Experimental study of stress-strain state of adhesive joints steel / carbon fiber under tension with a bend by digital image correlation

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Abstract. This paper presents a study of characteristics of an evolution of deformation fields in surface layers of medium-carbon low-alloy specimens under compression. The experiments were performed on the "Universal Testing Machine 4500" using a digital stereoscopic image processing system Vic-3D. A transition between stages is reflected as deformation redistribution on the near-surface layers.

1. Introduction

It is impossible to perform a strength analysis of important composite constructional elements without a knowledge how the composite destructs. Dissipative processes lead finally to the development of cracks during plastic deformation. This requires investigation of a behavior of steel-carbon fiber adhesive joints on all the deformation phases from the initial till the out-of-limit phase.

An adhesive joint loses its strength continuously while a load increases. On the plastic phase of deformation of a loaded composite junction, one can observe a local loss of shear strength. Flows of deformation defects originate on mesoconcentrators of stress and move in the direction of the maximum shear stress. Each flow causes highly localized simultaneous shifts and turns of the material [1, 2]. To better understand these processes and reveal the mechanics of a deformation destruction it is necessary to study the evolution the deformation defects flows in the adhesive joints.

Non-uniformity of deformation's development can occur not only due to the direction of an external load but also because of a structural heterogeneity of a composite that originates on the formation phase. In case of layered composite metal-glue-carbon fiber we have different characteristics and different micro and macro structure of each layer. This leads to the different deformation processes in each layer causing a destruction of the layered composite.

During a long operation of adhesive joints there originate multiple defects that change the characteristics of the material. In this new defect state the joint still has a remaining bearing strength. This means that the mechanical characteristics are defined by the interaction of regions with different defects in different structural elements of the joint.

Composite materials are difficult to study at every deformation phase [3]. It is shown that an adhesive joint under a tensile deformation has localized deformation in various locations on a surface of a specimen. With a growth of the deformation, one can observe an evolution of deformations from a chaotic to the regular wave deformation with a specific wavelength. This makes important the studies of the behavior of adhesive junctions at supercritical deformation phase.

The object of this study is an angle with a simulated defect strengthen by carbon fiber and a resin binder (figure 1).

The goal of the research is to study *in situ* evolution of the distribution of local deformation regions in the near surface layers of composite fabrics and main metal angle under a tensile load.

2. Materials and methods

2.1. Adhesive joint metal/carbon fiber

We have prepared specimens of adhesive joints. Figure 1.a shows the adhesive specimens to be tested under an eccentric tensile deformation.

To ensure full utilization of the applied CFRP material, surface preparation of the steel must be undertaken to enhance the formation of chemical bonds between the adherend and the adhesive. This requires a chemically active surface that is free from contaminants. Most surface treatment involves cleaning, followed by removal of weak layers and then re-cleaning [4].

The most effective means of achieving a high-energy steel surface is by grit blasting [5, 6].

We used a steel roller stock angle as bases for the specimens. The mechanical characteristics of the steel were studied in the previous experiments.

The second component of the specimens was a unidirectional carbon fabric FibARM Tape-200/300. The mechanical characteristics of the lamellae are presented in table 1.

A resin compound FibARM Resin 530+ was used as a binder for the external reinforcement. The mechanical characteristics of the glue are presented in Table 1.

Table 1. Mechanical characteristics of the materials

Mechanical characteristics	Material		
	Steel	Carbon fabricFibARM Tape-200/300	GlueFibARM Resin 530+
elastic modulus E, GPa	212	~165	-
yield point, MPa	231	-	-
ultimate strength, МПа	335.4	-	-
aspect ratio, %	24.65	-	-
tensile strength, MPa	-	~ 2800	-
shear strength of Glue specimens (7 days at 23°C), MPa	-	-	~ 13

2.2. Experimental methods

The tensile tests were performed on the «INSTRON 3386» machine with a maximum tensile load of 100 kN (10.19 kgF). The deformation was performed at a constant speed of 0.3 mm/min. A digital optical system VIC-3D [4, 5] was used to investigate the evolution of the deformed state

To measure deformations on the surface of the specimen the cameras were installed opposite to the inner fold of the angle to ensure that the filmed surface will fit into the intersection of depth-of-fields of the cameras (figure 1, c). The point of intersection of optical axes matched the surface of the specimen to provide a high quality image. The value of the angle between optical axes was 30 degree. The calibration of the cameras resulted in the definition of the variable associated with positioning and specific parameters of the cameras: focal distance and sensor’s midpoint (a point on the sensor that corresponds to the center of a lens), distances and angles between cameras X, Y, Z.

As the result we have obtained data about the change in positions of the lenses in 3D space. Displacement fields in our case is a projection of shifts along the OX axis (lateral deformation), OY axis (longitudinal deformation) and along OZ axis (lateral deformation) of local surface regions [6].

