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EXPERIMENTAL INVESTIGATION ON STIFFNESS AND STRENGTH OF SINGLE-LAP Z-PINNED JOINTS IN A LAMINATED CFRP STRESS-RIBBON STRIP

Aleksandr K. Arnautov[1]✉, Vladimir Kulakov[2], Janis Andersons[3], Viktor Gribniak[4], Algirdas Juozapaitis[5]

[1, 2, 3]*Institute of Polymer Mechanics (IPM), University of Latvia, Aizkraukles iela 23, LV–1006 Riga, Latvia*
[4]*Research Laboratory of Innovative Building Structures, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT–10223Vilnius, Lithuania*
[5]*Dept of Bridges and Special Structures, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT–10223Vilnius, Lithuania*
E-mails: [1]*alexander.arnautov@pmi.lv;* [2]*vladimir.kulakov@pmi.lv;* [3]*janis.adersons@pmi.lv;* [4]*viktor.gribniak@vgtu.lt;* [5]*algirdas.juozapaitis@vgtu.lt*

Abstract. Carbon fiber-reinforced polymer (carbon-polymer) is an advanced lightweight composite material with high strength and excellent resistance to corrosion and fatigue. Over the past decades, application of fiber-reinforced polymers has been spread from the aerospace to other branches of industry such as automobile and civil engineering. Unidirectional carbon-polymers have a high potential for replacing steel in tensile members. Recently, the *first* carbon-polymer stress-ribbon bridge has been constructed in Germany. The non-laminated strip-loop carbon-polymer thin strips were used as the load bearing components in this bridge. In comparison with the laminated components, the applied cables are characterized by a more uniform strain distribution though reduced structural integrity. Alternative jointing technologies of carbon-polymer laminates are considered in this paper with an intention to increase the structural integrity and reliability of the production. Tensile behavior of the single-lap joints was investigated experimentally. Three types of the joints were considered. Adhesive joint was set as the reference. The overlap region of the mechanically fastened joints was produced using 9, 25, or 36 steel needles (z-pins) of 1 mm diameter. The proposed hybrid joints were additionally connected with adhesive increasing the load-bearing capacity of the reference joint up to 230%. Concerning the brittle fracture of the adhesive counterparts, the extended progressive failure process within the hybrid joints is responsible for the improvement.

Keywords: carbon fiber reinforced polymer (CFRP), laminate, single-lap joint, stress-ribbon strip, test data.

1. Introduction

Over the past decades, application of fiber reinforced polymer (FRP) composites has been spread from the aerospace to other branches of industry such as automobile and civil engineering. Efficiency of the production and gathering of structures made of FRP composites is closely related with reliability and cost-effectiveness of the fastening technologies. Three types of joints are common for the composite structures: mechanically fastened joints, adhesively bonded joints, and hybrid mechanically fastened-adhesively bonded connections. A single-lap fastening is the most commonly used configuration of the joints. The mechanically fastened joints using bolts, pins or rivets remain the main type of connection for the structural composites. In the current engineering practice, adhesive joints of FRP are increasingly used as a prominent alternative to the mechanical connectors. Duthinh (2000), Baena, da Silva (2008) and Thoppul *et al.* (2009) provided a detail description of design problems concerning these two types of the joints.

The mechanical fastening requires drilling holes in the jointed components. Recent studies conducted by Bodjona, Lessardand (2015), Saleem *et al.* (2015) and Gamdani *et al.* (2015) can be mentioned amongst many others dedicated for analysis of stress distribution at a hole in laminated composites. Cutting the reinforcing fibers and introduction of the stress concentrators lead to reduction of the mechanical properties of the joints. The stress distribution is dependent on the laminate geometry, structural parameters (e.g., layup, anisotropy of material)

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and loading conditions. William (1985) obtained significant in a statistical sense negative correlation between load-bearing capacity of composite plate and a diameter of the hole. Callus (2007) reported that needles of a diameter ≤1.0 mm distributed at the distance greater than 3–5 diameters cause no deterioration of the mechanical characteristics of the jointed composite plates and promote a uniform distribution of the stress. Presence of ±45° plies, with optimum amount of 30% to 50% of the total content of fibers, noticeably reduced concentration of the stresses (Gamdani *et al*. 2015; Schläpfer, Kress 2014).

