

Experimental and FE analysis of Bonded Single-lap Joints Strengthened by Self-tapping Screws

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Abstract - Lap joints based on low-modulus polyurethane adhesives are being increasingly utilized in vehicles for automotive and railway mass transit. From the one hand, significant elasticity of such adhesives allows to fill relatively large gaps formed while gluing large-scale structure elements and ensures high production effectiveness of the structures. From the other hand, polyurethane sealants cannot provide the effective shear loads transfer, which is significantly important for automotive and railway vehicle's frames with load-carrying skin made of composite sandwich panels, which predominately takes the shear loads of a metal frame.

In this study the experimental and FEA analysis carried out for the strengthening method of bonded single-lap joints by means of small diameter self-tapped metal screws (diameter – 2.5 mm). The adherents made of GFRP, the sealant used as low modulus polyurethane adhesive.

Strengthening improves the load transfer due to the shear of metal transversal elements and prevents the delamination usually caused by peel stress at the ends of a joint.

In addition, the special method employed for the stiffening of joints with self-tapped screws under cyclic loads. The method involves a filling of gaps between screw and composite bearing face by room-hardened epoxy resin. The analysis of specimen's cross-section and cyclic tension-compression tests show, that the healing results to stiffening of joint due to the enlargement of element-adherent interaction area and the reduction of residual damages of GFRP, which occurred after screwing.

Index Terms— *screwed/bonded joint, self-tapped screw, composite, microdamage healing*

I. INTRODUCTION

There is a wide range of solutions for automotive and railway mass transit, which allow to significantly reduce the weight of structure frame by using stressed skin made of composite sandwich panels [1].

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Due to significant stiffness difference between a metal frame and a sandwich panel with fiberglass skins, the last one predominately takes only shear loads of metal frame.

By the analogy with automotive glazing, design trends of assembly unification require using low-modulus polyurethane sealants for the process of sandwich panels gluing. These sealants are able to fill the relatively large gaps formed by geometry tolerances usually used for mating large-scale elements of metal frame and stressed skin. Joints obtained by using this technology can be classified as single-lap joints.

Bonded single-lap joints come with several features caused by their geometry and manufacturing process characteristics:

- a shear of single-lap joints is responsible for significant peel stress in the adhesive layer [2];
- the quality of bondline depends on a variety of factors and generally is not permanent [3,4].

These features affect on the quality and mechanical properties of bonded joints and require a further development of joints strengthening methods, which principally were resulted in the combination of mechanical fasteners and bonding technique [4] (hybrid bolted-bonded, riveted-bonded and z-pin reinforced joints). Transversal reinforcement elements are able to significantly improve the load-capacity of a joint because they prevent the delamination usually caused by high peel stress, which occurred at the ends of a joint due to the bending of adherents.

There are three most common reinforcement elements in hybrid joints:

- z-pins with the diameter less than 2.5 mm [5–7];
- fasteners and rivets with the diameter more than 4.5 mm [8–11].

The major issue with the first group of reinforcement elements ensuring that the threads are not in intensive contact with the composite material due to their small diameter and smooth shape. So to achieve the effective load-capacity of a joint a plenty of z-pins is required. For joint strengthened by z-pins with the diameter equaled to 0.5 mm, those relative areal density should be equal to 2% (16 elements per 225 square mm or one square inch) [5]. This feature provides additional requirements for manufacturing process related with special equipment and results in the higher manufacturing costs compared to appropriate costs for original bonded joints. From another glance a composite material with holes of a small diameter is less sensitive to

the stress concentration effect. This fact makes strengthening by z-pins efficient enough to be used in high-loaded structures.

Reinforcement elements of the second group has the diameter about 4.5 mm. Using those elements together with washers ensures required strengthening at low values of relative areal density (just one element per square inch) and maintain manufacturing process simple [8]. But holes of a large diameter in composite materials related with a negative stress concentration effect.

Another perspective strengthening way uses elements which have the advantages of both previous types. These elements are the self-tapping screws with a small diameter (2.5mm). But these elements are not recommended for composite materials because they may damage and erode composite bearing face, result quickly in elongated holes and reduced stiffness of a hybrid joint [4], [12, 13].

In this study the experimental and FEA analysis carried out for the strengthening method of bonded single-lap joints by using small diameter self-tapped metal screws (diameter – 2.5 mm). The adherents made of GFRP, the sealant used as low modulus polyurethane adhesive.

