HEAT GENERATION IN DYNAMIC LOADING OF HYBRID RUBBER-STEEL COMPOSITE STRUCTURE

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SUMMARY

Heat generation of a hybrid rubber-steel sandwich structure in dynamic loading was investigated. The structure was tested in compression and in four-point bending. The results were compared with theoretical values and a similarity was observed. A rough estimation of recommended operation conditions for the test specimens could be defined.

Keywords: rubber, steel, hybrid composite, sandwich structure, dynamic tests, heat generation.

INTRODUCTION

Rubber to metal bonding has enabled widespread use of rubber-steel structures in engineering applications. Sandwich rubber-steel structures are familiar e.g. in vibration damping elements, shock and sound absorbers [1]. The damping device applications involve dynamic loadings, for which the viscous part of the viscoelastic nature of rubber assorts well. However, excessive viscous behavior generates also unfavorable phenomena such as stress relaxation, energy losses during stress cycles, heat generation and temperature rise during flexing. During loading cycles heat is generated in the rubber by conversion of mechanical energy to heat due to internal friction of the molecular chains [2]. The rather low thermal stability of rubbers makes them sensitive to heat generation that may limit the utilization of the rubber-steel structures [3].

In dynamically loaded rubber-steel sandwich structure the heat generated by hysteresis during cyclic deformation may play an important role in the degradation because the thermal properties of rubber and steel differ significantly. Difference in coefficient of thermal expansion can lead to interfacial strains in a rubber–metal composite structure. For example the coefficient of thermal expansion of styrene-butadiene rubber (SBR) is 250×10^{-6} 1/K, and of low carbon steel 12×10^{-6} 1/K [3, 4]. In addition, the thermal conductivity of rubber is low when compared to that of steel (K_{SBR}=0.25 W/(mK) [3] and K_{steel}=51.9 W/(mK) [4]). Therefore, the heat generated in the composite structure can cause local heating in the rubber part, which may undergo degradation reactions and thus lead to loss of mechanical properties. If rubber components are used at temperatures over their maximum service temperatures, changes in the crosslink structure and thus some hardening can occur. Even higher temperatures lead to breakdown in the structure, net softening of the rubber, and finally to charring and embrittlement of rubber. The heat generation is also strongly affected by fillers, ambient temperature, and loading frequency of the structure [3]. Several researchers have examined the heat generation in filled rubbers [5-7]. In addition, filled rubbers experience a softening effect, known as the Mullins effect, under cyclic loading. It leads to decrease in the elastic modulus due to breakdown of weak bonds between rubber molecules and filler particles. The softening is strong in the beginning of cyclic loading but decreases after a few cycles. [3, 8, 9]

Apart from heat generation, also the heat loss of a rubber component must be considered. If a rubber block is placed between two heat sinks, e.g. steel sheets that are kept at a fixed temperature T, the heat generated uniformly in the rubber will diffuse via the interfaces to the heat sinks and the form of the equilibrium temperature distribution within the rubber will be parabolic in form. The maximum temperature reached in the bulk rubber can be calculated from equation

$$T_{\max} = T + \frac{fU_d H^2}{8K} \qquad (1)$$

where f is the frequency of the loading cycles, H is the thickness of the rubber component, K is the coefficient of thermal conduction of rubber and U_d is the amount of energy generated per cycle. U_d can be defined by equation

$$U_d = \pi E_1 \tan \delta \varepsilon_0^2 \approx \frac{\pi \sigma_0^2 \tan \delta}{E_1} \qquad (2)$$

where E_1 is the elastic modulus of rubber, $\tan \delta$ is the loss factor, ε_0 is the maximum strain σ_0 is the maximum stress. The loss factor describes the energy converted to heat during cyclic loading and it depends on temperature and frequency. The maximum value of tan δ is reached when the external frequency equals the natural frequency of Brownian motion. [3, 10]

Besides heat generation, repeated loading of rubber may cause eventually a fatigue failure [11, 12]. Applications of rubber-metal laminates are usually loaded under compression why it is important to examine the relation of heat generation and failure of the structure. Even though rubber is virtually incompressible, the ability of rubber component to bulge allows it to compress under loading. The level of bulging depends on the shape factor. The shape factor of rubber component describes the ratio of loaded area and the area free to bulge and thus relates to the stiffness of the component. The larger the area free to bulge, and thus the smaller the shape factor, the softer is the rubber component [9]. The thickness of the rubber layer affects the heat buildup because heat conduction path length from rubber to steel increases with increasing rubber thickness.

