Proceeding Paper

Specimen Setup for Lifetime Investigations of Rubber Materials in the Compression Range †

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Abstract: Fatigue of rubber in compression is of high interest for many industrial applications. In this contribution, new lifetime investigations of filled EPDM rubber are performed in the compression range. A new test rig with measuring device is applied, which enables high-precision compression tests up to 80% (engineering strain). Due to a special design of the specimen holder, a nearly homogeneous strain field can be achieved. As a result, new fatigue studies in the compression range (displacement- and force-controlled) can be conducted. In addition, it can be concluded that crack initiation and failure occur in the nearly homogeneous deformed measuring zone.

Keywords: specimen setup; lifetime investigations; fatigue; compression tests; rubber materials

1. Introduction of Fatigue Specimens

Lifetime predictions of elastomers are of high interest for many technical applications—in particular when these components are important functional elements, like dampers, seals, tires or chassis bushings. All these aspects give an idea of the importance of lifetime predictions for elastomer components. In literature, a large number of durability test specimens can be found. It can be observed that primarily shear as well as tension and/or compression specimens are applied. In [1–3], a cylinder-shaped shear specimen is depicted. In comparison to this, in [1,4–16], durability specimens for uniaxial tension and/or compression tests are listed. The specimen geometries can be classified as follows: cylinder specimen [1,4,12], dumbbell-shaped [5,10,11,13,14,16] and diabolo-shaped [6–9,15]. However, the presented durability specimens are not suitable for compression tests higher than 30%. Thereby, the homogeneous uniaxial compression is an important deformation state for many technical applications. In [17], a dumbbell specimen is depicted, which already leads at 30% compression to high deviations from the homogeneous stress state (see Figure 1, right).

Figure 1. Inhomogeneous deformation in compression for a dumbbell specimen, FE-simulation with evaluation (figure from [17], labelling in English).
Another disadvantage, besides the inhomogeneity in the measuring zone, is that the maximum level of compression is limited. Furthermore, higher compressions lead to an abrupt contact between the middle section and specimen holder (cf. Figure 1, left). All these aspects indicate that the standard dumbbell is not the best choice for homogeneous lifetime tests in the compression range.

In [12], a cylinder sample is presented, which is vulcanised to metal plates. In the compression range, the cylinder sample shows an inhomogeneous distribution in the measuring zone (see Figure 2, left).

This can be explained by the fact that wrinkling occurs at the radius close to the metal plates. For this reason, Ref. [12] recommended the measurement data up to 30\% in compression. In Figure 2 (right), the relative error measure is depicted. As can be seen, the error measure strongly increases after 30\% in compression. As a consequence, this cylinder sample also seems to be unsuitable for homogeneous lifetime tests in the compression range.

In Refs. [18–20], a new specimen setup is presented, which enables high-precision tension–compression tests up to a compressive strain of approximately 70\% (engineering strain). Due to a special design of the specimen holder, a nearly homogeneous strain field can be achieved. In Figure 3, the stress–strain curves for the standard dumbbell as well as for the new specimen setup are depicted.
Consider that, for better comparison, the dumbbell specimen from Figure 1 is also depicted (here called standard dumbbell). As it can be seen, the new specimen setup shows a significant better characteristic in homogeneity and also in achievable maximum in compression. In Figure 3, a nearly homogeneous deformation state can be achieved up to a compressive strain of 50%. After this, increasing deviations from the nearly homogeneous deformation state can be observed. However, the specimen setup enables new possibilities in the field of material characterisation. For further information regarding the numerical development, the optimisation and the experimental testing (for quasi static tests), see the previous works of [18–20].

Note that numerical studies have shown that the maximum stress (in terms of amount) occurs in the nearly homogeneous deformed measuring zone (cf. [20]). In this way, the new specimen setup would be ideally suited for fatigue tests. In the next section, the new specimen setup shall be applied for lifetime investigations of rubber materials in the compression range. It should be mentioned that the specimen setup can also be applied for tension and combined tension–compression tests.

2. Experimental Setup and Measuring Device

In this section, the new specimen setup shall be tested for lifetime investigations of technical rubber materials. For this, the experimental setup is described first. In Figure 4, a servo-hydraulic testing machine from INSTRON (8801) with a clamping device and implemented specimen setup is depicted.

