MECHANICAL ASPECTS OF HIGH DAMPING RUBBER

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SUMMARY

Natural rubber is applied frequently in civil engineering structures because of its high elasticity, high damping and large elongation at failure. A very important application is elastomeric bearings for seismic isolation of structures. They are usually assembled by horizontal alternating layers of rubber and reinforcing metal shims. In a special design the shims are inclined by an angle, so the horizontal stiffness is different in the two in-plane directions, which is beneficial in for establish proper seismic isolation. If this bearing is subjected to a lateral displacement the response of the rubber layers isn't any more simple shear, as in the horizontal layout. Therefore more effort is needed in the constitutive description of the material. To better understand the material behavior the chemical composition is described. Next the important properties of a rubber compound developed especially for rubber bearings is presented. Finally some aspects of mechanical behavior is discussed, followed by the future work that will be done.

Keywords: high damping rubber, base isolation

1. INTRODUCTION

Rubber has many useful applications in engineering, cause of his special properties. Nowadays many important products that meet high requirements are made of rubber, such as tires, seals, vibration mounts, bearings for bridges and for seismic isolation.
The concept of seismic isolation provides a protection to structures against dynamic excitations. The increased cost in construction becomes very efficient during future earthquakes. In the field of seismic isolation rubber bearings were found to be very capable, because of the beneficial properties. The characteristic properties of rubber are: (1) it can undergo very high deformations, up to several 100% in simple tension, (2) the typical stress–strain plots are highly nonlinear, (3) the material appears as (nearly) incompressible.
In the traditional design bearings for seismic isolation are assembled by alternating layers of rubber and reinforcing shims, which are horizontally disposed. These bearings have the same horizontal stiffness in the two principal in-plane directions. In seismic protection it is beneficial to have different stiffness in the two in-plane directions to provide a better protection to very distinct dynamic characteristic structures, such as

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bridges. Therefore a special design is investigated, where the reinforcing shims are inclined by an angle, see Figure 1. This leads to a higher stiffness in the direction of the inclination angle. In the other direction the shims have no inclination and therefore the same stiffness as the flat bearings (Dorfmann, Castellano, Bergmeister, 1997).

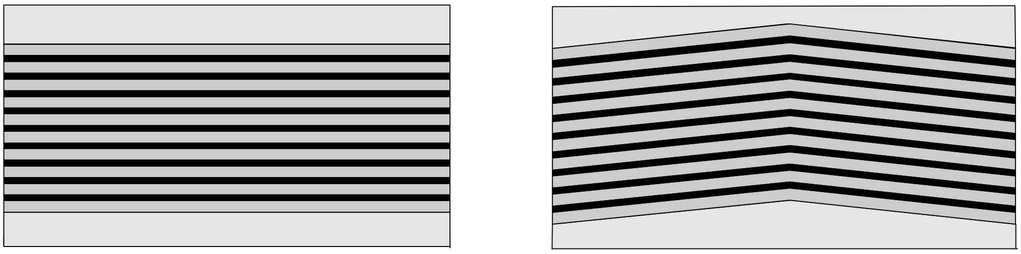

Figure 1: Section of bearing in conventional (left) and new design (right).

When a lateral displacement is applied the rubber layers of the flat bearings respond in simple shear, this is not the case for the bearing with the inclined shims. In this case more effort is needed to describe the constitutive behavior of the material and find a suitable material model for a finite element analysis. By doing this a more extensive knowledge of the material behavior is necessary. To better understand the material a short representation of the chemical constitution, the main mechanical properties and some aspects of mechanical modeling are given in the following.

2. CHEMICAL CONSTITUTION AND COMPOUNDING

From a chemical point of view rubber is a hydrocarbon, described by the chemical formula $(C_5H_8)_n$. C_5H_8 is called an isoprene and natural rubber is built up of regular sequences of isoprenes, which are arranged in cis-configuration, forming long chains of high elasticity, see Figure 2. The chains are kinked and lie in the material like agitated snakes, they are perfectly regular in the backbone and have freely rotating links at given distance.

