

Engineering, A Survey

This special of 'Natuurrubber' deals with rubber in engineering applications. The following papers take the reader on a journey along calculation methods with FEA and computers, some spectacular, but also some general applications, compounding aspects and relevant properties, etc.

In the first paper attention is given to the historical development of the mechanical design aspects of rubber products with the emphasis on the empirical methods developed by the Rubber-Stichting and the MRPRA, still sufficient for simple constructions. The next three papers are dealing with calculations and analysis of rubber components by some FEA computer programs. One paper shows the relation between compounding and physical and mechanical properties. The other papers give examples on the use of rubber as an engineering material. For those readers who are not familiar with rubber technology, some typical rubber terminology used in the papers, is shortly explained in subtexts. Many papers and books have been published on the subject, some are (very) old but in our opinion still worth studying, some are of more recent date. The literature at the end of this issue, deals with both categories and is only our selection, not pretending to be complete.

The editors



Bearings sector door 'Maeslantkering' (see p.15)

Special on Engineering Contents

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History

The use of natural rubber in engineering applications began at the middle of the nineteenth century. For instance already in 1850 rubber springs were used for dray wagons. A more spectacular application, described in many publications is the use of 12 mm thick rubber blocks in 1889 to support a railway viaduct in Melbourne. Today the original NR parts are still functioning adequately. An inspection and analysis of the rubber in 1963 showed a perfect condition. In analysing the rubber a very primitive formulation was found, as might be expected. Little is known about the design aspects and it is doubtful if any systematic approach was used.

After the founding of the Rubber-Stichting in 1936 with the aim to propagate the proper use of NR - also by engineers - many papers were published about the static and dynamic mechanical properties of rubber, the application as anti-vibration material and data about rubber as an engineering material. This work was mainly done by C.W. Kosten and lead a.o. to his thesis '*Over de elastische eigenschappen van ge vulcaniseerde rubber*' (1942, 'On the elastic properties of vulcanized rubber'). These publications, however old, are still useful and worth studying. Kosten developed simple formula for calculating the deformation of rubber blocks under compression, introducing in a genius way a clever method to deal with the shape factor, Young's modulus etc.

That his work has not lead to a world-wide acceptance has several reasons. Most of his publications were in Dutch and World War II hampered general circulation. Moreover, Kosten left the R-S during the war. Later on the R-S took up the subject again, but had to stop its research activities in 1955.

In the meantime at the BRPRA (later MRPRA) in England the subject obtained more attention and it was especially P.B. Lindley who promoted with an unique approach the way engineers can calculate simple rubber components. This lead in 1964 to his famous small 'blue' book '*Engineering Design with Natural Rubber*' in which he used a.o. a different approach for the shape factor. After four editions and a reprint his work is still available. After his death MRPRA edited in 1992 a complete revised edition.

Both approaches (Kosten and Lindley) made it possible for engineers to calculate in a rather simple way and relatively accurate the deformation of rather simple components under

Hardness

This is the most often measured property of rubber. The hardness as measured by for instance a Shore A Durometer is closely related to the modulus of elasticity (Young's modulus). A Shore Durometer measures the penetration of a conically shaped indenter into the rubber. The result is expressed in a value between 0 and 100 Shore A (Sh A). Engineering rubbers usually have a hardness between 55 and 75 Shore A

Avoid tensile strains

Stretching a rubber makes it more sensitive to environmental influences like ozone in the air and also can lead easily to premature rupture. Therefore it is essential to avoid tensile strains and to design in such a way that the rubber is compressed whenever possible.

On the other hand, rubber is almost incompressible, meaning that compression in one direction usually causes tensile strains in other directions. For optimal long term use, compressive strains between 15 and 35% are quite common whereas tensile strains should be avoided as much as possible.

Another simple rule is that products which will be used under dynamic loadings preferably should be designed in such a way that there is always a positive stress in the direction of loading (never allow the stress to become zero).

quasi-static conditions. For more complicated rubber articles including an irregular shape (seals) or a complicated structure (tyres) this approach is of course not sufficient.

Due to the development of Finite Element Analysis (FEA) and computer simulated models it is nowadays possible also to calculate stress-strain behaviour in more complicated rubber articles. The book '*Engineering with Rubber*' edited by A.N. Gent treats this subject extensively. The complications originally encountered with rubbers, such as non-linear behaviour and visco-elasticity, are nowadays more or less overcome as notified from contributions to this issue of *Natuurrubber*. Modelling with FEA is however not adequate yet for dynamic behaviour and effects of hysteresis and strain history; research on these aspects is going on.

Furthermore, one has to realize, that the information obtained never can be better than the information fed into the computer. The latter statement means that the best results come from calculations based on parameters measured on the actual compound to be used for the product.

Empirical methods

In many cases however, the use of sophisticated and costly computer programs is not necessary because the empirical formulas based on the 'old' methods can be used. The empirical approaches of Kosten and Lindley will be discussed in short below.

The stiffness of a product does not only depend on the elasticity of the rubber, but also on its shape. Rubber is nearly incompressible. Uni-axial compression of a rubber layer whose loaded areas are constrained (e.g. by bonding) causes the rubber to bulge laterally at the force-free area. The result is that it is rather easy to compress for instance a cylinder with an height which is about the same as its diameter, whereas it is very difficult to compress a cylinder with a height which is small compared to its diameter. In the latter case, the rubber from the center only can 'escape' by moving to the side which asks for a lot of energy.



Both Kosten and Lindley take the shape in account to correct for this apparently higher modulus in compression. Both also use for rubber in the first instance the simple Hookean formula

$$\sigma = E_0 \cdot \epsilon$$

σ = stress, E_0 = Young's modulus, ϵ = relative compression (strain). This formula is a good first approximation when the deformations are not too large.

Kosten found that when using an apparent ('work') height h_0' , instead of the real height h_0 and using E instead of E_0 the compression can be calculated rather accurately.

$$\text{For a cylinder } h_0' = h_0 - d/8 \text{ (when } h_0 > d/4) \\ E = 5M_{25}$$

where d = diameter and M_{25} = modulus at 25% elongation.

$$\text{For a long strip } h_0' = h_0 - 0.22b \text{ (when } h_0 > b/2) \\ E = 6.67M_{25}$$

where b = width.

He also estimated a correlation between M_{25} and hardness. This simple approach works surprisingly well.

Lindley works with a shape factor S , defined as the ratio of one loaded area to the total force free area.

$$\text{For a cylinder } S = \frac{d}{4 h_0}$$

$$\text{For a block } S = \frac{l \cdot b}{2 h_0 (1 + b)}$$

$$\text{For a long strip } S = \frac{b}{2 h_0}$$

where l = length.

Instead of the Young's modulus he uses as compression modulus E_c .

$$E_c = E_0 (1 + 2k \cdot S^2)$$

k is a numerical factor. The Young's modulus has a relation with hardness and goes from about 0.9 MN/m² for a hardness of 30 Shore A to about 9.4 MN/m² for a hardness of 75 Shore A. The value for k is also depending on the hardness and goes from 0.9 for 30 Shore A to 0.5 for 75 Shore A.

In the revised edition of his bulletin:

$$E_c = 3G (1 + 2S^2)$$

where G = shear modulus, to be obtained from measured relationships, between G at different strains and the hardness.

Using these empirical formulas, a first estimation of the deformations under a given stress can be made without knowing the exact properties of the rubber to be used. For simple constructions such estimations will be sufficient and more expensive simulations by use of a computer can be avoided. For critical applications more calculations have to be carried out. These can be done by using other rather simple empirical formulas or by computer models. For both it should be noted that all calculations will still be an estimation of what is likely to happen in practice. The real behaviour depends on the exact compounds used and many hardly to define details in use like small deviations in temperature, tolerances and so on. However, whatever method is used, the best way to have good products still is testing the prototype product under practical conditions or at least under simulated service conditions.

This paper deals only with deformation aspects. Also the fatigue resistance, influenced by the dynamic stress-strain behaviour, is very important. This complicated subject is treated in most of the recent literature in the literature list.

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² Rubber-Stichting.

Marc Computer Programs for Rubber in Engineering Applications

Dr. Ir. Bert Knops¹

Rubber is used extensively in many applications because of its unique performance and a number of specific properties like:

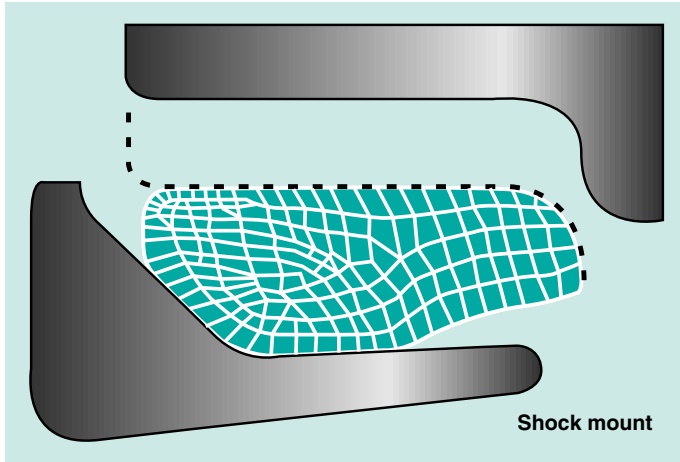
- excellent energy absorption and damping characteristics;
- resilience, low hysteresis and flexibility;
- long service life at ambient temperature;
- ability to seal against moisture, heat, and pressure;
- moldability in different hardness and stiffness;
- non-toxic properties.

Until recently rubber products used in engineering applications and components as a part of an engineered product were often developed by trial and error. A rubber component was developed with a Computer Aided Design-package (CAD) and a prototype was built. Based on experimental testing, a new model was re-

designed, produced and tested. In order to shorten this development loop and also to obtain a better understanding of the behaviour of a rubber component the Finite Element Analysis (FEA) method can be applied.

The FEA method is a Computer Aided Engineering (CAE) technique to determine the behaviour of components under external loads. At first the component is divided into a large number of small pieces (elements) that are connected at their corner points by nodes. Next the finite element approach results in a large number of coupled equations where the unknowns are the degrees of freedom in the nodes. In a mechanical analysis these unknowns are the displacements and rotations. Finally, these nodal unknowns are determined by solving the total system of equations.



