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RESEARCH ARTICLE

Temperature dependent examination of brake cylinder membrane (Part I) FE Modelling of the tension examination of cord-reinforced specimens

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Abstract

The present paper shows the standard uniaxial tensile testing, material law identification and finite element simulation of a rubber-cord composite membrane structure used in railway brake systems. The membrane transforms air pressure growth to unidirectional movement within a wide temperature range. A complete procedure will be detailed for the mechanical characterization of the highly complicated sandwich compound built on simple tensile tests. The authors analyze mechanical procedures during deformation using MSC. Marc commercial finite element software. The paper points out the importance of temperature and orientation on an orthotropic structure and highlights the necessity of a reliable material law especially for rubber-cord composites.

Keywords

Brake cylinder membrane · rubber composite · tensile test · finite element method

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1 Introduction

One of the critical components of membrane brake cylinders in railway and public road vehicles is rubber-cord composite brake membrane. The brake membrane is operated by pressurized air of several bars, conducted behind the membrane, as a result of which the membrane is displaced some tens of mm in the axial direction while the maximum braking force can be increased up to several tens of kN through a gear transmission. After braking, the membrane is returned to its original position by a conical screw spring. The mechanism described is based on the fact that the rubber is sufficiently soft to undergo substantial deformation due to the impact of pressurized air of several bars. However, as a consequence of highly temperature dependent behaviour characteristics of rubber materials, at low temperatures the mechanical behaviour of a rubber membrane may change to such extent that it can critically reduce the braking force (connected to membrane displacement) achievable at identical pressures.

This study presents the experimental background of a material law suitable for modelling the material behaviour of a rubber-cord composite developed in the course of research and development, the results of these experiments, the phases of evaluation and the FE implementation and verification of the material law produced, both at room temperature and at low temperature (-60^{o}C).

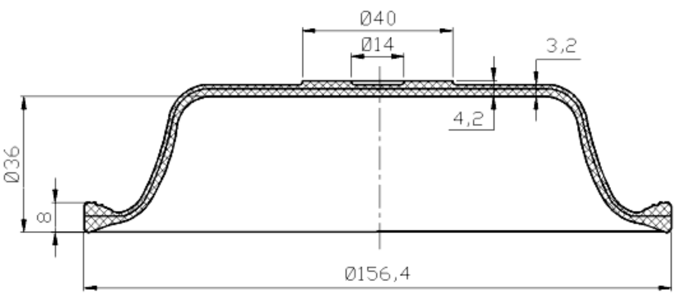

Fig. 1. Brake membrane with main dimensions

2 Tensile tests

Uniaxial tensile tests required for setting up the material law were performed on standard specimens on a Zwick 005 tensile

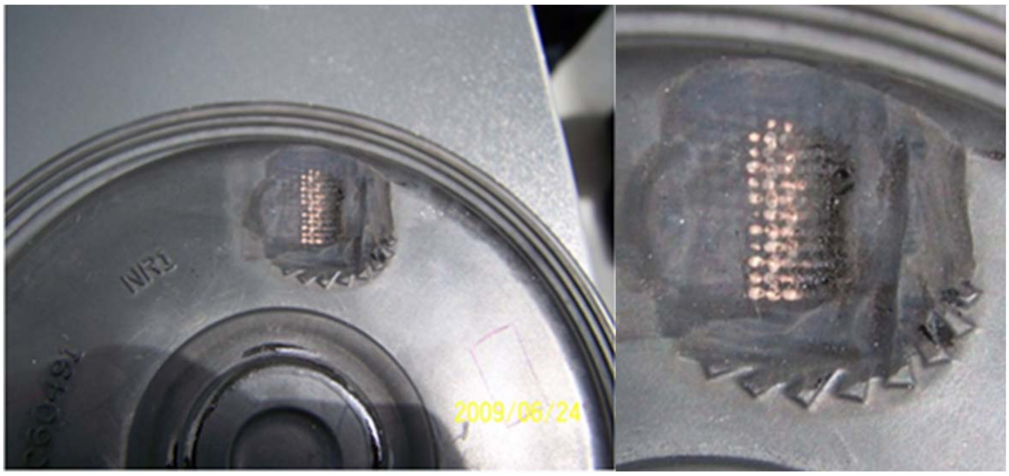

Fig. 2. Reinforcing fabric orientation exposed.

