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RESEARCH ARTICLE

Temperature dependent examination of brake cylinder membrane (Part II) FE Modelling of cord-reinforced rubber membrane behaviour

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Abstract

The present paper shows two special compression tests and finite element simulations created for the examination of a rubber-cord composite membrane structure used in railway brake systems. The membrane transforms the air pressure growth to unidirectional movement within a wide temperature range. After the material characterization detailed in [1]*, the authors studied the whole composite membrane structure using specimen level compression tests. Having repeated the measurements at different temperatures it can be concluded that the whole membrane produces the same hardening by decreasing temperature as the reinforcement layer in the membrane. The measurements were also analysed using commercial FE software.*

Keywords

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

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1 Introduction

Important components of membrane brake cylinders in railway and public road vehicles include brake cylinder membranes made of cord-reinforced rubber.

The brake membrane performing braking is operated by pressurized air of several bars, conducted behind the membrane, as a result of which the membrane is displaced even in excess of some tens of mm. As the brake shoes are pressed against the brake disk during their motion, the braking force can be increased up to several tens of kN through a gear transmission. The membrane is returned to its original position by a conical screw spring. The mechanism described can only be realized if the membrane behaviour is sufficiently soft, meaning that it can be considerably deformed by pressurized air of several bars. As a consequence of highly temperature-dependent behaviour characteristic 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 specimen-level tests in the framework of a research and development assignment, the results of such experiments, the phases of evaluation, and the FE implementation and verification of the complex material model produced in [1], both at room temperature and at low temperature (-20 ^{o}C). As the temperature-dependent behaviour of the brake cylinder primarily depends on the temperature-dependent properties of the rubber membrane with a reinforcing inlet, it is necessary to examine the brake cylinder membrane independently of its installation environment. In the course of tests, the membrane was pressed by surfaces of small and large diameter, respectively, laid on the plane sheet, in a way that in the first case the rim of the membrane could be displaced freely in the radial direction; in the second case – taking installation conditions more into consideration – the free radial displacement of the membrane rim was prevented.

2 Radially non-hindered compression tests

Measurements to study the specimen-level behaviour of the membrane were performed on standard specimens on a Zwick 005 tensile testing machine at the Laboratory of BME Department of Polymer Engineering. Fig. 1 shows the measurement arrangement. The membrane to be examined was laid on a plane steel sheet and displacement load was exerted from above, through a shaft of 35 mm diameter, while the membrane's force reactions were measured.

