Mechanical behaviour of pre-tensioned glass fiber reinforced composite tubes subjected to internal pressure

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Abstract: - The paper presents an original method to increase the loading capability of glass-fabric/polyester-resin tubular composite laminates by applying supplementary internal stresses in thin-walls cylinders with only a few wound layers. An original device has been developed to attain this end. Various tube specimens with different disposal of reinforced material were carried out. The specimens have been heated at a proper temperature and then an elastic material was pressed at the inner of the tubes. While keeping the internal pressure, the specimens were cooled and then discharged. Then, the pre-tensioned specimens were subjected to internal pressure until weeping occurs. Using this method of pre-tension, the loading capability of glass-fabric/polyester-resin tubular composite laminates is increased up to 43%. A theoretical approach regarding the cross-ply and balanced angle-ply composite tubes is presented.

Key-Words: - Pre-tensioning, Internal stresses, Loading capability, Glass-fabric/polyester-resin, Hollow composite laminates, Weeping pressure, Cross-ply composite, Balanced angle-ply composite.

1 Introduction

The purpose of pre-tensioning glass-fabric/polyester-resin tubular composite laminates is to introduce internal stresses in tube wall structure that can work against the operational stresses. These internal stresses increase tube loading capability and its cracking limits. To attain this aim, an original device has been designed and developed [1].

In practice we can encounter two special cases of tubes: the cross-ply composite tube (denoted AC-tube) and the balanced angle-ply composite one (denoted ±E-tube). The AC-tube consists from unidirectional reinforced plies with the same basic elasticity constants. The entire thicknesses t_1 (fibers on axial direction) and t_2 (fibers on circumferential direction) can be different (fig. 1).

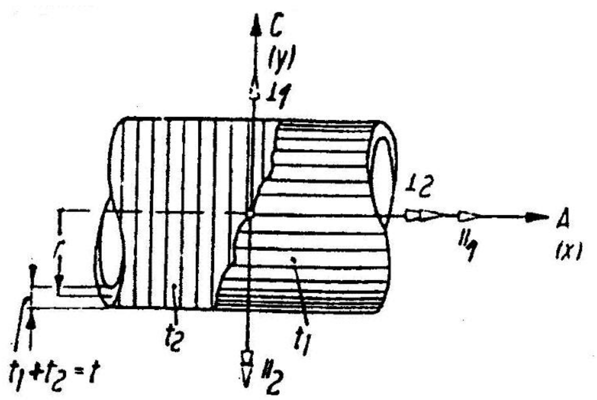

Fig. 1. Cross-ply composite tube (AC-tube)

We suppose that the individual plies of cylindrical tubes are orthotropic ones and the wall thickness t is much smaller than their curvature radius, r. Therefore, the loadings of the tubes wall are:

$$\sigma_C = p \cdot \frac{r}{t}, \tag{1}$$

$$\sigma_A = p \cdot \frac{r}{2t}, \tag{2}$$

$$\tau_{AC} = 0, \tag{3}$$

where A and C represent the axial respective the circumferential direction of the tube.

For the AC-tube subjected to internal pressure, the elasticity laws for the entire wall thickness are [2, 3, 4, 5]:

$$\begin{bmatrix} \sigma_A \\ \sigma_C \end{bmatrix} = \begin{bmatrix} t_1' \cdot c_{II} + t_2' \cdot c_\perp & c_{\perp II} \\ c_{\perp II} & t_1' \cdot c_\perp + t_2' \cdot c_{II} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_A \\ \varepsilon_C \end{bmatrix}, \tag{4}$$

where c_{II}, $c_\perp$ and $c_{\perp II}$ are the elastic constants and the relative thicknesses t_1' and t_2' can be expressed as following:

$$t_1' = \frac{t_1}{t}; \quad t_2' = \frac{t_2}{t}. \tag{5}$$

For the individual plies:

$$\begin{bmatrix} \sigma_{A1} \\ \sigma_{C1} \end{bmatrix} = \begin{bmatrix} c_{II} & c_{\perp II} \\ c_{\perp II} & c_\perp \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_A \\ \varepsilon_C \end{bmatrix}, \tag{6}$$

$$\begin{bmatrix} \sigma_{A2} \\ \sigma_{C2} \end{bmatrix} = \begin{bmatrix} c_\perp & c_{\perp II} \\ c_{\perp II} & c_{II} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_A \\ \varepsilon_C \end{bmatrix}. \tag{7}$$