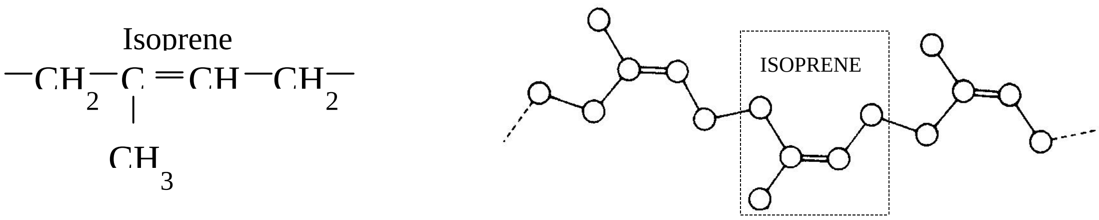

Figure 2: Structural formulae of one isoprene molecule (left) and structure of a chain molecule (right), (after Treloar, 1975).

In raw rubber we have only a few weak crosslinks between the chains. When subjected to a external force the chains disentangle and break up crosslinks. Thus, material flows and undergoes large displacements until breakage of links or an equilibrium state is reached. By vulcanizing (Treloar, 1975 and Gent, 1992) additional crosslinks are established and a coherent network is formed. If then subjected to a external load the respond is (visco)elastic. When rubber is dynamically loaded, a part of the energy is stored in the medium, that can be released by unloading or breakage of crosslinks. The

remainder of the energy is dissipated by thermal effects. With an increase of cross-link density the network becomes more tight and the motion of the chains become more impeded. The network is incapable of dissipating much energy, which results in high hardness, low elongation and brittle fracture. Thus rubber has a optimal cross-link density range for practical use, that must be high enough to prevent failure by viscous flow, but low enough to avoid brittle failure.
To improve properties rubber is often reinforced by particulate fillers, such as carbon black and silica. For the filler it is of importance that the particles are very small and posses high specific surface area. When filled compounds are strained to a large extent, they show the effect of strain softening. This phenomenon is probably caused by the breakdown of weak chemical bindings between filler and rubber molecules. Unfilled or lightly filled compounds do not show a significant degree of stain softening.
After the material is molded, rubber can stay in a crystalline, a rubbery or a glassy state, depending strongly on temperature, but also on compounding. The motion of the chains is strongly influenced by the thermal energy in the system. By lowering the temperature to a point where any motion is eliminated, the rubber becomes hard and rigid like glass. This temperature is called the glass transition temperature and is –71°C for unvulcanized and a few degrees higher for the vulcanized rubber. On the other side rubber can be safely used up to a ambient temperature of about 60°C.
To determine durability, tests were performed (Fuller, Gough, Pond, 1992) on two bridge bearings, in use for over 30 years. The tests showed that their stiffness have increased only by 5 % for one and 15 % for the other bearing. Accelerated ageing tests (Fuller, Muhr, Pond, 1996) on high damping rubber testpieces showed that the oxidative ageing extends only 2 mm into the rubber block.

3. MECHANICAL BEHAVIOR OF HIGH DAMPING RUBBER

The high damping rubber is a special development done by the Tun Abdul Razak Research Center (TARRC), Brickendonbury, UK. The main mechanical properties of rubber are characterized by quantities like bulk modulus, shear modulus at certain strains, tensile strength, elongation at break, damping and hardness. For the high damping rubber compound the main mechanical constants are listed in Table 1.

Property	HDR
Bulk modulus (MPa)	2500
Tensile Strength (MPa)	13.5
Elongation at Break (%)	700
Shear modulus [a] (MPa)	0.55
Damping [a] (%)	14
G(-20)/G(20)	2.2
[a] at 100% strain and 0.5 Hz.	

Table 1: Mechanical properties of high damping rubber on a testpiece: 2mm thick, 25 mm diameter, T=23°C (given by the TARRC).

