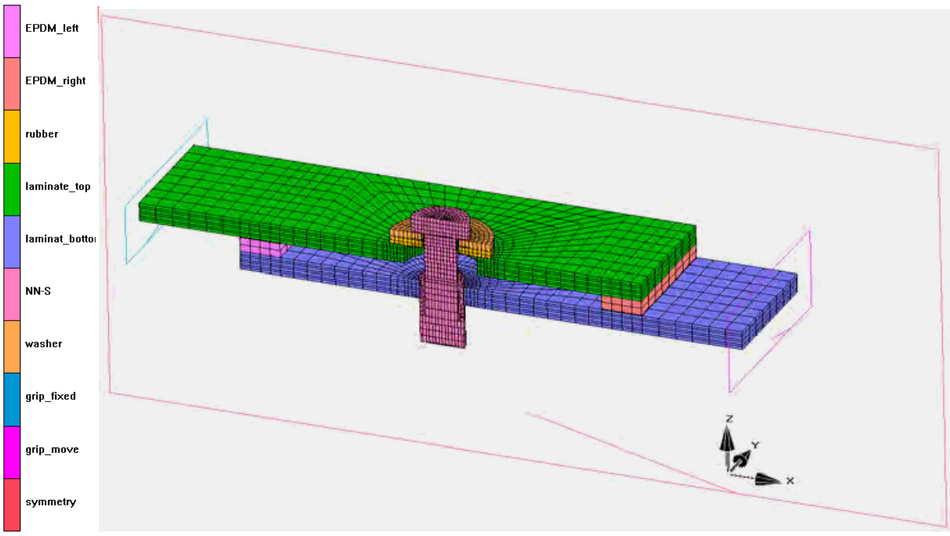

Fig. 3. RN-B joint numerical model

Rys. 3. Model numeryczny złącza NN-S

TABLE 1. **Material constants for RN-B joint material components**

TABELA 1. **Stałe w modelach materiałowych złącza NN-S**

	Material constant	M	F
poly-mer-matrix lami-nase	Young's modulus E_1, MPa	8250	16550
	Young's modulus E_2, MPa	8250	16550
	Young's modulus E_3, MPa	4150	5000
	Poisson's ratio ν_{12}	0.390	0.155
	Poisson's ratio ν_{23}	0.235	0.234
	Poisson's ratio ν_{31}	0.118	0.0707
	shear modulus G_{12}, MPa	3200	2300
	shear modulus G_{23}, MPa	3100[1]	2400[1]
	shear modulus G_{31}, MPa	3100[1]	2400[1]
	tensile strength X_t, MPa	95.7	269
	compressive strength X_c, MPa	216	202
	tensile strength Y_t, MPa	95.7	269
	compressive strength Y_c, MPa	216	202
	tensile strength Z_t, MPa	70	70
	compressive strength Z_c, MPa	231	344
	shear strength S_{xy}, MPa	91	32.6
	shear strength S_{yz}, MPa	35.9	22.5
	shear strength S_{zx}, MPa	35.9	22.5
	ultimate normal strains at tension e_{1t}	0.014	0.021
	ultimate normal strains at compression e_{1c}	0.031	0.011
	ultimate normal strains at tension e_{2t}	0.014	0.021
	ultimate normal strains at compression e_{2c}	0.031	0.011
	ultimate normal strains at tension e_{3t}	0.017[2]	0.020
	ultimate normal strains at compression e_{3c}	0.061	0.100
	ultimate shear strains g_{12}	0.043	0.050
	ultimate shear strains g_{23}	0.040[2]	0.045
	ultimate shear strains g_{31}	0.040[2]	0.045
A2-70	Young's modulus E, MPa	200000	
	Poisson's ratio ν	0.235	
		EPDM	SR1986
rubber	C_{10}, MPa	0.00796	1.67
	C_{20}, MPa	-	21.8
	C_{30}, MPa	-	0.514
	bulk modulus B, MPa	79.6	16695.9

The MSC.Marc system offers Mooney-Rivlin models group for modelling rubber (hyperelastic) materials based on the strain energy function and described by respective $C_{ij} > 0$ constants. The latter are determined using the 'Experimental Data Fit' module available in the MSC.Mentat pre-processor. The rubber components of the RN-B joint are best approximated with the Yeoh model described by C_{10}, C_{20}, C_{30} coefficients. The'Mean Strain Energy' adaptive failure criterion has been applied.