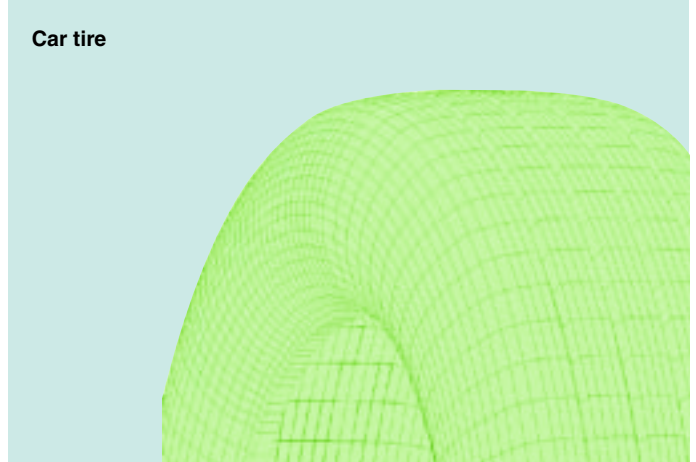
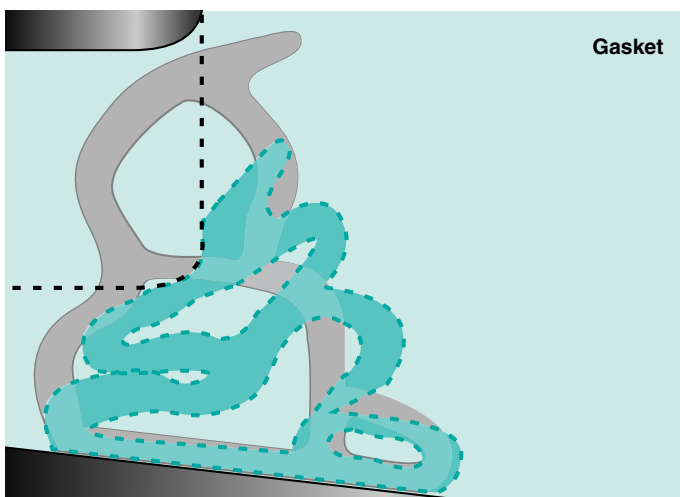


The FEA method can be used to determine the behaviour of a rubber component. However, proper analysis of rubber components requires special material modelling and non-linear finite element analysis tools that are quite different than those used for metallic components. The unique properties of rubber are such that:

- it can undergo large deformations under load, sustaining strains of up to 500% elongation in engineering applications;
- its load-extension curve shows a markedly non-linear behaviour;
- its visco-elastic behaviour exhibits significant damping properties, unlike with other materials its behaviour is time- and temperature dependent;
- it is nearly incompressible. This means that its volume does not change appreciably under stress.

Efficient and realistic analysis for design of rubber products relies on several important concepts:

1. *Non-linear material behaviour* - compressible or incompressible material models, time and temperature effects, presence of anisotropy due to fillers, textile and metal components, hysteresis due to cyclic loading.
2. *Automatic determination of material parameters from test data* – the most troublesome step for engineers is to ‘curve fit’ test data and derive parameters necessary to characterize a material.
3. *Dynamic behaviour* – this concerns hysteresis, harmonic analysis of time- and frequency dependent visco-elastic materials and implicit versus explicit direct time-integration methods.



4. *Modern automated contact analysis techniques* – friction effects, and the use of ‘contact bodies’ to handle boundary conditions at an interface.
5. *Graphical ‘user interface’* - issues related to model preparation, non-linear analysis and ease-of-use of the simulation software.

Some of these options are available in a number of finite element packages. One of the options, that differs per package and is very important for the analysis of rubber components, is the contact algorithm. The deformation of the rubber component is quite often determined by the contact between the rubber and other components. This is the case, for instance, for bearings, dampers, seals, tyres, etc. Because the contact region is not known in advance and because the quality of the solution is depending strongly on the accuracy of the contact, it is important to deal with the contact in an accurate, natural and user-friendly way.

Because Marc has since more than 25 years experience in the field of non-linear FEA, all the options mentioned above are standard features in the FEA-package. Especially the automatic contact algorithm, where the user does not have to define things like ‘gap elements’, ‘interface elements’, ‘contact stiffness’, etc. is one of the key developments at Marc and is available in the package already for more than 10 years.

On the basis of the experience of and feedback from a lot of customers that are using the FEA-package for rubber applications the user-friendliness, quality and robustness of Marc is continuously improved. This has resulted in a software package that is ‘state of the art’ in the field of mechanical and thermal, static and dynamic, non-linear FEA of rubber.

In the figures one can see a few relatively simple applications that were analysed with Marc. In all these applications contact is included which again shows that in many rubber applications the quality and accuracy of the solution is strongly dependent on the contact algorithm that is used.

¹ Marc Analysis Research Corporation-Europe, Zoetermeer, The Netherlands

Resilience

The term resilience can be explained best by thinking of a ball: when one drops a rubber ball and it bounces back to almost the dropping height, the rubber is called ‘highly resilient’, when not the resilience is low.



Diana is a large scale general finite element computer program. Its development has been initiated at TNO Building and Construction Research in the early 70's. At TNO the program still enjoys a continuous development and maintenance plan to keep pace with the ever changing needs of engineers and technologists. Currently, top scientists of major Dutch and foreign technical research institutes and universities are involved in the development of Diana. These developers are members of the Diana Foundation which coordinates the research activities.

Analysis of a Rubber Conveyor Belt

The following example, excerpted from the Diana users manual, illustrates the analysis of a rubber conveyor belt. Such a belt usually consists of several layers of polymer material like rubber and reinforcement in different directions. Figure 1 shows a simple laminate of two textile layers, core rubber and surface rubber.

This type of rubber conveyor belt breaks down when the rubber material and the fabric disintegrate by failure of the fabric-rubber interface. In this example the stress distribution in the core rubber is determined to investigate the stress concentration near an incision in the conveyor belt. For this purpose incisions are made in a representative portion of the belt as indicated. The belt is loaded by a fixed displacement in X direction. At the incisions the applied force must be transferred from the upper fabric to the core rubber and then to the lower fabric.

The finite element model for the part within the dashed box of figure 1 is easily generated with Diana's mesh generator. In this example we apply quadrilateral plane strain elements: regular eight-node elements for the fabric and special nine-node elements with additional pressure degrees of freedom for the rubber material. The mesh consists of 8×1 elements for

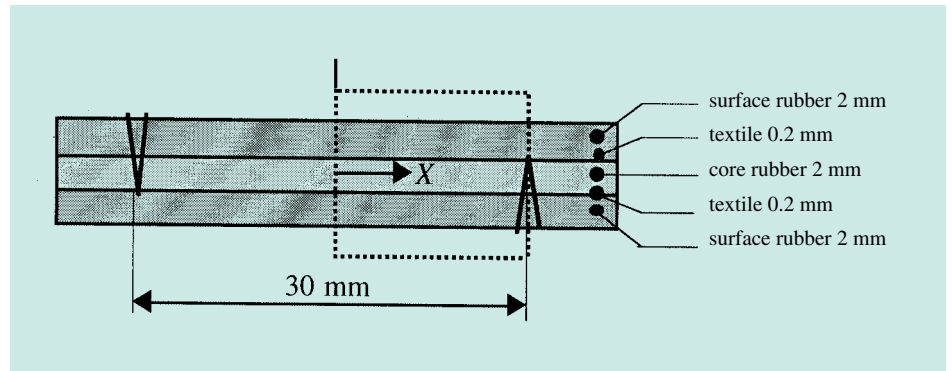


Figure 1: Conveyor belt with incisions.

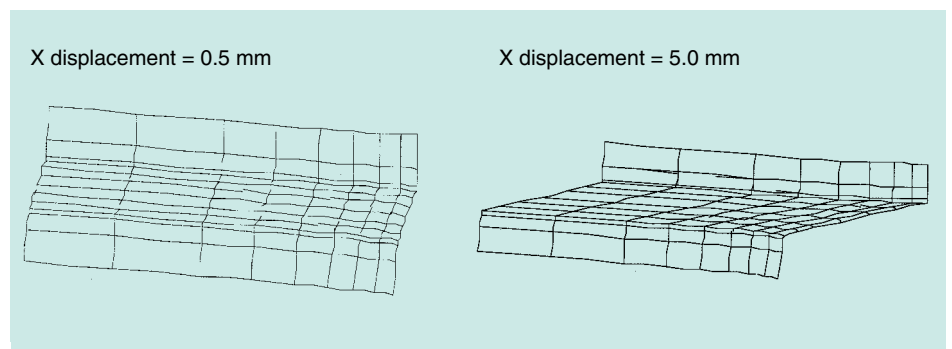


Figure 2: Deformed mesh (true scale).

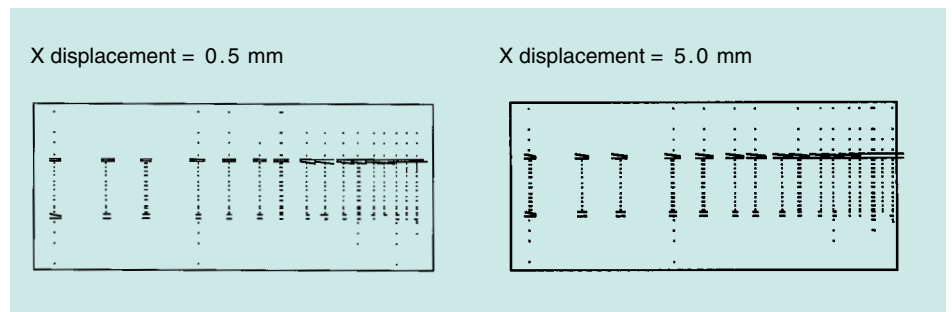


Figure 3: Principal Cauchy stresses.

