UDC 666.1.037.6:11.01
APTEFF, 37, 1-192 (2006) BIBLID: 1450–7188 (2006) 37, 97-106
Original scientific paper

INVESTIGATION METHOD OF TORSIONAL PROPERTIES AND DAMAGES OF GLASS/EPOXY COMPOSITE PIPES

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Pipes made of composites glass fiber/epoxy resin are predominantly used in the chemical industry, construction, infrastructure and war technique. The pipes made for this purpose are in their use exposed to static and dynamic loading. Depending on the purpose, the pipes, especially those in complex structures, can be loaded by torsion. In that case, exceeding allowed tensions can cause damages such as cracking the fibers and matrix delamination. These damages can lead to the appearance of cracks on the pipes and in many cases to complete breakage of the pipe. Because of this, it is very important to evaluate composite pipes exposed to torsion and find out in which way the construction is weakened, what actually is the main goal of this paper.

KEYWORDS: Glass/epoxy composite material; torsion; damages

INTRODUCTION

Materials which were traditionally used in the industry plants are now successfully replaced with composite materials. Pipes, tanks, pressure vessels, and even reactors made of these materials are nowadays more and more used. Their advantage is relatively small mass, good relation strength-mass and stiffness-mass, with good static and dynamic properties, good corrosion-proof, simplified manufacture, time needed for installation. For any use it is necessary to know mechanical properties assessed for smooth and plane samples. However, the problems occur when examining cylindrical samples. Then the properties used for plane samples can not adequately be used, nor can the behavior of the cylindrical material be described by using several elasticity constants at the same time. For

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composite pipes the relation load (F) and extension (Δl) becomes illinear, turning almost all extensions in the function of several different elasticity constants. According to this, mechanical properties of a sample of the examined material in such cases are not only a function of its structure but its geometry must be considered as well.

Many researchers have tried to find out torsion properties of different composite pipes structures (1-7). For example, Kocks and Stout (5) in their work wrote that torsion testing is useful but cumbersome: useful as a technique to determine large-strain plastic behavior in a plane-strain mode; cumbersome because the testing of a solid rod provides reliable data only in the simplest of circumstances, for example, when there is no strain hardening or rate sensitivity. The testing of short thin-walled tubes is widely regarded as the best current technique to determine general constitutive behavior; a drawback is the requirement for large specimen blanks and the complex machining procedure. They have undertaken a similar series of tests on just four rods plus one short tube for comparison. They found the results from the two types of torsion test in excellent agreement; however, it was not a critical test.

Restrained shape memory alloy (SMA) wires, as actuators, are wound and pasted onto the outside surface of a thin-walled circular tube at angle of α° with respect to the tube axis in the (6). This paper presents a mechanical model of a thin-walled tube, pasted with actuators (SMA wires), the analyses of the mixed deformation, of compression and torsion, of the tube and the relation between the angle of twist and the temperature in a temperature cycle. The theoretical predictions are validated with static experiments.

Further in (7) the authors presented results from torsion tests conducted on 36 multilayered, filament-wound, glass-epoxy tubes. Configurations with helical windings and with alternating helical and circumferential windings were investigated for various winding angles. Under small loadings, shear moduli deduced from linear shear stress-strain curves were found to be in reasonable agreement with analytical predictions. Under larger loadings, various degrees of nonlinearity in shear stress-strain curves were encountered, depending on the helical winding angle. Experimental torsional strengths were defined by a 0. 2-percent offset yield stress or by maximum stress when large nonlinearities did not exist. These strengths were compared with torsional buckling predictions for orthotropic cylinders, and with mterial strength predictions based on orthotropic yield criterial and elastic stress analysis. Computed elastic buckling stresses were considerably higher than the experimental strengths for most of the test specimens except for those with only 30 and 45 degree windings. Experimental torsional strengths were found to correlate with conventional yield predictions if predicted yielding in certain layers were ignored or if unrealistically large transverse tensile and shear strengths of unidirectional laminae were employed in the analysis.

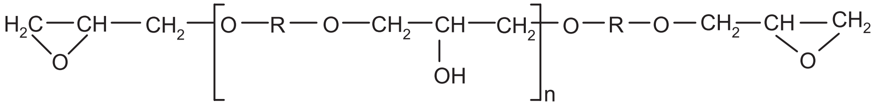
The objectiv of this paper was the examination of glass/epoxy composite pipes on torsion since they are more and more used in the chemical industry as an alternative material to metal. In a comparison of these and steel pipes the advantage over the steel ones is a lower price, as well as anti-corrosive properties which cut off the expenses for additional protection. The material of the examined pipe was chosen because of its large spectrum of usage in the pipelines for corrosive liquids, pipelines laid on the bottom of the seas and for ventilation pipelines resistant to corrosive substances.