The tube strains are:

$$\varepsilon_A = \frac{1-\upsilon_{\perp II}\cdot\upsilon_{II\perp}}{E_{II}}\cdot\frac{\hat{\sigma}_C}{2K}\cdot\left[\left(t_1'+t_2'\cdot\frac{E_{II}}{E_\perp}\right)-2\upsilon_{\perp II}\right], \quad (8)$$

$$\varepsilon_C = \frac{1-\upsilon_{\perp II}\cdot\upsilon_{II\perp}}{E_{II}}\cdot\frac{\hat{\sigma}_C}{2K}\cdot\left[2\left(t_2'+t_1'\cdot\frac{E_{II}}{E_\perp}\right)-\upsilon_{\perp II}\right], \quad (9)$$

$$\gamma_{AC} = 0\,, \quad (10)$$

where:

$$K = t_1'\cdot t_2'\left(\frac{E_{II}}{E_\perp}+\frac{E_\perp}{E_{II}}-2\right)+1-\upsilon_{\perp II}\cdot\upsilon_{II\perp}\,, \quad (11)$$

E_{II}, $E_\perp$, $\upsilon_{\perp II}$ represent the basic elasticity constants and $\hat{\sigma}_C$ is the stress that acts in the circumferential direction of the composite tube. At the Poisson ratio, the first index represents the shrinkage direction and the second one is the loading direction that produces this shrinkage.

The stresses in each ply of the composite tube are expressed as following:

$$\sigma_{II1} = \frac{\hat{\sigma}_C}{2K}\left[t_1'+t_2'\frac{E_{II}}{E_\perp}-\upsilon_{\perp II}\upsilon_{II\perp}-2t_2'\left(\upsilon_{\perp II}-\upsilon_{II\perp}\right)\right], \quad (12)$$

$$\sigma_{II2} = \frac{\hat{\sigma}_C}{2K}\left[2(t_2'+t_1'\frac{E_{II}}{E_\perp}-\upsilon_{\perp II}\upsilon_{II\perp})-t_1'\left(\upsilon_{\perp II}-\upsilon_{II\perp}\right)\right], \quad (13)$$

$$\sigma_{\perp 1} = \frac{\hat{\sigma}_C}{2K}\left[2(t_1'+t_2'\frac{E_\perp}{E_{II}}-\upsilon_{\perp II}\upsilon_{II\perp})+t_2'\left(\upsilon_{\perp II}-\upsilon_{II\perp}\right)\right], \quad (14)$$

$$\sigma_{\perp 2} = \frac{\hat{\sigma}_C}{2K}\left[t_2'+t_1'\frac{E_\perp}{E_{II}}-\upsilon_{\perp II}\upsilon_{II\perp}+2t_1'\left(\upsilon_{\perp II}-\upsilon_{II\perp}\right)\right]. \quad (15)$$

In the case of the balanced angle-ply composite tube (±E-tube), the unidirectional reinforced plies present the same mechanical properties and the fibers develop on parallel helicoidally lines (fig. 2). The entire fibers quantity, fibers that are disposed under the angles α = +ω and –ω, is half the fibers quantity disposed on axial direction.

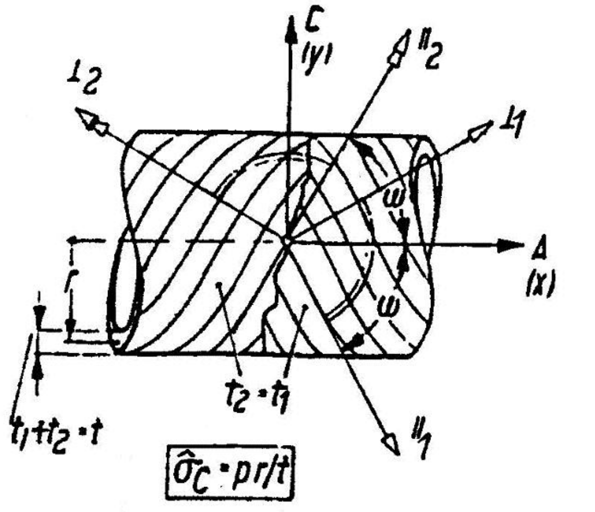

Fig. 2. Balanced angle-ply composite tube (±E-tube)