The material constants for the RN-B joint components, determined from the authors' experimental tests, are collected in Table 1.

In order to model the contact between respective groups of deformable finite elements, the 'Touching' ('Node To Segment') option has been chosen. The bilinear Coulomb friction model has been selected, described by static friction coefficients and the ultimate stresses of the values presented in Table 2. The moving grip moves at a constant velocity at 0÷10 mm intervals.

TABLE 2. **Bilinear Coulomb friction model parameters**

TABELA 2. **Parametry modelu tarcia biliniowego Coulomba**

Friction couple	Static friction cofefficient μ [-]	Ultimate stress σ_{lim} [MPa]
composite - composite	0.39	91
composite - steel	0.29	91
composite - SR1986	0.60	5.0
composite - EPDM	1.10	0.2
steel - steel	0.15	435
steel - SR1986	0.40	5.0

The problem has been solved using the full Newton--Raphson method and the displacement and force convergence criteria at 0.10 tolerance. An adaptive load time increment has been used. The introductory simulations compared to the experiments have revealed that the RSF (Residual Stiffness Factor) should be equal to 0.2. This factor defines the initial stiffness part equal to the residual stiffness of the elements during progressive failure. Hiperelastic materials undergo large deformations at the technological hole zone. On the other hand, laminates are characterized by small strains. Thus, large deformation and large strain options must be selected and the total Lagrange description must be used as well.

Figure 4 depicts the simulated *F-s* (tension force - traverse displacement) curves corresponding to the total/updated Lagrange descriptions, against the background of the experimental results. The FI2 failure index contours corresponding to displacement *s* = 10 mm are illustrated in Figure 5.

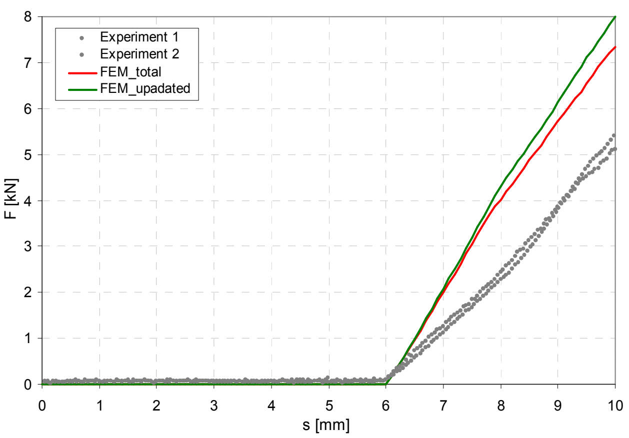

Fig. 4. *F-s* simulated curves for total/updated Lagrange descriptions

Rys. 4. Symulowane przebiegi F-s dla dwóch ujęć opisu deformacji Lagrange'a

2D MODELLING OF RN-B JOINT

The 2D numerical model for the RN-B joint has been constructed and tested in order to simplify longitudinal flanges connections modelling in reference to the engineering calculations of polymer-matrix laminate covers statics. 2D modelling is based on 3D modelling using the translational stiffness coefficients derived from the RN-B joint tensile test. The concept of 2D modelling constitute the following items:

1. laminate plates are meshed using shell elements and neglecting technological clearances
2. finite elements in the RN-B joint zone are of dimensions 20 x 20 mm suitable for further modelling of longitudinal flanges of laminate covers
3. each RN-B joint is represented by a single bushing-type finite element described by respective translational stiffness coefficients resulting from 3D modelling of the RN-B joint, including technological in-plane clearance
4. rubber elements existing in the RN-B joint are neglected in 2D modelling.

Two types of finite elements are applied in 2D modelling, i.e. Element_75 for laminate plates and Element_195 for the RN-B joint. Element_75 (Bilinear Thick-shell Element) is a 4-node 2D bilinear finite element having 3 translational and 3 rotational DOFs at each node [7, 8]. Element_195 is an elastic-damping structural element exhibiting non-linear or frequency-dependent behaviour. The element topology is depicted in Figure 6.