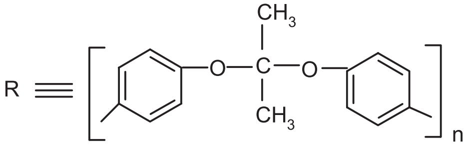
EXPERIMENTAL

Composite pipes have been fabricated in the lab conditions. The basic structural components were: glass woven with orientation 0º/90º as a reinforcement and epoxy resin as matrix. Mass part of the reinforcement was 65%. Pipes were fabricated manually (8), winding around the cylindre, taking care that on each winding resin is carfully pushed out so that no air bubbles stay in. Hardening was done at room temperature, and after that the pipe specimens for mechanical tests were cut. The dimensions of test pipes (length, diametar and thikness) were ∅300 × 50 × 2.5 mm.

Reinforcement properties. Glass woven on the basis of silicate glass which contains alkali up to 1% with specific mass 550 g/m² were used for reinforcement. It were made of "E"-glass fibers which have good mechanical, hydro-thermal and electrical properties. Glass woven was made by classical procedures of spinning.

Epoxy resin used as matrix material, was a polycondensation product of 2,2-bis- (4-hydroxyphenyl) propane (bisphenol A) and epichlorhydrin:





while 3-aminomethanol-3,5,5-trimethanolcyclohexylamine, a modified cycloaliphate aminewas used as crosslinking agent (hardener).

After balancing and dimension control, composite pipe is exposed to torsional examination in order to record static resistance of composite pipe on torsional strain. This examination enabled the determination of the following parameters (9):

- Static torsional moment on the bound of elastic deformations ($Mt_{el.}$) with the appropriate angle of torsion (φ_{el}); and
- Maximum static torsional moment (Mt_{max}) with the appropriate angles of torsion (φ_{max}).

Composite pipe was examined on a device for torsional load (torsional actuator) which can achieve maximal static load of ±10000 Nm and maximal rotation angle of ±50°. Test system with the composite pipe is shown in Fig. 1.

The actuator uses hydraulic power and an appropriate servo valve. The basic structure of the actuator provides flexible moving because of the reactions of the object being testing on alternating rotational loads. The second function provided by the actuator aligning of the testing component achieved by the flexible device. Rotational part of the actuator has an adapter for connecting the testing object. Rotor of the actuator has an adaptional part which connects the area between the actuator and the holder of the sample or elastic diaphraghm.

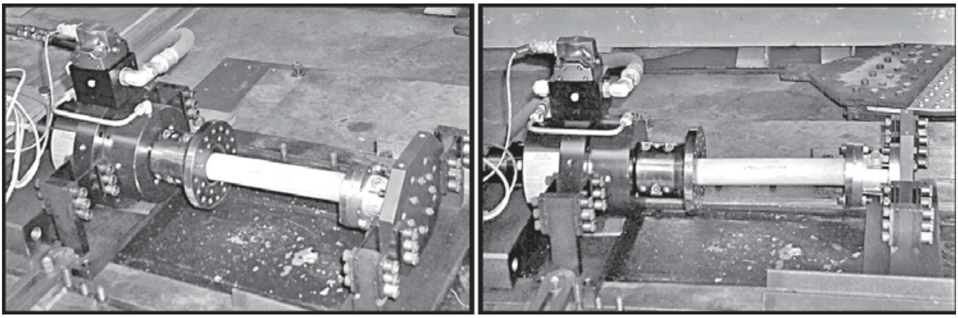


Fig. 1. Test system for composite pipes

Compensation of axial and angle retreat is realized by elastic diaphraghm, which reduces the reaction when the forces exceeds the actuator limit. Bending upon axial loads which occur on the testing sample is neutralized by the reaction link on the other side. Reaction link is done as a model of reaction torsion sensor which suffers installing the sample on a plane panel or a desk. Reaction torsion sensor gives a precise signal proportional to the achived torsion.

Angular Displacement Transducer (ADT) gives to the actuator electric signal through the flexible link, which is propotional to position angle. Rotation of the actuator forms return signal (0 V up to ±10V) from ADT to the amplifier. Amplifier gives a high level of DC signal, which is directly proportional to the torsion angle. Rotation is constant and it does not depend on torsion. Acceleration is also limited by management because of low level of inertia between rotation supplier and bearing. ADT is a precise differential condenser, connected as a stable part of the oscillator, demodulator and a provider of the allowed level DC input and DC output.