In this study the heat generation in a styrene-butadiene rubber-steel sandwich structure was examined. This type of hybrid composite can be used in structural components of heavy machine industry to replace bulk steel structures. Conventional designs of many components involve unnecessarily heavy and oversized structures, why redesigning them with the sandwiched rubber-steel composite, may lead to notable weight reductions. The applications are typically exposed to dynamic loadings, where the unique properties of rubber may be used to restrain the propagation of vibrations to other machine parts. As the tolerance to thermal stress is a significant property of the hybrid rubber-steel composite, it is important to study the heat generation of the structure in dynamic loading, especially when the realistic maximum service temperature for SBR is 70-80 ºC [3]. Therefore, the SBR-steel sandwich structure was tested under dynamic compression and flexure.

MATERIALS AND METHODS

A sandwich structure, consisting of two structural steel sheets (EN S235) and a styrene-butadiene rubber (Trellex 60) layer filled with carbon black, was examined. Shore A hardness of the investigated SBR was 60. The thickness of steel sheets was 5 mm and the SBR layer thickness 15 mm. Approximately 0.5 mm variations in the rubber layer thickness were observed in the test specimens resulting from processing inaccuracy. The sandwich was manufactured by vulcanizing the rubber component between surface treated steel plates under compression and heat. The specimen sizes were in compression tests 100x100 mm^2 and in four-point bending tests 25x45 mm^2. The shape factors were 1.67 and 4.76, respectively. Four-point bending tests were carried out in quarter-point loading where the lower supports span length was 200 mm.

In total six specimens were tested in compression and three in bending. One of the test specimens was tested statically and the others dynamically for both test modes. The force-displacement data were recorded from static tests and used to determine the suitable load levels for dynamic tests. For the static tests the deformation rate was 2 mm/min and the maximum load 60 kN. The dynamic tests were conducted to study the heat generation of the rubber. Test parameters for the dynamic tests, which are shown in Table 1, were selected so that the deformation took place elastically. In addition, the shape factor of rubber was taken into account to correlate the test parameters with the real operating conditions. The dynamic loading profile was sinusoidal.

Table 1. Dynamic test parameters for compression and bending tests.

Compression			
Specimen	**Frequency [Hz]**	**Time [h]**	**Compression of the rubber [%]**
C1	2	12	28%
C2	2	12	7.50%
C3	6	12+36	7.50%
C4	2	12	18%
C5	6	12	18%

Four-point bending			
Specimen	**Frequency [Hz]**	**Time [h]**	**Deflection of the structure [mm]**
B1	2	12	3.4
B2	6	12	3.4

The compression and four-point bending tests were conducted with a servo-hydraulic MTS 810 testing machine using a 100 kN load cell. The tests were carried out by using load control. The load and displacement data were used to determine the loss factor of the rubber-steel structure. In the four-point bending tests also a linear variable differential transducer was used to measure the deflection of the test specimen. The test setups are shown in Figure 1.