Adhesive bonding is a quite natural technology for joining structural members made of FRP composites with polymer matrix. In the adhesive joints, the loads are transferred mainly due to the shear effect. Such connection is efficient for controlling the fatigue resistance of thin-skinned structures (Pantelakis, Tserpes 2014) and strengthening purposes (Grbniak *et al*. 2014, 2015). However, effectiveness of the adhesive bond is limited by a relatively low inter-laminar shear strength (Arnautov *et al*. 2015). Furthermore, failure of the adhesive joints is often brittle. To increase strength, delamination toughness and impact resistance, the adhesively bonded joints are often reinforced in the through-thickness direction by stitching (Aymerich *et al*. 2005; Pingkarawat *et al*. 2014) or z-pinning (Chang *et al*. 2006; Ko *et al*. 2015). Detail description of the connection mechanism of stitches and z-pins can be found in the literature (Rugg *et al*. 2002).

Microstructural changes of the laminates during the pinning process may have either beneficial or adverse influence on the mechanical properties. Chang *et al*. (2006) obtained 40% increase in strength of the single-lap joint of carbon fiber reinforced epoxy cross-ply laminate by inserting the fibrous z-pins in the overlap region though evident resin-rich zones at the pin locations. Mouritz (2007) reported that the z-pins, much thicker than the reinforcing fibers, induce an asymmetric waviness of the fibers leading to reduction of the in-plane mechanical properties of the laminates.

Most of the aforementioned studies were focused on benefits of the pinned joints such as an improved delamination toughness, impact resistance and strength. Though contributed to the clarification of the interaction mechanism between stitches and laminate, these works do not adequately explain the effect of various stitching parameters on the fracture performance of the joints. The main disadvantages of the stitched laminates can be related to the reductions in in-plane mechanical properties due to a failure and misalignment of the fibers and increased concentration of the resin (polymer) around the needles (Aymerich *et al*. 2005).

Alternative jointing technologies of carbon fiber-reinforced polymer (CFRP) laminates is the object of this research. Due to high strength and excellent resistance to corrosion and fatigue, unidirectional lightweight CFRP cables has a high potential for replacing steel in tensile members (Schlaich *et al*. 2015). The Cuenca footbridge (Spain) with CFRP bands, having the total length of 216 m, is the eighth stress-ribbon bridge in the world. The CFRP ∅41 mm cables were specially manufactured by Acciona for this project (Liu *et al*. 2015). The CFRP stress-ribbon bridge constructed in Germany can be mentioned as another example of application of GFRP strips (Fig. 1). In this project, the non-laminated strip-loop cables were used as the load bearing components – stress-ribbon strips (Schlaich, Bleicher 2007). In comparison with the laminated components, the strip-loop cables are characterized by a uniform strain distribution though reduced stiffness and increased creep (Liu *et al*. 2015).

With an intention to increase the structural integrity and reliability of the production, alternative jointing technologies of CFRP laminates are considered in this paper. Tensile behavior of the single-lap joints was investigated experimentally. Three types of the joints are considered. Adhesive joint is set as the reference. The overlap region of the mechanically connected joints was produced using 9, 25, or 36 steel needles (z-pins). Damage of the laminated CFRP adherends due to cut fibers at the locations of z-pin insertion is minimized by reducing diameter of the z-pins. Steel z-pins of 1 mm diameter are inserted into the overlap region after curing of the epoxy resin that allows preventing the appearance of resin-rich zones and waviness of the fibers around the pins. The proposed *hybrid* joints were additionally connected with adhesive for improving the toughness and ultimate strength.