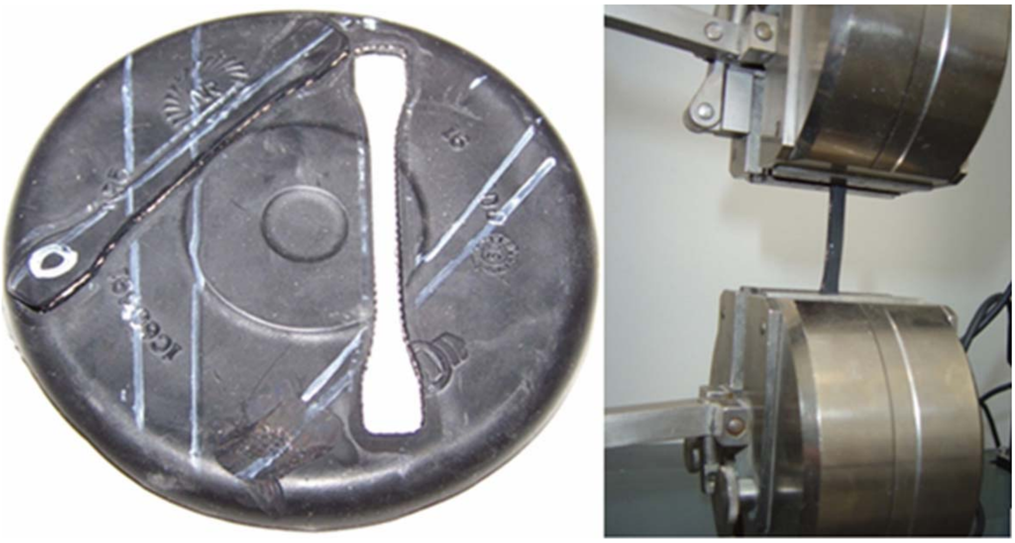

Fig. 3. Specimens cut in the grainline and at 45°; fixed specimen.

testing machine at the Laboratory of BME Department of Polymer Engineering. Fig. 1 shows the cross-section and main dimensions of the cord-reinforced rubber membrane.

In order to perform impact studies of the cord reinforcement in the rubber structure, specimens were cut in the grainline and at a 45° angle therefrom. The rubber layer of the membrane was scraped off (Fig. 2) in order to cut specimens of the desired orientation and the direction required for cutting was set. Fig. 3a shows the grainline of the reinforcing fabric and the 45° angle therefrom. Fig. 3b shows the specimen fixed in the measuring equipment.

Specimens cut in the grainline and at a 45° angle were 3.57 mm and 3.54 mm thick and 4.99 mm and 5.02 mm wide, respectively. The standard deviation of thickness along the length of specimens did not exceed 5 %. In the course of measurements, the base length L_0 was 56 mm. Three tensile tests were performed at a test speed of 100 mm/min at each case. Specimens were fixed manually in between the jaws of the testing machine, so the force / pressure rate at fixing was not specified in the course of tensile tests. Specimens were loaded by 50 N.

Fig. 4 shows the average measurement results of grainline and

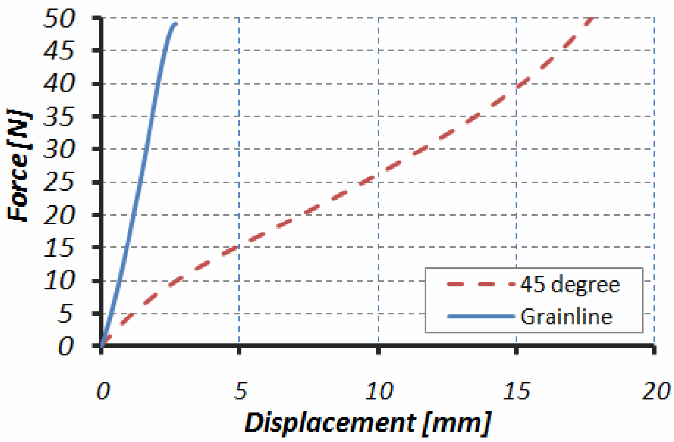

Fig. 4. Average of measured force vs. displacement curves in case of grainline and 45° specimens

