Realization effects of postcritical deformation the regularities for GFRP in tensile tests

D S Lobanov¹, O A Staroverov¹, M P Tretyakov¹

¹ Centre of Experimental Mechanics, Perm National Research Polytechnic University, 29 Komsomolsky AVE, Perm 614000, Russia
cem_staroverov@mail.ru

Abstract. Experimental data on mechanical behavior of polymer composite material on the postcritical deformation stage were presented. The typical dependences effect of deformation rate and temperature in a wide range (high and low) on the regularities of deformation and the realization degree of postcritical deformation stage on tensile test were obtained. The tests were carried out on the specimens of constructional glass-reinforced plastic with various lay-up sequences. Test runs were carried out at different loading rates (between 0.1 and 10 mm/min); in a wide temperature range (between -40°C and 200°C) and with different stiffness. The loading conditions are determined under which the degree of implementation of the postcritical stage of deformation increases.

1. Introduction
The change-over to new constructional materials (polymer composites) instead of the conventional materials in recent years has become widespread in industry and engineering, in particular when designing reliable constructions for aviation, space and energy purposes and technical objects in building industry. When implementing composite materials, the issues of analyzing the fracture and survivability conditions, reliability and the assessment of the catastrophic fracture of composite products are of particular importance.

From the analysis of the references it follows that the postcritical stage of deformation of polymer composite materials of various types is not paid sufficient attention, the descending leg of the deformation diagram is not considered as a source of information on the behavior of materials, but is often discarded when presenting experimental data and, as a result, is not taken into account when designing and estimating the safety of constructions. However, information on the presence and conditions for the implementation of the postcritical stage of deformation of polymer composites seems to be necessary for an accurate estimation of the carrying capacity margin and predicting the survivability of composite load-bearing elements, and can be used in designing and safety estimating of the constructions [1-4].

The processes of structural fracture of inhomogeneous media (layered, fibrous, granular composites) can occur in equilibrium and result in appearance of a descending leg of the deformation diagram at the postcritical stage [4]. The implementation of the postcritical stage of deformation results in increased survivability and, hence, in safety of constructions, in use of reserves of the carrying capacity of objects.

The work objective was an experimental study of the behavior of constructional glass-reinforced plastic at the postcritical stage of tensile deformation under conditions of different loading rates and a wide temperature range.
The objects of study were specimens of constructional glass-reinforced plastic based on VPS-48 prepreg and an epoxy binder with various lay-up sequences, made with commercial technology using autoclave molding.

2. Testing methods and equipment’s

Tensile tests were carried out on the basis of the core facilities centre "Centre for Experimental Mechanics" of the Perm National Research Polytechnic University (CCU CEM PNRPU) on the Instron 8850 servohydraulic test system using the Instron 2620-601 hinged extensometer with a deformation measurement error of no more than 0.15% and on the Instron 5882 electromechanical system, which comprises a non-contact video extensometer and a temperature chamber with an operating temperature range between -100º and +350ºC [5].

The tensile research program is shown in table 1. Before starting to perform the program, one carried out the preliminary tests of glass-reinforced plastic specimens with different base lengths of the working area. The objective of the preliminary tests was to select the geometric parameters of the specimens at which the implementation of the postcritical stage of deformation was clearly defined. The standard specimens were taken as a basis in the form of a double-sided blade with a working area length \( l_0 = 75 \) mm and width \( h = 18 \) mm. The specimens with working area length \( l_0/2 \) and \( l_0/4 \) were also tested.

![Image]

**Figure 1.** The type of fracture and deformation diagrams of glass-reinforced plastic [±45°] specimens with different lengths of the working area (75 mm, 37.5 mm and 18.75 mm)

| No. | Step name                                                                 | Test conditions                                      |
|-----|---------------------------------------------------------------------------|------------------------------------------------------|
| 1   | Deformation and fracture of the glass-reinforced plastic at various loading rates | Temperature: 22ºC; Loading rate: 0.1 mm/min; 1 mm/min; 10 mm/min; |
| 2   | The influence of the temperature on the behavior of the glass-reinforced plastic at the postcritical stage of deformation | Temperature: -40ºC, 0ºC, 22ºC, 120ºC, 200ºC; Loading rate: 1 mm/min; |
| 3   | Estimation of the combined influence of stiffness, loading rates and temperatures on the implementation of the postcritical stage of deformation | Temperature: 22ºC, 120ºC, 200ºC; Loading rate: 0.1 mm/min; 1 mm/min; |

