ENHANCED BONDED COMPOSITE JOINTS BY SMALL DIAMETER SCREWS

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1 Introduction

Bonded composite joints are ideal for aircraft and civilian structures as they offer enhanced specific properties and case-tailored performance. But the joint is usually the weakest part among the components of assembled structures. The nature of weakness is debonding or delaminating due to shear and transverse peel stress concentration near the ends of conventional lap-joint [1, 2]. There are many structural improvements to smooth these concentrations like chamfers at the adherend ends (sharpening), two types of adhesive: soft at the ends and rigid in the middle, etc.

New developments such as through-thickness reinforcements (z-pin) offer great potential for improving joint efficacy [4, 5]. Selective use of z-pins in highly-stressed regions can limit damage progress, and prevent the delaminating mechanism.

The scope of this work is to incorporate instead of z-pins the small diameter screws (SDSs) in hybrid adhesive systems in order to enhance the shear strength by control of tensile transverse stresses and stiffness at the ends of lap-joint. There is also shown small enough holes don’t effect on the in-plane strength of fiber reinforced plastics. It is really valuable for glass-fiber mat reinforced plastics (GFMRP) because of their inhomogeneity and random microstructure [6, 7].

The SDS enhanced adhesive system can be tailored to prevent debonding with linking adherends and transmitting some shear forces through SDSs.

The presence of thread on the SDS' surface provides extreme pull-out force doesn't connected with shear strength of polymer matrix as it is in typical z-pin modified joint.

Modern analytical and numerical estimations of structural strength are based on two different methods: fracture mechanics with taking into account of singularities, for example, at the ends of bond line [8, 12] and nonlocal approach [9, 10], where stress-strain state considered as averaged on specific area (i.e. finite element size) and compared with corresponding ultimate strength. It can be noticed that significant nonlinearities of stress-strain diagrams of fiber mat reinforced composites forces scientists to decline fracture mechanics and take into account modified nonlocal approach as main method for strength estimation.

2 Experiment

2.1 Materials and samples

The samples proposed here to analyze the behavior of bonded and hybrid assemblies with composites are presented in figure 1. A composite adherends were made of glass-fiber mat (density 600 g/m^2) and room-cured poly(vinyl)ester Polylite 440-M850 matrix. This GFMRP consisted of three layers of mat with total thickness about 2 mm. GFMRP is in-plane isotropic and has increased transverse shear strength in comparison with typical fabric reinforced composites with the same volume fraction of fibers. The role of film adhesive was provided by the same material – single-layer's glass-fiber mat composite (film thickness is about 0.6 mm).

The width of the bonded section was 20 mm. Length of bond-line was 20 mm with extra 1 mm on both ends to get smoother shape (this extra gets 3-5% of increasing strength in comparison with samples without extra length of film).

For hybrid adhesive system Zn-coated steel SDS has inner diameter 2 mm and outer diameter 2.9 mm, length of threaded part 6.5 mm, hidden cone head (standard DIN 7982), figure 1b. No.1 – composite material, No.2 – adhesive layer.

The sequence of technological procedures was stated as: preparation and curing bonded joints, drilling hole's diameter of 2.0 mm and outer cone chamfers and only after that all SDSs were coated by poly(vinyl)ester matrix and tightened by hand in places. All joints were post-cured in the oven at 60°C during 4 hours. There were made of five samples of each type of joints, and 5-7 samples for each kind of test for getting in-plane, through-thickness and shear stress-strain diagram of GFMRP (adherend and adhesive material).

2.2 Testing of material and joints

All tests were provided with INSTRON 5882 loading frame (Bluehill 2 software) at room temperature with use of wedge grips and 1 mm/min of cross-head rate.

Shear test for getting through-thickness shear modulus of adhesive material (GFMRP) was done using double-lap tapered joint with thick steel adherends and GFMRP as adhesive [8]. Thickness of adhesive was 4 mm, bond-line length – 20 mm.

To get transverse modulus and tensile strength there were made the cube-like thick samples (10x10x10 mm) bonded with room-cured epoxy resin to metal ends for grip in tensile testing machine.

In-plane isotropic elastic behaviors are: E_x=E_y=8.7 GPa, ν_{xy}=0.28; through-thickness ones: E_z=2.2 GPa, ν_{xz}=ν_{yz}=0.40; G_{xz}=G_{yz}=0.90 GPa. Tensile and shear strength characteristics are: X_t=Y_t=220 MPa, Z_t=75.2 MPa, S_{xy}=68.5 MPa, S_{xz}=S_{yz}= 52.3 MPa. Here E, G and ν - modulus of elasticity, shear modulus and Poisson's ratio; X, Y and Z – tensile strength and S – shear strength.