The element may by associated with six property groups depending on the analysis type, including mechanical properties. The stiffness properties can be defined directly by translational and rotational stiffness coefficients or by respective force-displacement diagrams. In nonlinear simulations, the stiffness properties can be determined versus time, increment number, location coordinates, frequency or temperature.

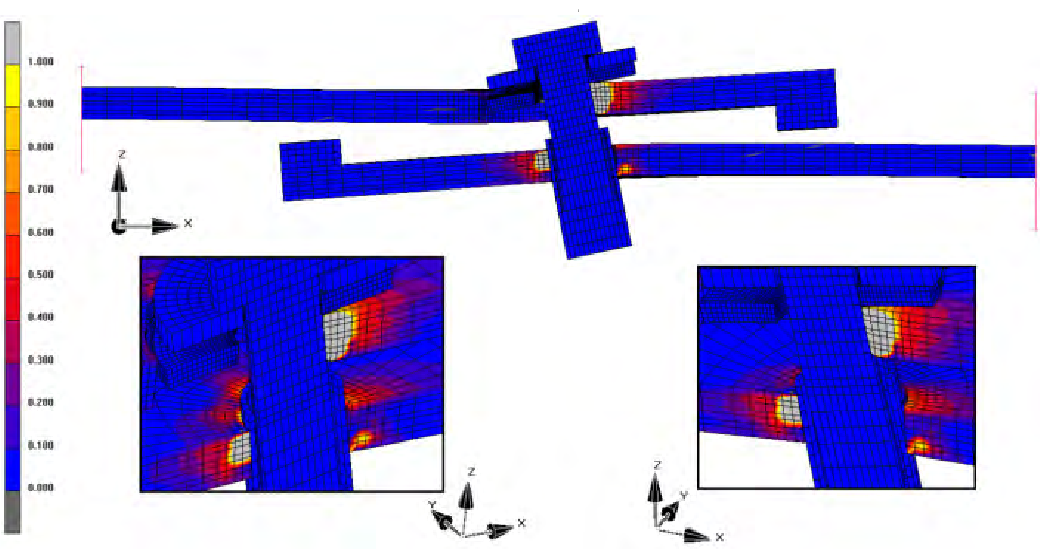

Fig. 5. FI2 failure index contours corresponding to displacement *s* = 10 mm

Rys. 5. Warstwice indeksu niszczenia FI2 odpowiadające przemieszczeniu *s* = 10 mm

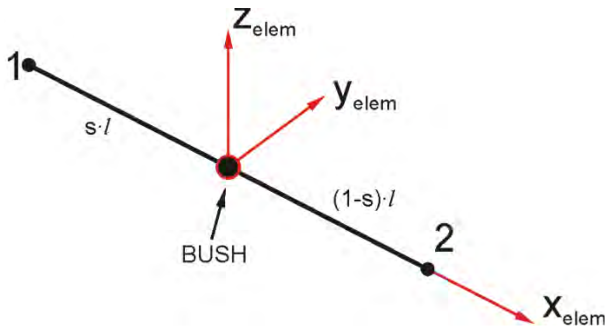

Fig. 6. Element_195 topology (3D Generalized Spring – CBUSH/CFAST Element) [7, 8]

Rys. 6. Topologia Elementu_195 (3D Generalized Spring – CBUSH/CFAST Element) [7, 8]

The elastic properties of Element_195 (Bushing) have been defined as translational stiffness factors in the form of *F-s* (force-displacement) diagrams in the global coordinate system. Translational stiffness factors in the *x* and *y* directions reflect the results obtained for respective 3D RN-B joint modelling. The diagram takes into account a 6 mm horizontal clearance (resulting from technological clearance) and 1850 N/mm horizontal stiffness after bolt-upper laminate contact. The vertical stiffness of the RN-B joint (in the bolt axis direction), corresponding to the tension state, in which the laminated plates are moving apart, is calculated approximately as the bolt axial stiffness - the nominal bolt length ratio. The latter is defined as the distance between the central surfaces of the laminated plates. The vertical stiffness of the joint amounts to 1.43x10^6 N/mm. The translational stiffness diagrams for Element_195 are presented in Figure 7. Owing to RN-B joint technology, the rotational stiffness coefficients are assumed to be equal to 0.