In the case of ±E-tube subjected to internal pressure, the elasticity laws for the entire wall thickness are:

$$\begin{bmatrix}\hat{\sigma}_A\\ \hat{\sigma}_C\end{bmatrix} = \begin{bmatrix}c_{11} & c_{12}\\ c_{12} & c_{22}\end{bmatrix}\cdot\begin{bmatrix}\varepsilon_A\\ \varepsilon_C\end{bmatrix}, \quad (16)$$

For the individual plies:

$$\begin{bmatrix}\sigma_{A1,2}\\ \sigma_{C1,2}\\ \tau_{AC1,2}\end{bmatrix} = \begin{bmatrix}c_{11} & c_{12} & 0\\ c_{12} & c_{22} & 0\\ c_{131,2} & c_{231,2} & 0\end{bmatrix}\cdot\begin{bmatrix}\varepsilon_A\\ \varepsilon_C\\ 0\end{bmatrix}. \quad (17)$$

From the concordance of the first two relations of the elasticity laws (16) and (17), it results:

$$\sigma_{A1} = \sigma_{A2} = \hat{\sigma}_A;\quad \sigma_{C1} = \sigma_{C2} = \hat{\sigma}_C\,. \quad (18)$$

The tube strains are:

$$\varepsilon_A = \frac{\hat{\sigma}_C}{E_{II}}\left(\frac{1}{2N}\right)\cdot\left[3(AF-D)\sin^2 2\omega+H-J\cdot\cos 2\omega-2L\right], \quad (19)$$

$$\varepsilon_C = \frac{\hat{\sigma}_C}{E_{II}}\left(\frac{1}{2N}\right)\cdot\left[3(AF-D)\sin^2 2\omega+2(H+J\cos 2\omega)-L\right], \quad (20)$$

$$\gamma_{AC} = 0\,, \quad (21)$$

The stresses in each ply of the ±E-tube are:

$$\sigma_{A1,2} = \hat{\sigma}_A\,, \quad (22)$$

$$\sigma_{C1,2} = \hat{\sigma}_C\,, \quad (23)$$

$$\tau_{AC1,2} = -/+\left(\frac{1}{2N}\right)\cdot\left[3AJ-(1-AB)\cos 2\omega\right]\sin 2\omega\cdot\hat{\sigma}_C\,, \quad (24)$$

$$\sigma_{II1,2} = \frac{\hat{\sigma}_C}{2N}\{3\left[1-(1-2AR)\sin^2 2\omega\right]-\cos 2\omega\}\,, \quad (25)$$

$$\sigma_{\perp 1,2} = \frac{\hat{\sigma}_C}{2N}\{3\left[1-(1-2AP)\sin^2 2\omega\right]+\cos 2\omega\}\,, \quad (26)$$

$$\tau_{\#1,2} = -/+\frac{\hat{\sigma}_C}{2N}\cdot A(B+3J\cos 2\omega)\sin 2\omega\,, \quad (27)$$

where:

$$A = \frac{G_\#}{E_{II}}\,, \quad (28)$$

$$B = \frac{E_{II}}{E_\perp}+1+2\upsilon_{\perp II}\,, \quad (29)$$

$$D = \frac{1}{2}\left(\frac{E_{II}}{E_\perp}+1-2\upsilon_{\perp II}\right), \quad (30)$$

$$F = 2\left(\frac{E_{II}}{E_\perp}-\upsilon_{\perp II}^2\right), \quad (31)$$

$$H = \frac{E_{II}}{E_\perp}+1\,, \quad (32)$$

$$J = \frac{E_{II}}{E_\perp}-1\,, \quad (33)$$

$$L = 2\upsilon_{\perp II}\,, \quad (34)$$

$$N = 2\left[1-(1-AB)\sin^2 2\omega\right], \quad (35)$$

$$P = 1+\upsilon_{\perp II}\,, \quad (36)$$

$$R = \frac{E_{II}}{E_\perp}+\upsilon_{\perp II}\,. \quad (37)$$

2 The pre-tension method

The pre-tension method consists in the accomplishment of following successive steps [6, 7].

First, the tube specimen is manufactured in the fabric-winding process. After curing, the specimen is pulled-out of the mandrel.

Second, the pre-tension device is positioned and fixed vertically.