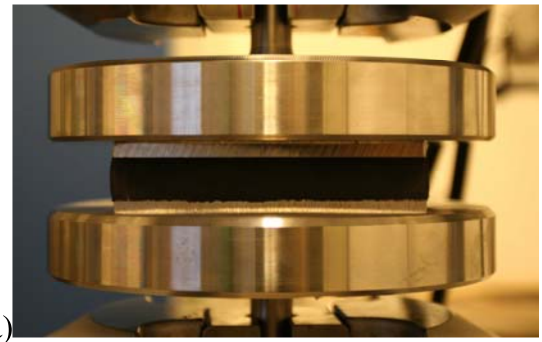
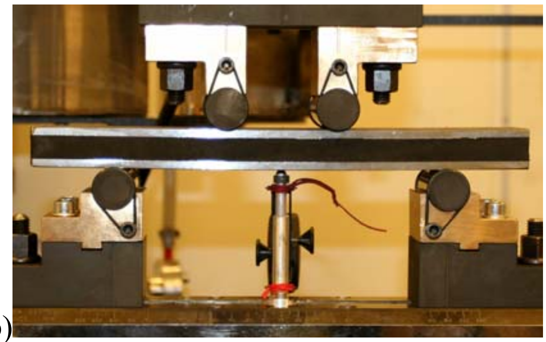
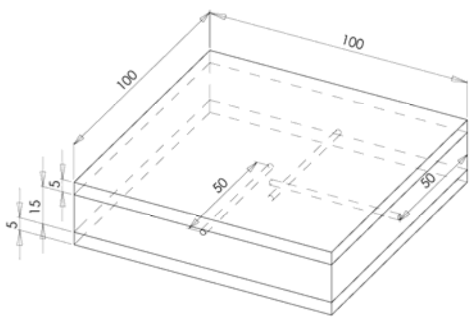
a)  b) 

Figure 1. Test setups for a) compression and b) four-point bending.

To enable the temperature measurements, three holes (diameter 2 mm) for thermoelements were drilled to each specimen. The temperature was designated to be measured from the rubber-steel interfaces and from the bulk rubber. In the compression test specimens the 50 mm deep holes located in the middle of three different sides of the specimen. One side was maintained intact. In the bending test specimens the holes located on the top of the specimen. Schematic pictures of the specimens are shown in Figure 2.



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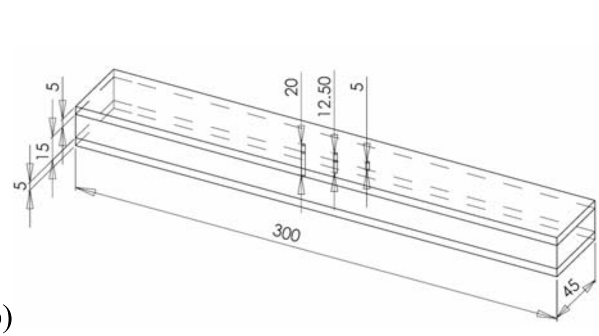

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Figure 2. Schematic pictures of a) compression and b) four-point bending test specimens. The locations and depths of the thermoelement holes are outlined in the pictures.

K-type thermoelements and a FLIR ThermaCAM PM 595 infrared camera were used in the temperature measurements. During thermography the emissivity value of 0.95, which is recommended by manufacturer for rubber, was used. Therefore, the temperatures of metallic parts cannot be determined from the thermal camera images. The thermal camera measured the surface temperature of the intact rubber layer in each test. Temperature from the bulk rubber and rubber-steel interfaces was measured continuously in one compression test (2 Hz, 28% deformation) by keeping the thermoelements inside the test specimen during the test. To avoid friction between the thermoelement and rubber [14], the temperature was measured in the other tests by suspending the test in preset intervals. The thermoelements were calibrated by comparing additional temperature data of the thermoelements with a mercury thermometer.

To determine the changes in the chemical structure or composition of the rubber before and after testing fourier transform infrared (FT-IR) spectra were recorded. The IR spectra were measured with Tensor 27 from Bruker Optics, equipped with germanium ATR accessory. For each spectrum 32 scans were collected with resolution of 4 cm^{-1}.

Dynamic mechanical analysis (DMA) was carried out for the virgin rubber layer to measure the dynamic properties of the studied SBR. The DMA tests were performed with Pyris Diamond DMA from PerkinElmer Instruments. The measurements were run in nitrogen atmosphere with frequencies 2 Hz and 6 Hz.

The characterization of the fracture surfaces of the rubber-steel structure was done by Leica MZ 7.5 optical stereomicroscope (objectives 0.5 and 2.0). The pictures were recorded by a Leica DFC420 camera (5 megapixel) connected to the microscope.