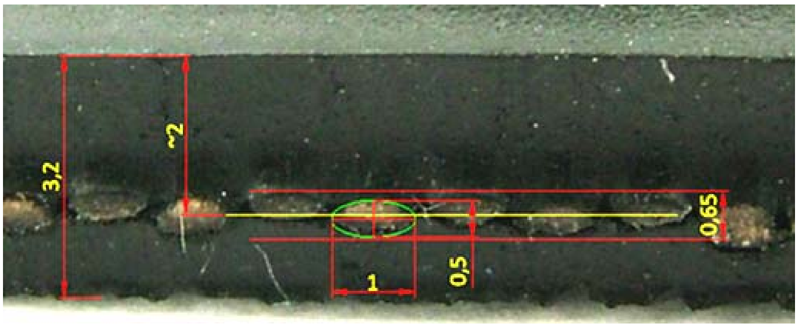

Fig. 5. Enlarged photograph and some dimensions of the cross-section of a cord-reinforced layer

45° specimens. Specimens cut at 45° display much softer behaviour than specimens cut in the grainline. The direct tension of the cord reinforcement dominate in the grainline case, while in case of specimens cut out in the 45° direction shear stress is characteristic of the textile inlet. The isotropic rubber layer behaves in the same way in each cases, independently of the position of the fabric. As the cord-reinforced layer is primarily subject to shear in case of the 45° specimen, the nature of the rubber will dominate in its characteristics. This measured force and displacement can be observed on a force vs. displacement curve as well, showing non-linear characteristics with an inflection accustomed for rubber materials.

3 Test analysis

The result of a tensile test is a force vs. displacement curve of the composite structure. This curve must be broken down into the rubber and reinforcement layers of the composite structure in order to obtain parameters able to describe the respective material behaviour. The approximative geometric features of the layers were determined in the enlarged photograph of the cross-section (Fig 5).

The membrane is 3.2 mm thick. By proper approximation, the cross-section of the reinforcing cords can be considered as an ellipse, the major axis of which is 1 mm and its minor axis is 0.5 mm. Furthermore, the enlarged photo shows that in contrast with the drawing of the membrane (Fig. 1), the reinforcement layer is approx. 0.4 mm displaced from the median plane of the membrane. Fig. 6 shows the model substituting the cross-section of the composite tensile specimen, including the main dimensions.

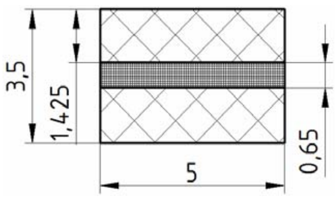

Fig. 6. Substituting model of tensile specimen cross-section

In the case of a 45° specimen, the cord reinforcement layer is subjected to shear stress, therefore the strain vs. specific deformation curve is primarily determined by the mechanical behaviour of the rubber. On the other hand, in the case of a specimen in the grainline, it can be assumed by proper approximation that the stress is taken up by the reinforcement inlet, so here the stress vs. strain curve was calculated using the cross-section of the cord-reinforced layer. Fig. 7 shows the correlations of engineering stress and strain as determined. The figure also specifies the approximate gradient of each curve. In the case of 45^o measurements, tensile stress of the rubber is coupled with the shearing stress of the cord fabric, therefore the adjusted 9.43 MPa modulus figure results from the conjunction of the rubber and the cord fabric. Hereinafter the elasticity modulus of the rubber will be taken into consideration at an estimated and reduced value of 5 MPa.