During torsional test return signal toward stabilizer for actuator control is obtained from Rotary Variable Differential Transformer (RVDT). This provider turns mechanical angle movement into electric output in the meaning of electric output broadcaster. Differential pressure cell is individual, two-chanell unit with measure tapes as pressure sensors. Depending on the use this cell can act as a stabiliser or output controller on the force actuator. Large inertial forces can cause differential pressure on the actuator over 20 MPa. These forces usually act when the actuator returns suddenly to the zero position, mostly if the chamber of the actuator is under pressure. Differential pressure cell forwards the signal to the controller which controls cylinder pressure and actuator position. It harmonizes the pressure in the servo valve in accordance with the actuator. By applying this option, pressure rising in the chamber is limited.

RESULTS AND DISCUSSION

Three composite pipes were tested. Static torsional load was led in continuosly and during the test the dependence detected was:

Torsion moment M_t - angle of rotation φ, [$M_t = f(\varphi)$].

Typical diagram is shown in Fig. 2.

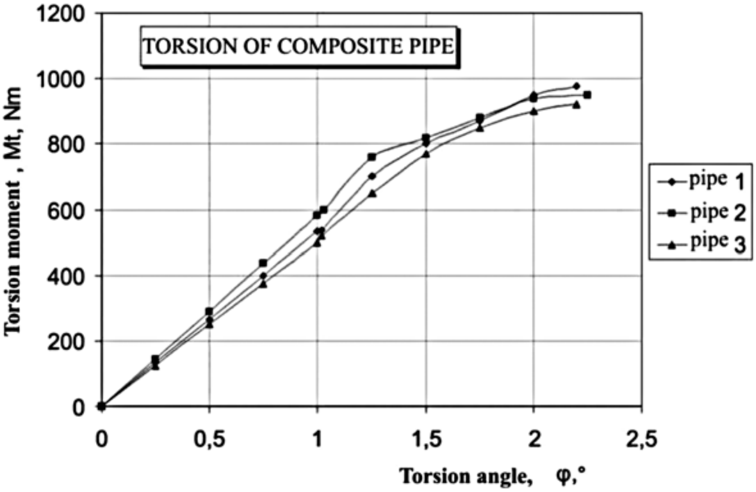


Fig. 2. Relationship between the rotation moment (M_t) and angle of rotation (φ), [$M_t = f(\varphi)$]

Results shown in Table 1 are taken from the diagram shown in Fig. 2.

Table 1. Results of static torsional test of composite pipe

	Mt_{el}, [Nm]	φ_{el}, [°]	Mt_{lom}, [Nm]	φ_{lom}, [°]
Pipe 1	537	1.01	975	2.20
Pipe 2	600	1.03	950	2.25
Pipe 3	520	1.02	920	2.20

Where the following is:
$Mt_{el.}$ - static torsional moment on the bound of elastic deformation;
$\varphi_{el.}$ - torsion angle on the bound of elastic deformation;
Mt_{lom} - maximal static torsional moment on a cracking bound; and
φ_{lom} - torsion angle during torsional moment of cracking M_t.

All pipes had cracks in the middle. Maximal deformations appeared in the cracked area on the pipe. According to the results from examination performed on three pipes the following can be concluded:

- Torsional moment on the bounds of elastic deformations is $Mt_{el.} = 540$ Nm;

and

- Maximal torsional moment on a cracking bound is $Mt_{lom} = 955$ Nm.

Character and appearance of all broken pipes is typical for the breaks made by torsion, Fig. 3.

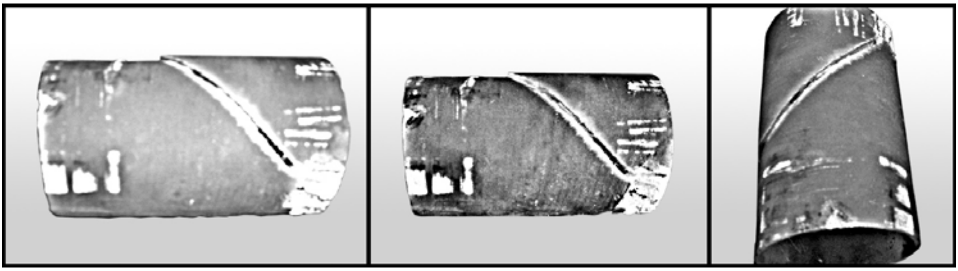


Fig. 3. A wiew of composite pipes after torsion break

The break is made under an angle, usually of 45° to the axis of the pipe. Considering micromechanical analysis of model and mechanisms on torsion, all known models and mechanisms of damage appear in the case of study on torsion load, because reinforcement has a dominant role in the crack initiation and crack propagation during the experiment. The appearance of critical state of stress, and with it, a crack is connected with fiber-matrix debonding after which the fibers cracked.