The force is measured with a load cell (nominal load 50 kN), and the deformation analysis is performed with a 2D optical measuring system from KEYENCE (TM-065T). The functional principle based on the transmitted light procedure. In Figure 4, the left monitor shows a 2D view of the deformed dumbbell. Note that, for compressions higher than 50%, the measuring zone of the dumbbell specimen is very limited (see the zoom in Figure 4). For this reason, a new measuring strategy for strain measurement is applied. The main idea is to measure the tangential strain in the symmetry plane to obtain the axial strain via geometric considerations. In [19], the derivation of the new measurement strategy is described. The evaluation equation is as follows:

\[
\varepsilon_{zz} = \left(\frac{\tilde{d}}{d}\right)^2 - 1 .
\]

In this equation, \(\varepsilon_{zz} = \varepsilon\) describes the engineering strain in an axial direction (z-coordinate). \(\tilde{d}\) denotes the reference diameter and \(d\) the current diameter of a cylindrical specimen. Note that Equation (1) is only valid for the case of ideal incompressibility.
\[ \frac{dV}{d\tilde{V}} = J_3^{-\frac{1}{3}} = 1 \]. In [20], various error investigations for the new measurement strategy are performed. As a result, Equation (1) is very robust against disturbances.

The tests were performed with specimens of a filled ethylene-propylene-diene monomer (filled EPDM) rubber (For reasons of confidentiality, only the basic components can be specified: EPDM, carbon black, plasticiser, accelerator, activator and sulfur for crosslinking). In Figure 5, the stress–strain curves are depicted for two different specimens.

\[ \varepsilon = (\tilde{d}/d)^2 - 1 \]

\[ T = F/A_0 \text{ in MPa} \]

![Figure 5](image)

Figure 5. Stress–strain diagram for filled EPDM rubber, deformation analysis was performed with a 3D DIC measuring system (figure based on [20], labelling in English).

As it can be seen, stepped compression tests up to a compressive strain of 73% are performed. Note that, for these measurements, a 3D DIC measuring system (GOM ARAMIS 4M) was applied. The reason is that, next to the strain measurement, the change of the center point of the dumbbell specimen can also be determined. This can be realised by a cylinder extrapolation of a DIC coated cylinder segment. For further information about DIC coating and cylinder extrapolation, see [20]. From the polar diagram in Figure 5, it can be observed that the change of the center points of the specimens is very small. This is also a validation that the specimen setup is not at a risk of buckling. For the planned lifetime investigations, the 2D optical measuring system from KEYENCE is applied. This has the practical advantage that the strain measurement can be performed data-efficiently compared to the more complex DIC measurement.

3. Fatigue Studies in the Compression Range

In the following, it is examined if the dumbbell specimen fails in the nearly homogeneously deformed measuring zone. For this purpose, a displacement-controlled compression test is performed for a mean load of \( \bar{F} = -15 \text{ mm} \) and an amplitude of \( \hat{d} = 5 \text{ mm} \) (corresponds to a maximum compression of 79%). The load signal is a sine function with a test frequency of 1 Hz. In Figure 6, the fatigued dumbbell specimen is depicted, front- and backside.

As a result, the crack initiation and crack growth occur in the measuring zone. The grey segment in Figure 6 is not a DIC coating, but an antioxidant that diffuses out from the dumbbell specimen. Furthermore, it can be confirmed that the dumbbell specimen is not at a risk of buckling. This is remarkable at these extreme compression levels and highlights the specimen setup. Next, the force–load cycle diagram is evaluated for this test, see Figure 7.
Figure 6. Fatigued dumbbell specimen of filled EPDM rubber, tests were performed with a servo-hydraulic testing machine from INSTRON (left) frontside and (right) backside.

Figure 7. Force–load cycle diagram in the compression range for a filled EPDM rubber (displacement-controlled test with a mean load of $\bar{u} = -15$ mm and an amplitude of $\hat{u} = 5$ mm).

It can be observed that the dumbbell specimen fails after 100,000 load cycles. In addition, slight fluctuations in force relaxation can be identified. Closer investigations indicated that the fluctuations correlate with the temperature of the hydraulic fluid of the servo-hydraulic testing machine (cf. red curve in Figure 7). However, the cycles to failure can be identified independently. After this basic test, a fatigue study will be conducted with variation of mean load $\bar{u}$ and constant amplitude $\hat{u}$. In Table 1, the number of cycles to fatigue are depicted for three different load levels.