The tensile and the shear stress-strain curves are highly nonlinear, see Figure 3. They show a high initial stiffness, that decreases with increasing strain, then the stiffness remains approximately constant and increases at the end. The first effect is seen as a consequence of the reinforcing filler, the increase in stiffness at the end arises from the finite extensibility of the chains and possibly also strain crystallization. The material is initially isotropic, but when rubber is strained, the chain molecules orientate in direction of straining, and the rubber becomes anisotropic. With repeated loading, crosslinks may be broken and the load carried by the rubber is lowered. After the first cycle the load is lowered most, but small changes are also observed after many cycles. This effect is called strain-softening (Mullins effect), see also Figure 5.

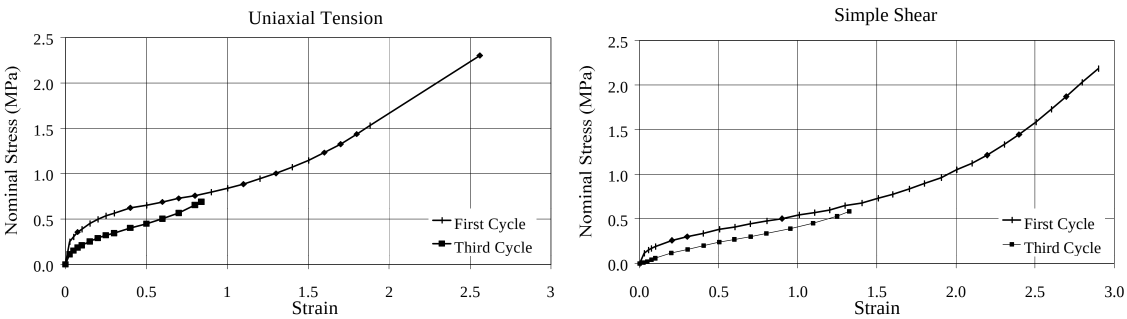

Figure 3: Tensile stress-strain and simple shear of high damping rubber (given by the TARRC).

The temperature has also a great effect on the rubber. Early studies of Gough in 1805 on unvulcanized rubber showed (1) that rubber held in stretched state, under a constant load, contracts (reversibly) when heated; and (2) that rubber gives out heat when stretched. These conclusions where confirmed by Joule on vulcanized rubber about fifty years later. These effects are called the Gough-Joule effects (Treloar, 1975). It can be seen in Figure 4 that the modulus for –20°C is 2.2 times the modulus at +20°C and the damping at –20°C is 1.3 times the damping at +20°C. The ratio of the moduli between –20°C and +40°C is 2.5, which is very high, when we consider this temperature range occurring between summer and winter.

Rubber subjected to cyclic loading dissipates energy in form of heat. This dissipation arises from the internal friction of the disentangling long chain molecules. This also provides the damping ability of rubber. Rubber is a very poor heat conductor with a thermal conduction coefficient of about $0.2-0.3\ W/m\cdot{}^{\circ}C$. Thereby a internal heat build up is induced. The generated heat depends on the strain amplitude, which is affected by the stiffness of the rubber and the load amplitude. It can be concluded that the rise in internal temperature is not necessarily produced by e.g. the ambient temperature or by sunlight. In Figure 4 the changes in modulus and damping up to strains of 150% are evaluated. The plot shows that the ratio between 5% and 100% strain for the modulus is 5.4 and for the damping is 1.5 For the design of applications it is very important to know that the modulus and also the damping are lowered due to temperature, strain and due to cyclic loading.

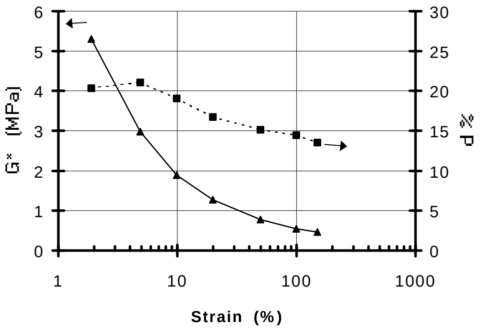

Figure 4: Effect of strain amplitude and temperature on shear modulus and damping (3^{rd} cycle data, strain sweep at 0.5 Hz)(given by the TARRC).