2. Motivation of the research

Stress-ribbon structural system can be considered as the most efficient for pedestrian bridges (Juozapaitis *et al*. 2015). A pre-stressed concrete deck with the shape of a catenary forms the stress-ribbon structure. The bearing structure consists of slightly sagging tensioned cables (bands), bedded in a thin concrete slab. The traffic is often placed directly on the concrete slab embedding the cables. Compared with other structural types, the stress-ribbon system is extremely simple though requiring massive anchorage blocks due to very large tensile stresses induced in the cables. Such structures can be either cast in-situ or formed of precast units. In the case of precast structures, the deck is assembled from precast segments that are suspended on bearing cables and shifted along them to their final position. Pre-stressing is applied after casting the joints between the segments to ensure sufficient rigidity of the structure according to the International Federation for Structural Concrete *Guidelines for the Design of Footbridges* of 2005.

The first CFRP stress-ribbon bridge has been constructed in Germany in 2007 (Schlaich, Bleicher 2007). Figure 1 shows the test of the bridge conducted in the laboratory of TU Berlin. The cable anchorage system is shown in Fig. 2. It consists of two round pins, a triangular steel box and two bolts for the connection to the foundation (Figs 2a and 2b). The non-laminated strip-loop cable system developed by Empa (Swiss Federal Laboratories for Material Science and Technology) was used as the load-bearing component in this bridge. The concept patented by Meier, Winstoerfer (2001) is shown in Figs 2c and 3a. A number of unidirectional reinforced layers formed from a single continuous thermoplastic tape comprises the CFRP strap. The tape is wound around the pins; the end of the outmost layer is fusion bonded to the outermost layer forming a close loop.

In comparison with laminated strips, the strip-loop cables (Fig. 3a) are characterized by a uniform strain distribution though reduced structural integrity. This paper introduces a solution for application of CFRP laminates as the stress-ribbon-strips that simplifies construction of the bridges. Figure 3b shows the considered scheme of the anchorage-loop that is formed during the polymerization process (Liu *et al.* 2015) and closed (connected) using the proposed hybrid joint. Mechanical parameters of the joint are the object of this experimental study.

Fig. 1. Load test of the CFRP stress-ribbon bridge (Schlaich, Bleicher 2007)

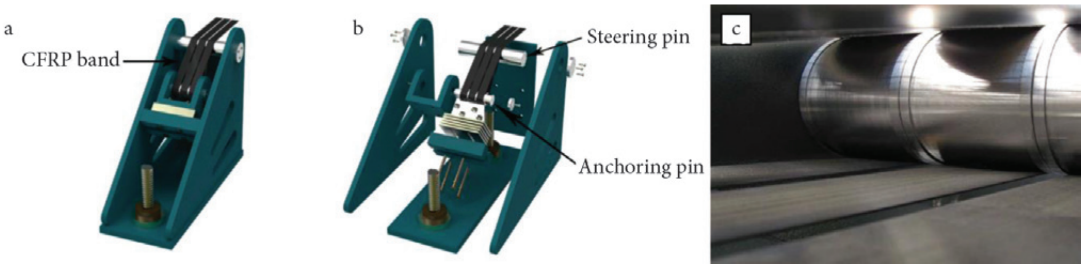

Fig. 2. Pin-loaded anchorage system (Liu *et al.* 2015): a – assembled; b – exploded schemes; c – internal view

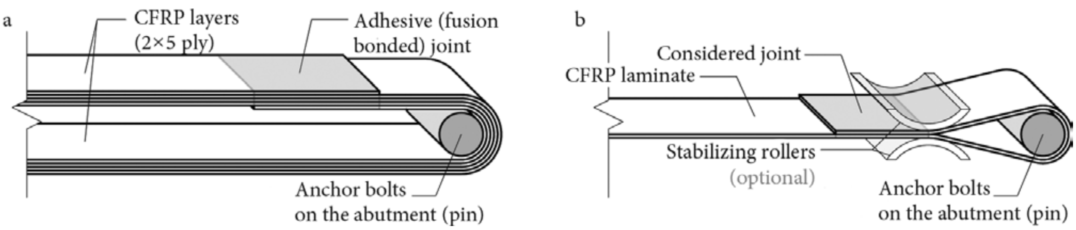

Fig. 3. CFRP stress-ribbon strips: a – non-laminated strip-loop (Empa); b – the considered single-lap joint for the laminated loop

