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MODELING OF HIGH PRESSURE COMPOSITE VESSELS

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Summary: *This study considers high pressure composite vessels made out of composite material reinforced with fibers, manufactured by winding. Mechanical properties of such composite are determined using homogenization method. Homogenization allows determining materials parameters on base of known properties of specific phases, such as matrix and reinforcement. Depending on the arrangement of fibers RVE (Representative Volume Element) is divided into subcells and homogenization can take place in several stages. Type and density of the division is based on complexity of the materials structure. Cell method allows to use nonlinear constitutive equations to describe each phase forming composite and various destruction models. It can be jointly used with other micromechanical models. In case of the composites reinforced with fibers useful are methods assuming periodicity of the structure. Composites possessing periodic structure can be described with use of the Eshelby method extended with implementation of cyclic boundary conditions. It means that displacement boundary conditions can be expressed in form of Fourier series.*

1 INTRODUCTION

The high pressure composite vessels are made out of composite material reinforced with carbon fibers. The vessels are manufactured by filament winding process, therefore mechanical properties of such composite depend strongly on the winding structure. Determining elastic parameters of these materials is an important issue. The most popular method is an experimental one, however it is expensive. Alternative method is homogenization of the materials parameters. Homogenization allows determining materials parameters base on known properties of composite phases, such as matrix and reinforcement. Depending on the filament winding pattern the RVE (Representative Volume Element) can be divided into subcells and homogenization can take place in several stages form micro to mezo scale, see Fig. 1. The numerical homogenization method allows to model complex geometry like filament winging pattern. It can be jointly used with other micromechanical models. In case of the composites reinforced with fibers useful are methods assuming periodicity of the structure. Composites possessing periodic structure can be described with use of the Eshelby method extended with implementation of cyclic boundary conditions. It means that displacement boundary conditions can be expressed in form of Fourier series.

In case of composites reinforced with fibers, as it is in case of composite pressure vessels, two stage homogenization can be applied. First stage of homogenization is used to determine mechanical properties of composite bundle with uniaxial aligned fibers. In the second stage, when effective material properties of the composite bundle are known, it is possible to extract next representative cell describing roving structure. Fibers have circular cross-section and are set in matrix in hexagonal way what is closest to the arrangement of fibers in real composites. Also material properties are known – spring constants of every phase.

Second stage of homogenization is used for determination of effective material properties of the composite reinforced with fibers. From the first stage of homogenization effective material properties of the composite bundle are known. Also material properties of the matrix are known. Because of the complex shape of the representative cell numerical homogenization seems most effective.

In here FEM is used what allows modeling of RVE with complex geometry. In case of numerical homogenization proper use of cyclic boundary condition is a key factor. Cyclic boundary conditions have to be used in such a way to force constant average deformation field in RVE:

Composite pressure vessels produced with winding method are complex technical objects. Complicated construction and complex aspects related to the production method make them very problematic. Composite pressure vessel is made of liner, boss and composite roving that works as a load carrying layer. Designing of the composite roving is the biggest challenge because it requires taking into consideration strength aspects (optimal fiber placement on the body and dome of the vessel) and also very important aspects related to the manufacturing technology such as slipping of fibers from the dome, proper impregnation of fibers, deciding on the thickness of the roving, etc. It should be considered that strength and technical aspects are closely related and optimal designing of the composite vessel is impossible without taking into consideration both of them. In addition it should be mentioned that each winded composite layer is heterogeneous with orthotropic mechanical properties and complex mechanism of drain of bearing capacities. Whole wrap strengthening of composite vessel is made out of several layers laid under different angels to the vessels axis what creates on the vessel various mosaic structures. Number of parameters determining strength of the composite vessel (thickness of the roving layers, number of layers, winding direction, number of interlaces, etc.) is a basic challenge during designing of the optimal structure.

Figure 1 presents scheme of the composite pressure vessel modeling including mechanics of composites in different size levels.