In another test high damping rubber bearings are subjected to compression and shear load. The compression load is applied first and kept constant during the test. Then the bearings are subjected to simple shear. The bearing is built of alternating layers of flat reinforcing shims and rubber layers. The rubber layers are therefore subjected to compression and simple shear. The shear strain is computed form the total number of rubber layers times their height. Special in these test is that the rate of applied shear strain is varied (Muhr, 1995) and the strain rates are 1, 10, 100, 200 $\% s^{-1}$. It can be observed in Figure 5, that for higher strain rates the stress is higher at the corresponding strains, and also that the breakage of a rubber layer occurs at higher stresses and higher strains. The stress at breakage for the strain rate of 200 $\% s^{-1}$ is about 1.7 times higher than at a strain rate of 1 $\% s^{-1}$.

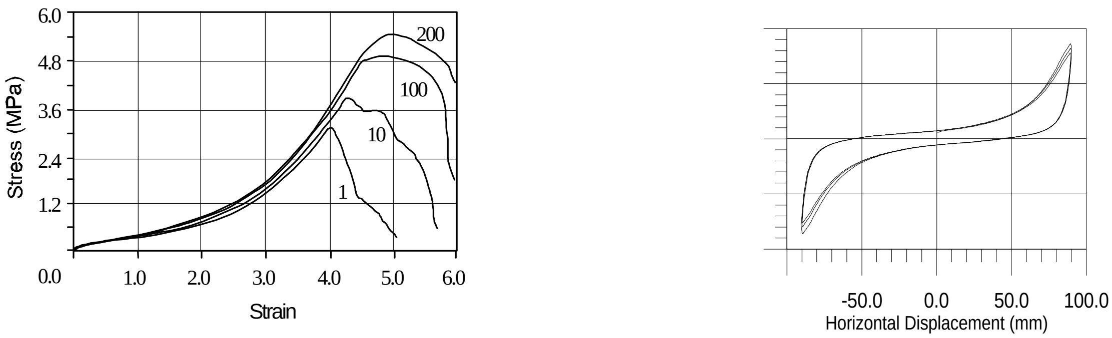

Figure 5: (a) Effect of strain-rate on shear-strain and shear-stress on High damping rubber bearings (23°C, 25mmÆ, h=6mm), the parameter is the strain-rate in $\% s^{-1}$, and (b) hysteresis loop for a displacement of 90 mm, g=428%, strain rate=12 $\% s^{-1}$, (after Muhr, 1995).

When we load and then unload a rubber specimen we can see that the loading path is not equal to the unloading path, see Figure 5b. This effect is called hysteresis. In our case we have load cycles and the plot is called a hysteresis loop.

4. MECHANICAL MODELS

Some aspects of different kinds of material behavior are discussed. At this point we do not investigate in thermodynamics (P. Haupt, 1993) and regard the material under isothermal conditions.

When classifying materials and selecting a proper model some effort should be done, before doing hasty interpretations. First it should be checked if the material is rate-dependent or rate-independent. In the case of rate-independence does the material show a hysteresis or not. In the other case, when the material is rate dependent, the loading process needs to be slowed down to end up with a quasi-static process. Then we can see if the material shows a quasi-static hysteresis. The proper model for the material is distinguished by: Rate-dependence or rate-independence, with or without hysteresis, with or without static hysteresis. This leads us to four different classes of material behavior, see Figure 6 and Figure 7. These four classes of materials and corresponding material theories are: (1) the elastic, which is rate independent and shows no hysteresis effect, (2) the plastic, which is rate independent, and hysteresis is incorporated, (3) the viscoelastic is rate dependent and has no quasi static hysteresis effect, and (4) the viscoplastic that is rate dependent and shows a quasi static hysteresis effect. The material models are commonly described by means of springs, viscous damper and friction elements. For every class of material discussed the rheological model is given.