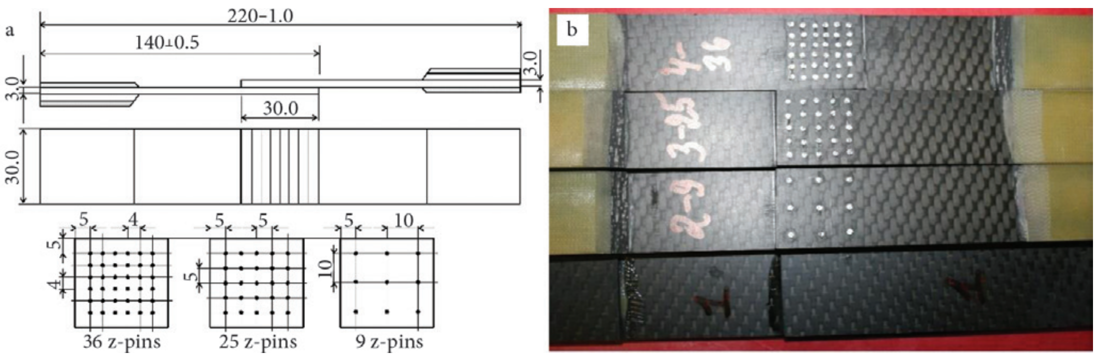

Fig. 4. Tested joints: a – geometry and distribution of the z-pins (dimensions are in mm); b – view on the specimens

3. Materials and test setup

The single-lap joints for CFRP, epoxy laminate with $[0°/90°/\pm45°]_s$ layup, were fabricated and tested according to the ASTM D-3983 using MTS 809.40 (*MTS Systems Corp*., Minnesota, USA) servo-hydraulic machine with 250 kN load cell. Laminated adherends were cut from the plates in the direction of carbon fibers of the 0° plies that was the loading direction in the tensile tests. Mechanical properties of the CFRP were determined by uniaxial tensile tests of the flat specimens according to the ASTM D-3039, obtaining the following values: tensile modulus $E_{11} = 56.0 \pm 0.8$ GPa, tensile strength $\sigma_{11} = 554.5 \pm 26$ MPa, and ultimate strain $\varepsilon_{11} = 1.03\%$.

Three types of the joints were considered: mechanically fastened with z-pins, adhesively bonded and hybrid (mechanically fastened and adhesively bonded). Adhesive joint was set as the reference. As shown in Fig. 4, the overlap region was 30 mm long and 30 mm wide. Effect of mechanical fastening on the ultimate strength was investigated distributing 9, 25, and 36 z-pins within the overlap region. The z-pins of 16 mm length and 1 mm diameter were made of carbon steel *S185* (*Erkrath*, Germany). The epoxy compound *Sikadur® 52* was used as the adhesive material. Mechanical properties of the z-pins and epoxy adhesive, according to the manufacturers' data, are as follows: for z-pins, tensile modulus 200 GPa, Poisson's ratio 0.31, ultimate elongation 18%, yield strength 420 MPa; for epoxy: tensile modulus 1.93 GPa, Poisson's ratio 0.31, ultimate strain 3% and tensile strength 42 MPa.

The ultimate strength and elongation of the joints were determined in monotonic loading at a crosshead speed of 2 mm/min. The test setup is shown in Fig. 5. At least six specimens were tested for each type of the joints. The applied load-displacement diagrams were recorded up to the failure of the joint. The shear stresses were calculated by dividing the applied tensile load by the total bond area. The ultimate shear stress and respective strain, and shear stiffness of the joints (in the range from 0% to 10% of the ultimate loads) were calculated as well.

4. Results and discussion

The shear stress-strain diagrams are presented in Fig. 6. It can be observed that the stress-strain curve of the adhesive joint (black line in Fig. 6) is almost elastic up to possessing the ultimate shear stress of 13.9 MPa. The instantaneously brittle failure of the reference joint was catastrophic that is typical for most adhesives.