During experiments it was observed that at lower moment loading cracks were located near the hollow layers, from there they spread, in that way pointing to the high influence of hollowness as the cause of damage. Moreover, it was noticed that there were more breaks on the outer and inner surfaces of the pipe, which were loaded the most during test. They are increasing in layers with the increase of strain level. Local deformations appear around the main break and along the direction of bending reinforcement. With the increase of stress and strain, delamination appears, which is initiated from the main break and developed between the layers of the structure, which can be seen from the SEM micrographs shown in Fig. 4 and Fig. 5.

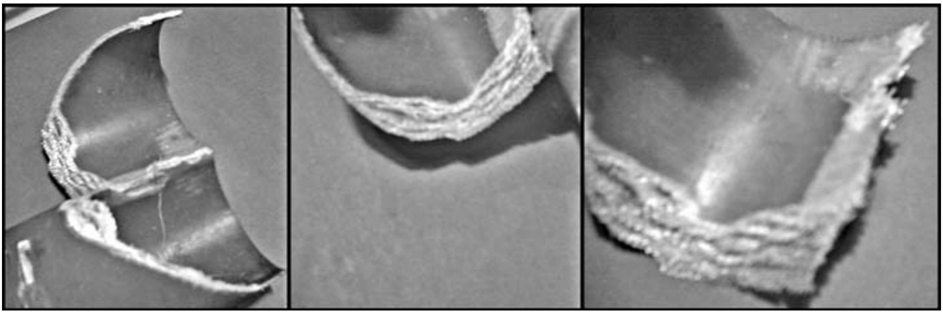


Fig. 4. Typical delamination in the pipe subjected to torsion

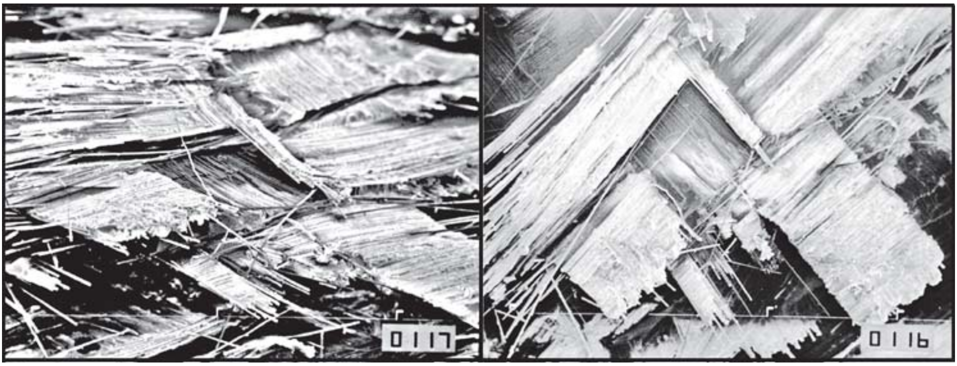


Fig. 5. Delamination of pipes

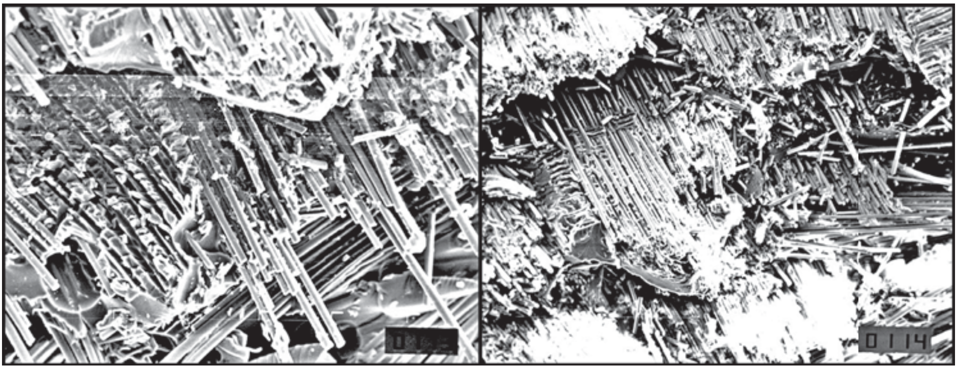


Fig. 6. The fiber break in the layers

On the broken samples, even at low magnification it is possible to see all characteristics of the break of material with the compliance of 0°/90° (Fig. 6):