Also the special method employed to prevent negative effects related with damaging and eroding composite hole-faces. The method uses a filling of gaps between screw and composite bearing face by room-hardened epoxy resin. The healing results to stiffening of a joint due to the growing of element-adherent interaction area and the reduction of residual damages of GFRP, which occurred after screwing.

In the second section the tests of strengthened specimens under longitudinal static and cyclic tension-compression loads are described. The third section presents the FEA analysis of specimen's quasistatic tension. Section IV discusses the results.

II. EXPERIMENTS

Several groups of joint specimens investigated under longitudinal static and cyclic tension-compression loads.

Five original and five strengthened specimens tested under static tension. The sketch of strengthened specimen is shown in Fig. 1.

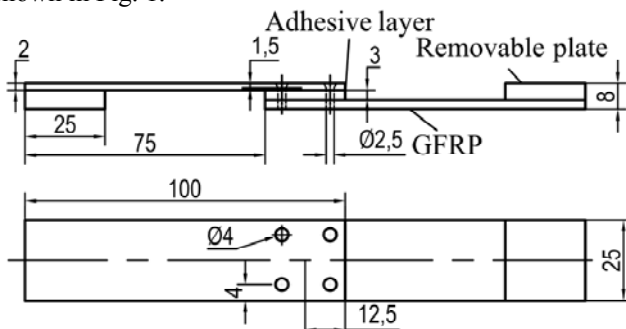


Fig. 1 The sketch of strengthened specimen for quasistatic tension tests

Glass fibre reinforced plastic adherent was made of polyester resin and glass mat with surface density equaled to 300 g/m²; metal adherent was made of hot-rolled sheet of mild steel. Adhesive with thickness 3 mm was low-modulus polyurethane sealant [14].

Steel self-tapping screws of 2.5 mm diameter were used

as reinforce elements [15]. The relative aerial density of reinforcement was equal to 4 elements per 225 square mm. Before screwing the fabrication holes of 2.0 mm diameter were drilled.

Cyclic longitudinal tension and compression tests were performed on fifteen strengthened specimens and fifteen stiffened ones (with damage healing): five on each of three load levels: 500, 600 and 700 N. Sketch of the specimen for cyclic tests depicted in Fig. 2.

The strengthened samples represent bonded joints reinforced with self-tapped screws according to technology described above.

Mounting process of reinforced elements in the modified samples was different in that the screws before mounting were immersed in the liquid epoxy resin ED-20 (100 parts by weight) with the hardener PEPA (10 parts by weight) and were screwed in fabrication holes. Then the adhesive composition was cured according to standard temperature condition (keeping at room temperature during 24 hours followed by oven cure at 80 °C for 4 hours and following oven cooling). All samples were manufactured in scientific and educational center "Composite Materials and Structures" of the South Ural State University.

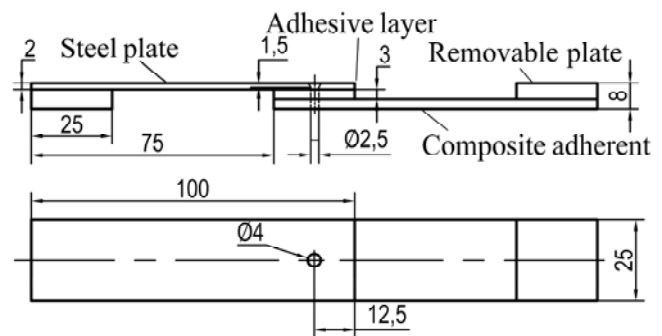


Fig. 2 Sketch a sample for cyclic tests, mm

Testing of the single lap joints samples was carried out on a general-purpose testing machine INSTRON 5882. Traverse movement speed was 5 mm/min, ambient temperature was 22 ... 24 °C. Loading conditions and specimen force-displacement diagrams under quasi-static tension are shown in Fig. 3, under cyclical tension-compression – in Fig. 4.

Typical jumps on force-displacement diagrams of bonded joints were caused by local delamination of the bondline on the ends of a joint.

Testing of strengthened joints showed an increase in the ultimate load which was greater by 40% at the average as compared to the original bonded joints. The failure occurred by cutting off self-tapping screws. The adhesive joints were fractured according to mixed adhesive-cohesive mechanism.

The following limit state conditions were taken for cyclic tests: for original specimens – an increase of their stiffness by 30% compared to the initial state; for modified specimens – attaining the same stiffness that the original specimens had.