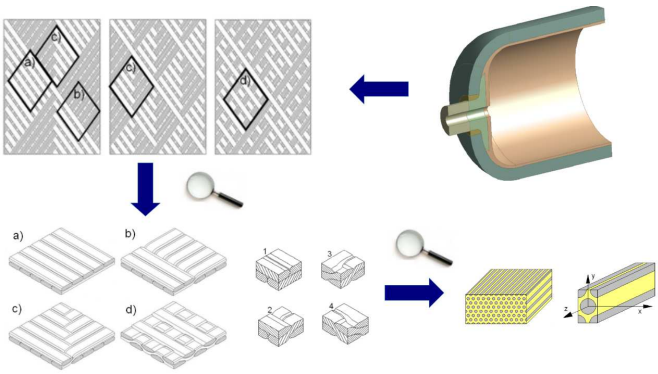

Fig. 1. Scheme of the idea of modeling composite vessel with taking into consideration different size levels.

2 ANALYTICAL HOMOGENISATION

In classical micromechanics it is assumed that material properties at the macro level are always homogeneous but unknown. Instead, at the micro level (inside RVE) are non-homogeneous but known. Thus, the task of micromechanics methods is determining material properties at the macro level (called „effective material properties”). The effective material properties combine averaged stress in RVE with the averaged strain, that is:

$$\bar{\sigma}_{ij} = \bar{C}_{ijkl}\bar{\varepsilon}_{kl} \tag{1}$$

$$\bar{\sigma}_{ij} = \frac{1}{V}\int_V \sigma_{ij} dV$$

$$\bar{\varepsilon}_{ij} = \frac{1}{V}\int_V \varepsilon_{ij} dV$$

where $\bar{C}_{ijkl}$ is the (elasticity matrix) elastic stiffness.

The purpose of the first stage of homogenisation is determining effective material properties of a composite reinforced with unidirectional fibres. In the presented example fibres are circular in cross-section and are distributed in matrix hexagonally (Fig.2), which correspond the best to distribution of fibres in real composites. The material properties are also known – the elasticity parameters for individual phases.

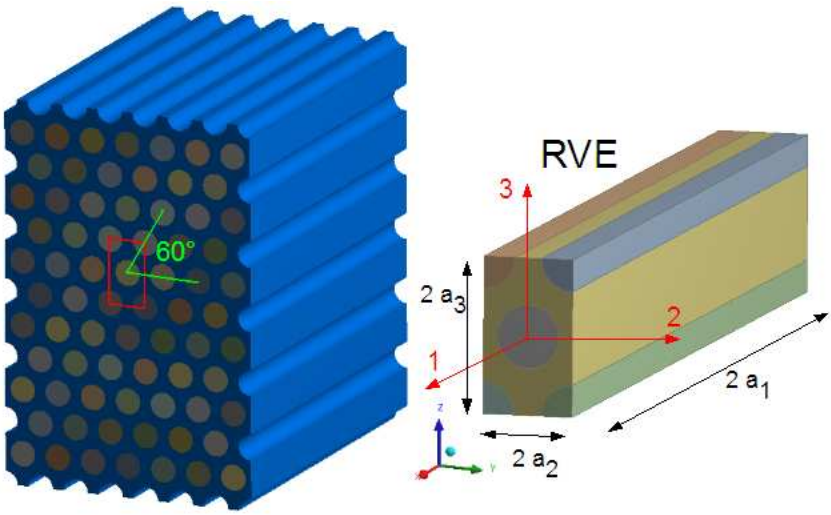

Fig. 2.Uniaxially oriented composite (unidirectionally) reinforced with fibres of circular cross-section and RVE.

The presented method of homogenisation is based on the solution of Eshelby, extended with taking into account the periodic boundary conditions. In accordance with this approach the effective elasticity tensor has the form of [1,2]:

$$\overline{\boldsymbol{C}} = \boldsymbol{C}^m - V_f \left[\left(\boldsymbol{C}^m - \boldsymbol{C}^f \right)^{-1} - \boldsymbol{P} \right]^{-1} \tag{2}$$

$\boldsymbol{P}$ – tensor describing geometry of inclusion
V_f – volume fraction of fibres in a composite
$\boldsymbol{C}^m$ – elasticity tensor of matrix (isotropic)
$\boldsymbol{C}^f$ – elasticity tensor of fibre (isotropic).
In case of hexagonal arrangement of fibres in the matrix it could be assumed that the effective elasticity tensor of the composite is transversely isotropic and can be written in a matrix form:
Hence, we could determine effective elastic parameters for the composite:

$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} & & & \\ C_{21} & C_{22} & C_{23} & & & \\ C_{31} & C_{32} & C_{33} & & & \\ & & & C_{44} & & \\ & & & & C_{55} & \\ & & & & & C_{66} \end{bmatrix} \tag{3}$$

$$\begin{aligned} E_1 &= C_{11} - \frac{2C_{12}^2}{C_{22} + C_{23}} \\ E_2 = E_3 &= \frac{(2C_{11}C_{22} - 2C_{11}C_{23} - 4C_{12}^2)(C_{22} - C_{23} + 2C_{44})}{3C_{11}C_{22} + C_{11}C_{23} + 3C_{11}C_{44} - 4C_{12}^2} \\ G_{12} &= G_{13} = C_{66} \\ \nu_{12} = \nu_{13} &= \frac{C_{12}}{C_{22} + C_{23}} \\ \nu_{23} &= \frac{C_{11}C_{22} + 3C_{11}C_{23} - 2C_{11}C_{44} - 4C_{12}^2}{3C_{11}C_{22} + C_{11}C_{23} - 2C_{11}C_{44} - 4C_{12}^2} \end{aligned} \tag{4}$$

3 NUMERICAL HOMOGENIZATION

Similarly as the analytical one, numerical homogenisation has the aim of determining effective elastic parameters for non-homogeneous material, based at the knowledge of properties of the elasticity matrix [3] (see: formula 3). Thus, in order to determine the values for the first column we solve the boundary conditions which forces the ε_{11} strain equal to 1. The remaining strain tensor components are equal zero.

$$\begin{aligned} &\overline{\varepsilon}_1 = 1,\ \overline{\varepsilon}_2 = \overline{\varepsilon}_3 = \overline{\varepsilon}_4 = \overline{\varepsilon}_5 = \overline{\varepsilon}_6 = 0 \\ &\overline{\varepsilon}_2 = 1,\ \overline{\varepsilon}_1 = \overline{\varepsilon}_3 = \overline{\varepsilon}_4 = \overline{\varepsilon}_5 = \overline{\varepsilon}_6 = 0 \end{aligned} \tag{5}$$

In doing so, we can determine components of the elasticity matrix in the first column. The components are being determined by calculating the average stress in the RVE at the given unit strain.

$$C_{11} = \frac{1}{V}\int_V \sigma_{11} dV \qquad (6)$$

$$C_{12} = \frac{1}{V}\int_V \sigma_{12} dV$$

$$C_{13} = \frac{1}{V}\int_V \sigma_{13} dV$$

By applying further the same procedure, all components of the elasticity tensor could be determined, column by column. Similarly as in the analytic homogenisation the matrix of composite elasticity treated as the homogenous medium is achieved:

$$\begin{bmatrix} \bar{\sigma}_1 \\ \bar{\sigma}_2 \\ \bar{\sigma}_3 \\ \bar{\sigma}_4 \\ \bar{\sigma}_5 \\ \bar{\sigma}_6 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & & & \\ C_{21} & C_{22} & C_{23} & & & \\ C_{31} & C_{32} & C_{33} & & & \\ & & & C_{44} & & \\ & & & & C_{55} & \\ & & & & & C_{66} \end{bmatrix} \begin{bmatrix} \bar{\varepsilon}_1 \\ \bar{\varepsilon}_2 \\ \bar{\varepsilon}_3 \\ \bar{\varepsilon}_4 \\ \bar{\varepsilon}_5 \\ \bar{\varepsilon}_6 \end{bmatrix} \qquad (7)$$

At that base we determine the elastic parameter already known to us

(8)

$$E_1 = C_{11} - \frac{2C_{12}^2}{C_{22} + C_{23}}$$

$$E_2 = E_3 = \frac{(C_{11}(C_{22} + C_{23}) - 2C_{12}^2)(C_{22} - C_{23})}{C_{11}C_{22} - C_{12}^2}$$