Although the shear stiffness of the adhesive joint is much higher than that obtained for the pinned joints, the load-bearing capacity of the mechanically bonded joints increases with the number of z-pins (Fig. 6a). The load-bearing capacity of the reference joint and the counterpart fastened with 25 z-pins are almost the same though 46% lower than obtained for the joint connected with 36 z-pins. Gradual failure and a higher ultimate strain observed in the *z*-pinned joints (Fig. 6a), requiring a significant release of the deformation energy, can be considered as the important advantage of the mechanically fastened joints in comparison with the adhesive reference.

The shear stress-strain diagrams shown in Fig. 6b illustrate deformation behavior of the *hybrid* joints. It is evident that these joints possess practically the same shear stiffness as the adhesively bonded joint accomplished by a prolonged failure process. Analysis of the deformation curves revealed that the initial failure of the hybrid joints was due to the fracture of the adhesive layer at a shear stress of about 10 MPa. The load-bearing capacity of the hybrid joints (Fig. 6b) was at least 18.5% higher than obtained for the mechanically fastened joints with the same number of the pins (Fig. 6a). A more than twofold increase in the load-bearing capacity was observed for the hybrid joint with 9 z-pins. The main mechanical properties of the considered joints are summarized in Table 1. Due to the higher stiffness of the hybrid joints, the ultimate shear stresses were reached at smaller strains than characteristic for the mechanically fastened counterparts (Table 1, Fig. 6).

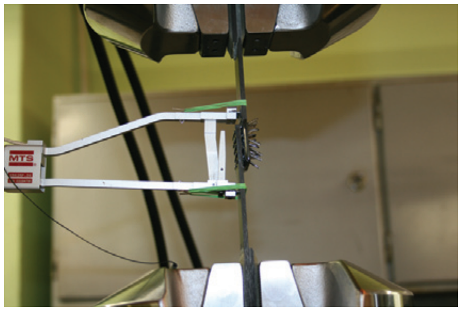

Fig. 5. Tensile test setup

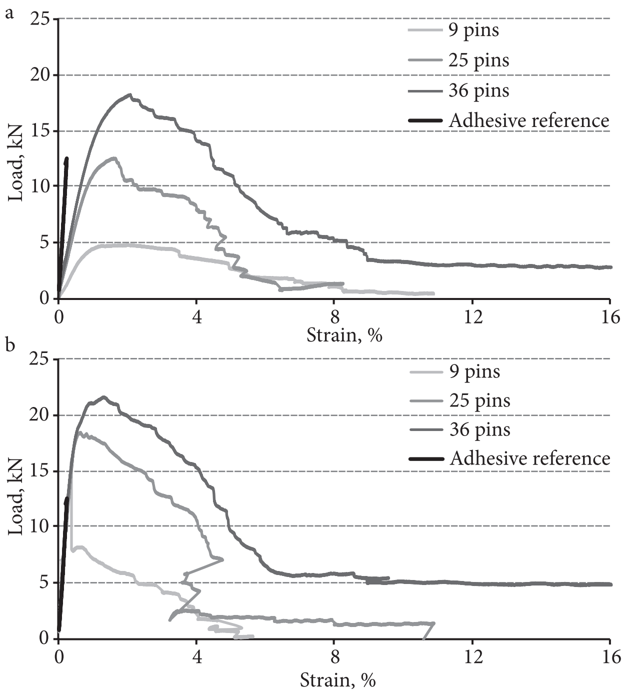

Fig. 6. Shear stress-strain diagrams of the tested single-lap joints: a – mechanically fastened samples; b – hybrid joints

