An original pre-tensioning technique of PMC tubes for dynamic applications

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Abstract: - The paper presents an original pre-tensioning technique 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 a specific 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, Cracking limits, Weeping pressure, Cross-ply composite, Balanced angle-ply composite, PMC tubes.

1 Introduction

The basic element of a fiber reinforced multilayered composite material is the unidirectional reinforced lamina. At the exterior loading of a multilayered composite material, in the lamina appear simultaneous normal and shear stresses acting predominant in the lamina plane. The stress along the fiber direction is taken over, almost exclusively, by the very stiff fibers in comparison with the matrix. Generally, the matrix strain at break is greater than the fibers one, so the composite tensile strength along the fibers direction will be determined by the high strength fibers. From this point of view, these normal stresses are not critical. Instead, the normal stresses acting perpendicular to the fibers direction and the shear stresses are dangereous since on the force action direction there are no fibers and as a consequence the stresses act directly on the matrix [1].

By embedding stiff fibers in comparison with the matrix, in the perpendicular to fibers direction subjected lamina appears a marked local increase of stresses that means a strong matrix local strain [2]. The possibility of a weak adherence between fibers and matrix leads to the conclusion that the lamina subjected perpendicular to the fibers direction can not reach even the matrix strength.

On the other hand, embedding stiff fibers in flexible matrix means that the Young modulus perpendicular to the fibers direction and the shear modulus increase strongly since the matrix material is replaced by stiff fibers material. This fact is very disadvantageous since, even in the case of a reduced loading, the lamina attract high stresses perpendicular to the fibers direction and shear stressesas well. Due to the lamina increased stiffness and as a conseqence of low strengths, the probability of appearance inter-fiber break is very high.

In a multilayered composite, at the cooling from the curing temperature, thermal internal stresses can form due to the obstacle opposed by the thermal shrinkage of different layers [3]. Since in an unidirectional lamina the coefficient of linear thermal expansion (CLTE) parallel to the fibers direction is lower than that perpendicular to the fibers direction, at the cooling appear tensile internal stresses perpendicular to the fibers direction.

Another type of internal stresses that are formed in a multilayered composite is represented by the swelling internal stresses due to the matrix moisture absorbtion. Since, due to the matrix swelling, the lamina expansion perpendicular to the fibres direction is grater than that along the fiber direction, in the composite are formed compression internal stresses perpendicular to the fibers direction and tensile internal stresses along the fibers direction. This internal stress state is one desirable. Of course, in some cases, the swelling internal stresses may

have a negative effect. For instance, by drying exterior layers of a multilayered composite these will contract. These shrinkages of the superior layers will be hindered by the still swelled interior layers, forming unfavourable tensile internal stresses [4].
Hopes regarding the increase of cracking limits of laminates have been put in carbon and aramidic fibers. The low transverse moduli of these fibers reduce the effect of the matrix strain increase. Unfortunately, these fibers present negative CLTEs along the fibres direction so that due to the high thermal internal stresses, the cracking problem remains serious even at the advanced composites. Some improvements regarding the increase of cracking limits of laminates can be obtained using cross-ply laminates with fine layers [5]. The cross-ply laminates are $[0/90]_{ns}$ laminates containing equal number of 0° and 90° thin plies. Possible cracks that may appear will be stopped by the immediate neighbour ply limits, so that long cracks can not be formed. There were undertaken different attempts to attain higher cracking limits. For instance, it was studied in what manner the flexibilized resins can increase the composite elasticity perpendicular to the fibers direction [6]. The results have remained behind the expectations since the flexibility compounds lower the adherence between fibers and matrix and in addition, the flexibilized resins present often a low chemical and heat stability. Roth and Grüninger [7] have explained the fact that the use of hollow fibers instead of ordinary fibers should lead to higher tensile strengths in the transverse plane. Hollow fibers present a low stiffness in the transverse plane and therefore participate stronger at the exterior strain of the matrix-fibers composite system subjected perpendicular to the fibers direction. In this way, the increase of the matrix strain reduce the local stresses peaks, phenomenon that should lead to higher tensile strengths perpendicular to the fibers direction. The accomplished tests and the real strengths values did not correspond with the expectations from reasons still unexplained. The early cracking in an unidirectional reinforced lamina as a result of both tensile stresses perpendicular to the fibers direction and shear stresses is one of the tickelish problem of fiber reinforcement technique of plastic materials.
The increase of loading capability of composite laminates can be accomplished introducing internal stresses in composite, so that at least partially, should be made up for the tensile stresses transverse to the fibers direction as well as dangereous shear stresses. A special importance is given by the manner and the types of internal stresses that could be introduced.