The values of parameters describing the mechanical behaviour of the cord-reinforced inlet can be calculated in the knowledge of the elasticity modulus of the rubber, based on grainline measurements. Formulas of mixing are applied for determination. According to our calculations, the value of specific stretching pertaining to load of F = 50N to be specified from laboratory measurements is $\varepsilon = 0.0465$. Thereby the elastic modulus of the reinforcing fabric inlet will be 309 MPa.

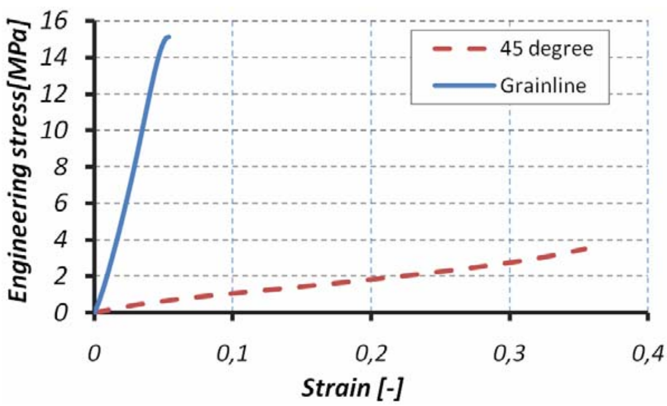

Fig. 7. Calculated strain vs. deformation curves and their steepness in grainline and 45° arrangement

The cord-reinforced part is taken into consideration as an orthotropic layer in FE calculations, therefore the elastic modulus calculated can be considered to be the elasticity modulus of the two main directions in the plane of the orthotropic layer. The value of the elastic modulus in the third main direction perpendicular to such plane cannot be determined from the measurements, but it can be assumed that its impact is negligible. Hereinafter the elastic modulus of the third main direction will be considered as 35 MPa (an estimate). Furthermore, measurements do not allow for the determination of the Poission ratios and the shearing stress modulus of the orthotropic layer, therefore these latter were determined by parameter tests using FE calculations. Values are shown in Table 1.

Tab. 1. Material properties of cord-reinforced rubber membrane layers

Constant parameter of rubber (c_{10})	***0.8 MPa***
Poisson-ratio of rubber	***~0.5***
Elastic modulus of cord-reinforced part in the 1. and 2. main planes	***309 MPa***
Assumed parameters	
Elastic modulus of cord-reinforced part in the 3. main plane	***35 MPa***
Poisson-ratio of cord-reinforced part	***0.3***
Shear modulus of cord-reinforced part	***2 MPa***

In addition to the measurements presented in this study, the material model specified is also used in FE calculations affected by different tensile and compressive behaviours characteristic of rubber materials. Instead of the characteristic elasticity modulus determined, the simplest hyperelastic (Neo-Hooke's) material law is used. In the Neo-Hooke's material law applied, the value of the constant material parameter to define deformation energy density is $c_{10} = 0.8$ MPa.

4 FE modelling of tensile tests

A 3D FE model was designed to verify the correctness of the material model detailed in the previous chapter. The geometric dimensions of the model correspond to the actual geometric dimensions of specimens used for measurements. The total length of the dogbone-shaped specimen is 80 mm, out of which 56 mm is the base length located between the jaws. Fixing of the specimen is in line with measurement conditions; the jaws are modelled by rigid plane sheets. Fig. 8 shows the FE model of the specimen and surroundings.

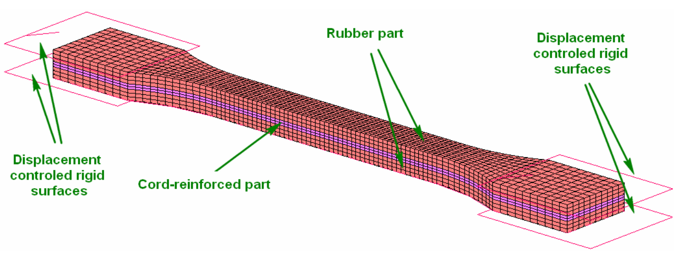

Fig. 8. FE model of tensile test

The model consists of 12000 brick elements of 8 nodes. In order to ensure the incompressibility, so-called Hermann-formula elements were used. The orientation of the main material directions of the orthotropic layer can be specified as compared to the main directions of the global coordinate system, thus both grainline and 45^o measurements can be calculated easily without changing any other model parameters, by only defining the angle of rotation. Fig. 9 illustrates the first main material direction defined for the grainline and the 45^o cases.