Table 1. Main characteristics of the single-lap joints

Type	Number of z-pins	Ultimate shear stress τ_{ult}, MPa	Strain at the ultimate load, %	Shear stiffness, MPa
Adhesive reference	–	13.9±2.1	0.24±0.07	48.9±0.6
Mechanically fastened	9	5.3±2.2	1.98±0.25	6.2±0.6
	25	13.9 ±2.4	1.59±0.28	14.2±0.7
	36	20.3±4.2	2.09±0.29	17.5±0.7
Hybrid	9	17.8±2.4	0.67±0.19	56.5±0.6
	25	20.5±2.9	0.78±0.21	57.5±0.8
	36	24.0±3.3	1.49±0.31	58.6±1.2

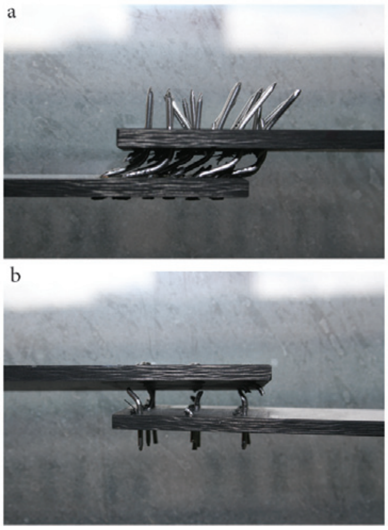

Fig. 7. Failure character: a – the hybrid joint with 36 pins; b – the mechanically fastened counterpart with 9 pins

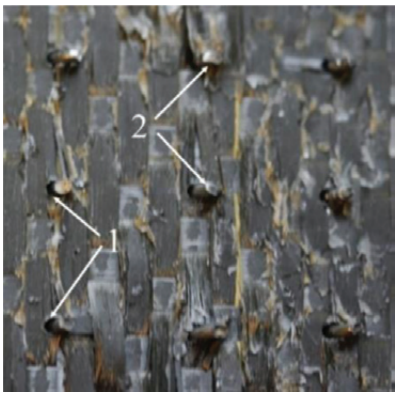

Fig. 8. Bearing (1) and shear (2) failure of the z-pins within the hybrid joint

Figure 7 illustrates the failure of the hybrid joint with 36 z-pins and the mechanically fastened counterpart with 9 z-pins. Developing cracks within the adhesive layer starts the progressive failure of the hybrid joint. Bending deformations and cut-off of the steel pins were observed at the increasing load. Due to the loss of the adhesive connection, the failure of the reference joints was brittle. Failure of the hybrid joint in consequence of bearing or shear of the pins can be observed in Fig. 8. Reduction of the number of pins results in shear failure of some of them. Independently on the presence of additional adhesive connection, such a failure mechanism was characteristic for all pinned joints.

This study extends previous findings, concerning the double-lap joints (Arnautov *et al.* 2015), for the case of analysis of applicability of the hybrid connection technology in producing the laminated stress-ribbon strips. Application of z-pins improved the mechanical properties of the joints. As can be observed from Table 1, the strength and the stiffness of the pinned-only joints was increased by 280% and 180%, respectively. For the hybrid joints, the pin effect is less evident though the 20% increase in strength and 230% in stiffness was achieved concerning the mechanically connected counterparts. The previous research (Arnautov *et al.* 2015) indicated that the proposed hybrid joint was rather effective for the double-lap joints (securing symmetric distribution of the tensile forces in the joint) – the 280% increase in both strength and stiffness (due to the additional adhesive connection) was observed experimentally. Thus, additional means are necessary to avoid eccentric load distribution of the forces in the joint (e.g., the confinement rollers schematically shown in Fig. 3b). Furthermore, a more specific research on the long-term behavior of the joins is essential for successful application of the proposed connection technology.

5. Conclusions

A new pinning technique for the single-lap joints of a carbon fiber epoxy laminate applicable for production of stress-ribbon strips of a pedestrian bridge has been proposed. The technique is based on application of thin steel needles of 1 mm diameter (z-pins) as through-thickness reinforcement of the joint. Tree types of the connections were considered: purely pinned, hybrid (additionally glued), and adhesive joints. The latter joints were considered as the reference. The mechanically fastened joints were produced using 9, 25, and 36 z-pins. Tensile behavior of the joints was investigated experimentally. The obtained results allow making the following conclusions:

1. Improvement of the mechanical properties of the joint is significantly correlated with the number of z-pins: the strength and stiffness (calculated in the range from 0% to 10% of the ultimate load) of the hybrid joints were increased up to 70% and 20%, respectively, concerning

the adhesive reference. Although increment in the shear strength related to the number of pins was less significant in the hybrid joints (concerning the pinned counterparts), stiffness of the pinned-only joints was found unacceptable for production of the stress-ribbon strips.