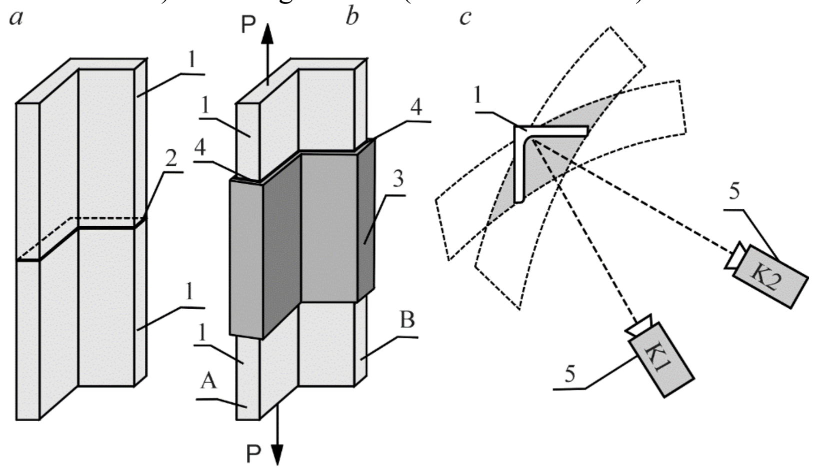

Figure 1.Experimental design for an eccentric tension: a –steel angle with simulated defect; *b*–adhesive junction metal/glue/carbon fiber and the load direction; *c*–digital cameras positioning. 1 – metal angle; 2 – simulated defect; 3 – carbon fabric; 4 – binder; 5 – digital cameras K1 and K2; A –loaded plate of the angle; B –not loaded plate of the angle

3. Results and discussion

The data about the deformation in the near to surface layers was measured using a VIC-3D system. This data was used to build a deformation diagram (figure 2) that shows the dependency of overall deformation on the value of a load. Besides that the VIC-3D system allowed to build the deformation patterns that represent a detailed evolution of the distribution of isolines of relative deformations during the load process (figure 3).

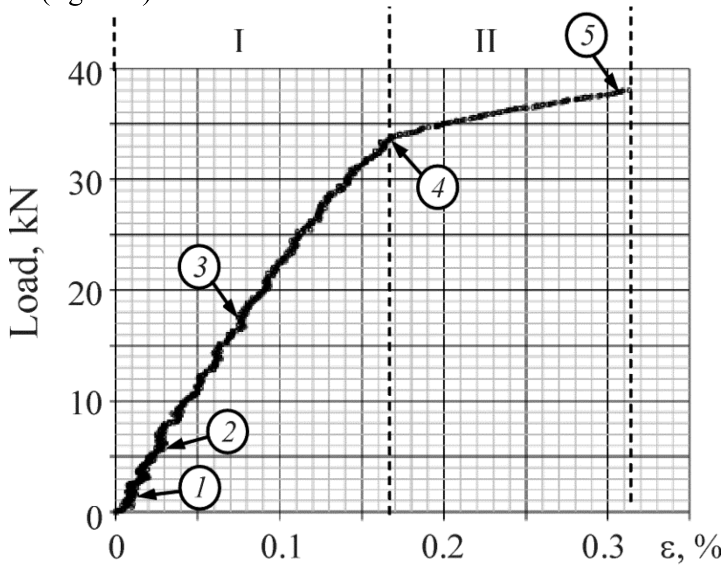

Figure 2. Loading diagram for the layered composite (metal-glue-carbon fiber). The digits show the regions of the diagrmation that correspond to the deformational patterns in the figure 3

We can distinguish 2 phases on the deformation diagram (figure 2). The first phase is an elastic deformation. The surface deformation patterns in this phase can be characterized by a chaotic distribution of local deformation regions with a distinguished overall deformed state. In this phase we can observe tension of the loaded plate of the angle (Plate A in the figure 1) and a compression on the not loaded plate (plate B in the figure 1). In the joint zone, we could observe origination and considerable increase of local deformation zones under a 8.2 kN with 0.038. This phase ends at 34 kN load and overall relative deformation value of 0.173%.

A transition to the elastic-plastic phase 2 is accompanied by the decrease of a strain-hardening coefficient $\theta = \partial P/\partial \varepsilon$ (figure 2) and a change in the positioning of structural elements (figure 3).We can observe origination of the first plastic deformation lines in the loaded plate of the angle in the region of the junction (Figure3, pattern 4). This phase ends at 38.2 kN load and overall relative deformation value of 0.323%.