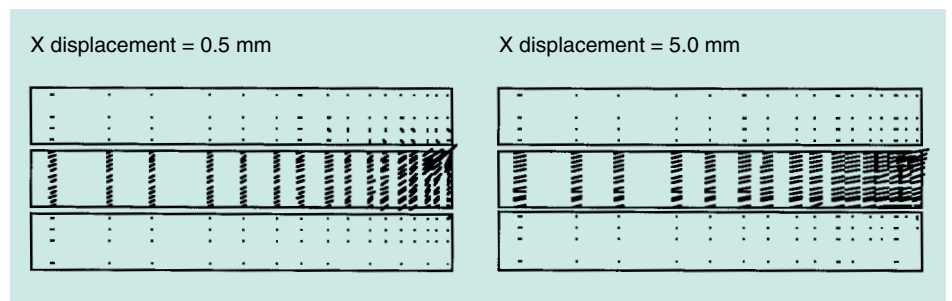


Figure 4: Principal Cauchy stresses in rubber.

each textile layer, 8×2 elements for each surface layer, and 8×6 elements for the core, which yields 96 elements in total.

For the 2 mm thick core rubber and the surface rubber, a simple Mooney-Rivlin

law is utilized as an estimation of the mechanical behaviour. For this example, the Mooney-Rivlin constants were derived from experimental results. For the fabric, for which a linear elastic isotropic material is adopted, a proper

stiffness for elongation and bending is specified.

The non-linear analysis is performed in two stages: first until a horizontal displacement of 0.5 mm (left hand in the figures 2, 3 and 4), then further until 5 mm (right hand in the figures 2, 3 and 4).

Figure 2 shows true-scale plots of the deformed mesh after the two analysis stages. In the beginning we see a rotation of the belt until the upper fabric approximates the X axis. For materials dealing with large displacements (geometrical non-linearity) and large strains a distinction can be made between the stress relative to the undeformed state, called the second Piola-Kirchhoff stress, and the stress relative to the deformed state, the so-called Cauchy or true stress.

Diana calculates the second Piola-Kirchhoff stress and transforms it to the Cauchy stress for output purposes, taking into account the change of orientation and area of the body. For small displacements and small strains both stress measures are identical. The plots of figure 3 show the distribution of the Cauchy stresses corresponding with the deformation states of figure 2. We see that in the core rubber hardly any stresses occur. This is due to its low stiffness for distortion deformations relative to the fabric. However, if we select only the rubber elements then the stress plots are scaled in a way that we can analyze the stress concentration in the core rubber, see figure 4.

Figure 5 shows two load-displacement curves of the point where the load is

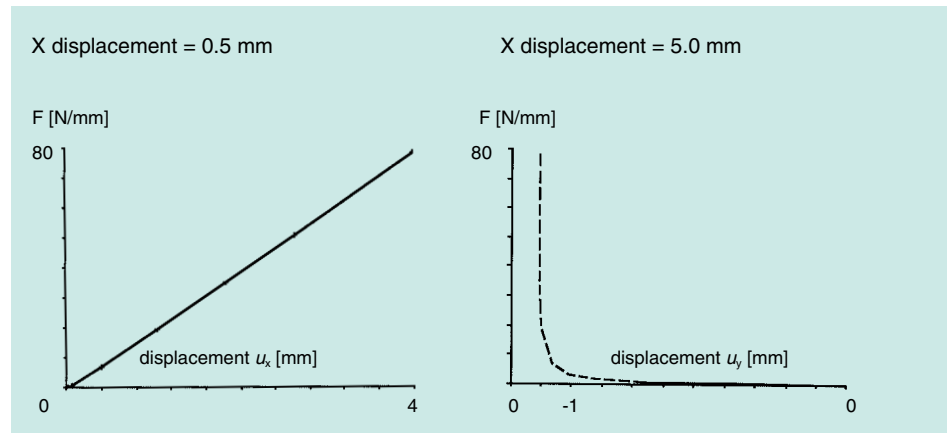


Figure 5: Load-displacement curve of loaded node.

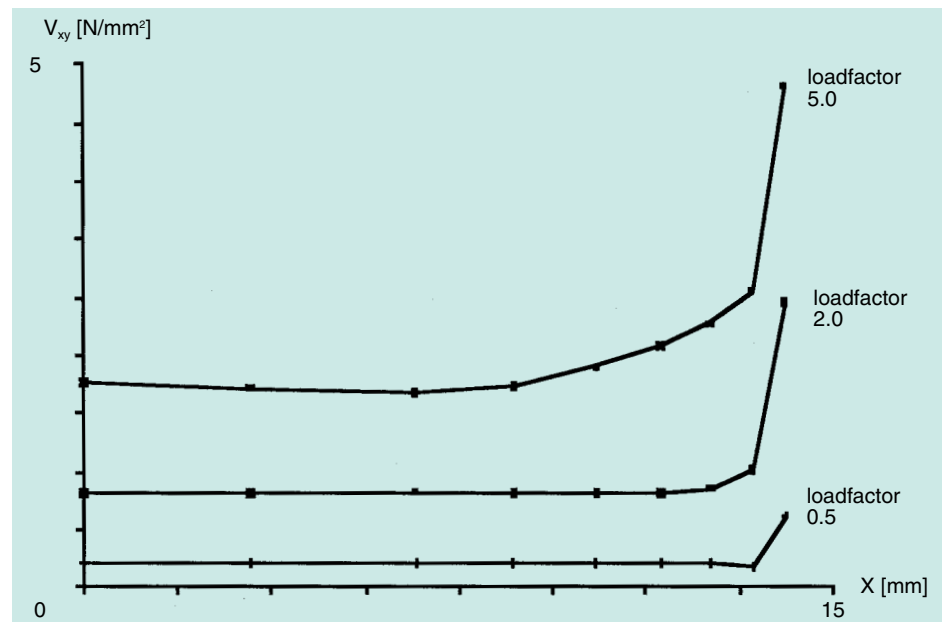


Figure 6: Cauchy stress v_{xy} in the rubber near upper fabric.

applied. The solid line, representing the relation between the load and the horizontal displacement u_x , is nearly linear due to the dominant influence of the textile. The dotted line demonstrates the rapidly increasing vertical displacement u_y at a low tensile force. At a force of 5 N/mm and higher the vertical displacement remains almost constant. In general, with these stiffening type of structural response, the regular Newton-Raphson solution scheme does not work properly. For this reason the modified Newton-Raphson solution scheme was selected in this example. In figure 6 the shear stress v_{xy} in the rubber, just beneath the top textile layer is plotted as function of the X coordinate.

As could be expected, high stresses occur near the right incision, from which it can be concluded that in this zone a delamination of the core rubber and the textile is likely to initiate. By varying

The rubber, or hyperelasticity model in Diana is a non-linear elastic model, accounting for large strains and large displacements. The material data defines a strain energy function. Three well-known models are available to describe the deviatoric part of the strain energy function, respectively attributed to Mooney-Rivlin, Besseling, and Ogden. The hydrostatic part of the strain energy function may be described via an incompressibility model, or via a linear or non-linear compressibility model.

the geometry of the used materials, the influence on the stress concentration can be studied.

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Developed by civil engineers from a civil engineering perspective, Diana's most appealing capabilities are in the fields of concrete and soil. Models for plasticity of metals, for instance applied for embedded reinforcements in concrete, are also available. Last but not least we mention the rubber model, which are suitable to analyze civil engineering structures, like tunnels and locks, which have rubber or rubber-like parts. However, the rubber model is also fit for analysis of complete rubber structures as we will briefly illustrate in the sequel of this article.



A Time-dependent Constitutive Model for Rubbers¹

Dr.ir. E.G. Septanika²

Introduction

In the applications of rubbers two problems often arise: one of them concerns their mechanical performance, while the other concerns their manufacturing process. During the manufacturing process extremely complex chemical interactions are being occurred, e.g. vulcanization, and other chemical interactions. At the same time, physical interactions are also occurred, e.g. formations of additional entanglements, rubber-filler attachments, and other type of physical bonding. These interactions, being primarily formed at the processing temperature and may become non-active or extremely low after cooling.

Further, in the cooling-down process a kind of re-arrangement of physical bonding may occur (yielding residual stresses). The net result of these kinds of re-arrangements should yield a relatively higher strength than before cooling, due to a lesser mobility of the rubber matrix and filler components. It is widely assumed that these kinds of molecular re-arrangements are responsible for the rubber hysteresis behaviour (also called Mullins' effect) in a short-duration repetitive deformation program, causing a permanent softening behaviour.

In the long run, due environmental influences (e.g. oxygen molecules and radiation attacks) a kind of alteration mechanisms may be occurred, in which some types of chemical interactions are multiplied while the others are deteriorated. The rate of alteration mechanisms may eventually depend on temperature. It is assumed that the rubber long-term behaviour is governed by these kinds of history-dependent alteration mechanisms. The rubber behaviour is being accompanied by inelastic time-dependent phenomena such as creep, stress-relaxation, permanent-set and also ageing-induced flexibility changes.

In this paper, a description of an adequate time-dependent constitutive model for filler-reinforced vulcanized rubbers will be shortly discussed.

Rubber hyperelasticity

In the rubber hyperelastic descriptions two major classifications often arise. The first group is based purely on experimental observations, so-called phenomenological-based models (e.g. the Mooney-Rivlin model, the Ogden model). In general, the capability of the models from this group depends on the number of model parameters in the strain energy expressions. The second group sought to explain the large-strain behaviour from the nature of rubber molecular structure, so-called molecular-

based models. The models from the second group are capable of describing the wide-range of rubber elasticity by using a fix number of model parameters. The present paper will mainly be focused on the rubber hyperelastic description according to the last group.

According to molecular-based models the overall (or the macroscopic) mechanical behaviour of rubbers can be described by means of a 3-D network of (polymeric) chains that are cross-linked at junction-points. A single chain can be thought as a flexible line of connected rigid-links (so-called chain-bonds) being randomly oriented. The chain deformation behaviour can be described either using the Gaussian or the non-Gaussian model. This approach is widely known as the network theory of rubber hyperelasticity. In this theory, it is assumed that the stress in the network arises primarily from the tendency of the chains to randomize the junction-points so as to maximize the entropy of the network. This is in contrast with crystalline solids where the stress is primarily due to the distortion of the inter-atomic potential fields, resulting in a change of internal energy relations obeying all types of rubber materials.

One of the crucial assumptions is that the entropy contribution from the fluctuation of junction-points is negligible compared to that of network chains. So, the network entropy should be obtainable by simply summing the contributions of each individual chain. Using statistical thermodynamics one can express the entropy of a chain in terms of the number of rigid-links, the length of a link and the distance between chain-ends. Further, by adopting the so-called affine-deformation assumption, the junction-points can be looked upon as discrete points according to the continuum model. Therefore, in the course of deformation the end-to-end vector is being transformed according to deformation-measures of the continuum model (e.g. through the deformation-gradient tensor). The macroscopic stress in the network can then be expressed in terms of the rubber modulus, the number of rigid-links and the amount of length-ratio of the chains.

