

DETERMINATION OF TENSION STRENGTH IN THE LONGITUDINAL AND CIRCUMFERENTIAL DIRECTION IN GLASS-POLYESTER COMPOSITE PIPES

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Polymer composite pipes with glass fiber reinforcement have today a wide usage in the chemical and process industries. The basic subject of this paper is the determination and distribution of stresses and strains in longitudinal and circumferential directions of glass-polyester pipes under tension test. Also, the tension strengths in both directions are determined out. Tension test was performed on an electro-mechanical test machine on flat samples and rings obtained by cutting of pipes produced by the method "Filament winding" with glass fibers reinforcement $\pm 55^\circ$. Also, the micromechanical analysis on fracture surfaces was done by SEM, which provided the knowledge about models and mechanisms of fracture on applied loading.

KEY WORDS: Glass-polyester composite pipe, tension test, ring test, micromechanical analysis

INTRODUCTION

Traditional materials in the chemical and process industries are today successfully replaced by composite materials. More and more pipes, tanks, reservoirs, pressure vessels are made of these materials. The advantages are in relatively small mass with good strength/stiffness ratio, good static and dynamic properties, as well as good resistance to corrosion.

The basic subject of this paper is to determine distribution of stresses and strains in the longitudinal and circumferential direction of glass-polyester composite pipe of defined construction subjected to tension. The basic hypothesis is that the current standard of choice, design and production of glass-polyester composite pipe does not give enough information about the behavior of pipes during the internal pressure, and this problem is still connected to the individual investigations which are conducted in individual world laboratories.

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An example of research is the paper (1) in which authors studied the dependence of reinforcement angle in polymer composite pipes subjected to internal pressure. The relationship between stress in circumferential and longitudinal direction (2:1) in the case of different angle of reinforcement has been checked out. Hoffman's criteria of crack was used. The analysis showed that angle of reinforcement has a great influence on the pipe strength and the optimal value for glass-epoxy, carbon-epoxy, and boron-epoxy composite pipe is approximately 45° - 55° (1). Deviation of this values increase the possibility of final fracture. There is a resemblance between the paper (2) and presented experiment. Mechanical properties of glass-polyester pipes with angle of reinforcement of $\pm 54^{\circ}$ and 90° were tested (2). Experiments were carried out with internal pressure and stresses and strains were measured in the longitudinal and circumferential directions. In (3), the authors also tested composite pipes subjected to internal pressure and found the values of stresses and strains in both directions. Also, they investigated the influence of stress distribution on creep. The subject of paper (4) is also the determination of stresses and strains in the longitudinal and circumferential directions, connected with the investigation of crack initiation and propagation. The final result was the knowledge about stress in both directions which does not cause cracks in the pipe and their propagation until the final fracture.

EXPERIMENTAL

Composite pipes have been fabricated in the lab conditions. The properties of used glass-polyester pipes were given in the official certificates of the particular producers of components. The producers of reinforced glass fibers are A.D. "OHIS" and "Vidoe Smilevski-Bato" from Gostivar (Macedonia) by certificate confirm "E" glass with 1% of alkali. Thermo-reactive resin was used as matrix by the producer "Color"-Medvode (Slovenia). Certificate was given for "COLPOLY 7510" for the type: UP/SOM- highly reactive, with low viscose polyester on the basis of ortophthalic acid and standard glycol.

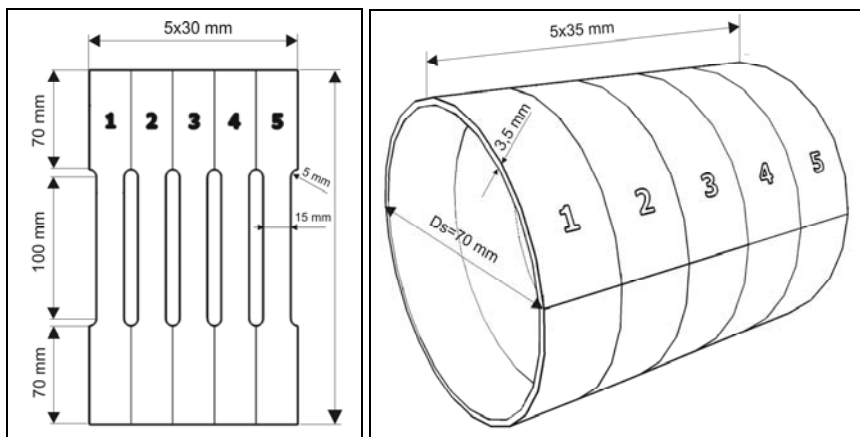


Fig. 1. Scheme of cutting of the test pipes; (left) flat samples R-BR; (right) rings P-BR