RESULTS AND DISCUSSION

Static tests

Static four-point bending and compression tests showed that the sandwich structure and its interfaces are stable at ambient temperature. The compressed specimen fully recovered after loading, but the four-point bending sample deformed plastically. The compression modulus (E=21 MPa) of the structure was calculated from the results of static compression test to determine the theoretical temperature rise in dynamic tests.

Dynamic tests

Heat generated in the compression test samples depended on the amplitude and frequency of the loading. During all four-point bending tests and compression tests with 7.5% deformation only minor heating of few degrees was observed. Moderate heating occurred when the deformation in compression was 18% and the frequency 2 Hz. When the frequency was increased to 6 Hz or the deformation to 28% the heat generation was strong, close to one hundred degrees. The results of the temperatures measured from bulk rubber during dynamic tests are shown in Figure 3.

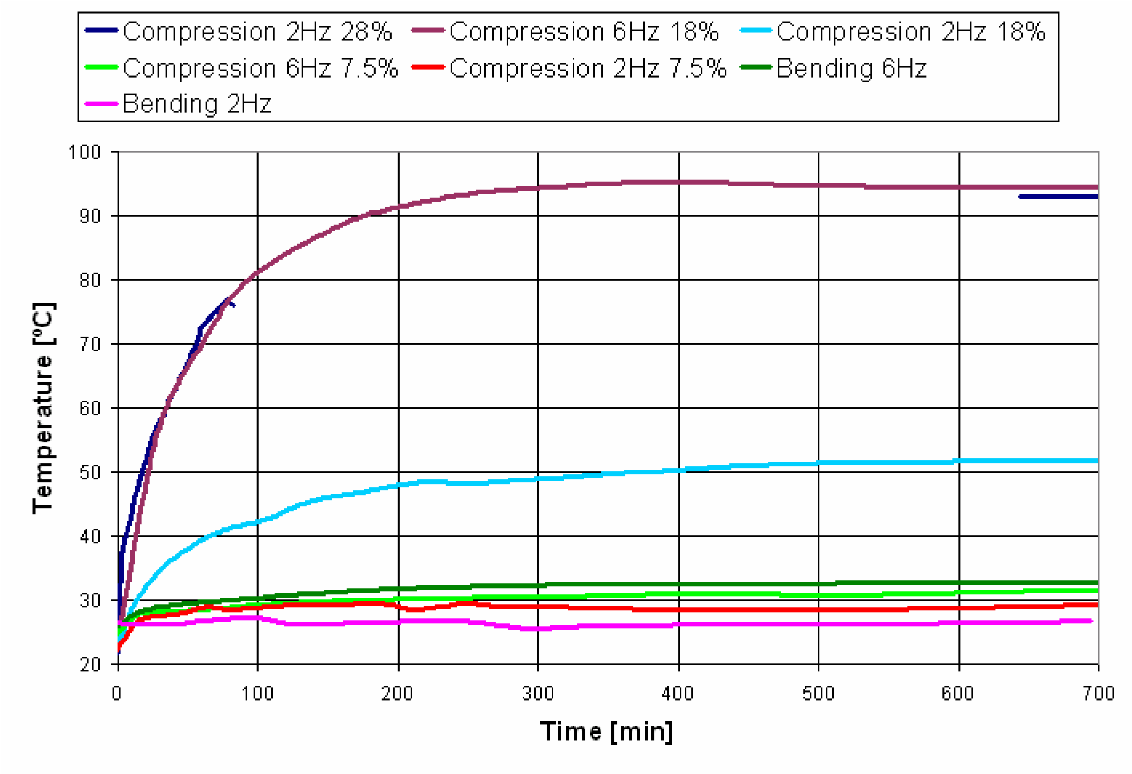

Figure 3. Heat generation of bulk rubber during dynamic tests.

Bulk rubber temperatures rose rapidly but stabilized within three hours. The temperature data of compression specimen C1 (2 Hz, 28%) is not complete, because the bulge effect extruded the thermoelement from the rubber during the test. The testing of specimen C3 (6 Hz, 7.5%) was continued for 36 hours to ensure that the temperature level was completely stabilized. However, no further temperature rise or rupture was observed in it.