Hysteresis model

It is assumed that the physical cross-links due to rubber-filler attachments, filler-filler attachments and entanglements are relatively weaker than the chemical cross-links. So, the physical cross-links may be ruptured under the application of relatively small external loads. It also appears that the strength of physical bonding are also temperature-dependent, i.e. the lower the temperature the stronger the bonding. Hence, in a typical stress-relaxation test at low temperatures, an initial stress decay is most probably caused by the slippage and rupture of the physical bonding. Further, it also appears that the character of the stress decay strongly depends on the filler concentration.

In a short-duration repetitive deformation test with increasing amplitude, the strain softening in the unloading path can then be thought as being caused by the slippage and rupture of the physical cross-links in the previous loading path.

Hysteresis

Deformation of a rubber requires a certain amount of energy.

Releasing afterwards does not return all energy: there will always be some loss. This loss becomes apparent by heat development, especially on repeated deformation. This is why tyres are hot after a long drive.



Tabel 1 Model Compound

Components	phr
SIR CV60	100
N550, FEF black	20
Light oil, e.g. <i>Fina Process Oil 2059 (Petrofina)</i>	2
Zinc oxide	5
Stearic acid	2
Wax blend, e.g. <i>Sunproof Improved (Uniroyal)</i>	2
Sulfur	3.25
CBS	0.8
Rheological properties of modified Indonesian rubber	
Mooney viscosity, 100°C	29
Mooney scorch, 120°C, min.	33
Scorch, ts1, min. <i>Monsanto Rheometer, 140°C</i>	11.3
Cure, tc'(95) <i>Monsanto Rheometer, 140°C</i>	28

Time-dependent model

The long-term time-dependent behaviour of rubbers is thought as being caused by an alteration mechanism involving chemical cross-links. Due to aging effects, the strong chemical bonding may be ruptured, and at the same time, a portion of chains is reformed comprising a microstructure different than the initial one. It is assumed that the newly formed chains do not contribute to the stress at the moment of nucleation (the so-called Tobolsky hypothesis). Therefore, due to ageing effect the whole network chains can be divided into the network of the initial chains and a number of networks that being formed by newly formed chains. By employing Tobolsky's hypothesis one is able to characterize the newly formed network chains by the corresponding deformation state in which they were nucleated.

Large-strain measurement system

For large-strain measurement purposes, an automatic and interactive measurement system has been developed based on image processing. This system is provided by a CCD-camera and an XYZ-positioner (i.e. a servo-controlled camera). Before measurement, the rubber surface is furnished by a number of polystyrene globules. During deformation the movement of these globules are closely monitored by the camera. Based on the globule positions, one can determine the state of deformation at the rubber surface as a function of the time. The camera position has been synchronized by means of a point-following procedure, in such a way that the globules are 'always' visible during measurement.

Numerical examples

The proposed time-dependent constitutive model discussed here, together with the corresponding material parameters, has been implemented in the finite element package Diana. In the implemented model both geometrical and material non-linearity have been taken into account. To demonstrate the capability of the proposed time-dependent constitutive model, a few examples are presented, selected from the author's personal work. The experimental data have been obtained by employing a particular rubber compound as specimens (tabel 1), which is a model compound based on Indonesian Rubber. In this compound the antioxidant is intentionally omitted, in order to accelerate the ageing process.

Long-term rubber creep

Long-term creep tests have been performed at a temperature of 80°C, in which the specimens are furnished by four globules with a diameter of about 0.1 mm. In these tests the specimen is loaded by a constant true-stress, which can be realized using the

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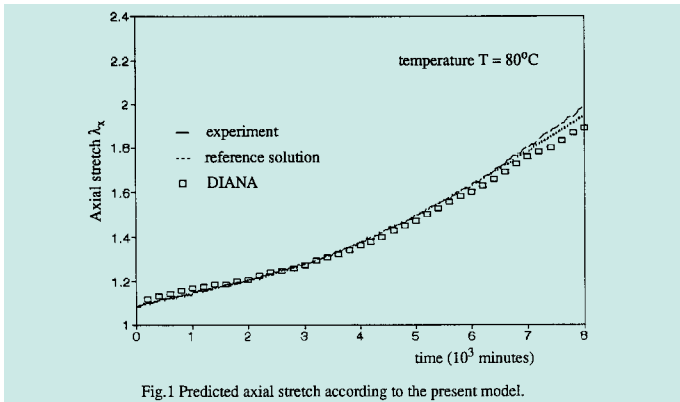


Figure 1: Predicted axial stretch according to the present model.

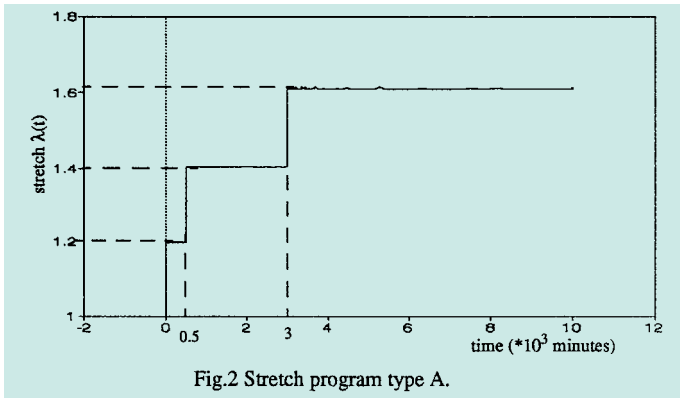


Figure 2: Stretch programme type A.

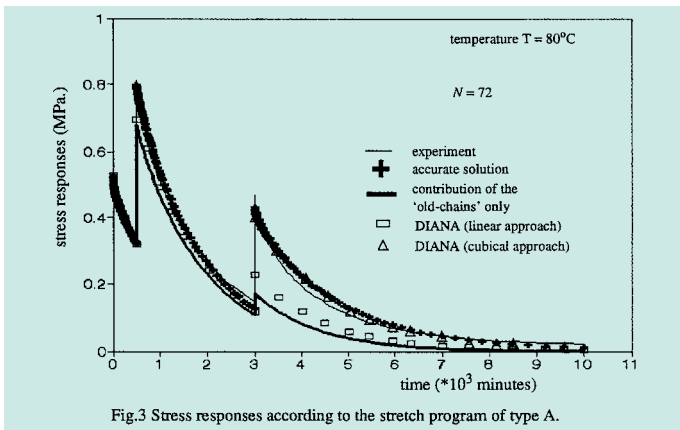


Figure 3: Stress responses according to the Stretch programme type A.

proposed large-strain measurement system. The time-dependent stretch $\lambda = L(t)/L_0$ is determined by using the relative globe positions. The results of measurements and the output of numerical calculations are presented in figure 1.

Multi-step relaxation tests

The existence of newly formed network can be investigated by means of multi-step relaxation tests, in which the specimen is subjected to a number of constant-strain level (figure 2). Without the interference of the newly formed networks, the instantaneous stiffness will be determined by the (damaged) initial network only. From experimental observations, it appears that the actual stiffness is higher than according to the prediction employing the old deteriorated network only. This phenomenon justifies the assumption of the newly formed networks. The result of investigations is depicted in figure 3.

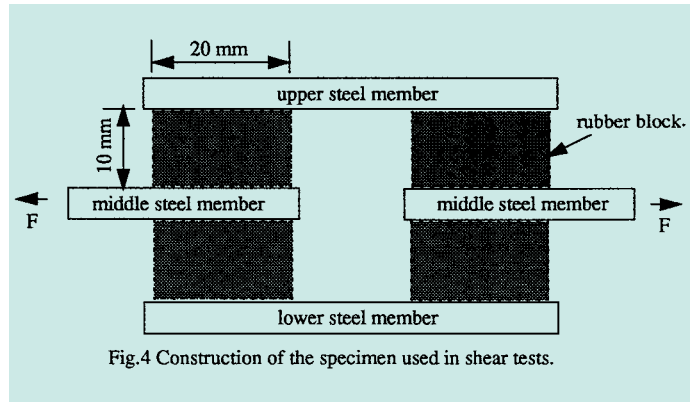


Figure 4: Construction of the specimen used in shear tests.

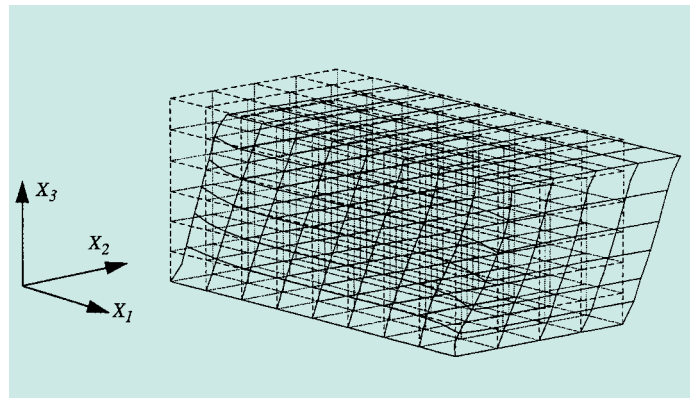


Figure 5: Mesh distribution (---undeformed — deformed)

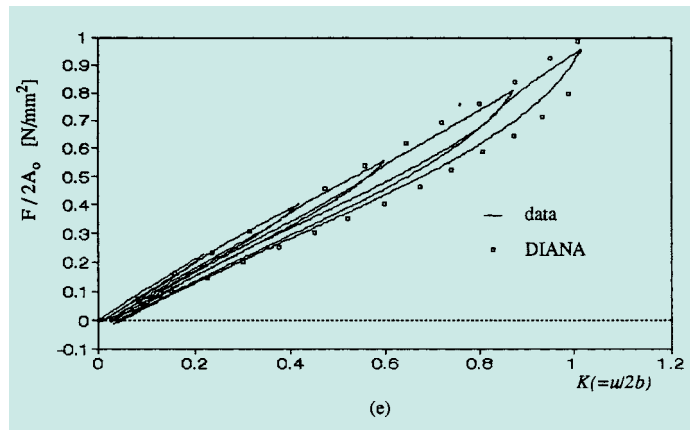


Figure 6: Stress-strain responses (Mullins' effect)

Hysteresis test of shear-blocks

The shear-blocks used for experiments contain four rubber blocks, which are bonded to four steel members (figure 4). To create shear deformation, a horizontal displacement is imposed in the middle steel members with a constant strain speed of approximately 100 mm/minute. This type of test demonstrates the capability of the proposed hysteresis model and the capability of the implemented finite-element model in describing a relatively complex 3-D deformation situation. The result of simulations is shown in figures 5 and 6.

