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Investigation of long-term mechanical response of rubber

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Abstract. This work deals with mechanical properties of rubber that is used as a damping element in modern tram wheels. Tests in simple tension, uniaxial compression, and simple shear were performed. Duration of the experiments varied from minutes to days in order to investigate permanent set and its dependence on previous loading history, especially maximum strain. Apart from measurements using the testing machine, hydraulic vise was used for measuring force at constant strain and an optical distance-measuring system was used for measuring the dimension of specimens in the loading direction after load removal. The aim of the research was to find out whether the final dimensions of specimens are the same as before loading and whether the force after return to zero strain attains zero. This knowledge is essential for reliability analysis of the resilient wheels that use the examined rubber.

Introduction

Elastomeric materials are widely used in various applications especially vibration damping elements and seals thanks to the ability to reach large deformations and good damping properties. There are also related effects such as strain induced softening or permanent set, which should be considered during the design of elastomeric parts [1].

For a qualified decision of which effects to incorporate into the material model, the qualitative behavior of the material must be carefully observed.

The objectives of this work were:

1. Measure the permanent set in given material and its dependence on loading conditions.
2. Determine the pace and amount of stress relaxation and its dependence on loading conditions.
3. Change of the above mentioned properties under repeated loading.

A simple test-naming convention is used throughout the text. Example: C1_10_2. The name of a measurement starts with a single character corresponding to the mode of loading: T for tension, C for compression, S for shear. That is followed by a number was assigned to each specimen to distinguish the individual pieces of rubber. The following number denotes relevant deformation in percent and the last number denotes the number of loading with the particular specimen. The above example, C1_10_2, denotes the compressive test of the specimen marked as No. 1, which was loaded up to 10% strain in loading direction during this test and it was the second test with this specimen.

The study is divided into three sections, each describing different set of experiments (according to the testing device used).

Permanent deformation in compressive specimens

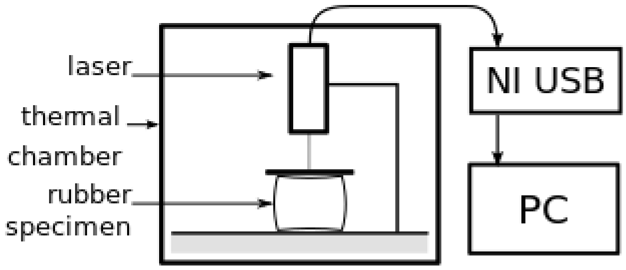

Figure 1 Scheme of measuring the relaxation of the compressive specimen using the laser distance-measuring unit.

In the first set of experiments, the compressive specimens were loaded with prescribed strain (at strain rate $0.4\,min^{-1}$), then unloaded and the height of the specimen was measured using the OPTO NCDT 2200-20 laser distance-measuring unit and National Instruments cRIO-9022 USB interface. To eliminate temperature-related effects, the specimen as well as the laser were placed into a thermal chamber (see Figure 1). The loading was done outside the thermal chamber.

The shape of compressive specimens was a cylinder with approximately 26 mm diameter and 26 mm height. The specimens were slightly conical due to the cutting technology (waterjet). In the case of large values of prescribed strain, the bases of the specimen were no longer planar (as also depicted in Figure 1). A thin composite plate was put on the upper base of the specimen during the measurement to deal with this.

Figure 2 shows height of the compressive specimens measured using the laser. Two specimens were used: C1 had been tested several times before this series of experiments (but never more than 25%), C2 was never subjected to any loading before start of this experiments. The amount of pre-strain is given in the name of each test as described in the introduction (the middle number stands for applied strain in percent). The last numeral in each name denotes the sequence of measurements; the first measurement in both cases was carried out without use of laser and their quality is not comparable with the latter, therefore, these first measurements are not shown. Moreover, the second laser-measurement of the first (C1_34_3) is not shown because it was only possible to reach 34% strain (due to the equipment used - we switched to the testing machine for pre-loading after the C1_34_3 test) which can not be compared to any of the latter measurements. The measurement C2_25_2 is shown in a separate plot in order to illustrate the effect of temperature changes; the laser and specimen were put into the temperature chamber after this test. Also the C2_50_3 test is missing due to the measuring device failure.