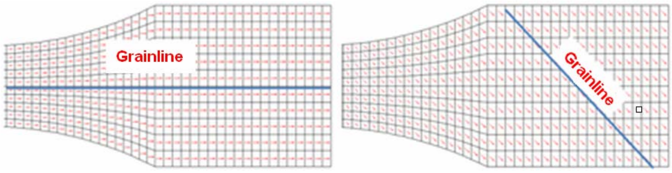

Fig. 9. Orientation of the FE model of the orthotropic layer

The calculation consists of two clearly separable parts. First, the specimen is fixed in between the force driven plane sheets representing the jaws. One of the plane sheets located on the two sides of the model approaches towards the other one driven by a pressing force of 100 N, straddling the elastic specimen. A 10 step incremental calculation was applied for obtaining a convergent solution. A friction coefficient of $\mu = 0.8$ was defined between the plane sheet and the meshed model to substitute for the ribbed jaws in the model.

The installation phase is followed by straining the specimen. This is performed by displacing the compressed plane sheets located on one side along the longitudinal direction of the specimen. Similarly to the measurements, force driving was applied. The 50 N load was applied to the model in 10 steps.

The longitudinal displacement and equivalent stress of specimens are shown in Figs. 10-13 in a way that the upper part shows the entire area while the bottom part shows only the longitudinal displacement and the stress area generated in the reinforcing cord inlet.

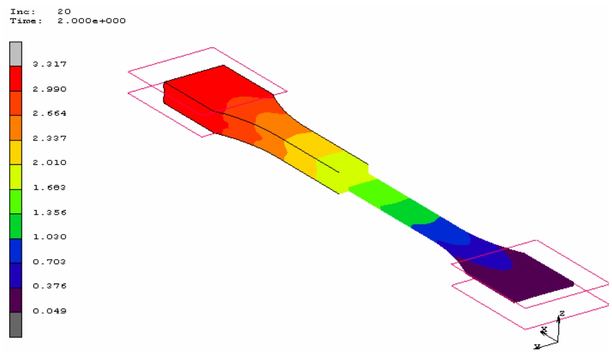

Fig. 10. Longitudinal displacement in the grainline specimen (max. 3.32 mm)

Comparing the calculations of the two specimen types, it can be established that displacements by a 50 N tensile force significantly differ from each other in function of the orthotropic orientation of the reinforcement inlet layer.

Longitudinal displacement in the grainline is 3.3 mm, and 18.7 mm in case of a 45° specimen. On the other hand, measured values were 2.7 mm and 17.6 mm, respectively. Higher values by calculation result from the fact that they represent

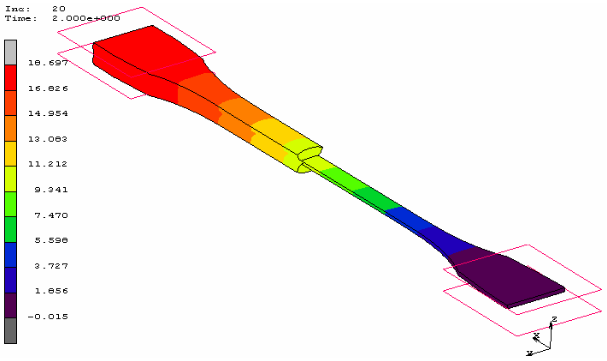

Fig. 11. Longitudinal displacement in the 45^o specimen (max. 18.7 mm)

