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PERFORMANCE RELATED PARAMETERS OF FLEXIBLE CONNECTIONS USED IN OFFSHORE PIPELINES

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ABSTRACT

Despite continued advances in rubber technology, the design of elastomeric flexible connections, used in offshore pipelines transporting high-pressure/high-temperature hydrocarbon fluid/gas mixture, remains more of an art than a science, primarily due to the intricate behavior of rubber. The mechanical response of rubber is dependent on time, temperature and mode of loading. It is susceptible to explosive decompression damage. Rubber's non-linear stress-strain curves, creep, hysteresis and other properties are influenced not only by the method of fabrication but also by age. If these characteristics are not accounted for properly, the result can be less precision in design compared with metals. At present, there are no codes or standards that directly address the design, analysis or evaluation of the elastomeric flexible connections used in offshore oilfield applications. Based on the results of the recent research, the significance of key parameters that affect the short term and long term structural performance of elastomeric flexible connections is presented in this paper.

Keywords: Elastomeric Joints, Laminated Rubber Bearings

INTRODUCTION

The versatility of elastomeric flexible connections (in comparison with long, tapered and fatigue sensitive metallic stress joints) has been duly recognized by the offshore oil and gas industry. These connections, also known as FlexJoints®, are commonly used in offshore pipelines transporting high-pressure hydrocarbon fluid/gas mixture to provide high axial and radial stiffness and high rotation and torsion flexibility required for optimal structural performance of pipelines that are subjected to high internal pressure and three-dimensional dynamic motions imposed by offshore environment.

Despite continued advances in analytical and manufacturing techniques, elastomeric flexible connection design remains more of an art than a science, primarily due to the complexity of rubber behavior.

On one hand rubber has myriad useful qualities. Rubber has a low modulus of elasticity, and is capable of sustaining high shear deformations while maintaining a high compressive stiffness. After such deformations, it quickly and forcibly retracts to essentially its original configuration. It is resilient, and yet exhibits internal damping. It can be processed into a variety of shapes. It forms an excellent bond with metals. It can be compounded to have widely varied properties. It does not corrode and requires no lubrication. It exhibits excellent fatigue resistance and durability. Owing to this versatility of rubber behavior, the designer has unlimited options in selecting the type and configuration of an elastomeric flexible connection.

On the other hand rubber has some complex characteristics. The mechanical response of rubber is dependent on time and temperature. It is susceptible to cavitation under tensile loads and explosive decompression damage when subjected to precipitous pressure fluctuations in high pressure fluid/gas environment. The non-linear stress-strain response, creep, hysteresis and other properties of rubber are influenced not only by the method of fabrication but also by its age and previous history. If measurements are not properly specified, or if material properties are not correctly considered by the designer, the result will be performance of low precision relative the designs using other, less complex materials.

A typical elastomeric flexible connection consists of alternate layers of rubber pads and steel laminates integrally bonded together (refer to Figure 1). Generally, the integral piece consisting of rubber layers and steel laminates is called a Flex Element, while the overall assembly is called a Flex Joint. The basic characteristic of a flex element is its ability to support a high compression load while accommodating high cyclic motions in shear. This is the basis of flex elements used in offshore pipelines, risers and TLP tendon applications where a high axial stiffness and rotational flexibility is required to alleviate flexure and torsional stresses while maintaining a high axial and radial stiffness. Referring to Figure 1, the axial tension and internal pressure are efficiently transformed to axial compression in the rubber layers that can freely shear spherically without introducing high bending stresses in the connecting pipes.

There are generally two basic types of elastomeric flex elements, spherical and cylindrical, that are commonly used in offshore oilfield applications, independently or in combination with each other in series or in parallel. The selection of the number and the best combination of these two basic types depends on the application requirements. Normally, the predominant motions, internal pressure, flow requirements, pipe end fixities and the spring rates are the major requirements that determine which combination would serve best.