¹ Summary of his Ph.D thesis 'A time-dependent constitutive model for filled and vulcanized rubbers', November 1998

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Natural Rubber (NR) is a very versatile engineering material. The applications of NR are still increasing both in diversity and extent. A few examples are: dock fenders, spring insulated buildings, bridge bearings, marine engineering, seals for tunnels and sluices etc.

Natural rubber has been successfully used as an engineering material for many years. That natural rubber is the most versatile engineering material can be shown by the following properties:

- hardness adjustable from very soft to very hard (ebonite);
- appearance from translucent (soft) to black (hard);
- electrically insulating or fully conductive;
- compounded to meet almost any mechanical requirement;
- silence noise and absorb vibration;
- protect, insulate and seal;
- available in any shape and surface roughness.

The choice of type of natural rubber depends on the purpose for which it will be used. Hence, it was felt necessary to produce rubbers that meet the requirements on the following criteria:

Stress relaxation

When rubber is deformed, counterforces are excited. These forces usually decrease with time after deformation. Stress relaxation measurements give insight in the rate of decay of the counterforces. This is important for sealing applications.

At ambient temperature and for a shorter period at higher temperatures, the stress decays linearly at a logarithmic time scale and is therefore expressed as a percentage of the initial stress per decade of time. Then, the decay of stress between 10 minutes and 100 minutes after stretching is the same as that between 1 day and 10 days or 1 month and 10 months. At higher temperatures, the stress relaxation behaviour depends in a complicated way both on temperature and shape c.q. volume of the product.



latex quality, non smelly, cost competitive and good (physical) properties. The different types of NR are specified in the Technical Specified Rubber (TSR) scheme which was first introduced by Malaysia (SMR). Nowadays, also new types of NR are available such as superior processing grades (SP/SA), epoxidized natural rubber (ENR), thermoplastic natural rubber (TPNR), deproteinized natural rubber (DPNR) and SUMAR (low smell natural rubber). A feature of natural rubber is that it can be compounded to have high resilience, high strength and high fatigue resistance simultaneously. The desired physical properties can be achieved by compounding.

To achieve required properties the raw natural rubber has to be compounded using ingredients such as carbon black, softeners, anti-degradants and a vulcanization system.

Raw natural rubber is a very high molecular material. To mix NR and ingredients the NR has to be masticated. Mastication shortens rubber molecular chains, resulting in a reduced molecular weight. Only than ingredients can be homogeneous distributed into the rubber.

The compounding rules to achieve the properties wanted are shortly given in the next part of this overview.

Hardness

Hardness and reinforcement are determined by the amount and the type of filler, by the degree of dispersion and by the cross-link density. Carbon black is the most common rubber filler in engineering applications. Sometimes white fillers such as silica and clay are used instead of carbon black. For maximum tensile properties about 25 volume percent carbon black is needed. To lower the hardness at that level softeners are used.

For low creep properties the level of carbon black should be kept to the minimum acceptable level. If the application requires a high resistance to abrasion a small particle size type

carbon black is necessary. The stiffness of a rubber product is determined by result of the modulus of the rubber, the mode of deformation, the shape of the product and its dimensions.

Modulus

The modulus of a rubber is also determined by the amount of filler. For a low modulus product normally low reinforcing blacks or (non-reinforcing) white fillers are used. The modulus can be influenced by the rubber grade (viscosity) and by the vulcanization system.

Low modulus properties could be reached by the use of a soluble efficient vulcanization (EV)-system, based on soluble accelerators, activators and low sulfur level. The modulus of black filled natural rubber is almost independent of the temperature over a range from about -20°C to over +100°C. Below -20°C the modulus increases as the temperature is lowered. The addition of 20 parts of di-iso-octyl sebacate (DOS) per hundred parts of natural rubber will lower the temperature performance by about 10°C.

High resilience

Resilience decreases as filler level is increased. For high resilience the filler level has to be kept to an acceptable amount to maintain (physical) properties. Medium particle size/high structure blacks give low hysteresis because only moderate amounts are needed to increase modulus.

High damping

High damping can be reached by filler/oil extensions using high viscosity oil or by blending with synthetic rubbers such as SBR, EPDM or NIR. The damping is a consequence of the synthetic polymer having a T_g not far under normal service temperatures. A further consequence of the proximity of the T_g to room temperature is that the modulus of the blend increases significantly below about 10°C especially when the proportion of the acrylonitrile/isoprene rubber (NIR) is high. For this reason the most useful blends are probably covered by the range NR/NIR from 90/10 to 70/30.



Low compression set

Engineering products with low compression set values in outdoor applications can be vulcanized with organic peroxides. However, large compression mould products are prone to scorch because it is not possible to delay peroxide vulcanizates by using delayed action chemicals. Secondly peroxide vulcanized products have a poor tear strength and are incompatible with anti-ozonants. Therefore, in practice, conventional vulcanization (CV) or semi-efficient vulcanization (SEV)-systems are normally used.

Low creep/relaxation

For good creep/relaxation resistance the filler content has to be kept at a minimum acceptable level and uses medium particle sized blacks. Replacement of stearic acid by zinc-2-ethyl hexanoate (ZEH) lowers the physical creep/relaxation rate. For a low creep/relaxation rate a soluble EV-system is advised. A relaxation rate of less than 3 % per decade of time is possible. By the use of the low sulfur system the long term behaviour of those products is very good. The good thermal stability keeps also the secondary chemical creep/relaxation and compression set at elevated temperatures comparatively low.

Cross-link density

The degree of cross-linking affects various properties. The cross-link density for maximum tear strength is slightly

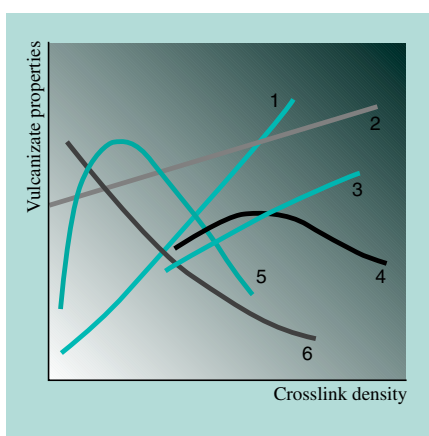


Figure 1: Vulcanizate properties vs. crosslink density.

1 Static modulus, extrusion resistance and blister resistance. 2 High speed dynamic modulus. 3 Hardness. 4 Tensile strength. 5 Tear strength, fatigue life and toughness. 6 Hysteresis, permanent set, coefficient of friction, elongation and compression set.

lower than for maximum tensile strength and abrasion. Resilience, compression set, creep and relaxation resistance are best at somewhat higher levels of cross-linking (figure 1).

Crystallization

Crystallization occurs when rubber is stressed or frozen. When rubber is stressed crystallization begins at moderate strains and at higher stresses more crystallites are formed. The reason for this phenomenon is that the crystallites are oriented in one direction of the extension. The crystalline structure is primarily responsible for the high strength and tear resistance. At low temperatures (-25°C) the rubber crystallize due to freezing. This effect is a reversible process, when temperature rises the formed crystals melt quickly. Vulcanized rubber crystallizes more slowly than raw rubber due to cross-linking. CV-systems (high sulfur systems) are extremely resistant to low temperature crystallization.

Bonding

The techniques for bonding are well known in the industry. For high bond strength the use of CV-systems gives the best results. For large products (bridge bearings) with a large surface area, semi-EV or EV systems could be used. In case of low temperature applications EV-systems crystallize rapidly, in that case high sulfur systems (CV) give products that are resistant to low temperatures. To obtain satisfactory bonds, the steel inlay's have to be well cleaned and avoid bloom on the rubber surface in the case of compression moulding.

Heat resistance

Heat resistance (including resistance to compression set, creep and stress relaxation at high temperatures) is performed by peroxide vulcanization. It gives the best possible thermal stability plus low creep rate, however, those vulcanizates have inferior mechanical properties. To attain the best heat protection, peroxide vulcanization must be carried out to completion (eg. post-cure) since un-reacted peroxide acts as a pro-oxidant. To overcome inferior mechanical properties, vulcanization based on soluble EV system could be used in conjunction with most powerful anti-degradants. By using anti-degradants a mixture of anti-oxidants is advisable,

because mixtures are more effective than a single anti-oxidant. For non-black compounds phenolic anti-oxidants are used because their non staining properties. There is evidence that for protection against high temperature ageing it is best to use an anti-oxidant that has a low volatility even though it may be less chemically active than a more volatile one.

Weathering resistance

Weathering of rubber is mainly degradation near the surface that can be attributed to the effects of oxygen, ozone and ultra-violet light. Engineering components made of rubber are seldom positioned in direct sunlight. UV-light is in rubbers for outdoor applications mainly no problem because carbon black in rubber acts as a UV-absorber. For non-black compounds phenolic anti-oxidants are used or UV-stabilizers. In most cases, traces of ozone attack the rubber surface when the rubber is stretched. Therefore it is advisable to include waxes or chemical anti-ozonants. For the use under static strains hydrocarbon waxes will prevent formation of cracks, provided that a wax appropriate to the exposure temperature is chosen. For dynamic strains an anti-ozonant of the substituted para-phenylene diamine class, either alone or with wax, is necessary. In special occasions it is possible to blend natural rubber with an amount of 25 phr EPDM rubber based on polymer.

Flex-cracking resistance

Fatigue life or flex-cracking resistance is highly sensitive to strain, decreasing as the maximum strain is increased. Components should be designed to operate, where possible, under static load over which the dynamic load is superimposed. For good flex cracking-resistance the use of para-phenylene diamine anti-ozonants is advisable. In particular alkyl-aryl derivatives are effective, they also provide protection against oxidation.