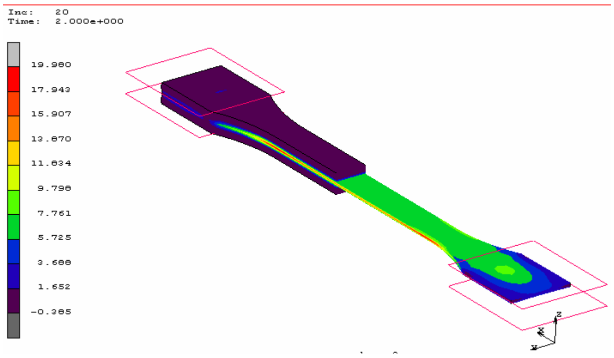

Fig. 12. Equivalent stress in the grainline specimen (max. 19.96 MPa)

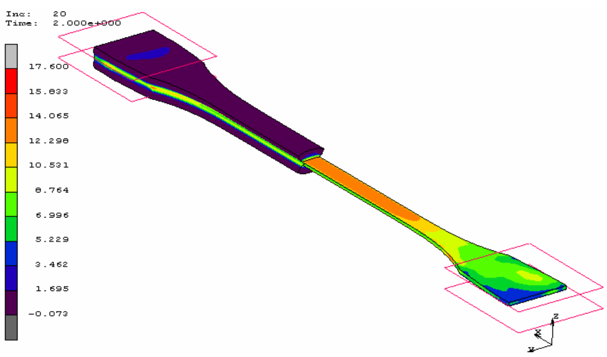

Fig. 13. Equivalent stress in the 45^o specimen (max. 17.6 MPa)

maximum displacements including e.g. the protrusion of the rubber as well.

Fig. 14 shows the cross-section of grainline and 45° specimens loaded by 50 N. It can be observed that the reinforcement layer hardly contracts in the grainline, while there is a considerable contraction in case of the 45° specimen which drags along the rubber layers as well. It is also a characteristic feature that there is a different stress distribution along the cross-section of the two specimens.

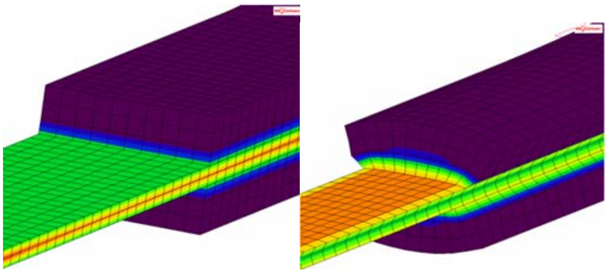

Fig. 14. Shape of the cross-sections in case of grainline and 45° specimens

Fig. 15 illustrates components of the stresses and strains in the longitudinal direction of the specimen along the nodes in the middle of the specimen sheet.

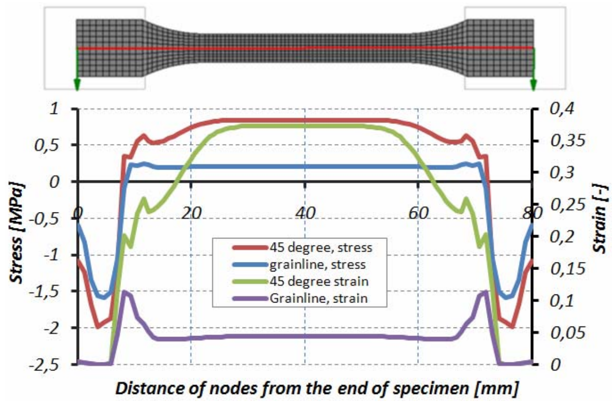

Fig. 15. Changes in longitudinal stress and strain components in the middle of the surface of grainline and 45° specimens

Based on calculations, hardly any longitudinal strain arises under the fixing surfaces. This is followed by a peak (where the plane sheet is pressed into the rubber material), and then an increase is followed by a phase of constant value. The curves displayed are symmetrical. The value of median constant strain is 0.044 in the grainline and 0.37 in case of a 45^o specimen.