2. Failure of the hybrid joints dissipates a significantly higher amount of deformation energy that increase safety of the proposed connector. The observed bridging effect of the z-pins, transferring the shear stresses through the crack, is the general benefit of the hybrid joints concerning the adhesive reference, which failure was brittle.

3. The hybrid connection reduces deformability of the joint – the elongation corresponding to the maximum load of the mechanically fastened specimens was twice the hybrid counterpart one.

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References

Arnautov, A. K.; Nasibullins, A.; Gribniak, V.; Blumbergs, I.; Hauka, M. 2015. Experimental Characterization of the Properties of Double-Lap Needled and Hybrid Joints of Carbon/Epoxy Composites, *Materials* 8: 7578–7586. http://dx.doi.org/10.3390/ma8115410

Aymerich, F.; Onnis, R.; Priolo, P. 2005. Analysis of the Fracture of a Stitched Single-Lap Joint, *Composites Part A: Applied Science and Manufacturing* 36(5): 603–614. http://dx.doi.org/10.1016/j.compositesa.2004.08.003

Banea, M. D.; da Silva, L. F. M. 2008. Adhesively Bonded Joints in Composite Materials: an Overview, *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 223(1): 1–18. http://dx.doi.org/10.1243/14644207JMDA219

Bodjona, K.; Lessard, L. 2015. Load Sharing in Single-Lap Bonded/Bolted Composite Joints. Part II: Global Sensitivity Analysis, *Composite Structures* 129: 276–283. http://dx.doi.org/10.1016/j.compstruct.2015.03.069

Callus, P. J. 2007. *The Effects of Hole-Size and Environment on the Mechanical Behaviour of a Quasi-Isotropic AS4/3501–6 Laminate in Tension, Compression and Bending*, Technical Report DSTO-TR-2077, Defence Science and Technology Organization, Fishermans Bend, Australia, 82 p.

Chang, P.; Mouritz, A. P.; Cox, B. N. 2006. Properties and Failure Mechanisms of Pinned Composite Lap Joints in Monotonic and Cyclic Tension, *Composite Science and Technology* 66(13): 2163–2176. http://dx.doi.org/10.1016/j.compscitech.2005.11.039

Duthinh, D. 2000. *Connections of Fiber-Reinforced Polymer (FRP) Structural Members: a Review of State of the Art*, Report NISTIR 6532, Structures Division, Bulding and Fire Research Laboratory, Gaithersburg, MA, 67 p.

Gamdani, F.; Boukhili, R.; Vadean, A. 2015. Tensile Strength of Open-Hole, Pin-Loaded and Multi-Bolted Single-Lap Joints in Woven Composite Plates, *Materials and Design* 88: 702–712. http://dx.doi.org/10.1016/j.matdes.2015.09.008

Gribniak, V.; Arnautov, A. K.; Kaklauskas, G.; Jakstaite, R.; Tamulenas, V.; Gudonis, E. 2014. Deformation Analysis of RC Ties Externally Strengthened with FRP Sheets, *Mechanics of Composite Materials* 50(5): 669–676. http://dx.doi.org/10.1007/s11029-014-9454-7

Gribniak, V.; Arnautov, A. K.; Kaklauskas, G.; Tamulenas, V.; Timinskas, E.; Sokolov, A. 2015. Investigation on Application of Basalt Materials as Reinforcement for Flexural Elements of Concrete Bridges, *The Baltic Journal of Road and Bridge Engineering* 10(3): 201–206. http://dx.doi.org/10.3846/bjrbe.2015.25