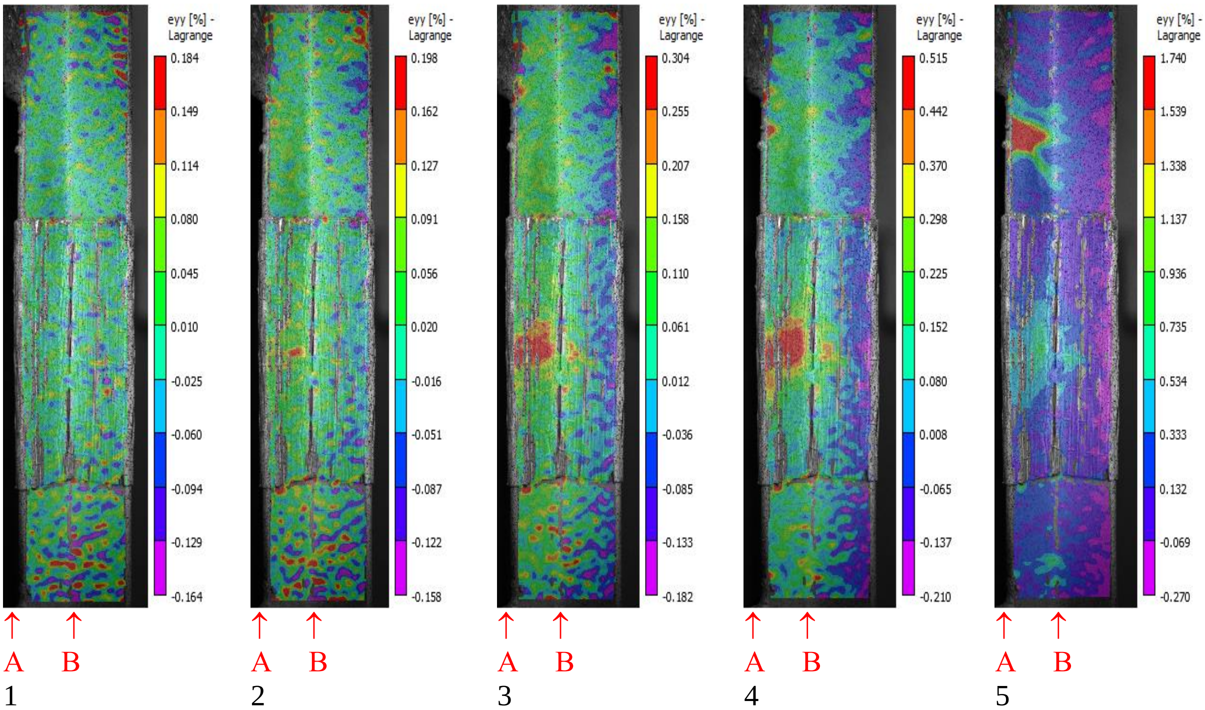

Figure 3. Patterns of vertical relative deformation of the inner surfaces of a steel angle and carbon fabric plates on the different deformation phases. A – loaded side of the angle; B – not loaded side of the angle. 1, 2, 3, 4, 5 — points in the figure 2

4. Conclusion

1. The results of the study showed a 2 phase deformation process on the strain-hardening diagrams for the steel angles joint by adhesion with carbon fabric plates under a tensile-turn load.
2. With the increase of loads and transition from the phase I to the phase II we can observe a decrease up to 8.5 times of strain-hardening coefficient θ. This is accompanied by the change in the way the structural elements are positioned.
3. On the phase II deformations of the both carbon fabric plates (loaded and not loaded) are almost similar. The local deformation regions that were observed on the phase I flow together to form a single area along the whole plate surface. This illustrates the change in the mechanics of deformation. However, a region of localized deformation on the loaded plate remains in the joint area, which originated by the end of the phase I.

Acknowledgement
The research was supported by the Tomsk State University Academic D.I. Mendeleev Fund Program in 2015-2016.

References

[1] Panin V E 1998 Modern problems of plasticity of solid bodies *Russian Physics Journal* **1** 7-34 (in Russian)

[2] Marushak P O, Panin S V, Student A Z et al 2013 *Deformation of destruction of thermoresistant steels* (Tomsk: TPU) p 236 (in Russian)

[3] Ustinov A M, Kopanitsa D G, Koshko B O et al 2015 *Development and localization of plastic deformations on a surface of metal specimens with layered composites:metal / glue / carbon fiber* (Tomsk: TPU) pp. 21-24 (in Russian)

[4] Mays G C and Hutchinson A R 1992 *Adhesives in Civil Engineering* (New York: Cambridge University Press) p 333

[5] Hollaway L C and Cadei J 2002 Progress in the technique of upgrading metallic structures with advanced polymer composites *Progress in Structural Engineering Materials* **4** **2**, 131-148

[6] Hutchinson A R 1987 Surface pretreatment – the key to durability, *Proceedings of the International Conference on Structural Faults & Repair*, University of London, July 1987, pp. 235-244

[7] Tretyakova T V 2014 VIC 3D software for studying non elastic deformations Mechanics of continua 7 pp. 162-171 (in Russian)

[8] Tretyakova T V, Tretyakov M P, VildemanV E 2011 *Estimating the precision using video system for deformation fields Reports of PGTU. Mechanics* (Perm: Perm. GTU) **2** 92-100 (in Russian)

[9] Ustinov A M, Kopanitsa D G, Potekaev A I et al 2015 Distribution of local deformations on the near-surface layers and scale effects of low alloy steel specimens *AIP Conference Proceedings* **1683** 020233