Determination of stress and strains of a composite tank used for liquid medical products

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Composite materials are made by combining two materials where one of the materials is a reinforcement (fiber) and the other material is a matrix (resin). The paper presents a theoretical approach regarding the mechanical behavior of glass fabric reinforced composite, an advanced material used for a liquid storage tank. As the most exposed part of the tank is the sight hole, the research was focused upon the stress and deformation of this part, which was subjected to the action of the stored materials pressure. The present paper deals with the study of the stress and deformation occurred inside some parts of a storage tank made of advanced composite materials as the material used for the structure consists of several layers with different properties.

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1. Introduction

As Romanian research in the areas related to biomedical engineering, in spite of its progress is still behind the progress at European and global level, it is necessary to establish a connection between related domains required by the development and advance in research topics, as well as improving the knowledge transfer towards economic environment. [13]

General concern evolved significantly towards determination of spectacular solutions, many times without considering the access of an average user to these new materials, techniques or technologies.

Composite biomaterials are processed in two or more distinct phases, with entirely different properties by comparison to the homogeneous material. The filler material in a composite may be shaped as particles, fibers or stripes. Fibrous or laminated stripes composite materials are anisotropic, while the ones with uniformly distributed particles inside a matrix are isotropic composites. [13]

Anisotropic composites have a higher strength than the isotropic ones. Anisotropic composites can be used only if the stress application direction is known. Also, it is necessary that each component of the composite should be biocompatible, meaning that the interface between the components should not be damaged by the working environment.

Finite element method (FEM) becomes more and more a general method used for solving different types of complex problems concerning both stationary and non-stationary phenomena from all engineering fields but also in other activity and research areas.

As far as the stress and deformation are concerned we may observe that the internal mechanical work is linked to three components of the stress in 2D coordinates, the normal plane component of the stress does not involve the cancelling of other strains or stresses.

From mathematical point of view, the problem is very similar to that of plane stress and deformation analysis, this is why the situation may be regarded as two dimensional.

By symmetry, the two components of the displacements in any 2D section of the body along the symmetry axis, completely defines the deformation state and obviously the stress state.

In order to control the complexity of the problem and “filter” the irrelevant aspects we need to accomplish a suitable mathematical model. This model should consider the fact that we are dealing with an anisotropic material, consisting of several layers and also that the loads and deformations along the contours are difficult to be obtained.

The internal stress and deformation field is locally influenced by the relative difference between the constituents’ properties, their size, shape and relative orientation as well as by the geometry of the repeating structures that form the advanced composite material.

2. Mathematical Modelling with FEM

The state of deformation of an element in a certain position can be described by the strains vector (specific) $\{\varepsilon\}$.

For the 2D stress condition, this vector has 3 components, meaning:[11]

$$\varepsilon = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} \tag{2.1}$$

The components of { ε } should also be expressed in terms of displacements in nodes. In a matrix form:

$$\{\varepsilon\} = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} =$$

$$= \frac{1}{2\Delta} \begin{bmatrix} b_i & 0 & b_j & 0 & b_m & 0 \\ 0 & c_i & 0 & c_j & 0 & c_m \\ c_i & b_i & c_j & b_j & c_m & b_m \end{bmatrix} \begin{Bmatrix} u_i \\ v_i \\ u_j \\ v_j \\ u_m \\ v_m \end{Bmatrix} \tag{2.2}$$

$$\{\varepsilon\} = [B]\{a\}^e \tag{2.3}$$

In (2.3), the general case, the so called initial strains are also included (independent of the load). These can be determined by different contractions, growth of various crystals or temperature changes, thus:

$$\{\varepsilon_0\} = \begin{Bmatrix} \varepsilon_{x0} \\ \varepsilon_{y0} \\ \gamma_{xy0} \end{Bmatrix} \tag{2.4}$$

More specifically, for a 2D stress condition in an isotropic material with the thermal expansion coefficient α, subjected to an increase of temperature of θ^e the following strains will occur due to expansions:

$$\{\varepsilon_0\} = \begin{Bmatrix} \alpha\theta^e \\ \alpha\theta^e \\ 0 \end{Bmatrix} \tag{2.5}$$

For a 2D state of strain

$$\{\varepsilon_0\} = (1+\nu)\begin{Bmatrix} \alpha\theta^e \\ \alpha\theta^e \\ 0 \end{Bmatrix}. \tag{2.6}$$

Vector of specific deformations becomes:

$$\{\varepsilon\} = [B]\{\alpha\}^e - \{\varepsilon_0\}\,. \tag{2.7}$$

Stress state in the elements.