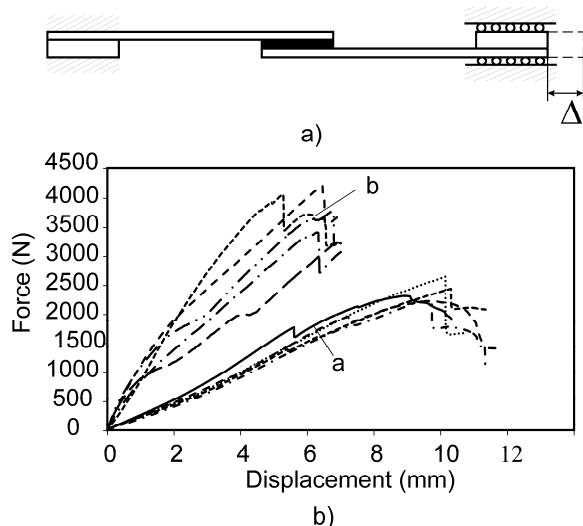


Fig. 3 Loading scheme of a specimen (a) force-displacement curves obtained under quasi-static tests (b)

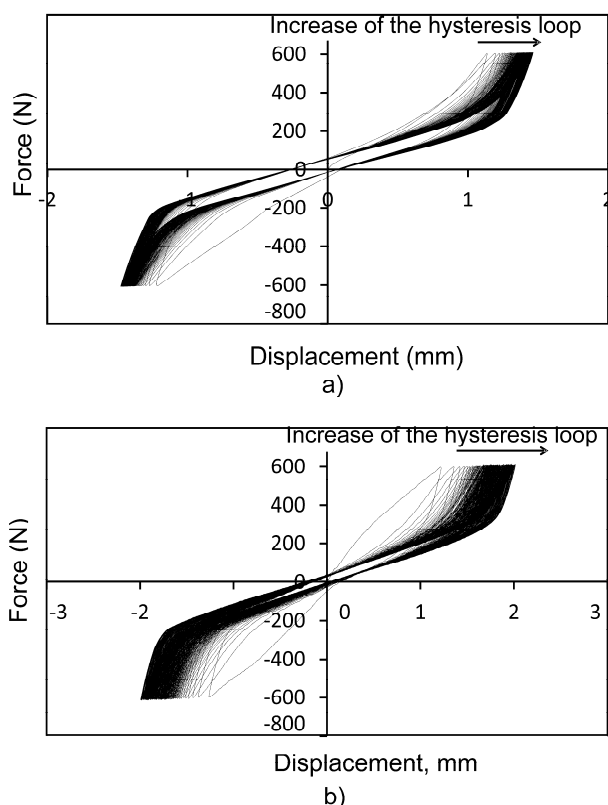


Fig. 4 Diagram of cyclic tests at the maximum load of 600 N: a) stiffened joint b) original joint

The nonlinearity of cyclic stress-deformation diagrams is provided by three main stages of hybrid joint behavior (Fig.4b):

- the presence of gaps between a self-tapping screw and a composite hole-wall formed during breaking-in stage (stiffness of the adhesive joint depends mainly on adhesive layer);
- gaps adjustment between a self-tapping screw and a hole-wall (stiffness of the adhesive joint depends on adhesive layer as well as self-tapping screw);
- interaction of self-tapping screw and the hole-wall (stiffness of the adhesive joint depends mainly on self-tapping screw).

To determine the equivalent stiffness of specimens the ratio between total load amplitude and hysteresis loop of force-displacement diagram was used. The results of cyclic tests are shown in Table 1.

On the average, the modified specimen demonstrate by 20% higher number of cycles before limit state and less by 15% less sampling variance compare to ones without damage healing.

TABLE 1

| Cyclic testing results of joints specimens | | | |
|--|-----|-----|-----|
| Maximum load value, N | 500 | 600 | 700 |
| The average number of cycles before limit state of stiffened specimens | 116 | 106 | 103 |
| Increase in the corresponded number of cycles compared to non-stiffened specimens, % | 28 | 26 | 18 |

III. CALCULATION

To analyze the stress state of strengthened joints under quasi-static longitudinal tension the finite-element model was developed via software ANSYS Mechanical. Model included the non-linearity of materials mechanics and stress concentration in the holes area for z-elements.

Since GFRP is a pseudoisotropic material, the model with bilinear isotropic hardening was chosen (pseudoplasticity in this case reflects the accumulation of dispersed microdamages). The model constants were determined from stress-deformation curves obtained from tension tests of standard specimens according to GOST 25.601-80.

The two-parameter hyperelasticity Mooney-Rivlin model [16] was used for the adhesive layer material. The model parameters were determined by approximating the stress-deformation curves of the standard specimens obtained under quasi-static tension. The specimen's deformation was measured by the Video Extensometer Instron 5882 AVE complex. The corresponded stress-deformation curves are shown in Fig.5.