Permanent set of the specimens can be observed in the results (Figure 2), especially for strains 50% and 72%, and it increases significantly with the strain applied as well as when the specimen is loaded for the second time to the same strain.

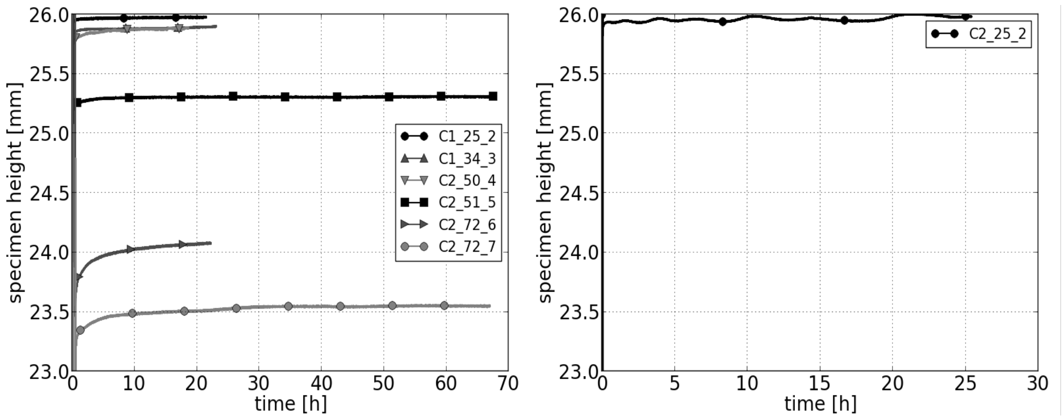

Figure 2 Height of compressive specimens measured using a laser. The second number in the names of the tests stands for applied strain in percent. The plot of C2_25_2 (right) shows the influence of temperature changes.

Relaxation test of compressive specimens using hydraulic vise

The other set of experiments were the measurements of force in compressive specimens under constant deformation. Hydraulic vise with a force-measuring unit VMC 130 and Spider 8 data acquisition system were used. The vise was originally used for multiaxial tests [3]. The device was not placed inside the thermal chamber.

The same type of specimens as in the previous case was used.

The specimens were loaded to strains between 5% and 15% and force was measured for a period of several hours.

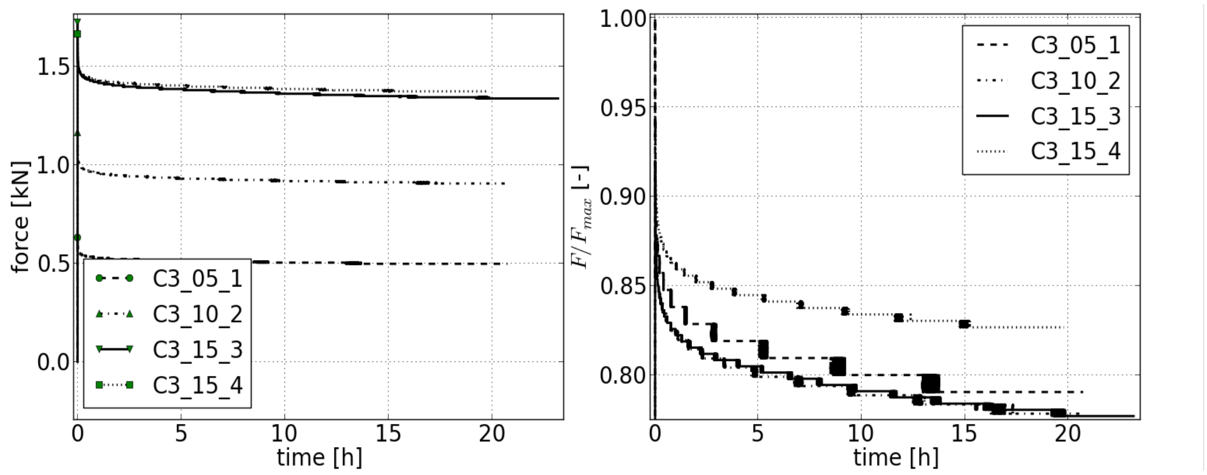

Figure 3 Force measured using the hydraulic vise for different strain values (left). Normalized values of force (right).