For the 2D state of stress the stress vector $\{\sigma\}$ is:[11]

$$\{\sigma\} = \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{Bmatrix} \frac{E}{1-\nu^2}\left(\varepsilon_x + \nu\varepsilon_y\right) \\ \frac{E}{1-\nu^2}\left(\varepsilon_x + \nu\varepsilon_y\right) \\ \gamma_{xy} \cdot \frac{E}{2(1+\nu)} \end{Bmatrix} =$$

$$= \frac{E}{1-\nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \gamma_{xy} \end{Bmatrix} \tag{2.8}$$

We denoted [D] – the elasticity matrix. This matrix depends only on the material properties, elasticity modulus, E and Poisson’s coefficient, υ, thus:

$$[D] = \frac{E}{1-\nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \tag{2.9}$$

This gives:

$$\{\sigma\} = [D](\{\varepsilon\} - \{\varepsilon_0\}) \tag{2.10}$$

After establishing the physical model, the equations corresponding to the mathematical model will be approached by help of approximating methods, except for some simple situations. The approximating methods usually accepted will unfortunately introduce some errors. In this situation, obtaining as accurate as possible numerical results is critical, considering also time and calculus amount. [11]

We found that weighted residue formulations are more general than variation principles that can be applied only for a certain type of operator.

Thus, variation techniques, finite differences, finite elements can be regarded as special cases of the weighted residue methods, the reversed situation being usually false.

Generally the approximation of numerical methods solution followed closely the progresses in hardware, software, of interactive and graphic techniques, becoming not only calculus methods but also computer adapted methods.

3. Results obtained by using MSC. Patran and MSC.Nastran regarding the stress and strains of the geometric model

The paper presents a theoretical approach regarding the mechanical behaviour of glass fabric reinforced advanced composite for liquid medical products storage tank.

The model was achieved using MSC Patran pre-processor/postprocessor and MSC Nastran processor. In the pre-processing stage, the finite elements geometric modelling requires the finite element model, which will be finally solvable by help of the programs kit meant for this purpose.[12]

A finite element modelling requires the material behaviour modelling, selection and personalization of finite elements; finite elements structure generation, introduction of boundary conditions and loads.

Deformation energy of finite element is quantified by the factor of deformation energy density.

For results we use the pre-processor MSC.Patran, with the Results menu.

The output data corresponding to the nodes usually include the problem unknowns, like displacements, temperatures, pressures, velocities.

The output data corresponding to the finite elements are different from one element to another, for example the internal forces, strains, deformation energy [12].

The structure is made of 8 different layers as shown in Table 1, the arrow representing the succession of the layers starting from the interior towards the exterior of the structure.

Table 1 Succession of material layers

Layers direction	***Layer(Ply)***	***Material type***
Inferior side	1	MAT600
	2	MAT600
	3	RT800
	4	RT800
	5	RT800
	6	RT800
	7	MAT450
Superior side	8	MAT450

The structure is made of 5 different layers as shown in Table 2, the arrow representing the succession of the layers starting from the interior towards the exterior of the better structure.

Table 2. Succession of material layers

Layers direction	***Layer(Ply)***	***Material type***
Inferior side	1	MAT600
	3	RT800
	4	RT800
	5	RT800
Superior side	7	MAT450

The output data of the nodes, as well as of the finite elements are stored in files that can be analyzed, studied and compared along the 3 directions.

The huge information amount is not possible to be presented in the paper but some of the most significant obtained results will be shown.