In-plane tensile stress-strain diagram of GFMRP and ransverse shear diagram had significant nonlinearity. For transverse tension the diagram is near linear till fracture.

For uniaxial tension of GFMRP, bonded single-lap joint and hybrid (screw/bonded) lap-joint average stress-average strain diagrams are shown on figure 2 (1 – GFMRP, 2 – bonded joint, 3 – hybrid one).

Average strength of hybrid lap joint is about 52-55% of tensile strength of GFMRP and 25-31% more than the strength of typical bonded single lap-joint.

2.3 Strain measuring

For averaging of visible inhomogeneity of single layer of GFMRP it needs to use several layers in structure's walls. And to insure of typical 'clip-on' extensometer's data it needs to apply strain-mapping technology [7,11].

For this aim we used stereo VIC3D system (Correlated Solutions, Inc., USA) together with clip-on uniaxial extensometer INSTRON 2620-604 with 25 mm of base length.

Visible surface of testing samples was covered by white paint and then black dots (speckle) by another paint.

Local strain differ significantly (-25…+50%) of average strain (0.48%) of extensometer during tension even in elastic part of diagram, figure 3. Because of random spreading of short fibers during the manufacturing process the density of reinforcement can vary from one place to another creating so-called 'natural' inhomogeneity. Thus, damage initiation occurs in unpredictable place leading to rupture at different loads. To decrease of variation coefficient (or standard deviation) of strength it needs to use multilayered composite. But for typical airplane or car bodies thickness of plates/shells is about 2-4 mm. For our material it will consist of 3-6 layers. In our experiment we used 3 layers into samples (cross section area 40 mm^2 and working volume about 1000-2000 mm^3) and had coefficient of variation of all kind of strength about 12-17%.

3. Numerical modeling

For investigation of stress state of lap-joints under tensile loading (in-plane shear) there were used of two kinds of software: SolidWorks for 3D-modeling and ANSYS Workbench (version 11) for finite element analysis (FEA). Type of finite element was 3D Solid 95 with linear function of stress-strain distribution inside element.

3D model was done for bonded single lap-joint with 20 mm of overlapping length and bond-line thickness 0.5 mm.

According nonlocal approach making FEA it needs to avoid of singularities to have the size of RVE (the representative volume element) or the minimum size 'A' of finite element mesh for limitation of gradient of stress/strain on this base.

After getting maximum of normal stress $max\langle\sigma_x\rangle_A$it needs to compare this stress with *effective* strength X_{eff}.

Here we used Hill's criteria of composite fracture:

$$\left(\frac{max\langle\sigma_x\rangle_A}{X_{eff}}\right)^2+\left(\frac{max\langle\sigma_y\rangle_A}{Y_{eff}}\right)^2+\left(\frac{max\langle\tau_{xy}\rangle_A}{S_{eff}}\right)^2\leq 1; \qquad (1)$$

Effective strength for significantly nonlinear mechanical response of composites in the area of stress concentrator can be calculated with use of specific energy [6]:

$$X_{eff}=\sqrt{E_x X_t \varepsilon_{xt}};\ Y_{eff}=\sqrt{E_y Y_t \varepsilon_{yt}};$$
$$S_{eff}=\sqrt{G_{xy}S_{xy}\gamma_{xy}}. \qquad (2)$$

Here ε_{xt}, ε_{yt}, γ_{xy} −ultimate strain under *tension* on *x*, *y*- directions and *shear*, respectively, in the points of ultimate stresses. Figure 4 illustrates this procedure.

For brittle behavior of material $X_{eff}=X_t, etc.$

So, tested material has X_{eff}=310 MPa, Y_{eff}=80 MPa and S_{eff}=120 MPa.

Minimum size 'A' of finite element mesh was taken 2.0 mm according recommendations [9] after testing of GFMRP stripes with typical concentrators until fracture and compare fracture load with calculations. There were used holes with diameters from 1 mm till 8 mm. Samples after tension are shown on figure 5.

By the way, here was stated that holes with diameters less than 2 mm cannot weak the tensile strength of GFMRP. That became the reason to use such small drill to prepare holes for placing screws on hybrid SDS/bonded single lap-joints.

In 3D models all contacts were stated as ideal bonded. All materials were linear elastic.

For sample with thickness of bond-line 0.5 mm calculated fracture load was 3.0 kN (nominal tensile stress 75 MPa). Experimental fracture nominal stresses have been in range 73-78 MPa.

It can be shown that the area of peak shear and peel stresses has the length about 2-3 mm at each end of lap-joint. Therefore it can be used SDSs with hide cone heads located in this area (as seen on figure 1b) and tightened to compress and link adherends. The efficacy of using SDSs is confirmed in practice; nominal fracture stress was about 110 MPa.