$$G_{12} = G_{13} = C_{66}$$

$$v_{12} = v_{13} = \frac{C_{12}}{C_{22} + C_{23}}$$

$$v_{23} = \frac{C_{11}C_{23} - C_{12}^2}{C_{11}C_{22} - 2C_{12}^2}$$

The presented procedure is used to calculate effective properties of composite yarn. Figures 3 and 4 show introduction of periodic boundary conditions on the RVE. The first of them shows the displacement for the six cases of deformation, starting from stretch in the direction of the Z axis (macro strain ε1 = 1) to the state of shear in ZX plane, which corresponds to a macro deformation ε6 = 1. The central point of RVE corresponds to the

point representative the cell in the macro continuum, therefore need to be fix during calculations. In Figure 4, point b) showing the stress map for imposed displacement in X direction with a value equal length of RVE in the X direction. The remaining degrees of freedom on the other walls must be fixed so that the average values of the remaining components of the strain tensor are equal to zero over the RVE. The next step is to determine the average stress in the RVE for each component of the stress tensor. In most FE codes this procedure is done automatically by integrating stress tensor over the volume of RVE. Proceeding further according this method, the six independent states of deformation can be imposed on RVE and for each of them the average stress and strain (in the RVE), can be calculated and thus all components of the tensor of elasticity are determined.