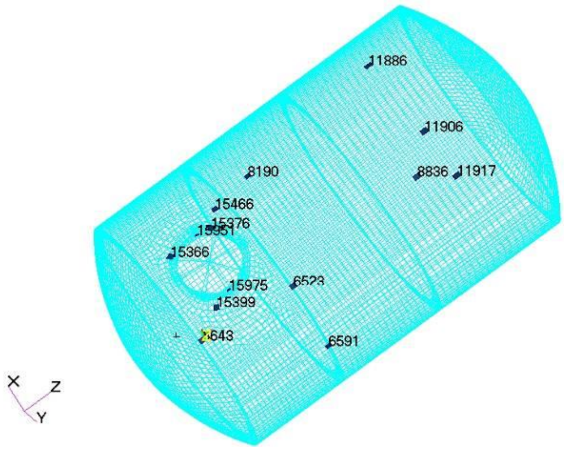

Fig. 1 Elements of the MAT-Roving studied storage tank in FEM

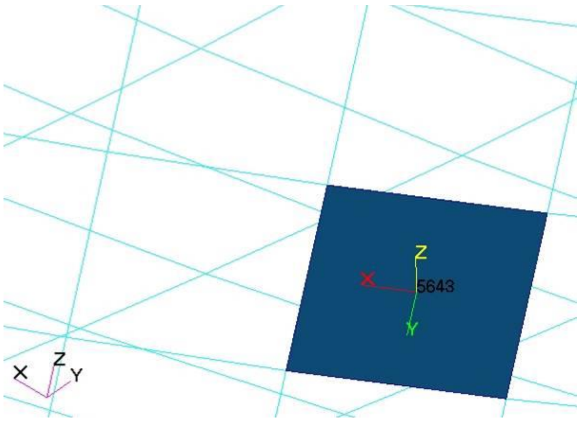

Fig. 2. Element 5643 of the presented tank

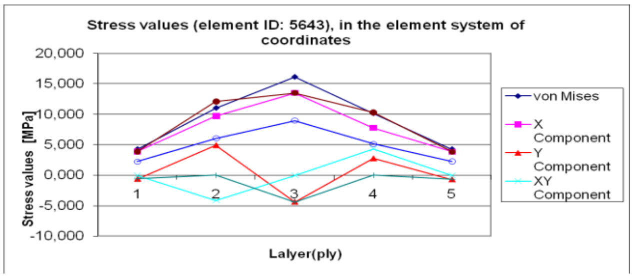

Fig. 3.3 Stress values (element ID: 5643), in the element system of coordinates

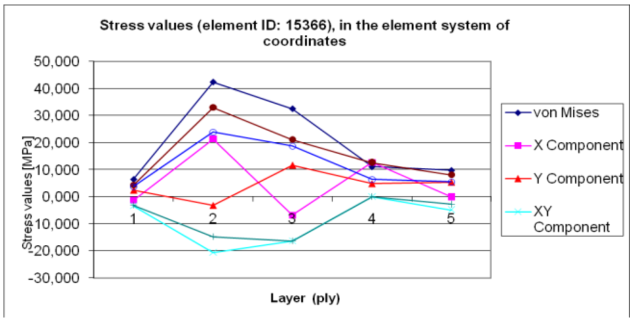

Fig. 3.4 Stress values (element ID: 15366), in the element system of coordinates

Table 3. Stress values for the element 5643 of the MAT-Roving storage tank

No. Elem.	Layer	von Mises	Stress X	Stress Y
5643	4	4.282	3.952	-0.597
5643	5	11.055	9.730	4.960
5643	6	16.156	13.519	-4.374
5643	21	10.177	7.811	2.795
5643	22	4.286	3.911	-0.671

No. Elem	Stress XY	Max Stress	Min Stress	Max Shear
5643	0.000	3.952	-0.597	2.275
5643	-4.131	12.115	0.000	6.058
5643	0.000	13.519	-4.374	8.946
5643	4.343	10.318	0.000	5.159
5643	0.000	3.911	-0.671	2.291

State of strains of the studied structure

Strains were determined by finite element method for MAT-Roving type composites, 8 layers and Roving, 8 layers.