Natural rubber (NR), neoprene (CR) and nitrile (NBR) are the three most commonly used elastomers in flex elements. The chemical names for NR, CR and NBR are polyisoprene, polychloroprene and butadiene acrylonitrile respectively. Each type of rubber has some unique characteristics. The selection of elastomer compound depends on many variables and is usually made on past experience. Some of the general characteristics of elastomers that are considered in the selection process include: hardness (durometer range as defined in ASTM D2240-86 [1]), tensile range, elongation, compression set, resilience, rebound, abrasion resistance, tear resistance, solvent resistance, oil or chemical resistance, low temperature usage, high temperature usage, aging and adhesion to metals.

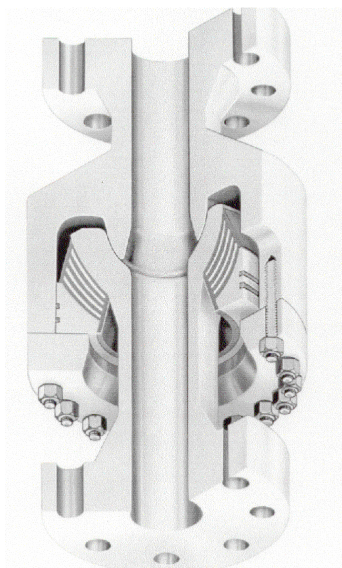

Figure 1: Typical Flex Joint Configuration

Advantages of an Elastomeric Flexible Connection

A plethora of unique advantages offered by Flex Joints have made them ideally suitable for offshore oilfield applications.

Since the flex element accommodates motion by simple flexing of its elastomer layers, there are no rolling and sliding elements as in more conventional joints. No lubrication or servicing of any kind is required since there is no friction or wear.

A simple one piece flex element can efficiently replace a complex universal joint with six degrees of freedom. The flex element performs as a "smart joint" with four nonlinear spring rates (axial, radial, cocking and torsion) that can be independently controlled. The ability to control the stiffness of this four-in-one spring gives the following unique options to the designers in their development of a structural system with optimum performance. Note that all four stiffnesses may not be important for a given application.

- The stiffness can be designed so that the combined effect produces a restoring force required to return the connected pipes to a desired position under various modes of loading.
- By merely varying the number and thicknesses of rubber layers and bonded steel laminates, major changes in the stiffness can be achieved without changing the overall envelope.
- The location of the focal point (center of rotation/reaction) can be easily controlled by altering the spherical radius of the rubber layers and steel laminates. The focal point can be located beyond the confines of the flex element to achieve an optimal interaction between various degrees of freedom.
- The inherent damping characteristics and visco-elastic behavior of the rubber layers can be exploited to cushion the shock loads and isolate the vibrations in order to achieve an optimal design for rate and time-dependent loading.

Fundamentals of Structural Behavior

The performance of a flex element is governed by its structural behavior and structural integrity. The structural behavior is dependent on overall stiffness while the structural integrity is dependent on the internal stresses and strains under static, dynamic, cyclic and thermal loads that elastomer layers and steel laminates can endure without catastrophic failure.

The nature and properties of rubber greatly influence the flex element's structural behavior and integrity. From a structural engineer's point of view, the two properties of rubber that give the flex element its unique characteristics are: (a) rubber can be sheared or stretched up to several times its original shape and still return to that shape upon release, and (b) rubber is nearly incompressible, i.e., Poisson's ratio is very close to 0.5 and the bulk modulus (or the modulus of volumetric expansion) is many times larger than the shear modulus (except in the vicinity of glass transition temperature).

The rubber elasticity (or hyperelasticity) is very different than the ordinary solids elasticity. As shown in Table 1, the typical mechanical properties of rubber are quite different from those of metals.

Table 1: Comparison of Mechanical Properties

Property	Rubber (Typ.)	Steel (Typ.)
Density, lb./in3	0.042	0.289
Elastic Modulus, psi	~ 500	~ 10^7
Breaking Extension, %	500 %	20%-50%
Elastic Limit, %	500 %	2%
Tensile Strength, psi	~ 10^3	8 x 10^4
Shear Modulus, psi	~150	~ 10^6
Bulk Modulus, psi	300000	~ 10^7
Poisson's Ratio	0.49	0.3
Specific Heat Btu/lbm-^{o}F	0.4	0.1
Thermal Conductivity Btu/hr-ft-^{o}F	0.1	31
Coefficient of Volume Expansion ^{o}F	4 x 10^{-4}	2 x 10^{-5}