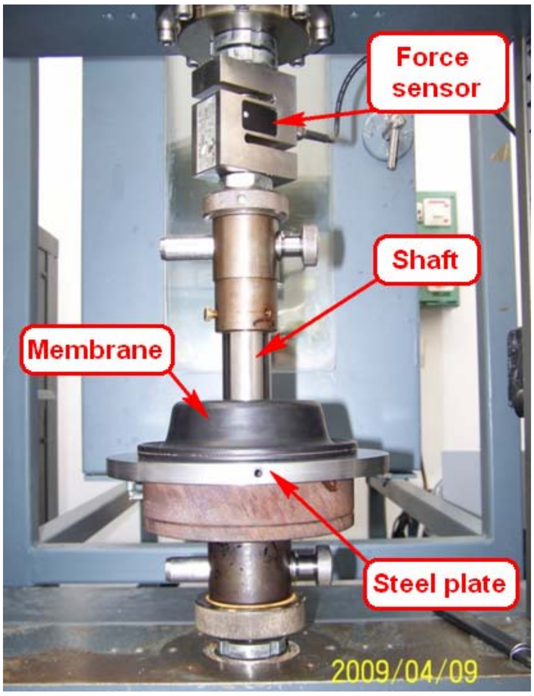

Fig. 1. Measurement arrangement of brake membrane test

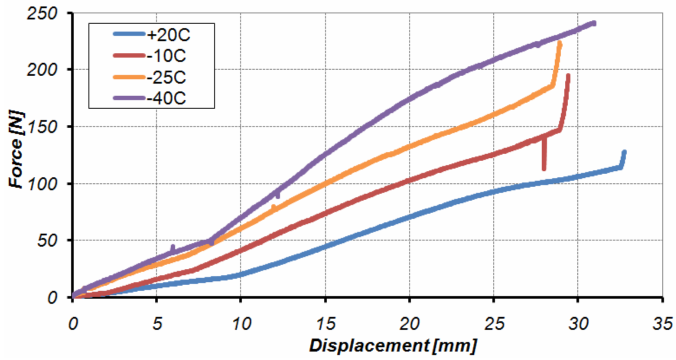

Fig. 2. Measurement results

Air from below the membrane is led out through the boreholes on the steel plate. Compressive tests of the brake membrane were completed using two membranes at +20 ^{o}C, -10^{o}C, -25^{o}C and -40^{o}C, respectively. Fig. 2 shows the force vs. displacement curves of the tests. As the temperature is reduced, the rubber membrane gets stiffened but it does not display a stiffness level higher by the order of magnitude expected. One of the reasons for this can be that the rubber material has not reached glassy temperature (meaning that its elastic modulus has not increased drastically), or that the rubber – located beside the reinforcing inlet – gets glassy other than according to a step function.

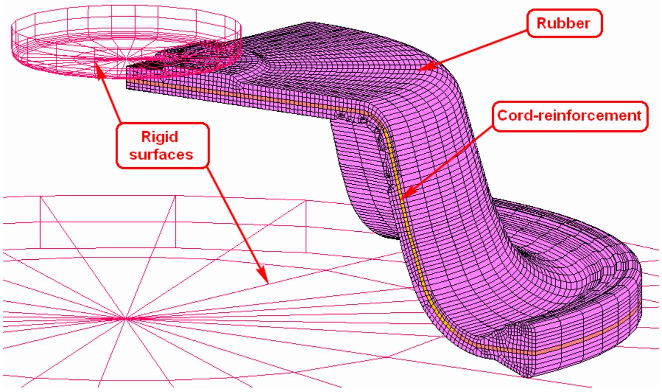

Fig. 3. FE model

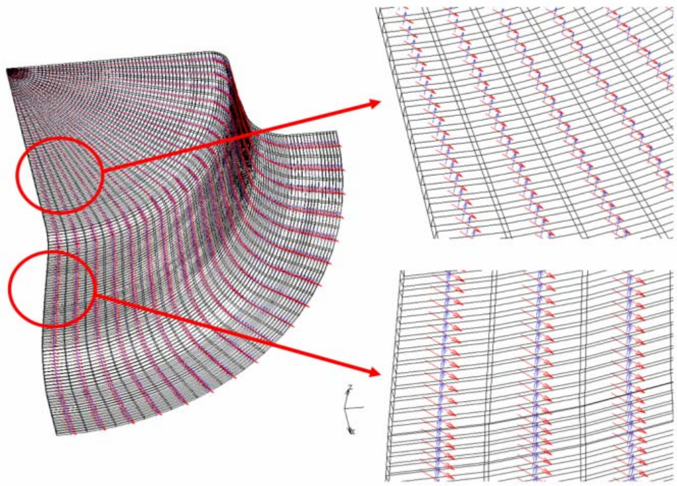

Fig. 4. Main material directions

3 FE modelling of non-hindered compression tests

Stress exerted on the reinforcing fabric within the rubber layer of the membrane changes in the course of membrane tests. As a consequence of manufacturing inaccuracies, the reinforcing inlet may be located within both the tensiled and the compressed zone. A composite structure provided with cord reinforcement is assumed to display different tensile and compressive behaviours, therefore membrane behaviours cannot be exactly described only by the material properties determined from tension [1]. Furthermore, material properties are influenced by the position of the reinforcement inlet within the membrane, adhesion between the rubber and the cords, the quantity of rubber impregnated within the cords, as well as by the distortion of the fabric smoothed into the mould in the course of manufacturing. All these impacts cannot be simultaneously taken into consideration in FE calculations, and attempts are only made to orthotropically model the side wall with a tendency of decreasing stiffness and to describe behaviour at a phenomenon level. In this interest, the compressive elastic modulus of the reinforcement inlet – 172 MPa – is used as the average of the modulus of the rubber and the reinforcement inlet on the side wall of