Figure 1 shows the type of fracture and deformation diagrams of glass-reinforced plastic specimens with different lengths of the working area (75 mm, 37.5 mm and 18.75 mm) at one deformation rate equal to 1%/min. All specimens were fractured in the working area. Based on the results of the preliminary tests, the dimensions of the working part of the specimen were selected so, that during their
testing one observes an implementation of the postcritical stage of deformation. The difference in the degree of implementation of the postcritical stage of deformation under tension of specimens with different length is associated with a change in the stiffness of the loading system with respect to the fracture area [6]. The use of short specimens allows to minimize the length of the specimen parts which are elastically deformed during loading. Further, all tests were carried out on the specimens of type C3 with a working area length \( l_0 = 18.75 \text{ mm} \).

3. Results and discussion
The research results obtained during the implementation of the test program are shown in table 2 in figures 2 and 3 in the form of deformation diagrams in the stress-deformation axes, where stresses were calculated as the ratio of the applied load to the initial cross-sectional area of the specimen.

![Figure 2](image-url)

*Figure 2.* Typical deformation diagrams of the glass-reinforced plastic specimens with layup \([\pm 45^\circ]\) at different tensile rates: 0.1 mm/min - full lines, 1 mm/min - dash-dot lines, 10 mm/min - dashed lines (a), and the glass-reinforced plastic specimens with layup \([0^\circ/45^\circ/0^\circ/-45^\circ]\) at temperatures: -40°C - blue full line; 0°C - blue dashed line; 22°C - black full line; 120°C - black dashed line; 200°C - red full line)

An increase of the deformation rate results in a known increase of the elastic and strength characteristics of the discussed composite material, but the degree of implementation of the postcritical stage of deformation decreases, and at rate of 10 mm/min and more the implementation of the postcritical stage was not observed.

According to the results of tensile tests in a wide temperature range (-40°C, 0°C, 22°C, 120°C, 200°C) it was noted that lowering the temperature results in an increase of the elastic and strength characteristics of the composite. The implementation of the postcritical stage is not significantly manifested, while an increase of the degree of implementation of the descending region of the deformation diagrams at a temperature of 200°C and higher can be noted. Qualitatively similar results on the influence of increased and decreased temperatures on the change of mechanical properties and the implementation of the
postcritical stage of deformation were obtained by the authors on other constructional glass-reinforced plastics [7-10].

When estimating the combined influence of stiffness, loading rates, and temperatures on the implementation of the postcritical stage of deformation (on specimens with a concentrator), it is noted that at temperatures of 22°C and 120°C for all groups of glass-reinforced plastic specimens and all loading rates, the degree of implementation of the postcritical stage of deformation is approximately the same.

**Table 2.** The mean values of the mechanical characteristics of the glass-reinforced plastic under tensile in different conditions.

| No. | Mean values of fracture strength, MPa | Mean values Elastic coefficient*, GPa | Temp., °C | Loading rate, mm/min | Opening diameter, mm |
|-----|-------------------------------------|--------------------------------------|-----------|----------------------|---------------------|
| 1   | 207.6                               | 17.7                                 | 22        | 0.1                  |                     |
| 2   | 229.6                               | 17.5                                 | 22        | 1                    |                     |
| 3   | 203.4                               | 17.1                                 | 120       | 0.1                  | 1.5                 |
| 4   | 208.1                               | 16.8                                 | 120       | 1                    |                     |
| 5   | 192.2                               | 11.4                                 | 200       | 0.1                  |                     |
| 6   | 211.2                               | 16.5                                 | 200       | 1                    |                     |
| 7   | 204.3                               | 19.9                                 | 22        | 0.1                  |                     |
| 8   | 217.0                               | 18.4                                 | 22        | 1                    |                     |
| 9   | 189.6                               | 16.6                                 | 120       | 0.1                  | 2.5                 |
| 10  | 197.4                               | 19.0                                 | 120       | 1                    |                     |
| 11  | 198.1                               | 12.0                                 | 200       | 0.1                  |                     |
| 12  | 196.1                               | 14.4                                 | 200       | 1                    |                     |
| 13  | 204.3                               | 18.5                                 | 22        | 0.1                  |                     |
| 14  | 217.0                               | 19.4                                 | 22        | 1                    |                     |
| 15  | 189.6                               | 17.9                                 | 120       | 0.1                  | 3.5                 |
| 16  | 197.4                               | 18.0                                 | 120       | 1                    |                     |
| 17  | 198.1                               | 13.4                                 | 200       | 0.1                  |                     |
| 18  | 196.1                               | 15.3                                 | 200       | 1                    |                     |