The values of force measured using the vise are shown in Figure 3. It can be seen that the force absolute value exhibits larger decrease (difference of force at maximum and relaxed state) for larger strain values. When normalized (also shown in Figure 3), the last test (C3_15_4, loaded to 15% for the second time) exhibits smaller decrease than when the specimen was loaded to the prescribed strain for the first time. A suitable explanation is that the material undergoes plastic deformation.

Relaxation of tensile specimens and cyclic loading of shear specimens

The last set of experiments was performed using the Zwick/Roell Z50 testing machine. Uniaxial tension and simple shear were investigated. The tensile experiments were significantly affected by temperature (see Fig Figure 5). The advantage of performing shear tests (over tension or compression) is that it is possible to achieve both positive and negative deformation.

The shape of the tensile specimens was similar to the usual dogbone shape, but the ASTM recommendation (see e.g. [Brown]) could not be met due to the size of the rubber segments from which the specimens were cut. The measured region of the specimen was 10 mm long (in the direction of prescribed deformation) and had rectangular cross-section with sides 5 mm and 6 mm (see Figure 4). The shear specimens were cuboids with edges 30 mm, 26 mm and 5 mm. The shear specimens were adhesively bonded to two metal plates that were held by the grips of the testing machine (Figure 4).

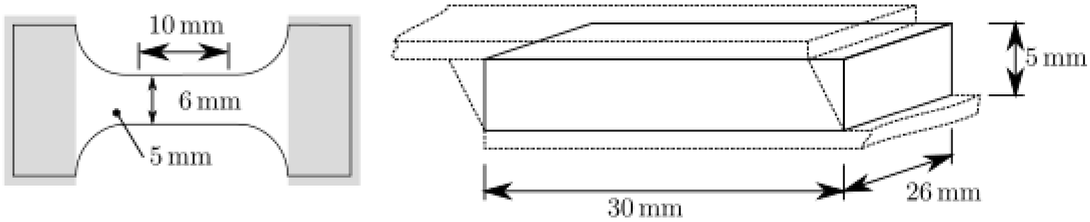

Figure 4 Tensile specimen (left): dimensions of the measured region are given (length and cross-section), the grey areas are held by the grips of the testing machine. Shear specimen: the deformed shape and the metal plates are depicted in dashed lines.

The prescribed strain in the case of tension was similar to the compressive relaxation test: The specimen was loaded by a finite strain rate ($0.4\,min^{-1}$) and the final displacement was held for several hours. The measured force (for strain values 5%, 10% and 15%) are shown in Figure 5. The temperature changes result in slow changes in measured force that do not agree with the expected behavior of the material. The unexpected raise in force (marked by arrows