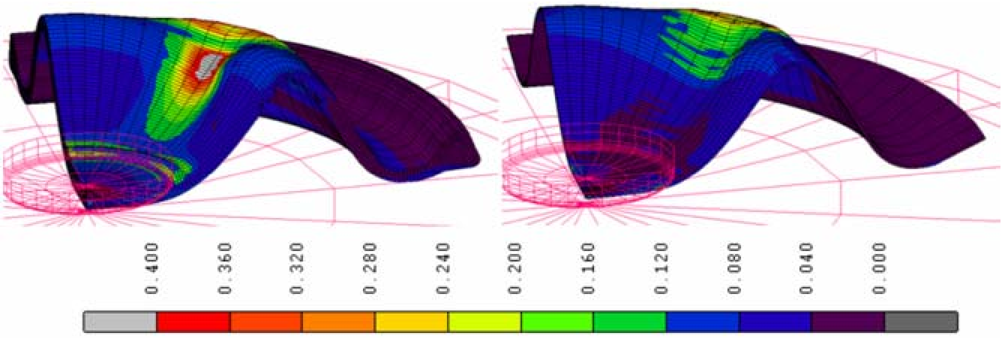

Fig. 5. Equivalent stress

the membrane. As regards on other parts of the membrane, including its plane surface, material properties correspond to those specified in [1].

Fig. 3 shows the FE quarter model describing the measurement. Fig. 4 shows the main material directions of the reinforcement layer in a global coordinate system. Along the plane surface (upper part of Fig. 4, the first main material direction is indicated by red arrows, and the third main direction by blue arrows. On the side wall of the membrane (bottom right figure) the first main material direction is shown by a blue arrow and the third main direction by a red arrow.

In the course of the analysis, a friction coefficient of $\mu = 0.4$ was defined between the surfaces.

Fig. 5 shows equivalent stress in the last phase of membrane compression: the figure on the left shows the entire membrane, while the figure on the right shows when the rubber layer under and above the reinforcement layer has been peeled off, enabling us to study stresses generated in the reinforcement layer as well.

Fig. 6 shows pressure distribution in the contact area on the part of the membrane in contact with the upper cylindrical shaft, and on its surface in contact with the lower steel plate. Load is transferred along a very small surface in both cases, resulting in relatively high contact stresses.

Fig. 7 shows the radial displacement, while Fig. 8 displays a photograph of the dented membrane for a comparison of the deformed shape. It can be clearly observed that the deformed shapes generated by measurement and calculation are in particularly good agreement.

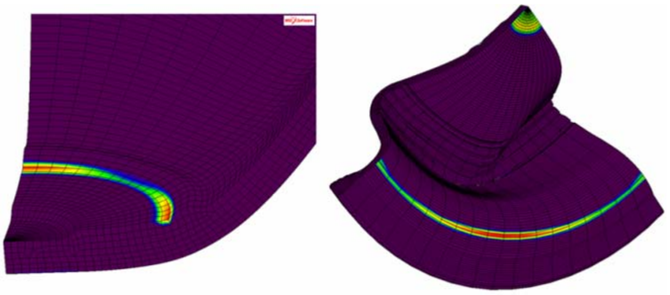

Fig. 6. Contact area and contact stress

Fig. 9 shows a comparison of calculated and measured force results in function of displacement.

4 Radially hindered compression tests

Specimen level tests were also repeated by hindering the radial displacement of the membrane's rim. The aim of the measurement is to ensure that the wall of the membrane is subjected only to compressive stress in the course of the compression test of the membrane, thus approximating the real measurement configuration. Fig. 10 shows the measurement arrangement, including the supplementary elements produced.

Compression tests were performed on a Zwick Z050 tensile testing machine at the Laboratory of BME Department of Polymer Engineering, at a testing speed of 10 mm/min, in 3 cycles. The pressing surface is moved down by 5 mm in the first phase, by 10 mm in the second phase, and by 15 mm in the third phase. The membrane was relieved before each cycle. Fig. 11 shows the average compressive test force vs. displacement curve of the membrane hindered in radial displacement.

5 FE modelling of hindered compression tests

The main material direction of the FE model and the material model applied and that of the inlet layer correspond to the model described in chapter 3. The friction coefficient between the upper surface and the membrane is $\mu = 0.1$, and $\mu = 0.4$ between the lower rimmed plane and the membrane (to take into consideration the rough surface of the chipboard cut out).

Fig. 12 shows radial displacement and the deformed shape.

Fig. 13 shows equivalent stress in the last phase of membrane compression: the figure on the left shows the entire membrane segment, while the figure on the right shows that the rubber layer under and above the reinforcement layer has been peeled off, exposing stresses generated in the reinforcement layer as well.

Fig. 14 shows pressure distribution in the contact area on the upper and lower parts of the membrane. Load is distributed along a very narrow surface in both cases.

Fig. 15 shows a comparison of calculated and measured force results in function of upper plate displacement.