The pipes were made by the method “Filament Winding”, with $\pm 55^\circ$ angle of glass fibers reinforcement. The specimens for tests, (flat specimens, R-BR, and rings, P-BR), were cut from the samples of pipes according to the standard dimensions, Fig. 1., the flat specimens $250 \times 25 (20 \text{ gage area}) \times 3.5 \text{ mm}$, and the rings $\phi 70 \times 35 \times 3.5 \text{ mm}$ (average values of all tested samples). The cut was done on machine type NC-2010 (Nr 95110, Ar 001) by the tools with diamond top and the moving speed which lowers the heating of the sample.

Testing of flat test specimens was done on a servo-hydraulic testing machine SCHENCK TREBEL RM 100, and ring test on the servo-hydraulic testing machine INSTRON 1332 with the controller INSTRON FAST TRACK 80800, using of hydraulic jaws. The testing was defined by standard ASTM D 3039 (5, 6). Six flat test specimens (P-BR) and six rings (R-BR) were tested. Loading was registered with measuring cell of the capacity of 100 kN. Displacements were measured by double extensometer HOTTINGER DD1.

RESULTS AND DISCUSSION

During the test the diagrams stress-strains ($\sigma-\epsilon$) were plotted, Fig. 2.

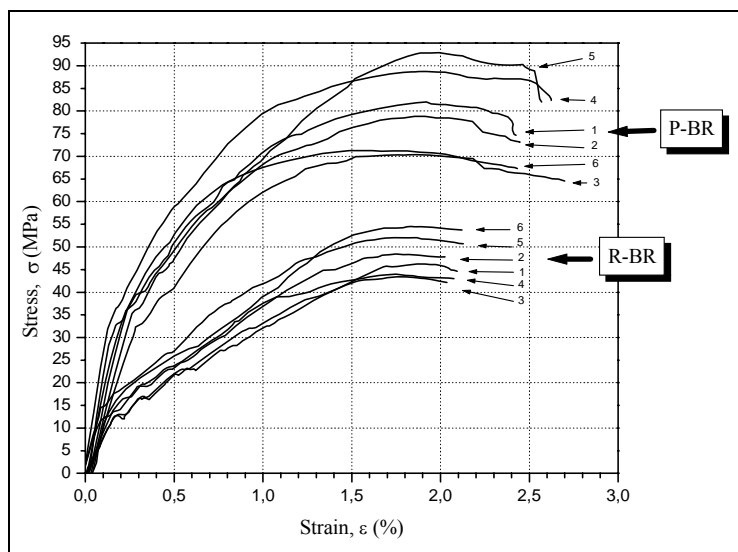


Fig. 2. Comparison of the stress-strain ($\sigma-\epsilon$) diagrams from the two tests

Tensile strength was calculated according to the Equation [1] for flat test specimens (longitudinal direction), and, according to the Equation [2] for the rings (circumferential direction):

$$R_{m,l} = \frac{P_{\max}}{b \cdot d} \quad [1]$$

$$R_{m,c} = \frac{P_{\max}}{2 \cdot b \cdot d} \quad [2]$$

where: $R_{m,l}$, in MPa, is the tensile strength in the longitudinal direction; $R_{m,c}$, in MPa, is the tensile strength in the circumferential direction; P_{\max} , kN, is the maximal applied load force; b , mm, is the width of test specimen (flat specimens or rings); and d , mm, is the thickness of test specimen (flat specimens or rings).

Module of elasticity $E_{(l,c)}$ (GPa) was calculated using Equation [3], and the relationship $\Delta P/\Delta \varepsilon$ was determined by linear regression of rectilinear parts of obtained stress-strains curves.

$$E_{(l,c)} = \frac{\Delta \sigma}{\Delta \varepsilon} = \frac{\Delta P}{\Delta \varepsilon} \cdot \frac{1}{2 \cdot b \cdot d} \quad [3]$$

Tension strength in longitudinal direction (flat samples, R-BR)

The calculated values of tensile strength and module of elasticity in the longitudinal direction are shown in Table 1.