The mixed laminate material model was declared in two steps. Firstly, two types of linear elastic - short orthotropic materials, describing separately the mat (M) reinforced homogeneous laminate and the fabric (F) reinforced homogeneous laminate, have been declared. The material constants of those homogeneous laminates, identified experimentally according to the respective codes, are summarized in Table 1. Secondly, the mixed laminate model has been created via stacking sequence declaration.

The ‘Touching’ (‘Node to Segment’) contact option has been applied between the laminate plates taking into consideration the bilinear Coulomb friction model (Table 2). The ‘Distance tolerance’ and ‘bias factor’ related to contact took the default values. Regarding the boundary conditions, the upper laminate plate was fixed to the grip surface, whereas the right nodes of the lower laminate plate could move in the *x* direction at a constant velocity at 0÷10 mm intervals. The remaining DOFs at the right nodes of the lower plate were fixed. The problem has been solved with the full Newton--Raphson method taking into account the displacement and force convergence criteria at 0.05 tolerance. The adaptive time increment has been selected.

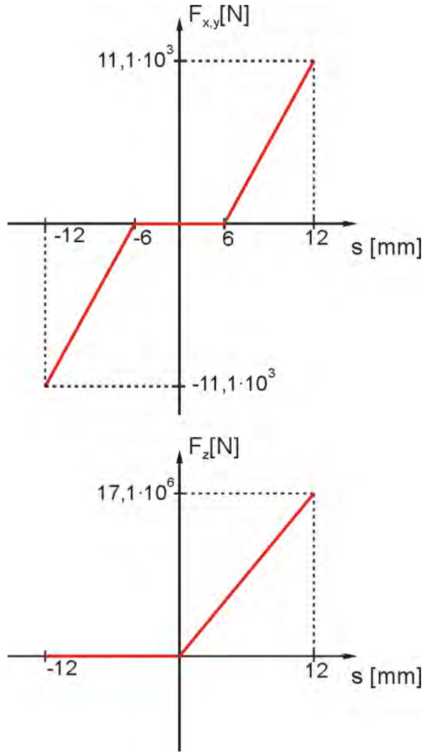

Fig. 7. Translational stiffness diagrams *F-s* for Element_195

Rys. 7. Deklaracja sztywności translacyjnych za pomocą przebiegów *F-s* dla Elementu_195

The *F-s* curves obtained from the 2D and 3D simulations, against the background of the experimental results (dots), are shown in Figure 8. In the elastic range (before progressive failure of the joint), the translational stiffness coefficients derived from the 3D simulations lead to good conformity of the *F-s* diagrams from the 2D modelling and experiments.

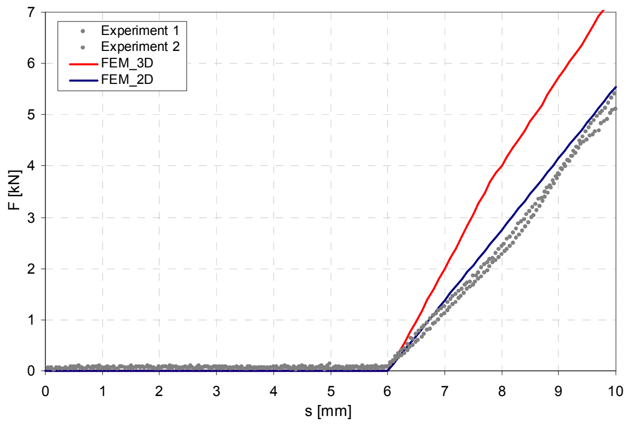

Fig. 8. *F-s* curves obtained from 2D and 3D simulations, against background of experimental results

Rys. 8. Przebiegi *F-s* uzyskane z symulacji numerycznej 2D i 3D na tle wyników eksperymentalnych

Figure 9 enables the comparison of 3D and 2D virtual deformations to the realistic deformation of the RN-B joint. One may observe good conformity of the simulated and experimental deformations, both qualitatively and quantitatively.