2 Theoretical approach

In practice we can encounter two special cases of tubes: the cross-ply composite tube and the balanced angle-ply composite one. The cross-ply composite 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).

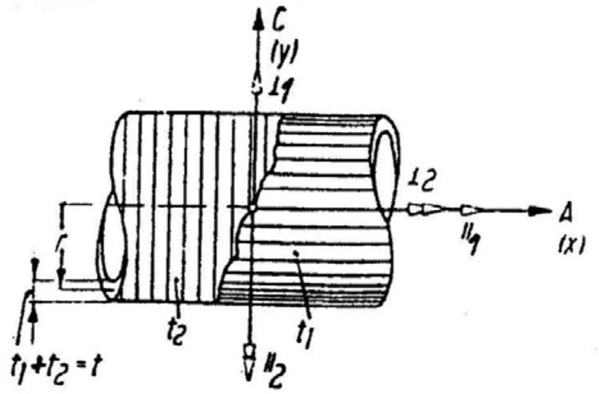

Fig. 1. Cross-ply composite tube

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 tube 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/circumferential tube direction and p is the internal pressure.
For the cross-ply composite 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:

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

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

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

where:

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

E_{II}, $E_{\perp}$ and $\upsilon_{\perp II}$ represent the basic elasticity constants and $\hat{\sigma}_C$ is the medium 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:

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

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

$$\sigma_{\perp1} = \frac{\hat{\sigma}_C}{2K}\left[2(t_1'+t_2'\frac{E_{\perp}}{E_{II}}-\upsilon_{\perp II}\upsilon_{II\perp})+t_2'\left(\upsilon_{\perp II}-\upsilon_{II\perp}\right)\right], \qquad (14)$$

$$\sigma_{\perp2} = \frac{\hat{\sigma}_C}{2K}\left[t_2'+t_1'\frac{E_{\perp}}{E_{II}}-\upsilon_{\perp II}\upsilon_{II\perp}+2t_1'\left(\upsilon_{\perp II}-\upsilon_{II\perp}\right)\right]. \qquad (15)$$

In the case of the balanced angle-ply composite 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.

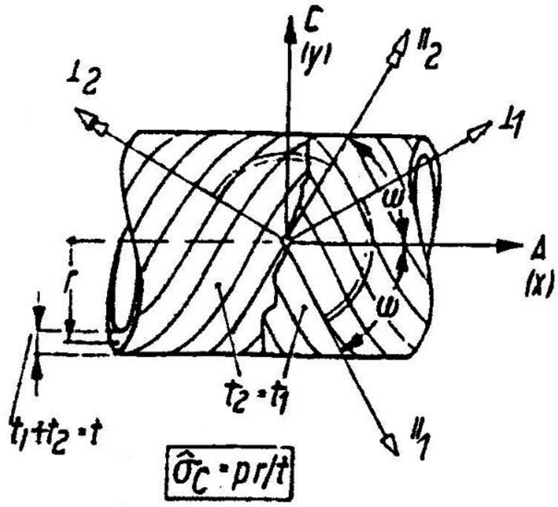

Fig. 2. Balanced angle-ply composite tube

In the case of the balanced angle-ply composite tube subjected to internal pressure, the elasticity laws for the entire wall thickness are:

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

For the individual plies:

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

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

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

The tube strains are:

$$\varepsilon_A = \frac{\hat{\sigma}_C}{E_{II}}\left(\frac{1}{2N}\right)\cdot\left[3(AF-D)\sin^2 2\omega+H-J\cdot\cos2\omega-2L\right], \qquad (19)$$

$$\varepsilon_C = \frac{\hat{\sigma}_C}{E_{II}}\left(\frac{1}{2N}\right)\cdot\left[3(AF-D)\sin^2 2\omega+2(H+J\cos2\omega)-L\right], \qquad (20)$$

$$\gamma_{AC}=0. \qquad (21)$$

The stresses in each ply of the tube are:

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

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

$$\tau_{AC1,2} = \mp\left(\frac{1}{2N}\right)\cdot\left[3AJ-(1-AB)\cos2\omega\right]\sin2\omega\cdot\hat{\sigma}_C, \qquad (24)$$

$$\sigma_{II1,2} = \frac{\hat{\sigma}_C}{2N}\{\,3\left[1-(1-2AR)\sin^2 2\omega\right]-\cos2\omega\,\}, \qquad (25)$$

$$\sigma_{\perp1,2} = \frac{\hat{\sigma}_C}{2N}\{\,3\left[1-(1-2AP)\sin^2 2\omega\right]+\cos2\omega\,\}, \qquad (26)$$

$$\tau_{\#1,2} = \mp\frac{\hat{\sigma}_C}{2N}\cdot A(B+3J\cos2\omega)\sin2\omega, \qquad (27)$$

where:

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

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

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

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

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

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

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

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

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

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

The basic elasticity constants of a composite can be determined either experimentally or from the basic fibers- respective matrix material data. The following relations are valid for isotropic fibers embedded in isotropic matrix. For the Young modulus along fibers direction, the mixture rule can be used:

$$E_{II} = \varphi \cdot E_F + E_M (1-\varphi). \quad (38)$$

Transverse to the fibres direction, the Young modulus will be:

$$E_{\perp} = \frac{E_M (1+0,85 \cdot \varphi^2)}{(1-\upsilon_M^2)\left[(1-\varphi)^{1,25} + \frac{\varphi \cdot E_M (1-\upsilon_M^2)}{E_F}\right]}. \quad (39)$$

The shear modulus, parallel and transverse to the fibers direction can be computed as following:

$$G_{\#} = \frac{G_M (1+0,6 \cdot \varphi^{0,5})}{(1-\varphi)^{1,25} + \varphi \frac{G_M}{G_F}}. \quad (40)$$

For the transverse shrinkage perpendicular to the fibers direction, at a parallel loading to these fibers, the following relation can be used:

$$\upsilon_{\perp II} = \varphi \cdot \upsilon_F + \upsilon_M (1-\varphi), \quad (41)$$

and the transverse shrinkage along the fibers direction, at a perpendicular loading to these fibers is:

$$\upsilon_{II \perp} = \frac{\upsilon_{\perp II} \cdot E_{\perp}}{E_{II}}. \quad (42)$$

The index F refers to the glass fiber and the index M to the matrix.

3 The pre-tension method

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 may increase tube loading capability and its cracking limits. To attain this aim, an original mechanical device has been designed and developed. It consists, generally, of the following parts: a support that can be properly positioned and fixed, a lower and upper piston that can perform only a translation movement and a silicone rubber that can be pressed at the inner of a tubular specimen.

The pre-tension method consists in the accomplishment of following successive steps [8], [9]. 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.

4 Mechanical behaviour of a $[55/-55]_3$ pre-tensioned composite tube

Using the above described pre-tensioning method, a $[55/-55]_3$ balanced angle-ply composite tube based on unsaturated polyester resin have been heated at 105°C (fig. 3). At this temperature, the matrix basic elasticity constants $E_{\perp p}$ and $G_{\# p}$ are strongly diminished until $E_{\perp p} \approx$ 250 MPa and $G_{\# p} \approx$ 100 MPa. According to these values and using the relations (38) – (42), in tables 1 – 3 the following input data are presented.