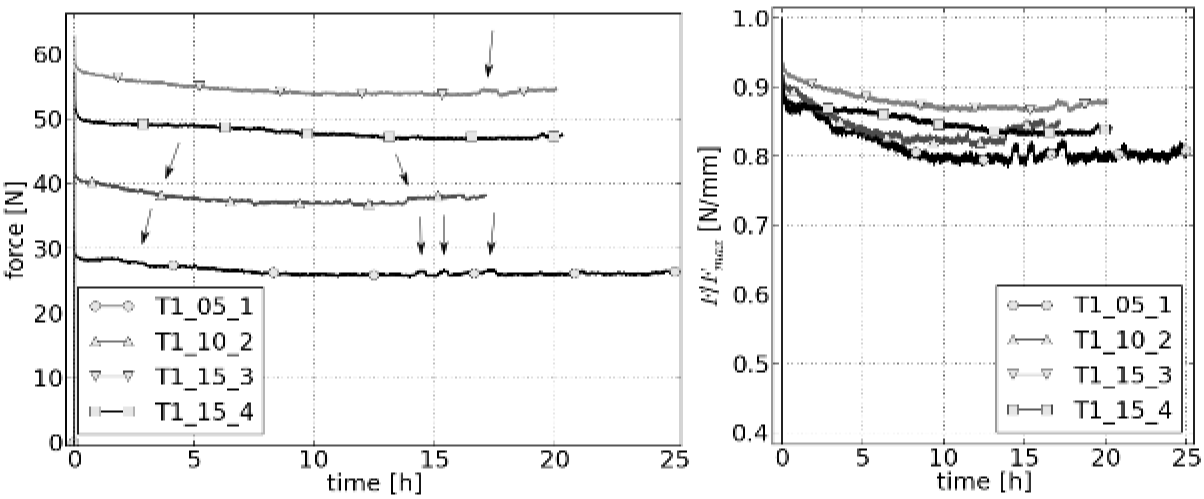

Figure 5 Measured force in the tensile tests. The effects of temperature changes are marked.

in the figure) result from dilatation of the testing machine parts, which causes increase in displacement on the specimen.

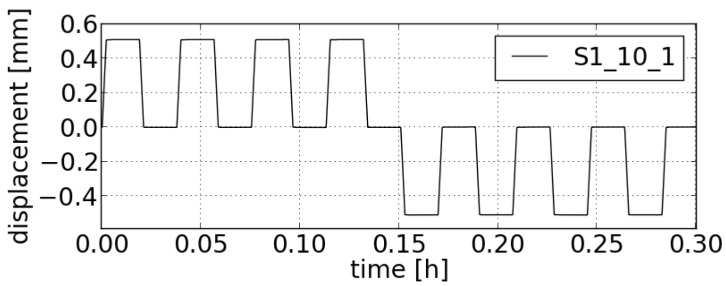

Figure 6 Example of prescribed cyclic loading in shear test.

Two different forms of loading were prescribed in shear. In tests S1_10_1 and S2_20_2, four cycles in positive strain and four cycles in negative strain were prescribed (see Figure 6). The specimen labeled S1_10_1 was loaded to maximum strain 10% and the duration of each relaxation dwell was 60 s. The specimen S2_20_1 was loaded to maximum strain 20% and the duration of each dwell was 120 s. Figure 7 shows comparison of these two tests using relative values (the modulus and relative time of the test).

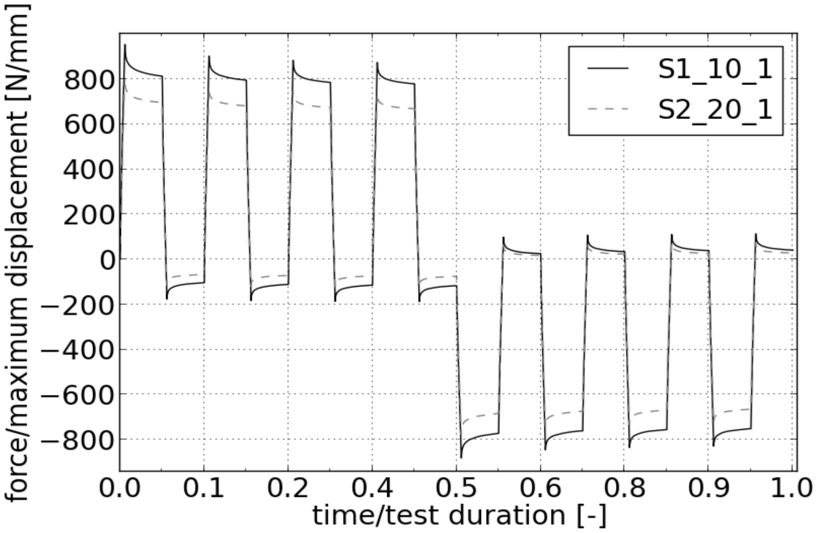

Figure 7 Simple shear test. The values of force and time have been scaled in order to get comparable curves for both measurements.