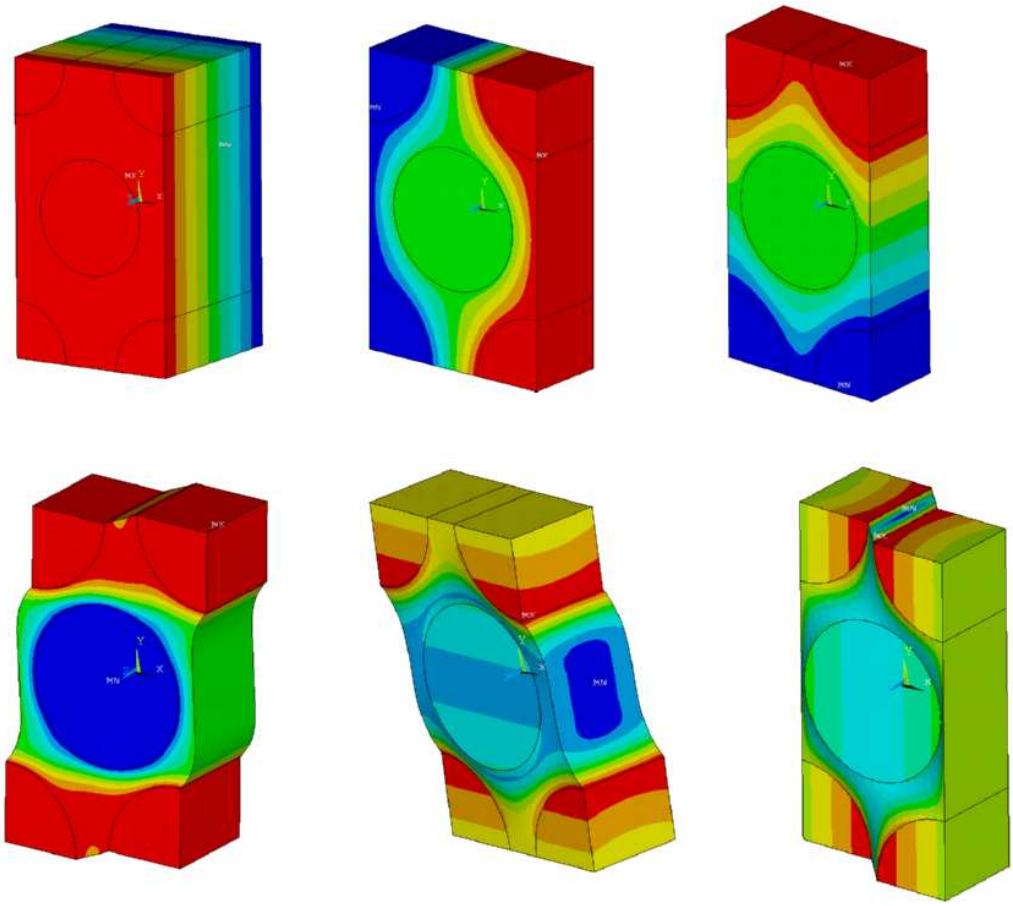

Fig. 3. Displacement imposed on RVE for six independent boundary value problems

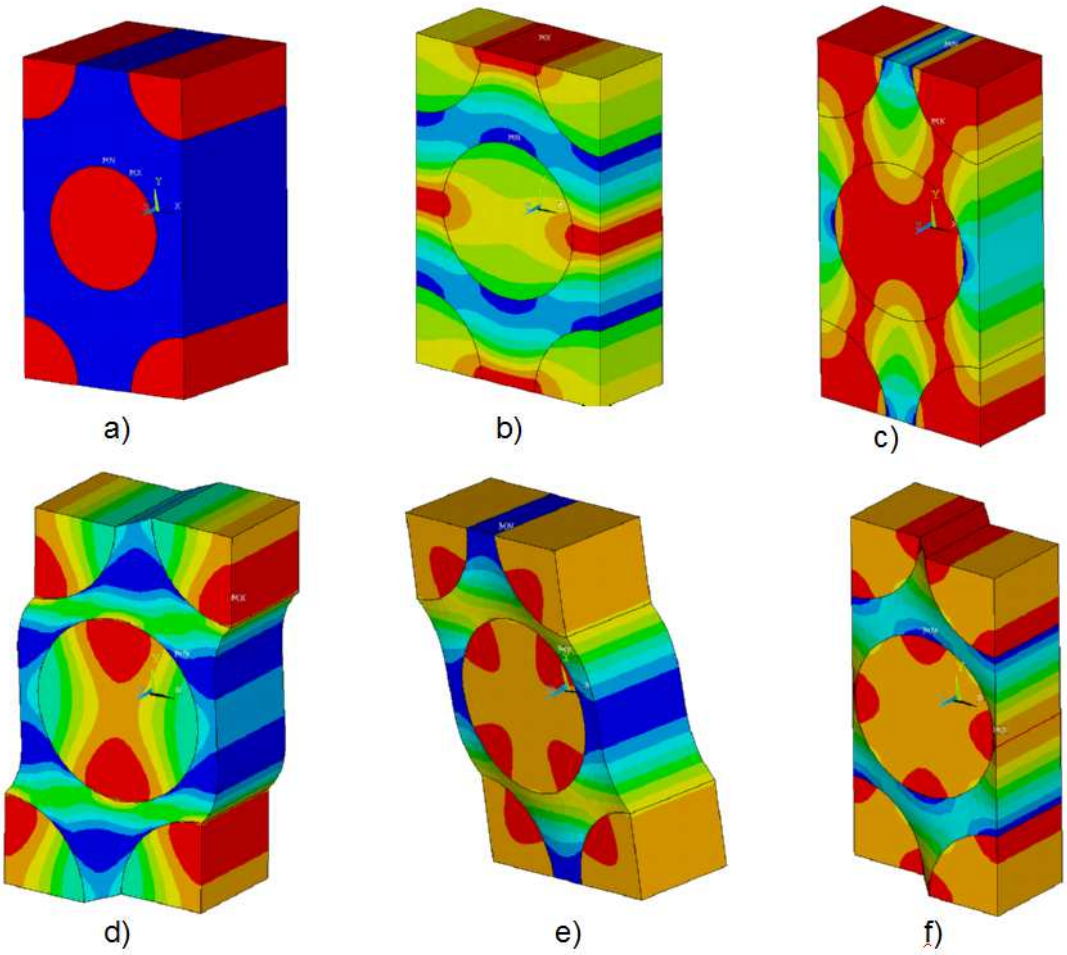

Fig. 4. Stress distribution in RVE for six independent boundary value problems.

4 FE MODEL OF COMPOSITE PRESSURE VESSEL

In this chapter the methodology of FE modeling of high pressure composite vessel is presented. Considered pressure vessel is consisting of aluminum boss, polyamide liner and carbon fiber reinforcement. The composite reinforcement is realized by filament winding process. The three main winding layers can be distinguished: hoop winding (layer), helical winding (layer) and intermediate layer with angle between hoop and helical layer. The composite pressure vessels have a specific design of the dome region because of the varying wind angles generated using the filament winding process. In presented design in order to ensure isotensoid behavior of the dome structure (constant stress profile) the 'Optimal Design' method [4] was used to determine the optimal dome profile.