Table 1. Test results of flat samples

Sample	Width of test specimen b (mm)	Thickness of test specimen d (mm)	Cross section A_0 (mm ²)	Maximal load force P_{\max} (kN)	Tensile strength $R_{m,l}$ (MPa)	Module of elasticity E_l (GPa)
R-BR-1	16.50	3.62	59.73	2.74	46	8.90
R-BR-2	15.72	3.41	53.61	2.57	48	8.90
R-BR-3	15.45	3.72	57.47	2.47	43	7.54
R-BR-4	13.55	3.48	47.15	2.08	44	10.90
R-BR-5	14.95	3.62	54.12	2.81	52	12.20
R-BR-6	15.15	3.48	52.72	2.85	54	9.75

The relative agreement of the obtained values of maximal load force P_{\max} can be noticed, except for the test specimen R-BR-4, which is of smaller geometrical dimensions area, and which crashed much earlier than the others during the test. That is the reason why this test specimen has the smallest maximal load force.

According to the results of six tested specimens, the average value of tension strength is 47.8 MPa, and the average value of module of elasticity 9.70 GPa. It can be concluded that for this kind of mechanical testing, there is relatively small deviation of measured and average values for tensile strength and module of elasticity. For tension strength minimal deviation is 0.4% for test specimen R-BR-2, maximal 13.0% for test specimen R-BR-6. As for module of elasticity, minimal deviation is 0.5% for test specimen R-BR-6, maximal 25.8% for test specimen R-BR-5.

The explanation for higher deviation of result of the module of elasticity is the fact that it was relatively more difficult to determine precisely the module elasticity because of the relatively unstable linear part of diagram in Fig. 2 and relatively small starting curve stress-strain ($\sigma-\varepsilon$). As for the tension strength, it is known that because of the angle of winding fibers and different distribution of tension along the axis of fibers, all the

fibers are not loaded in the same way. The result of that is the different moment of breaking fibers, that is, some fibers break under lower and some under higher loading (Fig. 3). Fibers that break easier cause disturbance in the zone of breaking and local tensions occur next to the broken fiber, so that it leads to different maximal loading force on the fracture.

Important influence of shear components of tension can be seen in the dependence of tension-strain ($\sigma-\varepsilon$), which is not linear (Fig. 2) for most of composites. Non-linear characteristics occurred on approximately 20÷25% of value of maximal stress. The increase of stress brought to the debonding and cracks between fiber-matrix connection and macro-cracks which cause fracture. The result of that is the break of fibers and local delamination, but pipe still carried out the loading. With further increase of load force, the local deformations were spreading, the whole groups of fibers broke, resulting in progressive delamination and final fracture. The fracture was followed by strong acoustic effect which was a consequence of the break of a great number of fibers.

Delamination of layers is certainly a phenomenon of destruction of these test samples. The delamination has the appearance (Fig. 4) which matches the interlaminar shear stress. The confirmation of these conclusions is the SEM micrograph shown in Fig. 5, where under the higher magnification we can see the previously mentioned phenomenon.

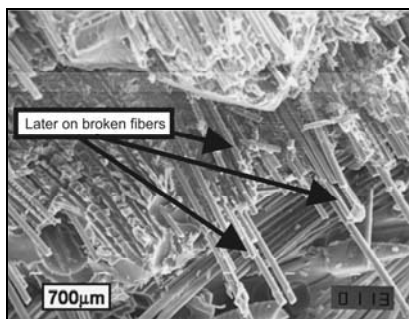


Fig. 3. Different time of fibers breaking shown by SEM



Fig. 4. Delamination of test specimen during the load

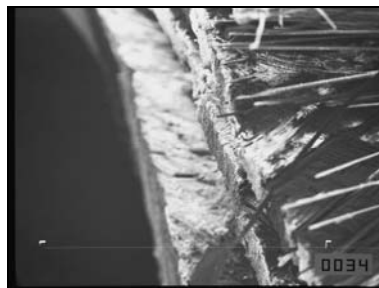


Fig. 5. Delamination under the interlaminar shear stress; SEM micrograph

Tension strength in circumferential direction (ring samples, P-BR)

The calculated values of tension strength in circumferential direction and module of elasticity are shown in Table 2.