Third, at this stage, the tube specimen is heated up to 10°C above the glass transition temperature T_G. In this field of temperature, the resin elasticity modules decreased quickly and the resin matrix became highly elastic.

Fourth, the heated tube specimen is introduced into the pre-tension device and then the silicone rubber is pressed at the inner of the tube. Since during the heating of the tube specimen the matrix elasticity moduli decrease, the inner pre-tension pressure will be taken over by the fiber network.

Fifth, while keeping the inner pre-tension pressure, the tube specimen is cooled at the environmental temperature.

Sixth, after cooling, the tube specimen is discharged from the inner pre-tension pressure. Now, the fiber network will relax and in wall structure will remain a status of internal stresses.

After these six stages, the tube specimen is removed from the device and it is stored 24 hours in a controlled atmosphere room (T = 20°C and 50% relatively air humidity). This is necessary to reduce the internal stresses relaxation due to possible strong temperature and humidity changes.

A special note regarding the silicone rubber used for the pre-tension operation can be added here. This material acts like a liquid with extreme high viscosity and its volume decreases very little with the increase of the pre-tension pressure, so that theoretically it can be considered incompressible.

3 Material and method

Two kinds of specimens have been used for the experimental tests. One type of specimens has been made at the company Anticorosiv SA Bucharest. These specimens have not been subjected to the pre-tension operation. The other types of specimens have been accomplished at Compozite Ltd, Brasov and have been pre-tensioned.

3.1 Specimens made at Anticorosiv SA

The tubes material used in tests is a thermosetting compound based on polyester resin reinforced with EWR-300 glass fabric. The tube wall structure was made in the fabric winding process. Geometrical elements and wall structure of the tubular specimens are presented in table 1.

Table 1

Matrix	Polyester resin
Reinforcement	EWR-300 glass fabric
Tube diameter	$D = 80^{+0,4}$ mm
Length of winding mandrel	L = 500 mm
Tube wall thickness	t = 5 ± 0,5 mm
Number of plies	n = 6
Plies thickness	t_{1-6} = 0,5 mm
Fabric winding angle	ω = +75°
Fibers volume fraction	φ = 20%

From total length of the tube, four specimens of about 125 mm length were cut.

3.2 Specimens made at Compozite Ltd

The tubes material used during tests is a compound based on glass-fabric reinforced polyester resin. The tube wall structure was manufactured very accurate in the fabric winding process. Fabric strips with dimensions 2000 x 250 mm used in the winding process were cut in length, width and at 45° against the production direction (fig. 3).

Geometrical elements, wall structure and pre-tension characteristics of the specimens are shown in tables 2-7.

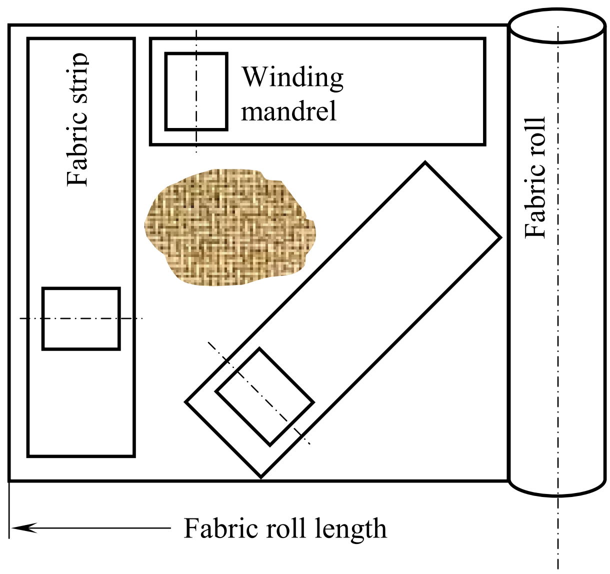

Fig. 3. Cutting method of fabric strips

The specimens were heated at an average temperature T = 105°C in a temperature controlled oven. From every specimen type, two pieces were accomplished, one of them were subjected to pre-tension. All types of specimens were subjected to the same pre-tension pressure of 1,37 MPa given by the pre-tension device. This pressure has been kept at the inner of specimens for 900 seconds in an environmental temperature of about 2°C.

After 24 hours from this operation, both the pre-tensioned and non-pre-tensioned tube specimens were subjected to internal pressure until weeping occurs. This weeping pressure produces irreversible damages in the tube wall structure, such as micro cracks and delamination.