Based on homogenization procedure the effective material properties of composite yarns have been computed. The transversely orthotropic material properties of yarns are presented in Table 1. The aluminum boss properties are presented in Table 2.

E1	GPa	130
E2	GPa	8.2
E3	GPa	8.2
ν12	-	0.36
ν12	-	0.36
ν23	-	0.38
G12	GPa	4.7
G13	GPa	4.7
G23	GPa	3.0

Table 1: Material properties of composite yarns.

E	GPa	73
ν	-	0.3

Table 2: Material properties of aluminum boss.

The dimensions of modeled composite pressure vessels (especially ratio of wall thickness to outer diameter) enforce usage of solid elements. The solids elements are necessary to adequately model stress distribution through the wall thickness. The presented FE-model is developed with the help of commercial software Ansys. Therefore, in order to model composite reinforcement the element ‘solid186’ is used. The element ‘solid186’ enables to model layer structure (layer option) thus hoop winding and helical winding can be easily modeled. In presented FE-model four layers of solid elements are used. Therefore total number of 57 real filament winding layers is distributed over those four solid elements layers (Fig.6). Additionally, the hoop winding layers are not presented in dome area, therefore the three part of composite reinforcement are distinguished in FE-model: cylinder part, dome part and transition part. The transition part models the dropped layers of hoop winding. The FE-model of composite vessel is presented on Fig. 5.

The composite pressure vessel was loaded with internal pressure of 175 MPa, which corresponds to average burst pressure of sample vessel. The stress distribution in each layer of cylindrical part is presented in Fig. 7.

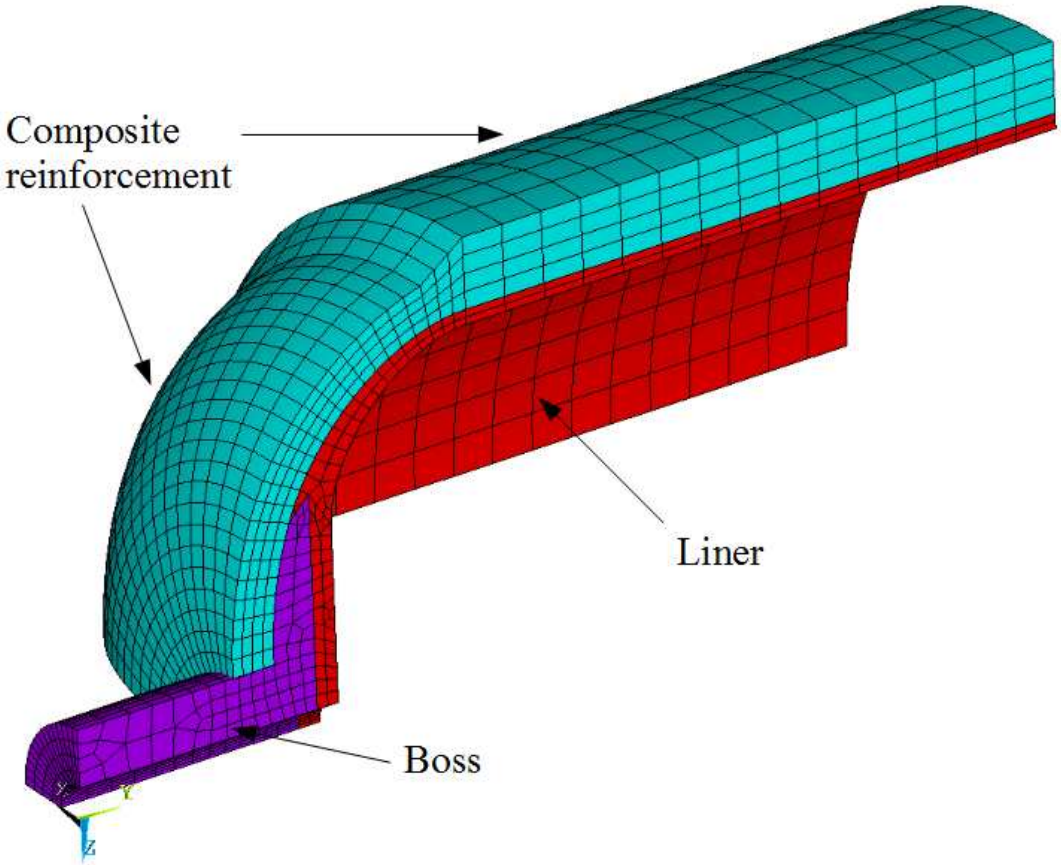

Fig. 5. FE-model of high pressure composite vessel.