5 Low temperature tests

Low temperature tensile tests were performed at Miskolctapolca, in the Institute for Logistics and Manufacturing Engineering of the Zoltán Bay Public Foundation for Applied Research. Similarly to the measurements at room temperature, two specimens – one in the grainline and an other one at 45° – were cut from two different membranes. The fixed specimens were cooled down to -60 ^{o}C in the climate chamber; temperature was measured by a thermocouple mounted on the jaw. In order for the rubber specimen to cool all throughout its volume, we waited half an hour after the thermocouple began to indicate -60 ˚C. Fig. 16 depicts a photo of the climate chamber covered with hoarfrost.

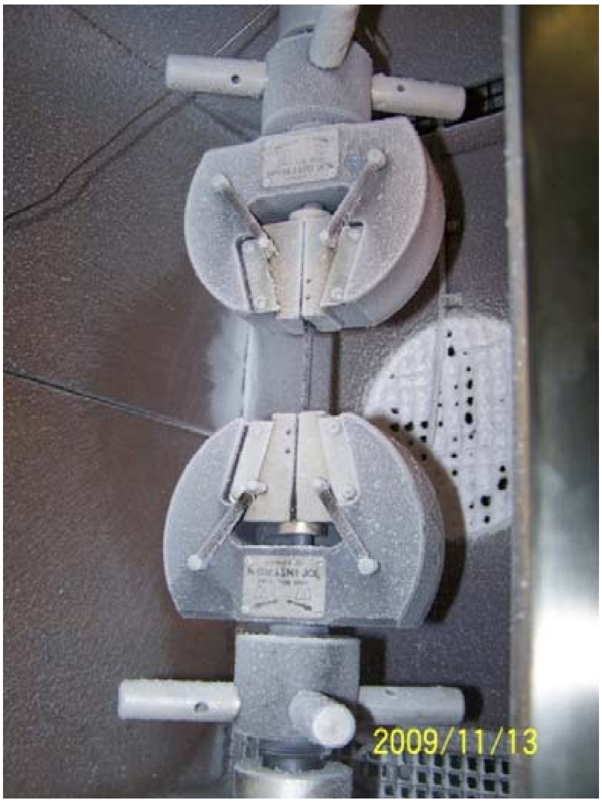

Fig. 16. Photograph of low-temperature tensile test after measurement

The specimens were loaded by a force of 50 N and displacement was measured in the meantime. The test speed was v = 100 mm/min. The forces vs. displacement curves obtained from the measurement were evaluated as described in chapter 3. In case of a F_0 = 50 N loading force, the average of correlating force and displacement figures is $f_0$1= 0.55 mm in case of specimens in the grainline, and f_{45} = 0.89 mm for 45˚ specimens. Based on such evaluation, it was established that being cooled down to -60 C, the 5 MPa elastic modulus of the rubber at room temperature increased to 180 MPa, while the substituting modulus value of the cord inlet changed from 309 MPa to 778 MPa.

6 Summary

This study presented an experimental and a numerical investigation performed in the framework of a research and development assignment to explore the behaviour of membranes applied in the brake cylinders of railway vehicles. The issue to be solved in this project was how a brake cylinder – operating seamlessly at room temperature – behaves at -60 ˚C. As a first phase of the work, the numerical manageability of mechanical behaviours characteristic of the complex composite structures presented in this study was investigated.

Tensile tests were performed on specimens cut in the appropriate directions and made ready for the tests. Afterwards, an evaluation method was developed which can be used for the approximate determination of the essential material properties of a numerical model substituting for the sandwich structure, based on the stress vs. strain curves of tensile tests. Evaluations were performed both at room temperature and at -60 ˚C. After measurement evaluations it was established that while the modulus of the cord inlet was doubled as a result of temperature change, the modulus of the rubber increased nearly 36 order of magnitude.

Finite element model was developed which is suitable for modelling specimens of discretionary orientation simply by changing the main material direction of the orthotropic element series integrated in the model. Based on a comprehensive modelling of the tensile tests performed, it was established that the material properties specified are suitable for modelling the composite structure accurately. Furthermore, simulations pointed out the different stress and strain states of specimens cut out in the grainline and at 45^o thereto, respectively, as well as the substantially different deformation states the collectivity of which induces direction-dependent behaviour as accustomed for composite structures.

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