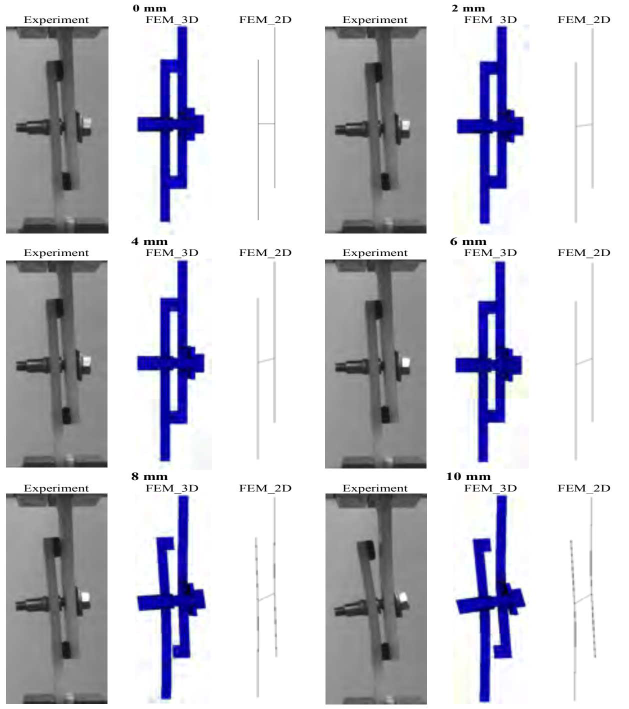

Fig. 9. Comparison of 3D and 2D virtual deformations to real deformation of RN-B joint (*s* = 10 mm)

Rys. 9. Porównanie deformacji wirtualnych 3D i 2D z rzeczywistą deformacją złącza NN-S (*s* = 10 mm)

CONCLUSIONS

The study develops the numerical modelling and simulation of a single rivetnut-bolt (RN-B) single-lap joint with in-plane and out-of-plane technological clearances, used to connect longitudinal flanges of glass-polyester segments of tank covers. The 3D modelling has been developed to simulate the tensile test in order to determine the translational stiffness of the joint. Next, simplified 2D modelling has been developed using the translational stiffness factors, shell finite elements and a bushing-type element. The simulated results are presented against a background of respective experimental results.

It has been pointed out that translational stiffness diagrams of the RN-B joint can be predicted from the 3D model and applied in the 2D modelling of longitudinal flanges connections. The flanges are components of glass-polyester composite segments used for building tank covers.

The 2D modelling of RN-B joints developed in the study can be applied in the elastic range (before progressive failure of the joint). Using 2D modelling in the engineering calculations and design of composite cover segments, index failures for 'Max Strain' and 'Hashin Fabric' failure criteria are recommended to be applied for mat-reinforced and fabric-reinforced laminas, respectively. The remaining options/values of numerical modelling and simulation parameters using the MSC.Marc code are set up in previous Sections. The index failures contours should be observed outside the flanges owing to their greater thickness compared to cover shells and simplifications done in the RN-B joints zones.

Acknowledgements

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REFERENCES

[1] McCarthy M.A., McCarthy C.T., Lawlor V.P., Stanley W.F., Three-dimensional finite element analysis of single-bolt, single-lap composite bolted joints: Part I - model development and validation, Composite Structures 2005, 71, 140-158.

[2] McCarthy C.T., McCarthy M.A., Three-dimensional finite element analysis of single-bolt, single-lap composite bolted joints: Part II - effects of bolt-hole clearance, Composite Structures 2005, 71, 159-175.

[3] Gray P.J., McCarthy C.T., A global bolted joint model for finite element analysis of load distributions in multi-bolt composite joints, Composites: Part B 2010, 41, 317-325.

[4] McCarthy C.T., Gray P.J., An analytical model for the prediction of load distribution in highly torque multi-bolt composite joints, Composite Structures 2011, 93, 287-298.

[5] Ireman T., Three-dimensional stress analysis of bolted single-lap composite joints, Composite Structures 1998, 43, 195-216.

[6] http://www.wasi.de/uploads/tx_smallwebfiledownload/Produktkatalog_NORM_polnisch_2011.pdf

[7] Marc 2008 r1, Vol. B, Element Library, MSC.Software Co., Santa Ana, CA, USA.

[8] Marc 2008 r1, Vol. A, Theory and User Information, MSC.Software Co., Santa Ana, CA, USA.

[9] Jones R.M., Mechanics of Composite Materials, Taylor & Francis, London 1999.