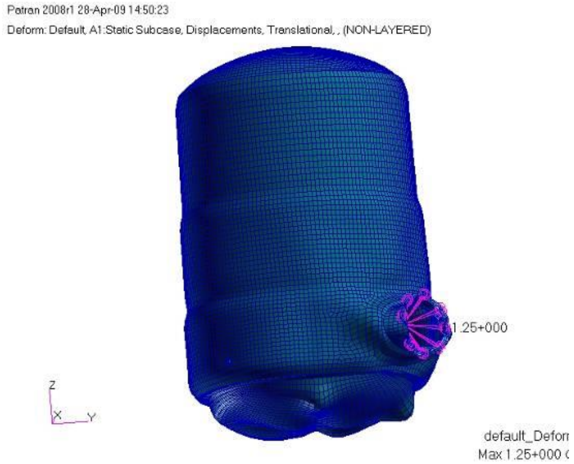

Fig. 3.5 Enhanced view of strain for MAT-Roving – 8 layers

By analyzing the MAT- Roving model strains, for 8 layers shown in fig. 5, we notice a maximum variation of 1.25, proving in fact that this material holds approximately 40 times more.

The strains of Roving type model of fig. 6, have the maximum variation of 0.747, with a much smaller deformation, nearly half of the MAT-Roving model with 8 layers.

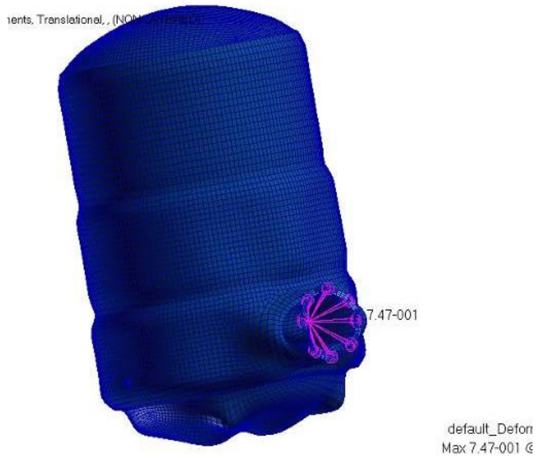

Fig. 3.6 Enhanced view of deformation for Roving-8 layers

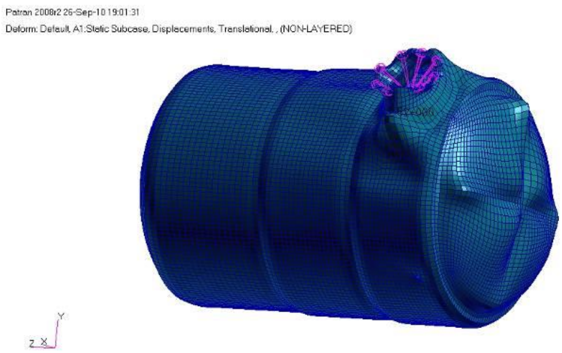

Fig. 7 Enhanced view of deformation for MAT-Roving - 5 layers

The strains of the model MAT-Roving with 5 layers, presented in Fig. 7 has the maximum variation of 2.52, meaning a double deformation by comparison to the first MAT-Roving material.

4. Experimental determinations on the optimized tank made of 5 layers using strain gauges

The method uses TER (electro-resistive transducer), stuck on the part subjected to analysis so that it might record very accurate its deformations, based on the principle that a deformation leads to a change in its electric resistivity. It was found that the specific variation of the transducer resistivity is between certain limits proportional to its specific deformation together with the part it is applied on.[2]

Stress is $\sigma = E \cdot \varepsilon$, where: ε-specific deformation $\varepsilon = \Delta l / l$; σ-Stress; E-elasticity modulus, the constant value for fiber being between $(0{,}06 \div 0{,}10)10^6$ MPa.

Reducing errors is the basic problem in the accurate measurements technique.

Precision is the global and most important quality of a measurement chain because it involves all other qualities like: sensitivity, correctness, fidelity etc.