Table 2. The results of testing of all ring samples

Sample	Width of ring b (mm)	Thickness of ring s (mm)	Cross section $2bs$ (mm ²)	Maximal load force P_{max} (kN)	Tensile strength $R_{m,c}$ (MPa)	Module of elasticity E_c (GPa)
P-BR-1	35.0	3.35	234.5	19.13	82	13.5
P-BR-2	35.0	3.35	234.5	18.47	79	13.1
P-BR-3	35.0	3.25	227.5	15.86	70	13.0
P-BR-4	35.0	3.15	220.5	19.48	88	12.9
P-BR-5	35.0	3.3	231.0	21.47	93	13.6
P-BR-6	35.0	3.45	241.5	17.21	71	12.8

The relative agreement of the obtained values of maximal load forces P_{max} can be seen, except for the test ring specimen P-BR-3, where the smallest value was obtained (Table 2). This ring cracked earlier than the others during the testing, so its calculated tension strength in circumferential direction is the smallest. It is assumed that because of this there is slightly irregularly set tool inside the ring which caused irregular increase of force, curved ring and earlier crack.

The average value of tension strength in the circumferential direction is 80.5 MPa, and the average module of elasticity 13.2 GPa according to results of six tested rings. Minimal deviation is 1.9% for the ring P-BR-1, maximal 15.2% for the ring P-BR-5. As for the module of elasticity, minimal deviation is 0.8% for the ring P-BR-2, maximal 3.0% for the rings P-BR-5 and P-BR-6.

The explanation of the presented results is relatively similar as with flat samples (R-BR). For the module of elasticity the fact that it was relatively difficult to determine precisely module of elasticity, because of relatively unstable linear part on the diagram and small starting curving of curve stress-strain (Fig. 2). It must be taken in consideration that the test was done by modified and specific method of testing of rings for tensile strength, so a specially made tools were used. Because of that, there were certain irregularities in the measurements that affected the results.

As for the analysis of the break itself, it has to be said that it occurred with a great stretch of ring samples (Fig. 6) and strong acoustic effect. It is characteristic that all tested rings had evident break with cracking of fibers in two directions (conditionally, crossed $\pm 45^\circ$). Also, stretching and bursting of fibers is characteristic which can be a consequence of the lack of matrix (Fig. 7). The fibers did not crack on exactly determined surfaces but randomly in all directions.

Also, the stresses-strains (σ - ε) curves shown in Fig. 2., are not linear for this testing either. The nonlinearity occurred on approximately 40% of the value of maximal load force. That is also the confirmation of the important participation of shear components of tension. The starting crack initiated in one of the layers by the breaking of connection fiber-matrix or cracking of fiber, which caused increased concentration of tension, was spreading further and caused the occurrence of macro-crack, leaving one group of fibers still together.



Fig. 6. Straining of rings during the testing

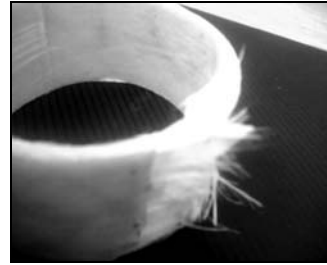


Fig. 7. Stretching and bursting of fibers under the lack of matrix

With a further increase of the loading and tension of macro-crack spread in the adjacent layers, causing delamination, but the ring still carried out the loading. Delamination is a phenomenon of the destruction of all rings (Fig. 8).

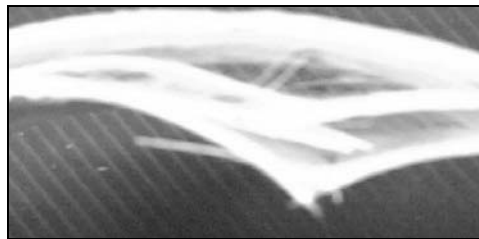


Fig. 8. Delamination of rings

Comparison and analysis of results of the two tension tests

Now we compare and analyze the results obtained in the both tests. Fig. 2 shows comparative stress-strain (σ - ε) diagrams, Fig. 9 the comparative calculated tension strengths and Fig. 10 module of elasticity from both tests. This kind of presentation is justified having in mind the condition of tension in pipes (cylindrical samples) and the fact that in the circumferential direction there are twice as high stresses compared to the longitudinal direction. In our experiment this ratio is approximately 1.7. On the other hand, it was expected because the structure of composite pipe is neither heterogeneous nor homogenous, and composite materials have different and specific mechanisms of damages and breaking.

Some major differences in the values of module of elasticity obtained in the two tests do not exist. It was real to expect that higher values would be obtained for the module of elasticity in the circumferential direction than for those in the longitudinal direction. In this case their relation is approximately 1.4.