Finally, the weeping pressure value of the pre-tensioned specimen is compared with the weeping pressure value of the non-pre-tensioned specimen.

Table 2. Characteristics of specimen type 1 (UP resin/Stratimat reinforcement)

Number of specimens	2
Matrix	UP resin
Reinforcement	E-glass fiber
Type of fabric	Stratimat
Tube diameter [mm]	$80^{+0,4}$
Tube length [mm]	100
Wall thickness [mm]	3,5 – 5
Number of plies	8
Plies thickness [mm]	0,43 – 0,62
Fibers volume fraction [%]	15
Pre-tension pressure [MPa]	1,37
Heating temperature [°C]	105
Cooling environment	Air
Pre-tension time [s]	900
Cooling environmental temperature [°C]	2

Table 3. Characteristics of specimen type 2 (UP resin/EWR-300 glass fabric reinforcement)

Number of specimens	2
Matrix	UP resin
Reinforcement	E-glass fiber
Type of fabric	EWR-300
Tube diameter [mm]	$80^{+0,4}$
Tube length [mm]	100
Wall thickness [mm]	2 – 2,6
Number of plies	8
Plies thickness [mm]	0,25 – 0,32
Strip cutting angle [°]	0 (in length)
Fibers volume fraction [%]	35
Pre-tension pressure [MPa]	1,37
Heating temperature [°C]	101
Cooling environment	Air
Pre-tension maintaining time [s]	900
Cooling environmental temperature [°C]	2

Table 4. Characteristics of specimen type 3

Number of specimens	2 (3A and 3B)
Matrix	UP resin
Reinforcement	E-glass fiber
Type of fabric	EWR-300
Tube diameter [mm]	$80^{+0,4}$
Tube length [mm]	100
Wall thickness [mm]	2,5 – 3,6
Number of plies	8
Plies thickness [mm]	0,31 – 0,45
Strip cutting angle [°]	45
Fibers volume fraction [%]	35
Pre-tension pressure [MPa]	1,37
Heating temperature [°C]	100
Cooling environment	Air
Pre-tension time [s]	900
Cooling temperature [°C]	1

Table 5. Characteristics of specimen type 4

Number of specimens	2
Matrix	UP resin
Reinforcement	E-glass fiber
Type of fabric	EWR-500
Tube diameter [mm]	$80^{+0,4}$
Tube length [mm]	100
Wall thickness [mm]	3,4 – 4
Number of plies	8
Plies thickness [mm]	0,42 – 0,5
Strip cutting angle [°]	90 (in width)
Fibers volume fraction [%]	35
Pre-tension pressure [MPa]	1,37
Heating temperature [°C]	104
Cooling environment	Air
Pre-tension time [s]	900
Cooling temperature [°C]	2

Table 6. Characteristics of specimen type 5

Number of specimens	2 (5A and 5B)
Matrix	UP resin
Reinforcement	E-glass fiber
Type of fabric	EWR-500
Tube diameter [mm]	$80^{+0,4}$
Tube length [mm]	100
Wall thickness [mm]	3,1 – 4
Number of plies	8
Plies thickness [mm]	0,38 – 0,5
Strip cutting angle [°]	0 (in length)
Fibers volume fraction [%]	35
Pre-tension pressure [MPa]	1,37
Heating temperature [°C]	107
Cooling environment	Air
Pre-tension time [s]	900
Cooling temperature [°C]	3

Table 7. Characteristics of specimen type 6

Number of specimens	2 (6A and 6B)
Matrix	UP resin
Reinforcement	E-glass fiber
Type of fabric	EWR-500
Tube diameter [mm]	$80^{+0,4}$
Tube length [mm]	100
Wall thickness [mm]	3,7 – 5
Number of plies	8
Plies thickness [mm]	0,45 – 0,62
Strip cutting angle [°]	45
Fibers volume fraction [%]	35
Pre-tension pressure [MPa]	1,37
Heating temperature [°C]	103
Cooling environment	Air
Pre-tension time [s]	900
Cooling temperature [°C]	1