In addition to bulk rubber temperatures also temperatures from rubber-steel interfaces were measured. As expected, the temperatures at the rubber-steel interfaces were regularly a few degrees lower than the temperatures in the bulk rubber. The explanation for the difference is the heat conduction from the rubber to the steel sheets and the test fixture.

Thermal camera images from specimen C1 at different points of testing are presented in Figure 5. The crack interiors are at higher temperature than the surface of the rubber which the can be noticed in Figure 5.b). Although the bulk rubber temperature measured with thermocouples was higher than the surface temperature measured with thermal camera, temperature curves were similar in form.

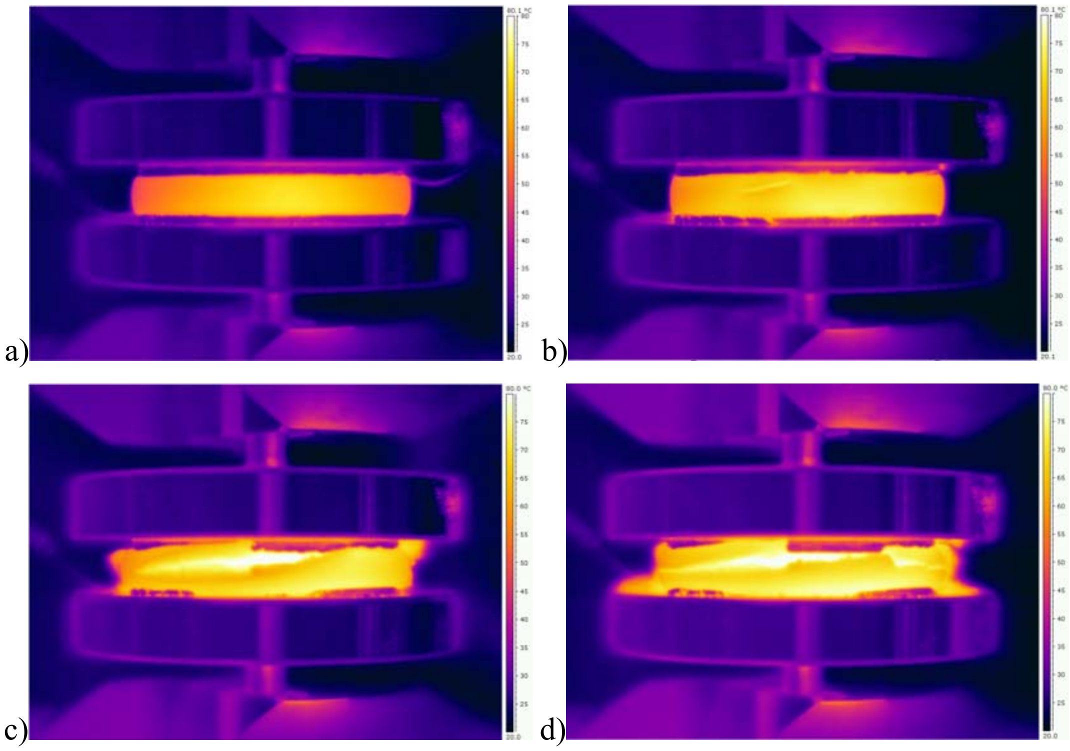

Figure 5. Thermal camera images taken of specimen C1 in compression test after a) 0.5 h, b) 4 h, c) 6 h, and d) 12 h of dynamic loading. The temperature scales are 20-80°C.

Visual inspection of the specimens after dynamic tests indicated that the rubber layers in compression samples C2 (2 Hz, 7.5%), C3 (6 Hz, 7.5%) and C4 (2 Hz, 18%) and in the four-point bending samples B1 (2 Hz) and B2 (6 Hz) were undamaged after testing. Fractures were observed only in compression samples C1 (2 Hz, 28%) and C5 (6 Hz, 18%), when the temperature of the rubber also exceeded the maximum service temperature of SBR. Although the holes of thermoelements formed localized stress concentrations, fractures appeared also on the intact rubber layer. The fractures were almost horizontal and they initiated typically in the middle of the rubber layer rather than at the rubber-metal interfaces, as can be seen in Figure 5. This could also be expected according to the stress distribution in the bulge surface [12]. The fractures grew during the tests towards the corners of the specimen. In addition, in specimen C1 (2 Hz, 28%) the edge of the steel sheets sheared the bulge near the interface.