The ideal elastoplastic deformation model was used for self-tapping screws. The design diameter of screw was accepted by interior cross section (internal thread diameter).

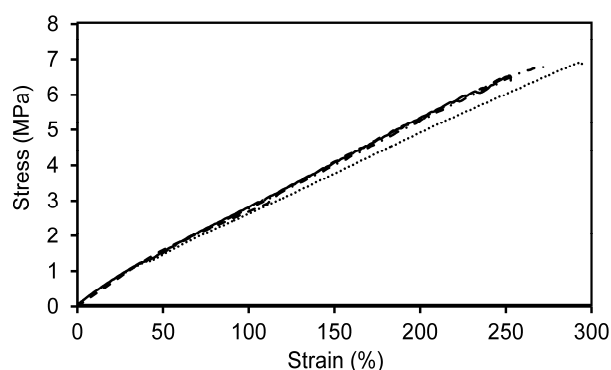


Fig. 5 Stress-strain curves for samples of adhesive layer obtained from tension tests

The loading scheme and the finite-element model of single-lap reinforced joint are shown respectively in Fig. 3 (b) and Fig. 6. The pseudoisotropic ideally elastoplastic material with reduced mechanical properties was used in the

zones around screws to incorporate the initial damages in glass fibre plastic, which occurred after screwing.

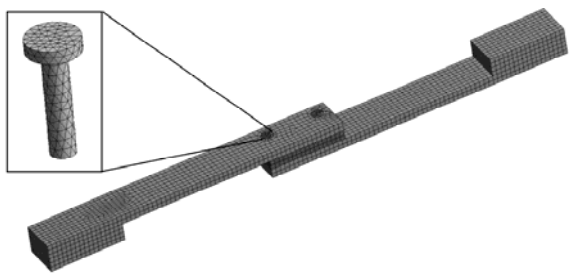


Fig. 6 Finite element model of single-lap joint

Parameters of the ideally elastoplastic material model of reduced properties (elastic modulus E , yield strength σ_T) and cylindrical region (diameter d) were determined by means of minimization between calculated and experimentally obtained force-displacement curves. The ranges of variation of the parameters were: $2.5 \leq d \leq 5$ mm; $0.25 \leq E \leq 12$ GPa; $75 < \sigma_T \leq 140$ MPa.

20-node solid elements were used for finite-element modeling. MPC contact algorithms of the type “bonded” were utilized to incorporate the interaction of glass fiber plastic and reinforced elements.

Simulated joint has following features, which provide numerical convergence problems:

- presence of materials with elastic modulus which differ more than 100 000 times (adhesive layer about 2 MPa, Steel about 210000 MPa);
- presence of hyperelastic and elastoplastic material models;
- large displacements and deformations (geometrical nonlinearity).

The solution stability was controlled by changing the value of load step increment (kinematic loading), varying the mesh size within the range of 1..2 mm for zones of expected material yielding. The range limits were accepted in accordance with the requirements for the minimum typical size of finite element enough for adequate volume averaging of fibrous polymer composite material properties [17]. To provide adequate stability and accuracy of results the load step (grip displacement) amounted to 0.08 mm, the minimum size of the finite element was 1.5 mm.

The force-displacement diagram depicted in Fig. 7 is the result of FE modeling described above. Calculated ultimate load and appropriate displacement are in the scatter band of experimental results.

IV. DISCUSSION

The analysis of specimen’s cross-section (Fig. 8a) demonstrates that self-tapping screws are responsible for initial damage occurred in composite adherents. The main damaging mechanism related with delamination, which caused by the screwing.

Damaged material was taken into account by using cylindrical domains with reduced mechanical properties, which were embedded in the FE model of strengthened joint. Material constants of initially damaged material were obtained by means of the minimization of residuals between

calculated force-displacement diagrams and the experimental data.

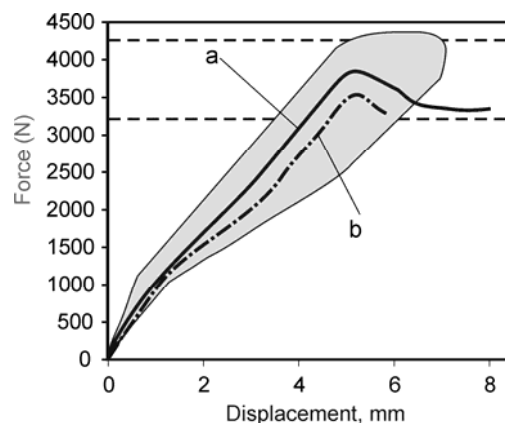


Fig. 7 Calculated force-displacement diagrams of strengthened joints: a) overlap length 25 mm; b) overlap length 17.8 mm (the scatter band of experimental results is marked by dotted lines)



a)



b)



c)

Fig. 8. Cross section of strengthened joint: a) damage distribution b) specimen after damage healing (stiffening) c) specimen before damage healing

The presence of damages together with inherent inhomogeneity of mechanical properties of GFRP causes relatively wide spread of test diagrams obtained under quasi static tension (Fig. 3b).