Determinations performed in resistive electric tensometry are frequently affected by systematic errors. There are numerous situations when the diminishing of measuring errors to acceptable limits can be done only by calculus, which are extremely complicated sometimes. [2]

But experimentally it was found that electro-resistive transducers provide a signal which is approximately proportional to the average of specific strains on the analyzed surface. This phenomenon is called the effect or tendency of integration of the transducer. It is manifested by non-uniform fields of deformations and represents a major source of errors. In the vicinity of a tensile concentration point for example, specific deformation is strictly localized. The transducer provides a signal, the closer to its maximum value, the smaller its grid is. [2]

Static zero was determined by help of the HBM KOMPENSATOR MK Hottinger Baldwin Messtehnik operator.

After the zero static was determined for each measuring point, the tank was filled with liquid in three stages, each stage representing 1/3 of the recipient volume, then using the MK operator, the stress in the structure was determined for the three fillings.

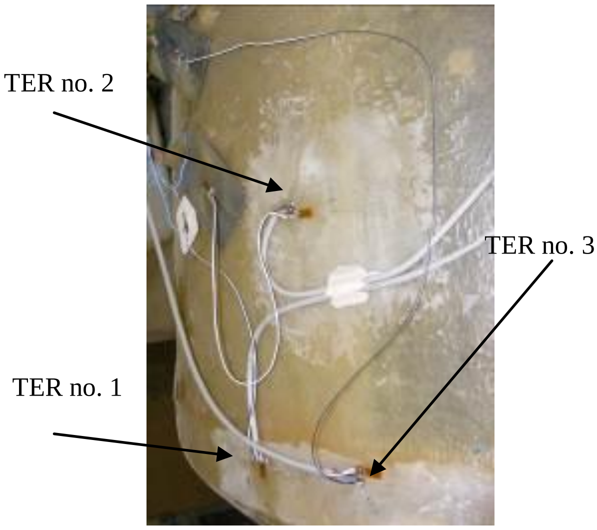

Fig. 8 Electro-resistive transducers applied on the storage tank

Table 4. Values of stress for the optimized tank during filling

Filling stages	σ for TER no.1	σ for TER no.2	σ for TER no.3
1/3 of the tank	-11800	-13900	-0,0247
2/3 of the tank	-16800	-23300	-24300
Full tank	-16300	-18000	-21400

Table 5 Stress values for the optimized tank during emptying

Emptying stages	σ for TER no.1	σ for TER no.2	σ for TER no.3
1/3 of the tank	-700	-9100	-6900
2/3 of the tank	-900	-12700	-4900
Empty tank	-2000	-9000	-2500

We find that the stress occurred in the tank structure are within the existing limits, presenting small values, meaning there is an over-dimensioning of the storage tank, which leads to the use of composites with less layers, smaller thickness in order to diminish the fiber and resin consumption for a reduced manufacturing cost.

In table 6 the results of stress distribution are presented, maximum of VM, X and Y, but also the minimum on X and Y.

Table 6. Stress distribution for tree materials

Criterion	Stress [MPa]	Compression [MPa]
σ_{VM}	29,4	-
σ_X	42,8	-25,7
σ_Y	29,4	-15

Finite element method became a general method for approaching various types of complex problems, regarding both stationary phenomena and non-stationary ones, in all branches of engineering sciences but also in other domains.

5. Conclusion

In the stress and strains plane we will be able to observe that the internal mechanical work is associated with three components of efforts in polar coordinates, the normal plane component of stress does not involve cancelling other efforts or stress.

By symmetry, the two components of displacements in any 2D section of the body along the symmetry axis completely define the strain status and obviously the stress status.

Due to MEF there are certain benefits in comparing and checking the strength of a material, we are able to determine stress and strain in the material and check if they are within normal limits, so that a lot of time is saved, the results come up fast, costs are lowered and every part of the material can be evaluated.

Using finite element method we are able to load several options, namely: change of load conditions, change of limit conditions, of their way of application upon the virtual model, out of which the optimal choice for the structure of the advanced material can be selected.

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