Table 1. Basic elasticity constants at pre-tension

Young modulus, $E_{II\,p}$ [MPa]	27350
Young modulus, $E_{\perp p}$ [MPa]	≈ 250
Shear modulus, $G_{\# p}$ [MPa]	≈ 100
Fibers volume fraction [%]	35
Poisson ratio, $\upsilon_{\perp II\,p}$ [-]	0.36
Poisson ratio, $\upsilon_{II \perp p}$ [-]	0.11

Table 2. Basic elasticity constants at pre-tension for isotropic materials

	E-glass	UP resin
Young modulus, E [MPa]	73000	≈ 95
Shear modulus, G [MPa]	29200	≈ 33
Poisson ratio, υ [-]	0.25	0.42

Table 3. Geometric and pre-tensioning data

Tube diameter [mm]	80
Plies thickness [mm]	0.4
Tube wall thickness [mm]	4
Internal pre-tension pressure, p_p [MPa]	1.37
Fibers winding angle [°]	± 55

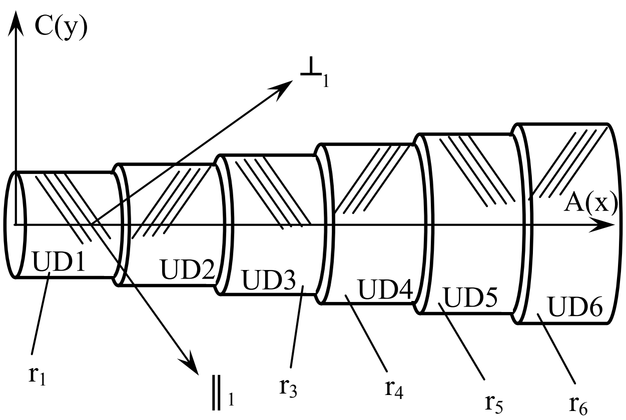

Fig. 3. Schematic representation of $[55/-55]_3$ tube windings

According to these input data, the relations (28) – (37) can be then computed. The pre-tensioning circumferential stresses, $\sigma_{C\,p}$ according to the tube winding 1 (ply UD1 and UD2) are:

$$\sigma_{C\,p1,2} = \frac{p_p \cdot r_1}{\sum_{i=1}^{2} t_i}, \tag{43}$$

for tube winding 2 (ply 3 and 4):

$$\sigma_{C\,p3,4} = \frac{p_p \cdot r_2}{\sum_{i=1}^{4} t_i}, \tag{44}$$

and for tube winding 3 (ply 5 and 6):

$$\sigma_{C\,p5,6} = \frac{p_p \cdot r_3}{\sum_{i=1}^{6} t_i}. \tag{45}$$

Similar judgements regarding the calculus of the pre-tensioning axial stresses can be made:

$$\sigma_{A\,p1,2} = \frac{p_p \cdot r_1}{2} \cdot \frac{1}{\sum_{i=1}^{2} t_i}, \tag{46}$$

$$\sigma_{A\,p3,4} = \frac{p_p \cdot r_2}{2} \cdot \frac{1}{\sum_{i=1}^{4} t_i}, \tag{47}$$

$$\sigma_{A\,p5,6} = \frac{p_p \cdot r_3}{2} \cdot \frac{1}{\sum_{i=1}^{6} t_i}. \tag{48}$$

Stresses and strains can be computed in all unidirectional tube layers, tube subjected to the internal pre-tensioning pressure p_p = 1.37 MPa and under the influence of temperature T = 105°C. The results are shown in table 4 - 6.