The example of noted inhomogeneity can be found in the study [18], which observed that transversal stiffness dispersion of GFRP is predominately determined by the fiber volume fraction, which, in turn, is governed by the normal law of distribution for randomly reinforced plastics. Also in study [18] proved that this dispersion is in inverse proportion with the square root of the layers number or the thickness of a material specimen.

Due to the adherent’s inhomogeneity their local stiffness and strength are vary from a one region around mounted screw to another. So it reflects in the appropriate scatter of the «force-displacement» diagrams.

In spite of initial damage in composite adherents, quasistatic longitudinal tension tests showed that strengthened samples demonstrate the growth of failure load by an average of 40% and stiffness – by more than 300%.

In order to heal initial damage and make strengthened joints more stable and stiff at cyclic loads the damage healing employed for composite material zones around self-tapping screws.

The specimen's cross-sections photos (Fig. 8b) evidence that the healing results in the increased element-adherent interaction area and also reduces the residual damage at GFRP bearing face (Fig. 8c).

Data treatment of the “force-displacement” diagrams obtained under cyclic tension-compression tests yielded the equivalent specimen stiffness as the function of cycles (Fig. 9). The equivalent stiffness determined as the ratio of a total load amplitude and hysteresis loop of the test diagram.

Fig. 9 shows that equivalent stiffness sharply decreases due to the intensive damage and delamination growth during first 20-30 cycles. After that the slope of the diagram becomes more stable. An exponential approximation shows that the diagram slope stabilizes after several hundred of cycles.

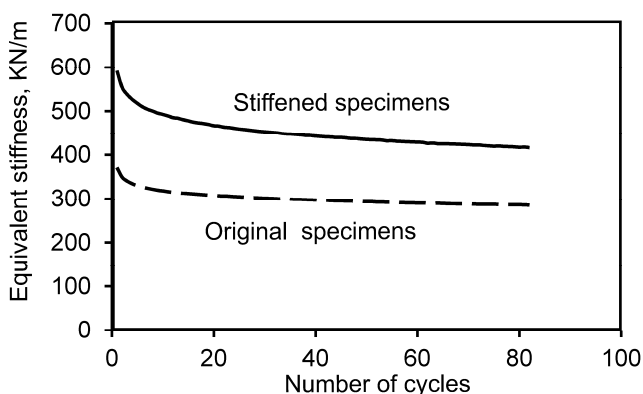


Рис. 9. History of changes of the equivalent stiffness when cyclic loading for the load level of 600 N

Stiffened specimens demonstrate more than 20% higher number of cycles before attaining the limit state and have about 15% less sampling variance compare to ones without damage healing.

Additional FEA analysis proved that a bonded-screwed joint with the overlap length shortened by about 30% to its initial value will have the same strength as an original one (Fig. 7b).

The shortened lap length promotes appropriate weight reduction of a joint by 20%. This confirms the efficiency of proposed strengthening method.

V. CONCLUSION

Proposed study presents the experimental and FEA analysis performed to the strengthening method of bonded single-lap joints by means of small diameter self-tapping metal screws (diameter – 2.5 mm). The adherents made of GFRP, the sealant used as low modulus polyurethane adhesive.

The strengthened joints demonstrated significant increase of critical load and stiffness compared to initial ones under

quasistatic longitudinal tension.

In spite of demonstrated strength improvement, screwing involves significant initial damages of glass fiber plastic adherents. Self-tapping screws damage and erode composite bearing face during loading process and result in the large scatter of force-displacement diagrams obtained under quasistatic tension. Also this is the main reason of the joint stiffness reduction during cyclic tension-compression tests.

In the order to reduce the negative effects mentioned above the gaps between self-tapping screw and composite bearing face were filled by room hardened epoxy resin.

The analysis of diagrams obtained from cyclic tension-compression tests shows that proposed method of damage healing (stiffening) promotes the both greater number of cycles before attaining limit state and higher equivalent stiffness of a joint.

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