6 Summary

This study presented an experimental and a numerical investigation performed in the framework of a research and development assignment to explore, at a specimen level, the behaviour of membranes applied in the brake cylinders of railway and pub-

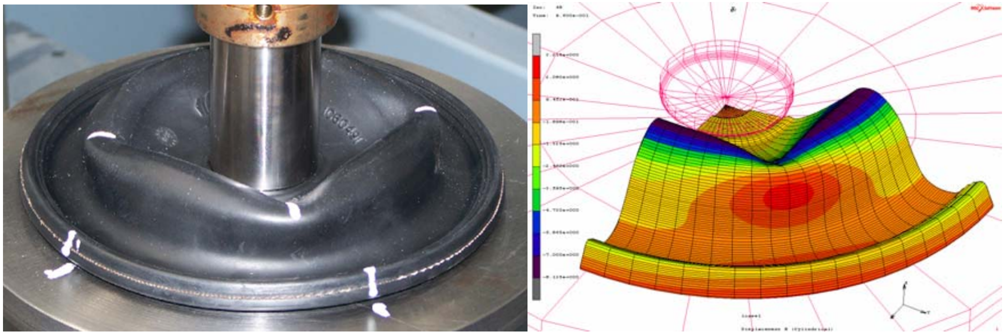

Fig. 7. Radial displacement

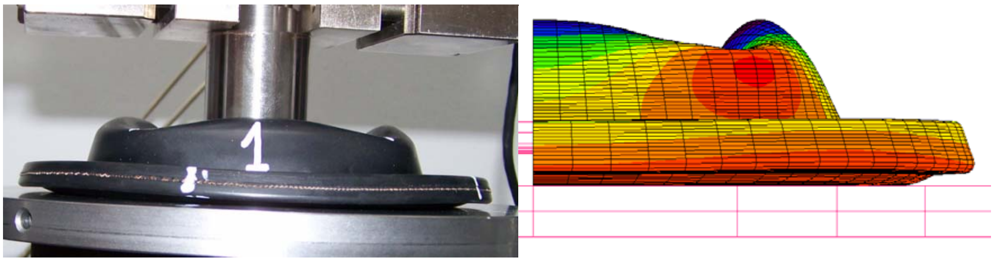

Fig. 8. Photo of dented membrane

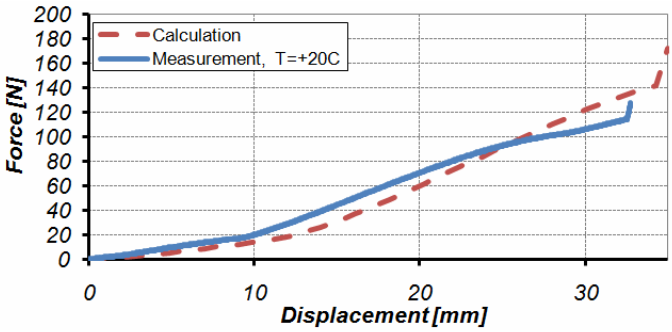

Fig. 9. Measurement and calculation results

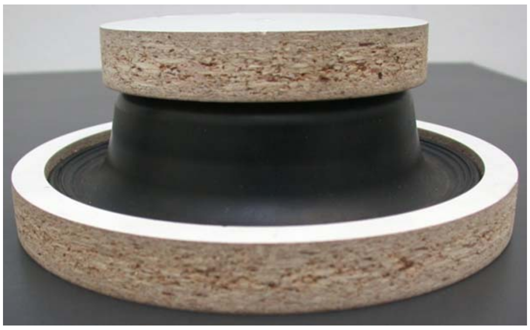

Fig. 10. Measurement arrangement

lic road vehicles. The issue to be solved in this project was how a brake cylinder – operating seamlessly at room temperature – behaves in cold environment.

As a second phase of the work, the numerical treatment of mechanical behaviours characteristics of the complex composite structures presented in this study was investigated in case of two special measurement configurations.