In the rubber layer of specimen C1 (2 Hz, 28%) also some structural changes were observed: separate small rubber particles and oily marks appeared on the rubber fracture surfaces. The segregated parts can be seen for example in Figure 6. The oily marks may originate from the process oils added to the rubber. Also the stearic acid and parrafinic acid, that are ingredients of the rubber, may have melted at temperatures over 80°C. In the IR spectrum of specimen C1 (2 Hz, 28%) a new set of peaks was detected, most probably arising from processing oil. For other specimens no changes in the IR-spectra were discovered after testing. On the interior of the fractures in the specimen C5 (6 Hz, 18%) no segregated particles were observed.

a) b)

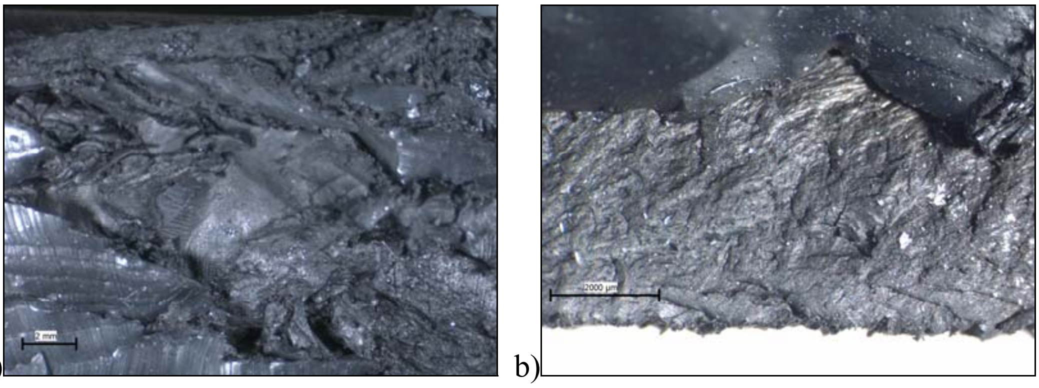

Figure 6. Fracture planes from a) specimen C1 and b) specimen C5. The scale bars are 2 mm.

When the measured temperatures are compared to those of corresponding theoretical values (Equation 1) first the loss factor tanδ needs to be defined. The loss factor tanδ for the SBR-steel structure was approximately 0.2 (measured by a conventional fashion for compression specimens from sine regression) and for rubber 0.19 (determined with DMA at 20°C). No significant difference was observed for the loss factors measured with DMA with different frequencies and the values agreed with literature [15]. The loss factor values for different samples are shown in Table 2. The loss factor value for specimen C1 was not possible to be determined, because of difficulties with servo-hydraulic material tester.

Table 2. tanδ values for dynamically loaded compression specimens measured from MTS data.

Specimen	**C1**	**C2**	**C3**	**C4**	**C5**
tanδ	-	0.21	0.26	0.27	0.21

The theoretical temperature was calculated from Equation 1 for compression test specimens using two different data sources for modulus and tanδ. The values were determined from DMA measurements and the servo-hydraulic material tester (MTS) data. In the theoretical temperature calculations the steel plates are expected to stay at 20°C. The theoretical and measured temperatures of bulk rubber are compared in Table 3.

Table 3. Theoretical and measured temperatures of cyclic loaded specimens under compression. Theoretical temperatures are calculated from Equation 1.