- Break of the layer of orientation 0° with axial breaks and pulled out fibers, which shows that the spreading of the break was done with fiber-matrix debonding and pulling out of fibers;
- Existance of axial breaks near the connection between the layers on the side of the layer of orientation 0°;
- Transversal break of the layer of orientation of 90° is mainly through the surface between fiber and resin, but without the visible changes in the resin. The lack of axial break in the layer of orientation of 90° is characteristic;
- Brittle break of fibers that points out the dominant axial component of strain; and
- Delamination.

Complete process of damage and mechanism of its development can be described in three phases:

- Initiation of the process of damage on the level of micro-break, either in the form of a break of the matrix in the zones without fibers, or layers of strengthening and the spreading on the border surface fiber-matrix happened before it;
- Delamination between the layers, which happened after transversal break in the case of purely straining loading and/or before that in the case of purely inner pressure (loading). This scheme can be changed according to the relationship of transversal and side strains ($\sigma_{zz} / \sigma_{\theta\theta}$). The appearance of micro-break happens before this damage; and
- Further development and connection of the breaks and delamination between the other layers that results in the final break.

Damage was different depending on the place where micro-breaks appeared:

- In the zone without fibers the cracks are normal on the direction of tension and caused the cracking of the matrix;
- In the zone with low density of fibers, micro-breaks are developed around the fibers and cause transversal breaks; and
- In the zone with high density of fibers, micro-breaks increased and connected with border surface fiber-matrix; there was transversal break.

CONCLUSION

Tests results provide the knowledge that can be very useful to the and become a good basis for the institutes and producers of pipes made of composites glass fiber/epoxy resin. They give the information about the following parameters:

$Mt_{el.}$ - static torsional moment on the bound of elastic deformation;

$\varphi_{el.}$ - torsion angle on the bound of elastic deformation;

Mt_{lom} - maximal static torsional moment on a cracking bound; and

φ_{lom} - torsion angle during torsional moment of cracking M_t.

Micromechanical analysis confirmed all theoretical assuptions analysis of the consequences of torsion of composite pipes. It can be seen, that under smaller moment loading, cracks were located near hollow layers and from there they spread, showing strong influence of hollowness as an initiator of the damage. Futhermore these breaks were higher in the number on outer and inner surface of the pipe, which were mostly loaded during torsion. Local cracks appear around the main break and along the direction of reinforcement. With the increase of stress and strain, appears delamination that is also initiated from the main break and developed further between layers of structure.

The significance of this contribution is manifold. First of all, this experiment set base and set appliances and following equipment for further experiments. Also, the methodology of the work was developed as well as the process of testing. The properties of pipe tested on torsion, moments, angles are found out and the stress and strains can be determined. The picture of the properties after torsion of pipes is complete when all known models of damage and micromechanical analysis of development of damage of break surface of the pipe are considered.

Therefore it can be concluded that the obtained results are new experimental contribution and they can be taken as an orientation and starting values for some further experiments. In the end, it should be said that this problem, up to now, has not been discuss systematically and with due professional care. Because of that, the responsibility in the process of finding the solution of the complex problem of composite pipes is therefore more important and more demanding.

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ИСПИТИВАЊЕ ТОРЗИОНИХ СВОЈСТАВА И ОШТЕЋЕЊА СТАКЛО/ЕПОКСИ КОМПОЗИТНИХ ЦЕВИ

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Доминантност примене цеви израђених од композита стаклена влакна/епокси смола је присутна у хемијској индустрији, грађевинарству, инфраструктури и ратној техници. Цеви израђене за ову намену су у експлотацији изложене деловању како

статичког тако и динамичког оптерећења. У зависности од намене, композитне цеви, поготово у конструкцијама сложеног цевовода, могу бити оптерећене на увијање. У том случају прекорачење допуштених напона проузрокује оштећења која се огледају у увијању и пуцању влакана, пуцању матрице и раслојавања (деламинације). У зависности од начина слагања влакана јављају се различити модели оштећења, односно појаве прслина. Због тога је врло важно дати оцену понашања композитне цеви изложене увијању односно испитивањем и анализом на преломним површинама доћи до закључака који су модели и механизми који се при овом оптерећењу јављају и како они утиче на слабљење конструкције, што и јесте предмет и циљ овог рада.

Received 24 July 2006
Accepted 18 September 2006