Table 1. Fatigue results in the compression range for filled EPDM rubber (displacement-controlled tests).

| No.: | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|------|------|------|------|------|------|------|------|------|------|------|
| $\bar{u}$ in mm: | -15  | -15  | -15  | -15  | -15.5| -15.5| -15.5| -15  | -16  | -16  |
| $\hat{u}$ in mm:  | 5    | 5    | 5    | 5    | 5    | 5    | 5    | 5    | 5    | 5    |
| Cycles to failure $N$: | 102,000 | 149,700 | 936,000 | 111,600 | 13,300 | 4500 | 9000 | 2850 | 2500 | 3800 |

Furthermore, it can be confirmed that, for all investigations, the dumbbell specimens fails in the measuring zone. In addition, the fatigue points from Table 1 are depicted in a double logarithmic diagram, see Figure 8.
Figure 8. Fatigue results in the compression range for filled EPDM rubber (displacement-controlled tests).

On the left ordinate the minimum displacement and on the right ordinate the measured strain are depicted (cf. Equation (1)). Moreover, the fatigue results are fitted with an equation of a line, see Equation (2):

\[
\log (|u_{\min}|) = m \log (N) + n \quad \text{with:} \quad m = -0.00946, \quad n = 1.35163 \tag{2}
\]

Note that the parameters \( m \) and \( n \) were calculated for \(|u_{\min}|\) in mm. Basically, these investigations give completely new insights into the fatigue behaviour of filled EPDM rubber in the compression range (initially displacement-controlled). Furthermore, it can be concluded that only at extreme compression (more than 75%) did the material fail at load cycles less than 1 million.

Next, force-controlled fatigue tests are carried out in the compression range. Due to this, much higher requirements increase for PID control due to the strong nonlinearity of rubber materials. In Figure 9, the stress–strain diagram as well as the load signal for the force-controlled tests are depicted.

As can be seen from the diagram, the filled EPDM rubber shows a strong nonlinearity for this extreme compression range. Nevertheless, the sinusoidal load signal can be realised for this test configuration (comparison between nominal value and target value show a remarkable correlation); see subfigure in Figure 9. Consider that such precision force-controlled tests can only performed in a limited range \( F \in [-1, -16] \) kN. In comparison to that, a force-controlled compression test up to a load of zero \((F = 0 \text{ kN})\) has not yet been satisfactorily realised. In Table 2, some first results of ongoing research for force-controlled tests in the compression range are presented.

Table 2. Fatigue results in the compression range for filled EPDM rubber (force-controlled tests).

| No.: | 1   | 2   | 3   | 4   | 5   |
|------|-----|-----|-----|-----|-----|
| \( F \) in kN: | -7.5 | -7.5 | -7.5 | -8.5 | -8.5 |
| \( F' \) in kN: | 6.5  | 6.5  | 6.5  | 7.5  | 7.5  |
| Cycles to failure \( N \): | 220,000 | 335,000 | 419,000 | 137,000 | 94,000 |
Figure 9. Stress–strain diagram for filled EPDM rubber (force-controlled test with a mean load of $F = -8.5 \text{ kN}$ and an amplitude of $\dot{F} = 7.5 \text{ kN}$).

Note that the point of fatigue can clearly be identified (not depicted here). In further studies, force-controlled compression tests up to a load of zero are planned.

4. Conclusions

In this contribution, a new specimen setup was applied for fatigue studies in the compression range. As a special feature, fatigue tests (displacement- and force-controlled) were performed up to a compressive strain of 84%. In addition, for these extreme compression tests, a nearly homogeneous deformation state can be achieved. By means of the new measuring strategy, the strain can be determined with high resolution in the measuring zone. Furthermore, the maximum stress (in terms of amount) occurs in the measuring zone. As a result, the crack initiation as well as the crack growth can be investigated in the area of interest. In further studies, combined tension–compression fatigue tests shall be conducted. Thereby, it shall be investigated how pre-conditioning in compression affects the fatigue in the tension range.

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Abbreviations

The following abbreviations are used in this manuscript:

EPDM Ethylene-propylene-diene monomer
DIC Digital image correlation
PID Proportional-integral-derivative

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