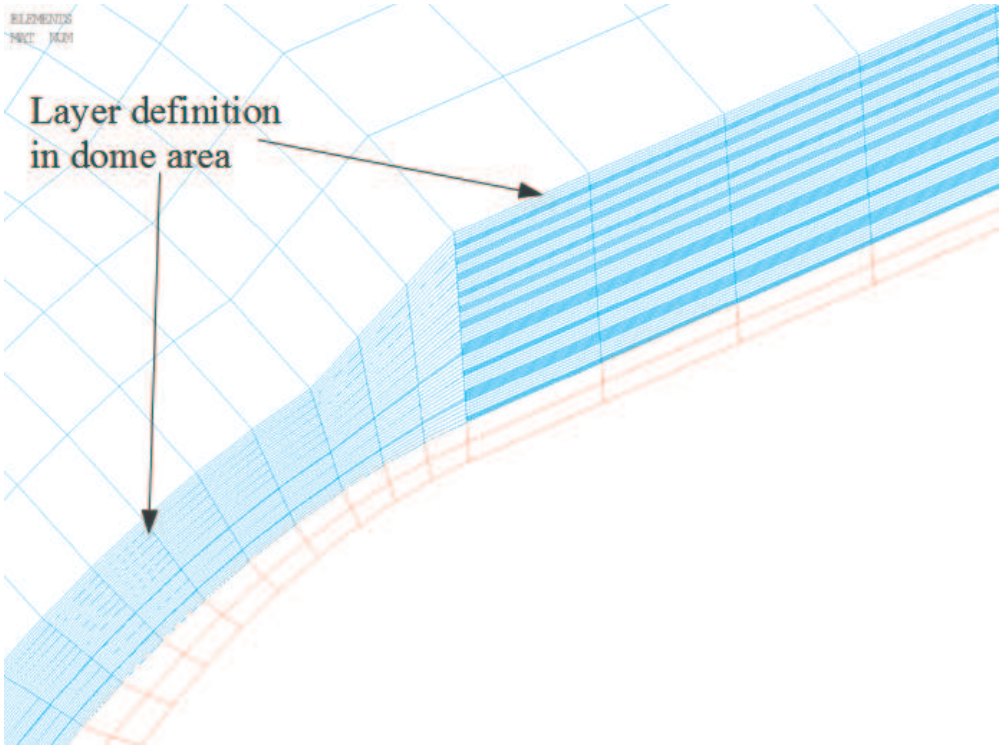

Fig. 6. FE-model with layers distribution in dome and transition area

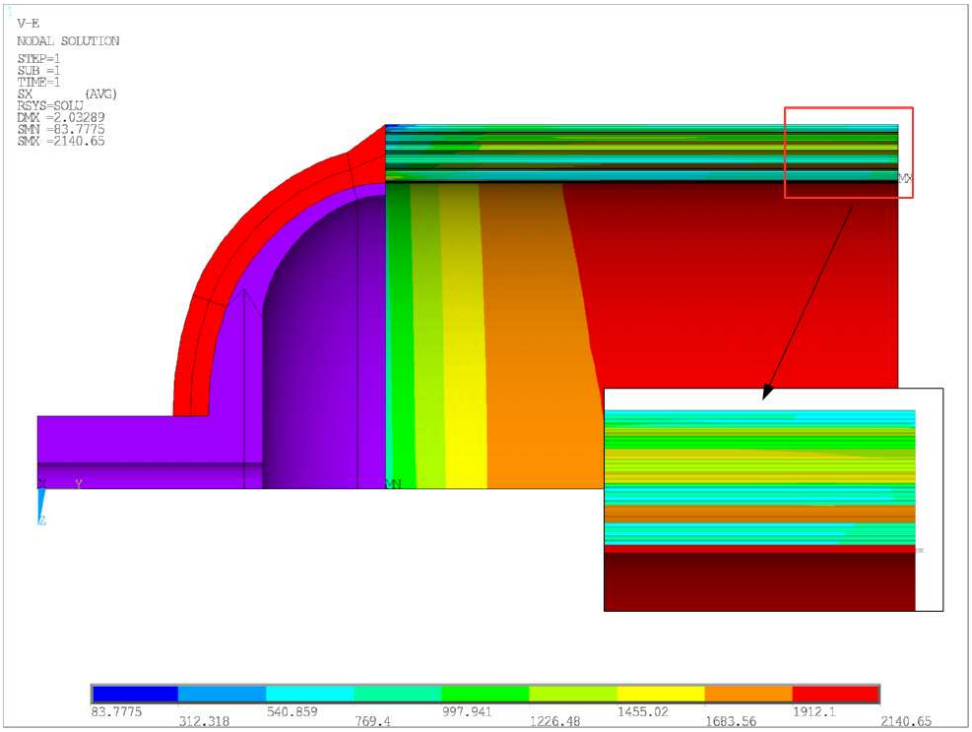

Fig. 7. Hoop stress in particular layers of the pressure vessel

5 SIMULATION RESULTS AND EXPERIMENT

Based on the developed numerical model of the pressure vessel displacement, strain and stress fields were obtained in the simulation of internal pressure loading. The results were compared with results of a burst pressure test. The axial displacements results obtained are in line with the measured values (3% difference at 100 MPa at 25 deg C) and the hoop stress in the