Specimen	**The compression of the rubber [%]**	**f [Hz]**	**Measured temperature [°C]**	**Theoretical temperature (DMA) [°C]**	**Theoretical temperature (MTS) [°C]**
C1	28%	2	93	328	-
C2	7.50%	2	29	28	26
C3	7.50%	6	31	43	43
C4	18%	2	51	94	98
C5	18%	6	94	243	201

The theoretical temperatures for specimens C1 (2 Hz, 28%) and C5 (6 Hz, 18%) were considerably higher than the observed ones. This results from the assumption in Equation 1 that the steel plates are at constant temperature and that no heat is consumed to structural changes, which were observed in these specimens. For the other specimens the theoretical and measured temperatures are closer to each other due to small heat generation that is assumed to reduce the error between the theory and experiments.

Minor softening was observed in the compression test specimens during the first hour of testing according to the displacement data. As discussed in the introduction, the softening of rubber is strongest in the beginning of the loading which was also observed in the tests. During the four-point bending test the deflection of the structure grew slightly, but the changes were small and no plastic deformation was observed after testing.

The rubber-steel structure should be designed so, that the deformation takes place elastically in the component. According to the results it can be assumed that dynamic bending does not cause significant heat generation and the component design can be done on the basis of temperature data from compression tests. Exact acceptable loading ranges for the investigated structure based on this study cannot be defined because of the limited amount of specimens and the rather short testing program. But on the basis of the tests a rough estimation of recommended operation conditions can be seen which is also demonstrated in Figure 7. It should be noticed, that the Figure 7 is valid only for the compression specimens investigated in this study and the shape factor corrections should be done for specimens with other dimensions.

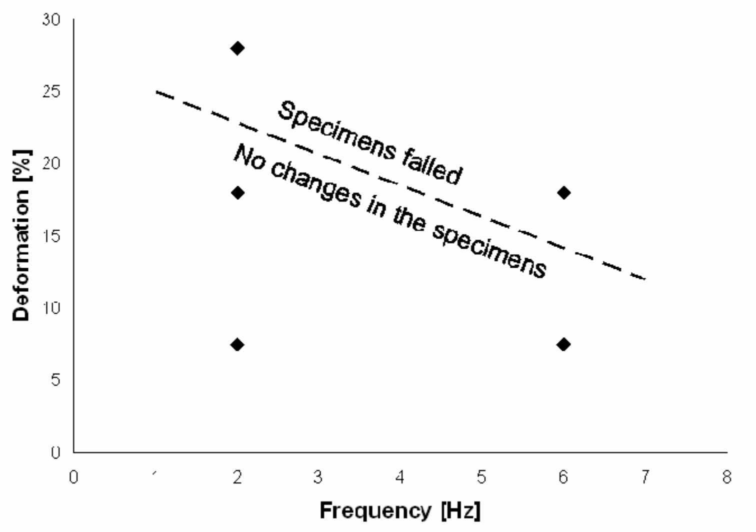

Figure 7. The acceptable loading range for the investigated compression samples.

To ensure the exact operating conditions for the investigated hybrid structure, several parallel tests should be done. In addition, tests at higher and lower temperatures and in other test modes would be important to carry out. If the fracture tolerance of rubber needs to be enhanced, the shape factor of the rubber layer should be increased. Thus the thinning of the rubber layers decrease the bulge effect. In addition, the heat buildup in thinner layers is less significant than in thicker layers. To maintain the required stiffness, the number of steel and rubber layers has to be increased.

CONCLUSIONS

The aim of this research was to investigate how a hybrid rubber-steel sandwich structure behaves under cyclic loading and tolerates the possible heat buildup in the rubber layer. The structure is designed to applications where it is exposed to long term dynamic loadings. A subject of interest was also the mode of failure.

It was observed, that the fractures appear in the rubber layer when certain load and frequency limits are exceeded. With small deformations the hybrid rubber-steel structure is suitable to be applied in structural components under dynamic loadings, but redesign must be done for harsh environments. The following conclusions were made:

1. Under high load levels the heat generated in the rubber exceeds service temperature of SBR and thus limits the utilization of the investigated SBR-steel structure.
2. The theoretical temperatures describe well the experimental temperatures of the investigated specimens when the deformation and frequency levels are low. When the load and frequency levels are higher, the theoretical temperatures are considerably higher than the observed ones.
3. Based on the results exact safety limits for the loading conditions are difficult to set, but with further research better estimations of recommended loading range can be given.

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