Juozapaitis, A.; Merkevičius, T.; Daniūnas, A.; Kliukas, R.; Sandovič, G.; Lukoševičienė, O. 2015. Analysis of Innovative Two-Span Suspension Bridges, *The Baltic Journal of Road and Bridge Engineering* 10(3): 269–275. http://dx.doi.org/10.3846/bjrbe.2015.34

Ko, M.-G.; Kweon, J.-H.; Choi, J.-H. 2015. Fatigue Characteristics of Jagged Pin-Reinforced Composite Single-Lap Joints in Hygrothermal Environments, *Composite Structures* 119: 59–66. http://dx.doi.org/10.1016/j.compstruct.2014.08.025

Liu, Y.; Zwingmann, B.; Schlaich, M. 2015. Carbon Fiber Reinforced Polymer for Cable Structures – a Review, *Polymers* 7: 2078–2099. http://dx.doi.org/10.3390/polym7101501

Meier, U.; Winistoerfer, A. 2001. *Multilayer Traction Element in the Form of a Loop*, US-Patent 6,209,279 B1.

Mouritz, A. P. 2007. Review of Z-Pinned Composite Laminates, *Composites Part A: Applied Science and Manufacturing* 38(12): 2383–2397. http://dx.doi.org/10.1016/j.compositesa.2007.08.016

Pantelakis, S.; Tserpes, K. I. 2014. Adhesive Bonding of Composite Aircraft Structures: Challenges and Recent Developments, *Science China Physics, Mechanics and Astronomy* 57(1): 2–11. http://dx.doi.org/10.1007/s11433-013-5274-3

Pingkarawat, K.; Wang, C. H.; Varley, R. J.; Mouritz, A. P. 2014. Healing of Fatigue Delamination Cracks in Carbon–Epoxy Composite Using Mendable Polymer Stitching, *Journal of Intelligent Material Systems and Structures* 25(1): 75–86. http://dx.doi.org/10.1177/1045389X13505005

Rugg, K. L.; Cox, B. N.; Massabo, R. 2002. Mixed Mode Delamination of Polymer Composite Laminates Reinforced Through the Thickness by Z-Fibers, *Composites Part A: Applied Science and Manufacturing* 33(2): 177–190. http://dx.doi.org/10.1016/S1359-835X(01)00109-9

Saleem, M.; Zitoune, R.; El Sawi, I.; Bougherara, H. 2015. Role of the Surface Quality on the Mechanical Behavior of CFRP Bolted Composite Joints, *International Journal of Fatigue* 80: 246–256. http://dx.doi.org/10.1016/j.ijfatigue.2015.06.012

Schlaich, M.; Bleicher, A. 2007. Spannbandbrücke mit Kohlenstofffaser-Lamellen (Carbon Fibre Stress-Ribbon Bridge), *Bautechnik* 84: 311–319 (in German). http://dx.doi.org/10.1002/bate.200710028

Schlaich, M.; Liu, Y.; Zwingmann, B. 2015. Carbon Fibre Reinforced Polymer for Orthogonally Loaded Cable Net Structures, *Structural Engineering International* 25(1): 34–42. http://dx.doi.org/10.2749/101686614X14043795570534

Schläpfer, B.; Kress, G. 2014. Optimal Design and Testing of laminated Light-Weight Composite Structures with Local Reinforcements Considering Strength Constraints Part I: Design, *Composites Part A: Applied Science and Manufacturing* 61: 268–278. http://dx.doi.org/10.1016/j.compositesa.2014.02.008

Thoppul, S. D.; Finegan, J.; Gibson, R. F. 2009. Mechanics of Mechanically Fastened Joints in Polymer-Matrix Composite Structures – A Review, *Composite Science and Technology* 69(3–4): 301–329. http://dx.doi.org/10.1016/j.compscitech.2008.09.037

William, L. K. 1985. *Stress Concentration Around a Small Circular Hole in the HiMAT Composite Plate*, NASA Technical memorandum 86038, Dryden Flight Research Facility, Edwards, CA, 18 p.

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