cylindrical part corresponds to the evaluated rupture stress (2% difference for the burst pressure at 25 deg. C). The calculated values axial displacement and rupture stress are presented in Fig. 8 and Fig. 9 respectively for various internal pressure values.

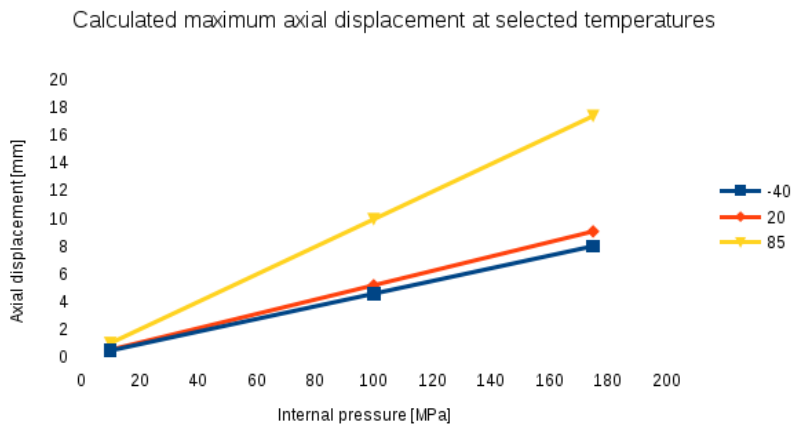

Fig. 8. Axial displacement obtained in simulation for various internal pressure loads and thermal conditions

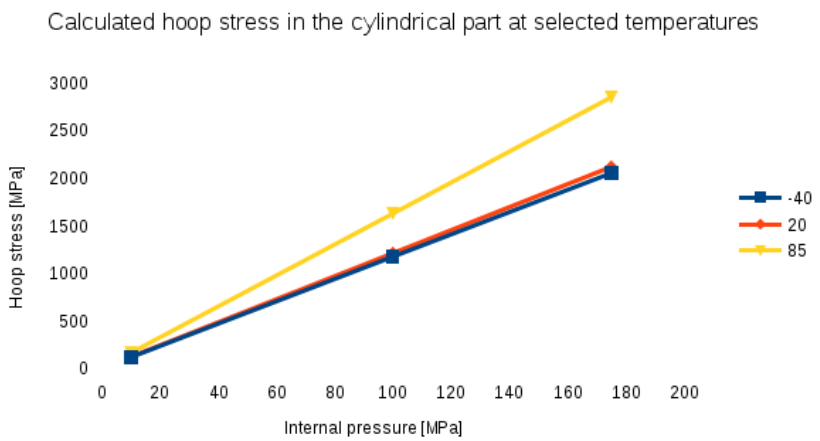

Fig. 9. Hoop stress in the cylindrical part obtained in simulation for various internal pressure loads and thermal conditions

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