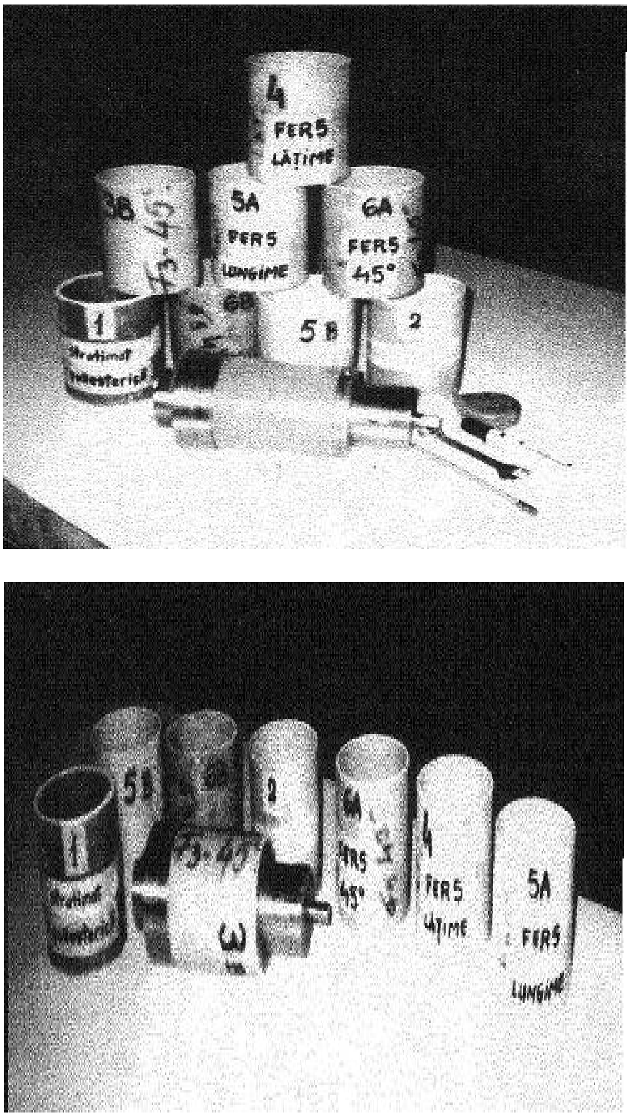

Fig. 4. Various tube specimens made at Compozite Ltd, Brasov, Romania

The high-pressure plant used in tests presents the possibility to adjust the pre-tension pressure in the range of 0 – 500 MPa. The pressure is introduced at the inner of the composite tube, in 1 MPa steps. This pressure is measured permanently by a transducer connected to an electronic block, which was initially calibrated to display the pressure in barr.

4 Results

The weeping pressures of some specimens are presented in the fig. 5 – 8 and fig. 9 shows the increase of loading capability of glass-fabric/polyester-resin specimens.