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Natural Rubber Bearings for Seismic Protection

Kevin P. Jones¹

During the 1998 International Rubber Study Group meetings in Bali there was a mild earth tremor which disturbed the sleep of some of the delegates and was strong enough to empty the contents of one briefcase onto the floor. It was sufficiently strong to create fear in some of the delegates who come from seismically quiet zones, but was insufficiently violent to disturb the writer who felt disappointed at missing an opportunity to experience one of nature's most awesome displays.

The present economic crisis in South East Asia may stem at least in part from the devastating earthquake which hit Kobe in Japan three years ago. This claimed more than 5,000 lives, injured more than 25,000 and destroyed over 45,000 homes. Motorways and railway lines collapsed at more than ten different locations in the city and the surrounding area. Rebuilding the city may take years and the destruction has had a significant effect upon the Japanese economy. The world fears the terrible economic effects which would result from a comparable event near Tokyo. In the Global Village everyone is in danger from the consequences of seismic activity, and it is surprising that so little is being done to mitigate the risks, especially as it is now widely accepted that prediction of seismic events is unlikely to be achieved, and even if it could be, the destruction of buildings would still continue.

On average 10,000 die each year from earthquakes: UNESCO estimated that 350,000 died from this cause between 1926 and 1950. When compared with global road accident statistics these fatalities may appear almost trivial until it is remembered that earthquakes are capable of enormous, simultaneous devastation over large areas. Many major cities are located on, or near, major centres of seismicity: these include Mexico City, Los Angeles, Tokyo, Kobe, Calcutta, Bombay, Cairo and Lisbon. Such events are capable of enormous disruption. Individual earthquakes have caused immense loss of life: Tang-shan in China claimed 665,000 lives on 27 July, 1976. 83,000 were killed in Messina in Italy in 1908. The numbers are almost beyond human comprehension.

Some areas are far more seismic than others. The countries on the Pacific Rim (Chile up to Colombia, through Central America, California, Alaska, Japan, the Philippines, and the Indonesian island arc are especially prone both in terms of severity and frequency (Bali was devastated twice within little more than a century). The areas near active mountain building, notably the Himalayas, the Middle East, and around the Mediterranean are also subject to frequent and violent events. The Greek island of Kephallonia (Kefallinia) tends to be decimated at intervals of about a century: unlike many parts of Greece, Kephallonia is not noted for its Classical antiquities. Most buildings post-date the almost-total devastation of 1953.

The International Rubber Research and Development Board and the Tun Abdul Razak Research Centre (MRPRA) have had a long association with the base isolation of seismic protection. The concept grew out of the far gentler realms of natural rubber bridge bearings and the introduction of bearings to isolate structures from the rumble of underground, or sub-surface,

railway trains. MRPRA (or its predecessors) had been associated with these developments since the 1950s and mid-1960s, respectively. This early involvement is returning great dividends as it has been possible to closely monitor the behaviour of the bearings installed under the Pelham Bridge in Lincoln, England and the Albany Court flats in St James, London.

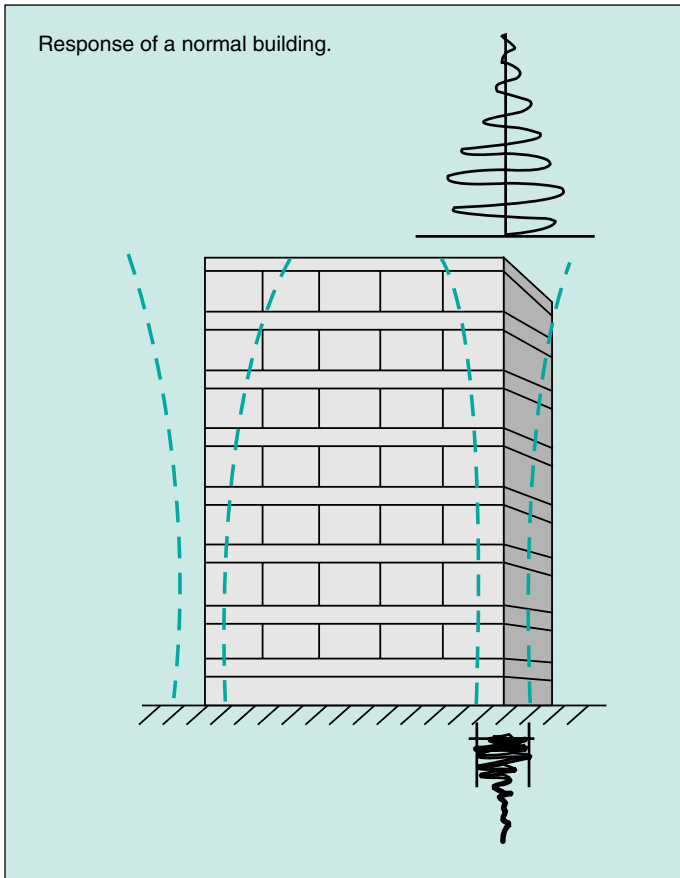
In the case of the Pelham Bridge, eight 37-year old bearings were removed from bridge for examination, although they still appeared to be in excellent condition. Tests showed that the average of their shear stiffnesses was only 7 per cent greater than the corresponding observation on an original prototype. Tests for oxygen content and reacted anti-degradants suggested that oxidation is confined to distances up to 10 to 20 mm from the surface. Tensile tests on the rubber indicated a drop in strength and elongation at break only at depths less than 10 mm below the surface which indicates that oxidative changes are confined to a relatively small surface region and that the bulk of large structural bearings age anaerobically. The bearing shear stiffness tests indicate that the anaerobic changes, at least for conventional structural bearing rubbers, are acceptable. In the case of the Albany Court flats, measurements show that creep has remained within the limits predicted when the building was constructed over thirty years ago.

The seismic isolation system is similar to that used for protecting buildings from the sound from trains in that it makes use of rubber/steel laminated bearings to support the whole building to enable its natural frequency to be reduced below that of the most damaging earthquake forces. The development of this base isolation system was begun in 1972 by two MRPRA physicists, Prof. Alan Thomas and Mr C.J. (Des) Derham, in collaboration with Prof. Jim Kelly, Director of the Earthquake Engineering Research Center at the University of California, Berkeley, where the system was subject to tests on a shaking table. In 1990, MRPRA was awarded the Plastics and Rubber Institute's (now part of the Institute of Materials) seventh Prince Philip Award for the development and successful application of natural rubber bearings for earthquake protection of buildings.

The world has become accustomed to the pictures of devastation caused by earthquakes, but it is rare to see moving images of earthquakes in progress as the cameraman is usually thrown off balance even if he is sufficiently brave to continue filming.

As mentioned in Mr Jones' paper not only in earthquake sensitive regions, buildings are built on rubber blocks. For European cities some examples are: In London some buildings (Bishopsgate/Liverpoolstreet station and Victoria Station building) are built on rubber blocks from Vredestein. The largest dimensions of the used blocks are 1200 mm by 1000 mm. Along the metroway in Amsterdam also some buildings are built on rubber blocks. In Rotterdam, around the old harbour, historical merchant houses were rebuilt on rubber blocks from Trelleborg Bakker.

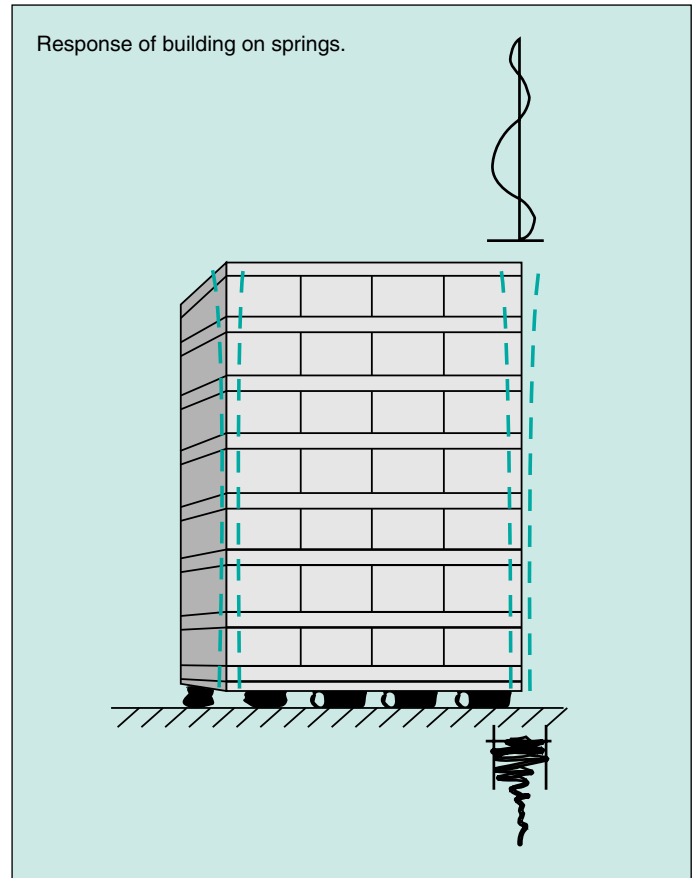




Far more convincing are pictures of shaking tables where the full recorded force of actual seismic events is fed into model structures. In the case of shaking table tests on structures protected by rubber bearings the table oscillated violently; the model structure swayed but gently whilst the bearings contorted into positions which appeared to defy what engineering components should do, but then so do tyres in everyday service. At that time staff at MRPRA met weekly to discuss current research. When shown the video images of shaking table experiments at the University of California the staff sat in awe, especially when they remembered that the five-storey model weighed 36 tonnes.

The first building to be protected from earthquakes using the MRPRA designed base isolation system was the Foothills Communities Law and Justice Center in San Bernardino, California, which was opened in 1985. The structure uses ninety-eight 0.4 m x 0.75 m bearings supporting loads of 30-270 tonnes, and is designed to resist a major earthquake of magnitude 8.4 on the Richter scale. It has experienced events of 4.5 and 5.5 magnitudes, and the bearings successfully reduced the forces on the building as predicted.