It can be seen that during the first four loading cycles the force decreases in each cycle, which can be attributed to cumulation of plastic strain. When returned to zero displacement, the force measured is negative due to nonzero inelastic (residual) strain and the permanent set increases in each loading cycle. This corresponds to steps 1.-5. in Figure 8 (dashed contour denote the shape of permanently deformed specimen). During the second series of loading cycles, with negative displacement (and strain) applied, the increase in force can be observed, which can be explained as evolution of plastic strain in the opposite direction than before (see steps 5.-7. in Figure 8).

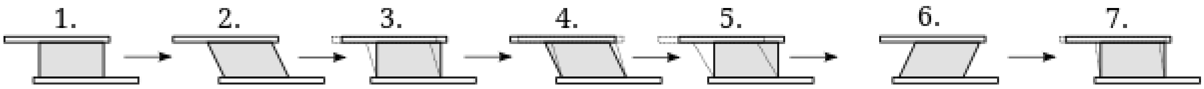

Figure 8 Evolution of plastic deformation during two consecutive loading cycles in different directions. Dashed lines denote the shape of the specimen corresponding to the permanent deformation that has been achieved during previous loading.

In the test S1_10_2 the specimen was also subjected to cyclic loading, but the prescribed maximum displacement (and strain) increased in each cycle by 2%. The duration of the relaxation intervals was 60 s at the maximum displacement and 12 hours at zero displacement. The dependence of measured force on time and on displacement is shown in Figure 9. It can be seen that the force does not approach zero value at zero deflection and that in the following cycles the residual force as well as the residual displacement increase in magnitude.

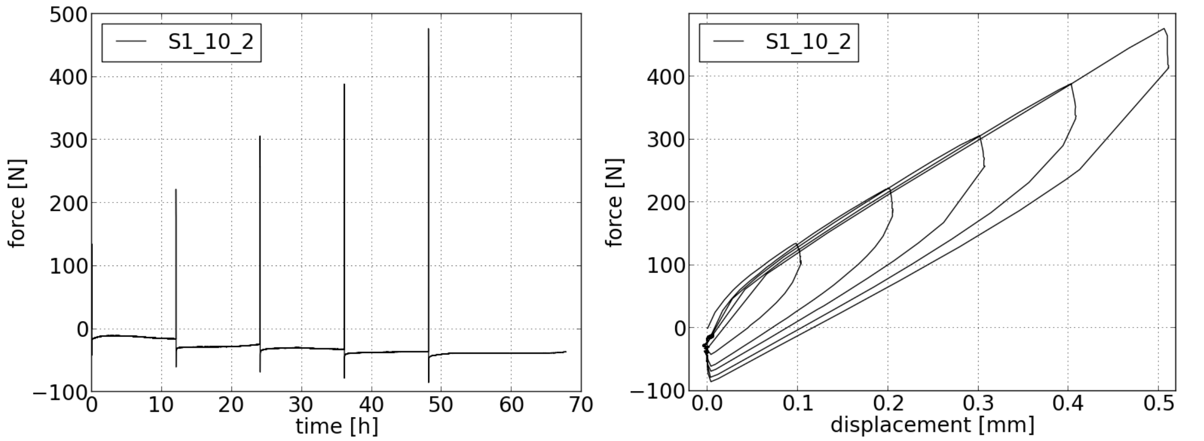

Figure 9 Measured force in S1_10_2: dependence on time (left) and on displacement (right).

Conclusions

In this work, several tests were performed to investigate long term mechanical behavior and permanent deformations of a specific type of rubber.

The most important observation is that displacement does not vanish after releasing the load and that the residual displacement magnitude increase when the loading is repeated. Similarly, the measured force remains nonzero after return to zero displacement. From the shear tests, it seems likely that this behavior of the material can be described by evolution of plastic strain. As for quantitative results, in the case of compressive specimens loaded below 50% strain, the residual strains after load removal were within 1%. The specimens loaded above 50% attained residual strains up to 9.4%.

It was also observed that the amount of decrease in displacement or force (from the instantaneous to the relaxed state) is much greater in the case of first loading than when the material is loaded for the second time.

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