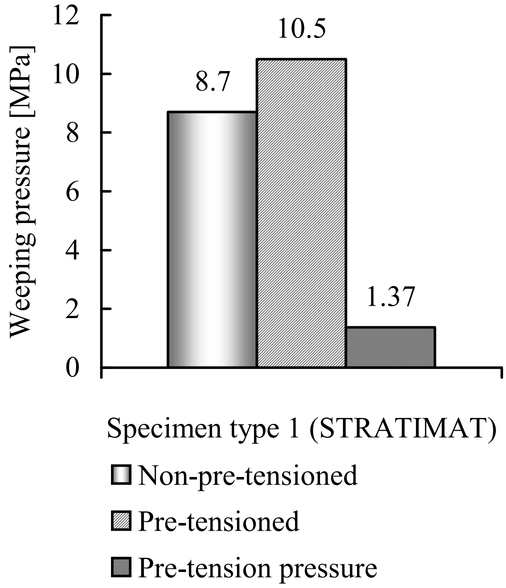

Fig. 5. Weeping pressures of specimen type 1

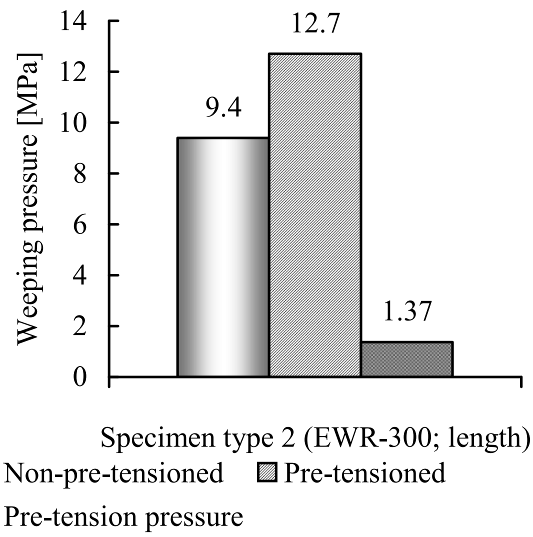

Fig. 6. Weeping pressures of specimen type 2

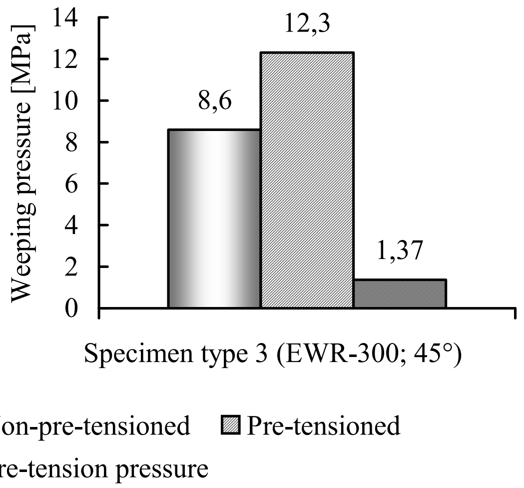

Fig. 7. Weeping pressures of specimen type 3

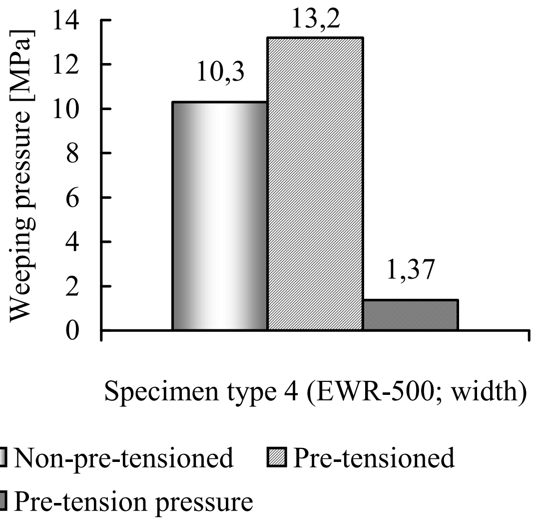

Fig. 8. Weeping pressures of specimen type 4

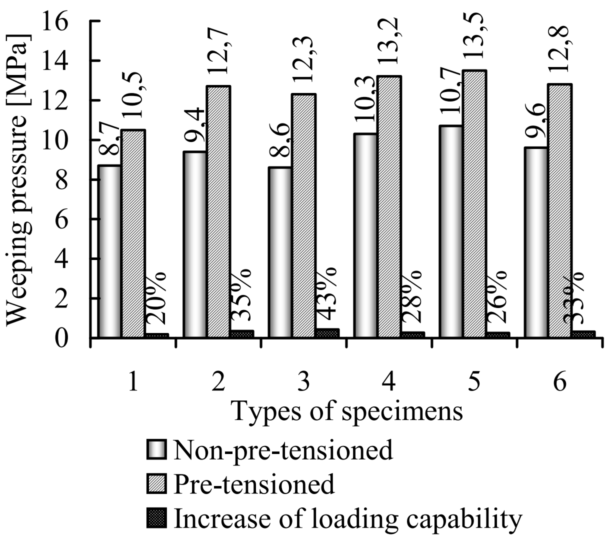

Fig. 9. The increase of loading capability of tubular specimens

5 Conclusions

Regarding the non-pre-tensioned tube specimens manufactured by Anticorosiv SA Bucharest, the mean weeping pressure was 16.45 MPa.

Using this original method of pre-tension, the increase of loading capability of glass-fabric/polyester-resin tubular specimens is situated between 20% (specimen type 1) and 43% (specimen type 3). This method emphasized a low structure endowment with internal stresses, which suppose a reduced pre-tension process due to a prudent choice of the pre-tension pressure. This pressure can cause micro cracks and other damages in the tube wall structure.

The choice of the pre-tension pressure represents a ticklish problem and depends decisively on the composite material type, the pre-tension method used and the pre-tension process parameters, especially the pre-tension temperature.

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