As the temperature-dependent behaviour of the brake cylinder primarily depends on the temperature-dependent properties of the cord reinforced rubber membrane, tests on the brake cylinder removed from the mechanism were intended, on the one hand, to verify the correctness of the material properties determined by elemental measurements, and on the other hand, to explore the orthotropic behaviour of the reinforcement inlet. Numerical modelling was hampered by the presence of extensive geometric non-linearity. In addition to radially non-hindered and hindered compression tests, the study showed that a membrane can be properly modelled at room temperature. Low-temperature

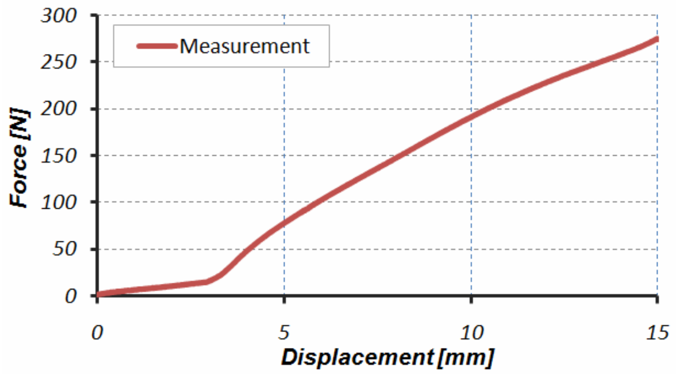

Fig. 11. Measurement result

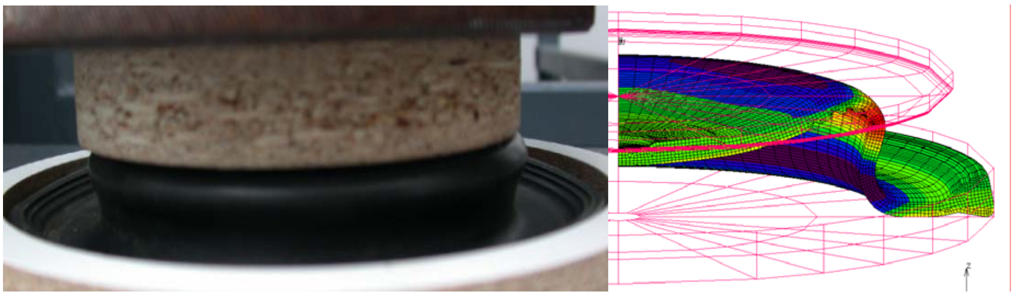

Fig. 12. Radial displacement and deformed shape

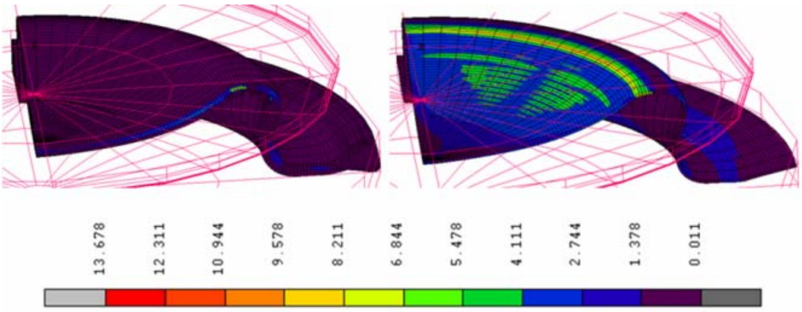

Fig. 13. Equivalent strain in the entire membrane and in the reinforcement layer

membrane measurements were also involved. Measurements performed at -40°C show that the stiffness of the membrane increases to nearly the double of that at room temperature.

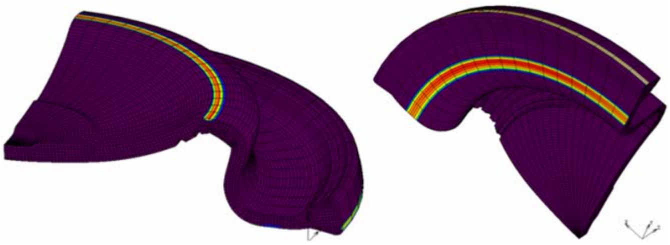

Fig. 14. Contact area and contact stress

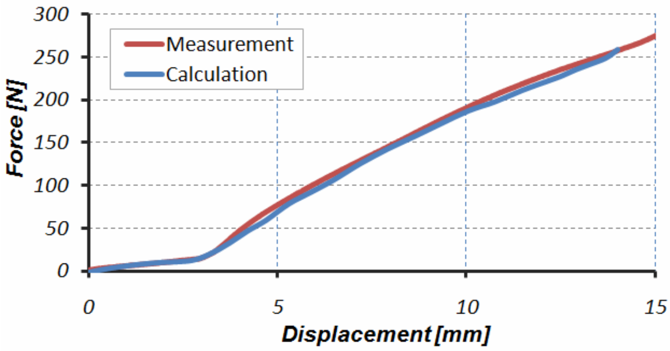

Fig. 15. Measured and calculated results

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