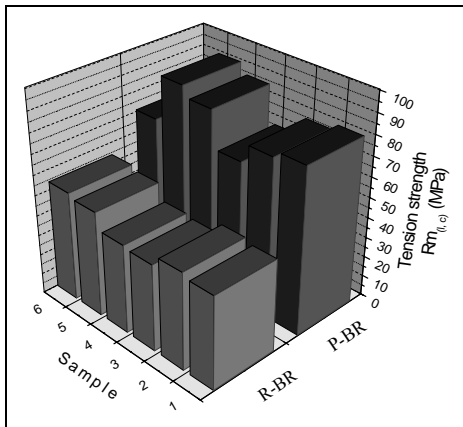


Fig. 9. Comparative presentation of the tension strength obtained in the two tests

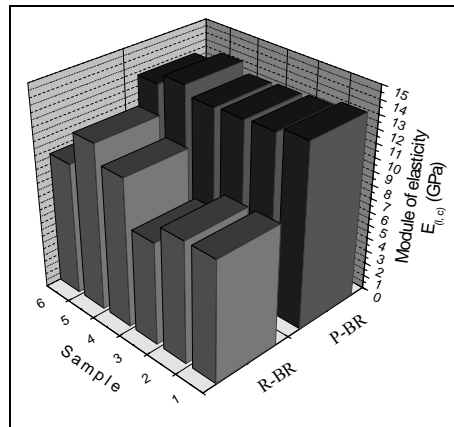


Fig. 10. Comparative presentation of the module of elasticity obtained in the two tests

CONCLUSION

The aim of the paper was the determination and distribution of stresses in glass-polyester composite pipes in the circumferential and longitudinal directions. Also, the tension strength in both directions were calculated. In the previously standard tests, performed on flat test specimens and rings, these properties were determined to get some starting points for further tests.

Fig. 2 can be used to explain the mechanisms of damage and crack behavior during the loading in both tension tests. The nonlinearity of diagram stress-strain was found ($\sigma-\varepsilon$) in both tests. It occurred at approximately 20÷25% of value of the maximal load force for samples R-BR and 40% for samples P-BR. This nonlinearity occurred in the first part of the curve, but it is continued in the whole process. The decrease of the curve slope occurred with increase of tension load in both tests. Thus, based on Fig. 2 the following conclusion can be drawn:

1. Linear part at the beginning of the curve for samples R-BR is much lower than for samples P-BR. Besides the determination of the curve defining the module of elasticity is difficult. As a result, maximal deviations of the calculated modules of elasticity for R-BR was much higher (25.8% compared to 3.0%). The cause of this nonlinearity in the beginning shows the fact that because of tension in the longitudinal direction slipping of fibers occurred, and this caused first cracks between the fibers and matrix and creation of zones of increased concentration of tension. On the other hand, during the stretching of rings strength of wound fibers was higher and they carried the loading;
2. We can explain the fact that the curve slope and values of tension strength of the samples P-BR are higher than for samples R-BR. During the loading of samples P-BR the matrix was stretching until it cracked, which the wound fibers were

carrying the loading. The crack appeared on the thickness of the ring, but the following layers took over the loading. The case of samples R-BR is different, and with these curves in the second, growing part, slight curving was seen. It can be concluded that even at a higher tension, there is seen almost linearity (to approximately 90% of maximal tension). This means that after the first cracks there was dominant shear stress which caused progressive delaminating and gradually, but equally lead to the final crack;

3. It is obvious that samples P-BR have higher tension strength, but also withstand higher strains.

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ОДРЕЂИВАЊЕ ЗАТЕЗНЕ ЧВРСТОЋЕ У УЗДУЖНОМ И ОБИМНОМ ПРАВЦУ У СТАКЛО-ПОЛИЕСТЕР КОМПОЗИТНИМ ЦЕВИМА

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Цеви од полимерних композита са стакленим ојачањем данас имају широку примену у хемијској и процесној индустрији. Предмет овог рада је одређивање и расподела напона и деформација у уздужном и обимном (тангенцијалном) правцу стакло-полиестер цеви при испитивању затезањем. Такође, одређена је и затезна чврстоћа у оба наведена правца. Испитивање затезањем је изведено на електромеханичким кидалицама на равним узорцима и прстеновима сеченим од цеви произведених методом намотавања, са намотавањем стакленог ојачања под углом $\pm 55^\circ$. Микромеханичка анализа је изведена на површинама прелома коришћењем СЕМ, на основу које су претпостављени модели и механизми настанка лома услед примењених оптерећења.

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