The Law and Justice Center is a major building and is intended to act as an emergency centre following a major seismic disaster. It was considered that the technique is also applicable to far more modest buildings, especially those appropriate to poorer countries. To demonstrate this a low cost apartment block has been erected using the technique near Bogor on the island of Java in Indonesia. The area is extremely seismic and it was hoped that it would be possible to test the structure within a short period. Construction was funded by UNIDO and the funds were channelled through the IRRDB. The building was a deliberately low cost structure of the sort appropriate to a



relatively poor country. As well as being suitable for housing it could also serve as a model for a pharmacy, or a station for local emergency services. Computers and radio transmitters would not be damaged during a severe episode. Protection is afforded by high damping natural rubber (HDNR) bearings.

TARRC, with UNIDO's assistance, was also involved in the construction of an eight-storey apartment block in Shantou, China, and in the retrofitting of an existing five-storey masonry building in Armenia with sixty bearings. If retrofitting had been applied to the Basilica of St Francis in Assisi, then the destruction and associated loss of life would have been spared and the famous frescoes would still be there for future generations. TARRC has offered advice on a great many projects from telephone exchanges in Italy to nuclear power stations in Scotland. Nobody has ever heard of a major earthquake in Scotland, although minor episodes occur quite frequently, but nuclear containment vessels need to be protected against even the slightest risk. Similarly, major bridges in nominally quiescent areas are usually protected just in case the unthinkable occurs.

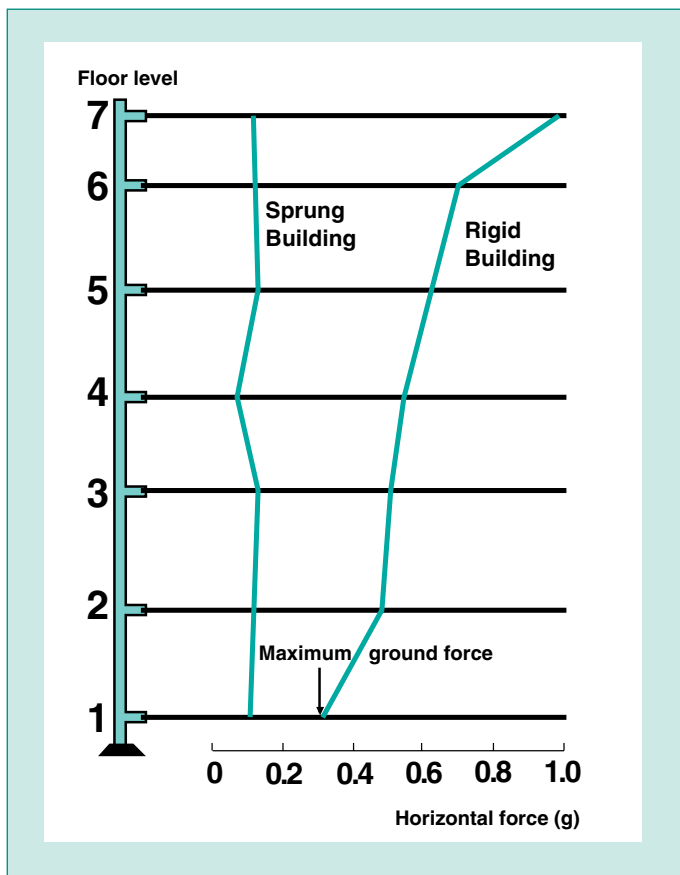
Reports from the Kobe earthquake suggest that most of the buildings which failed were erected at least 25 years ago, before strict rules on construction were introduced. The extent of damage was compounded by the spread of fire among wooden buildings from fractured gas mains. Graphic news footage showed the hazard to office workers posed by movement of furniture and cabinets. Newer buildings designed to resist earthquakes did so, and emergency services and communication networks worked as intended.

In Kobe, the West Japan Center, mounted on lead-rubber bearings, was shaken and performed well. The peak ground

acceleration at the foundation was 0.31g, whereas those at the first and sixth floor levels were respectively 0.11g and 0.10g. The isolators experienced a peak deflection of 100 mm. The Matsumura-Gumi Laboratory which uses high damping rubber, experienced a ground acceleration below the isolators of 0.28g in a north/south direction. The corresponding figures at the first floor and roof were 0.15g and 0.20g. The accelerations at the roof of a nearby fixed-base structure were up to 0.99g.

The Northridge earthquake which struck at the Fernando Valley region of Southern California on January 17th 1994, caused at least 55 fatalities and about 5000 injuries. More than 25,000 dwellings were estimated to be uninhabitable, and the cost of the total damage was thought to be \$20-30 billion. In most cases damage was confined to older structures that would not satisfy current construction codes. This was true of both buildings and the road system.

Three base-isolated structures were subjected to strong ground motion during the Northridge earthquake. The University of Southern California Teaching Hospital (USCTH) and the Los Angeles County Fire Command and Control Facility (FCCF) use natural rubber bearings, whereas the third is mounted on helical steel springs. The USC hospital is supported on 68 lead-rubber and 81 rubber bearings. The base-isolation system performed very well during the earthquake; the hospital remained fully functional and there were no reports of damage to equipment. The acceleration experienced was the highest of any base-isolated building to date. The peak acceleration at the foundation was 0.37g, but those at the ground and roof levels were only 0.13g and 0.21 g respectively. The damage to an



Base isolation reduces the forces in the building to below those in the ground.

adjacent fixed-base hospital totalled \$350 million; it suffered major disruption due to damage to pharmaceutical stocks.

The Fire Command and Control Facility is mounted on 32 high damping natural rubber bearings. It remained fully functional during the earthquake. The acceleration experienced in one direction was about half that (0.18g) at the ground. The response in the other direction was slightly compromised due to the seismic gap having been bridged in a recent repair. The records from these two buildings provide key confirmation of the efficacy of base isolation using rubber bearings. The displacements experienced by the buildings during the earthquake, however, were well below the design level.

In both these earthquakes the performance of base- or seismically-isolated buildings was very good. Seismic isolation offers superior protection to buildings and contents as was proven in these earthquakes. Both the USA and Japan have well-defined procedures for approving the construction of seismically-isolated buildings. There is in general, however, a cost penalty in these countries for installing base isolation because the superstructure has to be as strong as that for a conventional fixed-base building. This is a major discouragement to architects and civil engineers wishing to use the base isolation system to protect property and lives. There is no possibility of offsetting the costs of the isolation system against savings in the superstructure. Moreover, at least in the USA, the level of protection required for a base-isolated building is higher than for a conventional building. This reflects the conservatism of the construction industry towards radical technologies.

Although some of the work on seismic protection was supported by international funding, mainly through UNIDO, Malaysia has also made a major contribution, which is ironic as it is a relatively seismic-free area. The scale of this contribution may be measured by the number of papers (at least sixty) published by TARRC on this topic. The original surmise was that high grade Malaysian natural rubber would gain from a new market which exploited the advantages of this material: it has always been assumed that quite modest shifts in natural rubber uptake can lead to significant improvements in the price for the commodity. Despite the continuing devastation around the world, and the obvious benefits of the technique which can be applied both to new construction and to existing buildings, uptake has been far less than might have been anticipated for such a worthy invention.

The IIRDB and TARRC are actively seeking funds through INRO to promote the base isolation technique. The need to remove the unjust penalty of requiring base-isolated buildings to be as strong as those protected by conventional strengthening needs to be overcome through the provision of information. If this can be achieved then the market for protecting buildings approximating to the model structure near Bogor is vast. If such protection was afforded in proportion to its potential then the effects of earthquakes could be hugely ameliorated. People living and working within structures would remain uninjured. Supplies, instruments and machinery housed in such structures would remain undamaged. Furthermore, the greater interest generated might lead to the technique being more generally applied to existing buildings.

The stormsurge barriergate 'Maeslantkering' in the Nieuwe Waterweg near Hook of Holland in the Netherlands has to do his job during high water and storm. This requires a heavy construction and for the rubber bearings to function during 100 years under static load, deformation, and intermediate dynamic loading.

Design

To design the rubber bearings for the stormsurge, calculation methods were used and when more detailed calculation was required, finite-element analysis was applied. A practical study of the fatigue behaviour under dynamic loading, was also carried out.

The rubber bearings were designed to accept loads and movements due to:

- static load of barriergate in semi-floating and dry dock situation, up to 17,000 kN per support;
- dynamic loads due to deformations of the gates following from building tolerances;
- movements and deformations of the gates due to temperature changes and wind up to 150 mm shear.

Because of the large loads and small spring stiffness required, the bearings are subject to large deformations in compression and shear. If a load- or deflection-frequency spectrum is available, for most cases the expected lifetime of a rubber bearing can be estimated.

The dynamic load aspects due to temperature (day-night and summer-winter) and wind, of the elements made it necessary to investigate the fatigue resistance of the bearing systems. The expected lifetime of the elements was calculated using load-and movement versus frequency spectra as supplied by the client. The lifetime was defined based on an accepted crack growth in the rubber material of the elements.

Product

Because of the required product properties with respect to large deformations, fatigue resistance and low temperature resistance, Natural Rubber was selected as basic material for these bearings. To confirm the mechanical and physical properties an appropriate compound was developed.

For the stormsurge barrier 'Maeslantkering', engineers calculated that 2 sets of 14 rubber bearing systems were required to support the barrier gates when parked in the dry docks, made in both riverbanks. The bearings consist of laminated elements, in one or two stacks. Depending on required spring stiffness, there were 3, 4 and 5 layer elements, bolted together. After assembly, the bearings were painted to improve corrosion resistance. Each element consisted of a sandwich of two steel plates and a rubber layer. All elements had the same construction and rubber hardness. The shape of the elements showed concave sides in order to improve compression and fatigue behaviour. The size of the bearing elements was 1200 mm × 1200 mm with a thickness of 114 mm. The total thickness of the bearing systems varied from 342 to 570 mm.

Testing

For specific projects like the Maeslantkering, the products have to be tested to show their compliance with specifications. After production all elements were tested on their mechanical properties such as their capacity to accept loads and movements.

Assembly of the bearing systems was done with selected elements in order to approach the required compression stiffness distributions as close as possible. The results of the tests were reported in inspection reports for approval by the client.

For this kind of specific projects it is common to make Quality Plans and Manufacturers Record Books in which all relevant information with regard to design, construction, production, testing, inspection and approval has been gathered.

¹ Trelleborg/Bakker, Ridderkerk, The Netherlands



The Maeslant stormsurge barrier.