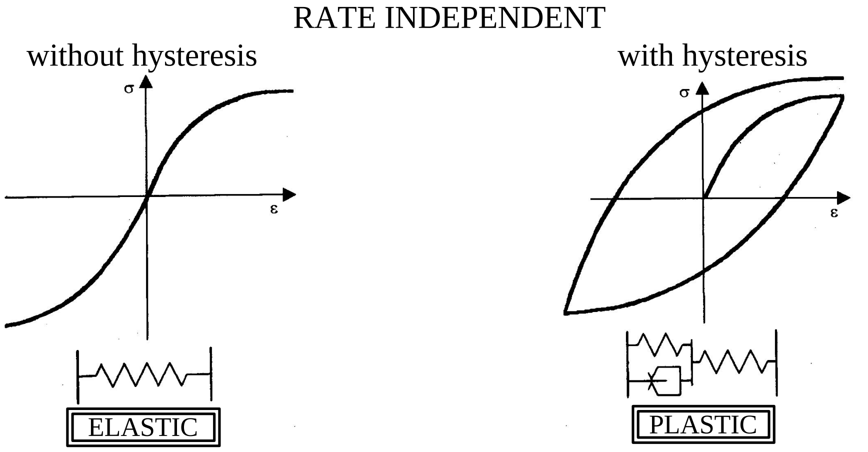

Figure 6: Stress-strain behavior of rate-independent materials (after Haupt, 1993).

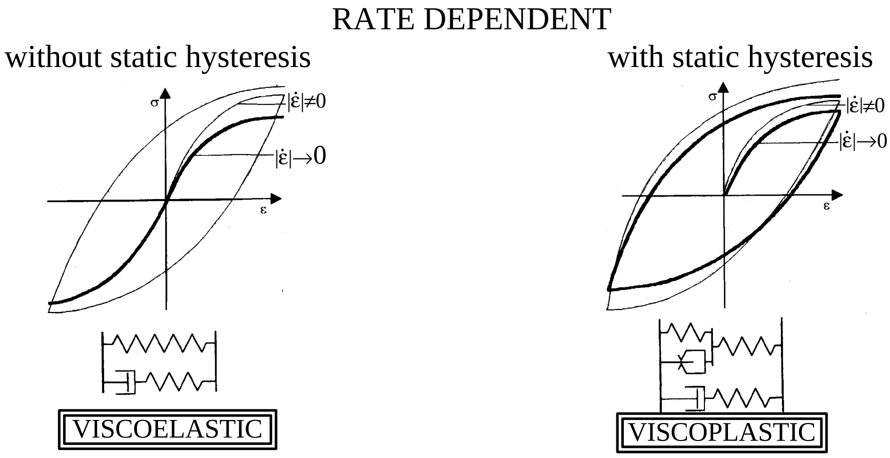

Figure 7: Stress-strain of rate dependent materials (after Haupt, 1993).

By simply regarding on the stress-strain plots no distinction can be made. To classify it is necessary to know of the rate dependence of the material. From the previous chapter we know that rubber is rate dependent. A dynamic hysteresis effect occurs in the strain cycles, performed at a strain rate of 12 $\%s^{-1}$, see Figure 5a and b. Rubber has no static hysteresis and is therefore a viscoelastic material. The viscoelastic material differs strongly from the elastic. Additional to the effects mentioned above is creep, relaxation, a frequency dependent stiffness matrix and damping. When the strain rates are very small rubber can be described as a hyperelastic material.

In the case of the high damping rubber bearings, presented in the introduction, the design process will be supported by finite element computations. The computations are done within the scope of the HARIS (High adaptable rubber isolation systems) project. In the finite element analysis the bearings are subjected to a constant compression load and then to a lateral displacement. As mentioned in the beginning the bearing with the flat shims responds in simple shear, this is not the case for the inclined one. For these computation a constitutive model that describes the behavior of rubber will be implemented into the finite element code abaqus.

5. CONCLUSIONS

In the beginning a new design approach for elastomeric bearings for use in the field of seismic isolation is presented. The main issue of this bearing is to have different stiffness in the horizontal two in-plane directions. The second improve to the bearing is the special compound developed to provide a high damping. The finite element code abaqus will be used to support the design process. But first investigation is needed to find a proper material model.

6. REFERENCES

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