4. Conclusion

Using of SDSs at the ends of bonded lap-joints has a great possibility to increase its transverse strength and prevent early peel fracture. Small holes for screws cannot decrease in-plane strength of adherends. The presence of thread on the SDS surface provide extreme pull-out force doesn't connected with shear strength of polymer matrix as it is in typical z-pin modified joint. The simplicity of this enhanced technology doesn't require the specific and expensive machines, because after typical bonding procedure it is needed only accurate drilling of small holes alongside of joint ends and tight SDSs by hand.

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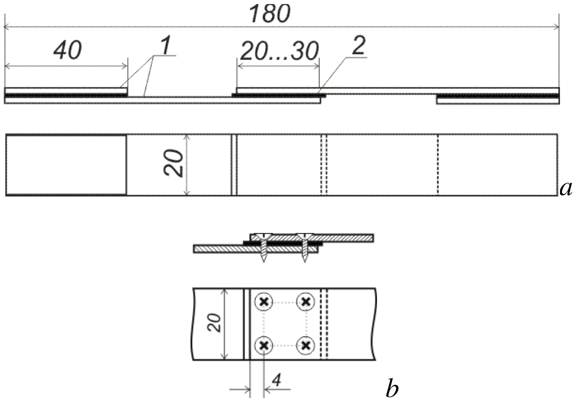

Fig.1. Geometry of bonded samples (*a*); SDS location (*b*).

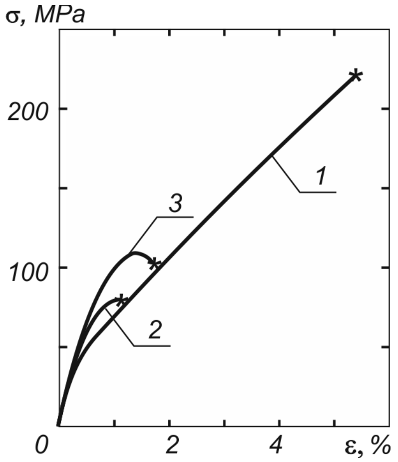

Fig.2.Average stress-strain diagrams: GFMRP (1), bonded lap-joint (2) and hybrid screw/bonded lap-joint (3).

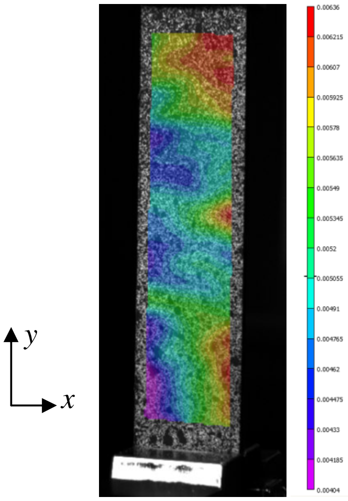

Fig.3. Strain map for ε_y. Average value 0.48%. Minimum 0.404%, maximum 0.636%.

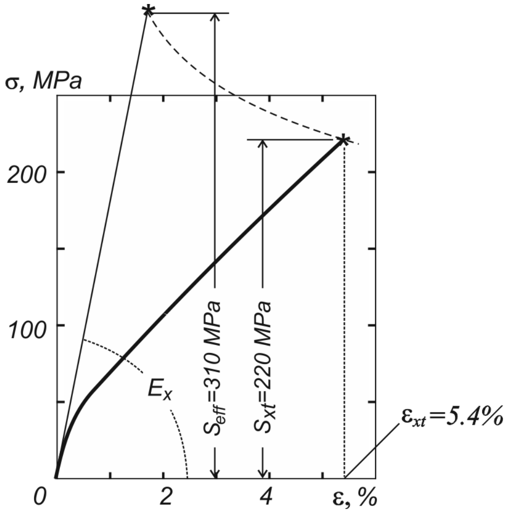

Fig.4. Effective strength of the composite material.

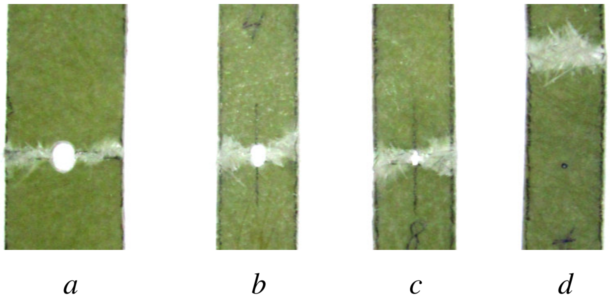

Fig.5. Samples with concentrators after tension. Diameter of the hole: 8 mm (*a*), 5 mm (*b*), 2 mm(*c*), 1 mm (*d*).