Rubber in the building industry? It is not the type of material you would expect builders to use. Most people are probably only familiar with the use of rubber in sealing strips for windows and doors, but it can be used for many other things as well.

The shape and size of rubber strips for doors and windows depends on the required sealing, the size of the windows or doors and the building's tolerances. The most important reason for using rubber in this form is that it allowed windowpanes to fit perfectly into their frames. Materials like wood, steel, plastic and aluminium rarely provide this kind of perfection, which means that cracks are unavoidable. Furthermore, even though it is in principle possible to initially fit these materials together during construction, changes in temperature, moisture and wind pressure will still lead to cracks and leaks in the long run. These can always be sealed with putty, but this has a negative effect on the way windows and doors function. An elastic material like rubber is ideal. It can fill cracks that change in size and it is therefore guaranteed to seal under all kinds of conditions. An additional advantage is that it gives builders more leeway in the sizes and the tolerances they use during construction. This has a positive effect on the cost price and is the main reason why rubbers are used in the building industry. Rubber can be found everywhere where tolerances can cause cracks that lead to leaks and draughts.

Specifications

People must have some degree of certainty that a seal will function properly over a long period (years). This can be obtained by drawing up a list of requirements that the materials used must meet. A list of requirements like this is called a specification. Every customer (user) can draw up a list of his or her own requirements, but it is often easier to use generally accepted specifications. Such specifications are for instance recorded in standards. For example, the extent to which the sealing properties of rubber strips allow cracks to vary as a result of fluctuations in weather conditions. The capacity of rubber to regain its shape is important in this type of situation. Measuring the permanent deformation (compression set) is a good way of determining this characteristic. If the compression set is low, the rubber will quickly regain its original shape after being subjected to pressure. In addition, rubber-sealing strips have to constantly apply pressure against a windowpane. The force with which they do this is an indication for the wind pressure they can seal off. Like all other polymers, the pressure exerted by rubber is not constant, and it gradually decreases over the course of time. If this happens

Compression set

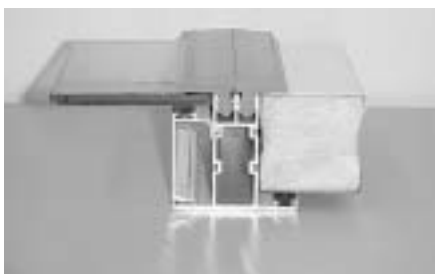
Everybody knows from own experience that rubber products not always return completely into their original shape after being deformed. The resulting deformation is called 'compression set'. A compression set test measures the ability of the rubber to return into the original shape after being deformed for a given time at a specified temperature. The result is always a value between 0 and 100, the first value meaning a full return, the latter no return at all.

too quickly, it will result in unwanted leaks after a relatively short period of time. One way of avoiding this is to include a requirement for the stress relaxation in the specification. If it remains below a prescribed level in an experiment, the long-term pressure exerted by the rubber on the windowpane can be guaranteed. However, oxygen, ozone, water, etc. also have a negative effect on its properties. To guarantee that a sealing strip will work properly, its resistance to ageing must also be included in the specification. Other details also have to be taken into account, such as the behaviour of the rubber at low temperatures, its tensile strength and, if applicable, colourfastness. If sealing strips made of a particular rubber compound meet all these requirements, and provided that the seal and the window frame have been well designed, it can reasonably be assumed that they will function properly for a long time.

What applies to windows is also true for doors and outside walls, although tougher requirements may have to be met because rubber sealing strips used, for example, in outside walls may have to support outer-wall sheeting. It is however the same principle. These are examples of relatively simple uses of rubber in buildings. If rubber-sealing strips leak, it is rarely a total disaster and, provided that the seals built into outer walls are not involved, most leaks are fairly simple to fix. With many other types of rubber applications it is a completely different story.

Underground

In areas where there is a risk of earthquakes, buildings are commonly placed on rubber blocks to absorb the tremors. In the Netherlands, this method is also frequently used for counter-acting the vibrations caused by, for example, road traffic, trains and underground railways. For smaller vibrations, rubber strips are also used. Clearly, rubber used in this way must meet stringent requirements - after all it completely supports the building. The long-term stability of this type of rubber is very



Example of an outer-wall construction incorporating various sealing strips.



Detail of a failed central heating radiator connection hose.



Hat membrane as used in an expansion tank in a central heating system.

important, its creep must be low and proportionate to prevent crookedly sagging. For rubber, this means low values for compression set and stress relaxation. Because it is located under a building where it is usually cool and dark, resistance to ageing is not as important as it is with sealing strips. On the other hand, sealing strips can for example be replaced after five or ten years, but this is much more problematical for rubber blocks and certainly for foundation strips located under a building. It means that these have to last for the complete life span of the building - with the present regulations this is about 50 years. There are no general standards or specifications for rubber foundation blocks under houses, but blocks like this are also used to support bridges and viaducts, for which standards exist. It is well possible to use these standards for blocks under houses provided the stiffness of the rubber is brought into line with the location.

Rubber is, however, used in more ways in underground construction. Rubber seals are often used, for example, to seal off and protect the contents of underground pipes. This is definitely the case when pipes are located below groundwater level. For example rubber-based putty or solid rubber plugs.

Standards

The rubbers used in water pipes - clamp fittings, quick couplings, taps, shut-off valves and hoses not only have to provide an effective seal that is guaranteed to last a long time, but they may not affect the quality of the (drinking) water. This means the rubber compounds used in the manufacture of these, at first sight, simple products, are extremely complicated. These requirements have of course been incorporated into standards. In the Netherlands, for example, by KIWA (Water Supply Products Testing and Research Institute of the Netherlands) in the BRL 2013/3 standard and more internationally the EN 681 standard, which in time will replace the standards in each EU member state. These standards all specify a large number of properties of rubber that guarantee that it will function properly for a long period. The standards for water pipes are also generally applicable for the use of rubber in sewer pipes, but in sewers the effect of the rubber on the quality of the water is not important.

The rubber products used in water pipes are also used with natural gas. The standards are however different. This is because natural gas is a hydrocarbon and effects rubber compounds in a totally different way as water does. Furthermore, the dangers of what can happen if there is a gas leak are much greater, which means that extremely tough and resistant rubber has to be used. In the Netherlands, Gastec uses for example the NEN 7212 standard. At a European level, EN 682 is applicable. This and other European standards (for example EN 549) will replace the regulations in the Netherlands. Because of the large number of different products, for example rubber sealing rings for natural gas and membranes for coal gas water heaters, several standards are applicable for the use of rubber in gas installations.

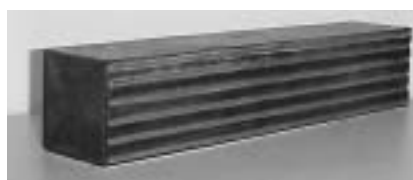
Tensile test

The tensile properties of rubbers are the tensile strength, meaning the stress, expressed as the force at the breaking point of a test piece divided by the original undeformed cross section of that test piece, the elongation at break and often the modulus at 100 or 300 % elongation. The modulus again is defined as the force at the given elongation, divided by the original cross section of the test piece.

The totally different uses of rubber may have made it necessary to formulate a wide range of standards, but these often have the same basis. Some of them are not applicable to builders, because they relate to the use of rubber in domestic appliances. In the building industry, rubber is also used in heating systems - boilers, pipes and tubes - carpet underlay, hoses and roof covering.



Example of a seal.



Cross-section of a support block.

Rubber clearly has a wide range of uses and for each use different factors have to be taken into consideration. If a product is easy to replace (for example windowpane sealing strips, tap washers, gas hoses), a life span of five to fifteen years can be regarded as reasonable. For products that are difficult to replace (for example support strips and foundation blocks, seals in outside walls, sealing in sewer pipes and tubes) the life span certainly has to be fifteen to fifty years. For all rubber products, the use of standards, if they have been drawn up, is the simplest method to guarantee their long-term functionality. If there are no standards available, it is tempting to use the first product that comes to hand, but this can cause significant problems and substantial damage. In this type of situation it is better to have specifications drawn up taking into account the intended function, the required life span, how simple it is to replace the products and the applicable European Directives for the building industry. Drawing up specifications for a product for which there are no standards is usually not a simple thing to do, because the (user's) demands and the (constructional) requirements are nearly always contradictory.

The question of whether it is worthwhile to go through all the complexities of drawing up specifications must be answered affirmatively. Problems regularly occur simply because so much rubber is used in the building industry. Usually, problems are easy to deal with, but in a few cases they cannot or can only be solved with a great deal of effort. The most common problems are leaking windows, burst hoses, leaking sealing rings and unwanted interaction with other materials (discolouring and decomposition). The wrong choice of polymer and careless or 'hasty' production often cause this kind of problems. Even

Tear strength

The tear strength is the force needed to let grow a tear made for this purpose into a test piece. For engineering purposes, one would like to know the tear energy. Unfortunately, none of the standardized test methods measures this correctly. They all measure a combination of the energy required to stretch the test piece and the energy required to let grow the tear.



though relatively cheap products are involved, the repair costs can be considerable because of the man-hours involved in dismantling and assembly and related damage to other products such as carpeting. In addition, a large number of complaints can lead to a great deal of irritation. With large construction projects, wrong choices often mean that large numbers of products may have to be changed. For example, if all the radiator hoses in the central heating system of a large office building are defective and have to be changed, and replacing each hose, including the removal of panel covers takes 30 minutes, the damage will amount to over NLG 15,000 for 500 hoses. This does not even include any related damage.

Building contractors rarely have to draw up specifications themselves. They usually receive them when they are awarded the contract for a particular project. However, specifications are often not stringent enough. This gives the contractor's buyer,

whose main priority is to find the cheapest product that meets the given requirements, too much leeway in purchasing materials. Drawing up specifications for different products more carefully is an important first step. Another problem in this respect is that rubber is usually black and you cannot see whether rubber products meet the set requirements without adequate inspection. A certification system or testing is needed to be able to check products properly when purchasing them. Building contractors or architects cannot be expected to have in-depth knowledge of rubber. When in doubt, they should not hesitate to call in an expert to draw up specifications, to verify measurements or for arbitration. This is often seen as an unnecessary cost, but it is certainly worthwhile if it helps to prevent damage from being caused. After all, the only way to know something is to measure it.

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