Table 4. Winding 1 stresses and strains

Stresses and strains at pre-tension	Winding 1	
	UD1	UD2
Circumferential stress [MPa]	69.18	69.18
Axial stress [MPa]	34.59	34.59
Circumferential strain [-]	0.0036	0.0036
Axial strain [-]	0.0038	0.0038
Shear stress, $\tau_{AC\,p}$ [MPa]	-47.57	47.57
Stress, $\sigma_{II\,p}$ [MPa]	102.53	102.53
Stress, $\sigma_{\perp\,p}$ [MPa]	1.28	1.28
Shear stress, $\tau_{\#\,p}$ [MPa]	0.013	-0.013

Table 5. Winding 2 stresses and strains

Stresses and strains at pre-tension	Winding 2	
	UD3	UD4
Circumferential stress [MPa]	34.93	34.93
Axial stress [MPa]	17.46	17.46
Circumferential strain [-]	0.0018	0.0018
Axial strain [-]	0.0019	0.0019
Shear stress, $\tau_{AC\,p}$ [MPa]	-24.02	24.02
Stress, $\sigma_{II\,p}$ [MPa]	51.77	51.77
Stress, $\sigma_{\perp\,p}$ [MPa]	0.64	0.64
Shear stress, $\tau_{\#\,p}$ [MPa]	0.006	-0.006

Table 6. Winding 3 stresses ands strains

Stresses and strains at pre-tension	Winding 3	
	UD5	UD6
Circumferential stress [MPa]	23.51	23.51
Axial stress [MPa]	11.75	11.75
Circumferential strain [-]	0.0012	0.0012
Axial strain [-]	0.0013	0.0013
Shear stress, $\tau_{AC\,p}$ [MPa]	-16.16	16.16
Stress, $\sigma_{II\,p}$ [MPa]	34.84	34.84
Stress, $\sigma_{\perp\,p}$ [MPa]	0.43	0.43
Shear stress, $\tau_{\#\,p}$ [MPa]	0.004	-0.004

It can be noticed that the stresses and strains decrease beginning from the inner to the outer tube surface.

5 Conclusions

The tubes material used during tests is a compound based on EWR-300 and EWR-500 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. Using this original pre-tensioning technique of PMC tubes, the increase of loading capability of glass-fabric/polyester-resin tubular specimens is situated between 20% and 43%. Regarding the mechanical behaviour of a balanced angle-ply $[55/-55]_3$ composite tube, the following conclusions can be drawn: due to the low values of internal stresses $\tau_{\# p}$, these can be neglected so that in the case of a tube pre-tensioning, the tensile internal stresses along the fibers direction $\sigma_{II\ pF}$ play a significant role in a further tube's reloading; these tensile internal stresses $\sigma_{II\ pF}$ can cause compression internal stresses in matrix $\sigma_{II\ cM} = -\sigma_{II\ pF}$ that act in the sense of the increase of tube's loading capability.

In the case of reloading the $[55/-55]_3$ composite tube, to reach the value of compression internal stress in matrix $\sigma_{II\ cM} = -102.53$ MPa, a tube reloading by an internal pressure of 1.74 MPa is necessary (fig. 4).

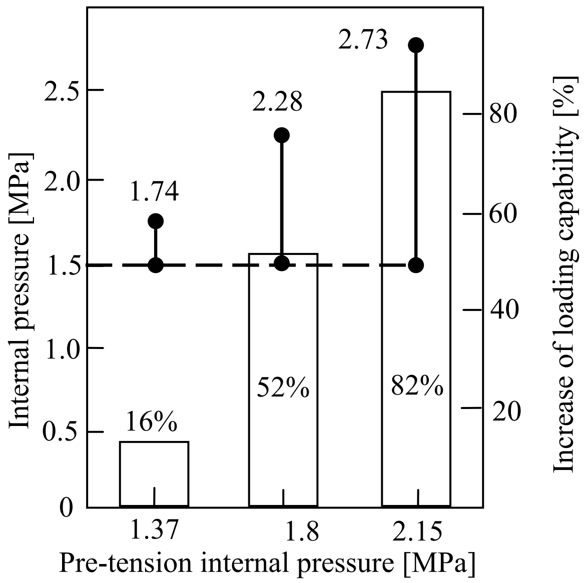

Fig. 4

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