* - In this case, the elastic modulus for the construction (specimen with a concentrator) was taken as the elasticity coefficient and was determined similarly to the elastic modulus from the diagram.
Figure 3. Typical deformation diagrams of glass-reinforced plastic specimens with a lay-up pattern 
$[0^\circ/45^\circ/0^\circ/-45^\circ]$ at loading rates of 0.1 mm/min (full line) and 1 mm/min (dashed line) with 
concentrators at 22°C (a, b), 120°C (c, d) and 200°C (e, f). Diagrams of specimens with a 1.5 mm 
concentrator - black colour; diagrams of specimens with a 2.5 mm concentrator - blue colour; 
diagrams of specimens with a 3.5 mm concentrator - red colour.

A significant increase in the degree of implementing of the postcritical stage of deformation is 
observed at a test temperature of 200°C for all groups of specimens at a loading rate of 0.1 mm/min. The 
extension of the descending regions along the deformation axis is 1.5 mm, 2.5 mm and 3.5 mm from the 
entire deformation diagram for specimens with concentrators, on average 17%, 11% and 18%, 
respectively, while at 22°C and 120°C the descending region for all groups of specimens does not exceed 
5-7% of the deformation diagram.

4. Conclusions

Therefore, the experimental test runs were carried out on realization of the postcritical stage of 
deformation on the specimens of glass-reinforced plastic with various lay-up sequences under tension 
tests. On the results of experimental tests one determined the typical dependences of the influence of the 
strain rate by a difference of two orders, the wide temperature range (between -40°C and 200 °C) and 
stiffness on the behavior patterns of the tested constructional glass-reinforced plastic and the degree of 
implementation of the postcritical stage of deformation under tensile tests.

References
[1] V E Vildemann, E V Lomakin, M P Tretyakov, T V Tretyakova and D S Lobanov 2018 Experimental studies of postcritical deformation and fracture of constructional materials: monograph. Perm: Publishing office Perm National Research Polytechnic University, 156 p ISBN 978-5-398-02104-2
[2] Tretyakov M P, Vildemann V E and Lomakin E V 2016 Failure of materials on the postcritical deformation stage at different types of the stress-strain state Procedia Structural Integrity vol 2 pp 3721-3726
[3] Tretyakov M P, Lobanov D S and Vildemann V E 2019 Study of the regularities of postcritical behavior and failure of specimens in the tests of composite materials Procedia Structural Integrity vol 17 pp 865–871
[4] Vildemann V E, Sokolkin Y V and Tashkinov A A 1997 The mechanics of inelastic deformation and fracture of composite materials Moscow: Nauka 288 p
[5] Lobanov D S 2015 Experimental studies of the deformation and strength properties of polymer composite materials and panels with filler: dis. ... cand. of tech. sciences. Perm - 148 p
[6] Vildemann V E and Tretyakov M.P 2013 Analysis of the effect of loading system rigidity on postcritical material strain Journal of Machinery Manufacture and Reliability vol 42 Issue 3 pp 219-226
[7] Lobanov D S and Babushkin A V 2017 Experimental studies of the high temperature influence on strength and deformation properties of combined glass organoplastics PNRPU Mechanics Bulletin No 1 pp 104-117
[8] Lobanov D S and Slovikov S V 2018 Mechanical behavior of a unidirectional basalt-fiber-reinforced plastic under thermomechanical loadings Mechanics of Composite Materials vol 54 No 3 pp 351-358
[9] Lobanov D S, Babushkin A V and Luzenin A Yu 2018 Effect of increased temperatures on the deformation and strength characteristics of a GFRP based on a fabric of volumetric weave Mechanics of Composite Materials vol 54 No 5 pp 655-664
[10] Babushkin A V, Lobanov D S, Kozlova A V and Morev I D 2013 Research of the effectiveness of mechanical testing methods with analysis of features of destructions and temperature effects Frattura ed Integrita Strutturale vol 24 pp 89-95

Acknowledgments
The work was carried out with support of the Russian Science Foundation (Project № № 16-19-00069) in the Perm National Research Polytechnic University.