A Poisson's ratio close to 0.5 means that rubber hardly changes in volume even under high loads so for most types of deformation there must be space into which the rubber can deform. The more restriction that is made on its freedom to deform the stiffer it becomes. When a rubber layer under compression is prevented from slipping at the loaded surfaces (by bonding or friction), its stiffness in compression depends on the shape factor, defined as the ratio of one loaded area to the total force-free area. A higher shape factor means a higher axial stiffness. The shear stiffness of a rubber layer is a function of shear modulus, loaded area and the thickness of the layer. The shear modulus (also referred to as secant shear modulus) is defined as the ratio of shear stress to shear strain at a particular strain. Since the shear modulus is low, and is not influenced by the shape factor, the shear stiffness of a layer is much lower than its axial stiffness. Rubber finds use in engineered components because of one or more of these unique properties.

The behavior of a typical rubber pad in compression and shear is schematically shown in Figure 2. As the rubber layer is compressed, the free edges bulge out to maintain a constant volume. As a result of this bulging, localized shear strains and tensile strains are developed at the extreme fiber of the free edges. When the rubber is sheared a direct shear strain is developed that is inversely proportional to the rubber thickness. Thus, there are two types of shear strains that a rubber layer experiences under combined axial load and shear deformation: (a) direct shear strain due to shearing action, and (b) Indirect or bulge shear strain due to bulging action.

Since the bulk modulus is more or less constant relative to the shear modulus, the latter is the most important parameter that governs the structural behavior of a flex element. As shown in Figure 2, the shape factor and consequently the vertical stiffness of a rubber block can be increased by inserting metal plates which divide the block into several layers. This provides constraints at the loaded surfaces of each layer and reduces the freedom of rubber to bulge. The shear stiffness is not altered by the presence of these horizontal plates. It is this feature of rubber layer and metal plate interaction that is used in flex element design to provide a high axial stiffness and high shear flexibility.

If the rubber layers and steel laminates are spherical with a coincident center, as in the case of a spherical flex element, the shear deformation of rubber layers transforms into cocking deformation about the center of the sphere called the focal point. The overall axial and cocking stiffness of the flex element is the respective stiffnesses of all the layers combined in series. The cross-section of a typical spherical flex element is schematically shown Figure 3. The deformed configuration is shown in Figure 4. Various components labeled in Figure 3 are self-explanatory. The purpose of the centering piece is to restrict the tri-axial tension in rubber (described elsewhere in this paper).

Flex joints are designed by integrating several considerations that include: performance requirements, environmental factors, load transfer, structural system configuration, failure criteria, and cost. Since spherical flex joints are the most common type used in offshore pipelines applications, this paper focuses on the performance aspects of the spherical flexible connections.

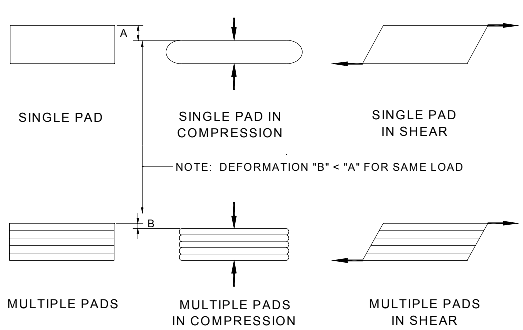

Figure 2: Behavior of a Rubber Pad in Compression and Shear

The main performance requirements that govern the flex element design are: (a) geometric constraints such as overall dimensions, physical interfaces with connected components and the extreme cocking angles that are dictated by the global system analysis (b) constraints on axial and cocking stiffness that is determined by the flexibility requirements of the riser/piping system, (c) structural integrity under ultimate loads that is dictated by the strength of materials and failure criteria and (d) durability under harsh environmental conditions such as cyclic loading, chemical attack, pressure variations, thermal gradients etc.

As mentioned earlier rubber has some characteristics that can adversely affect the structural performance of a flex element, if not properly accounted. The objective of this paper is to show the significance of some of these characteristics and how they affect the structural performance of flex elements used in offshore pipelines transporting high-pressure/high-temperature hydrocarbon fluid/gas mixture.

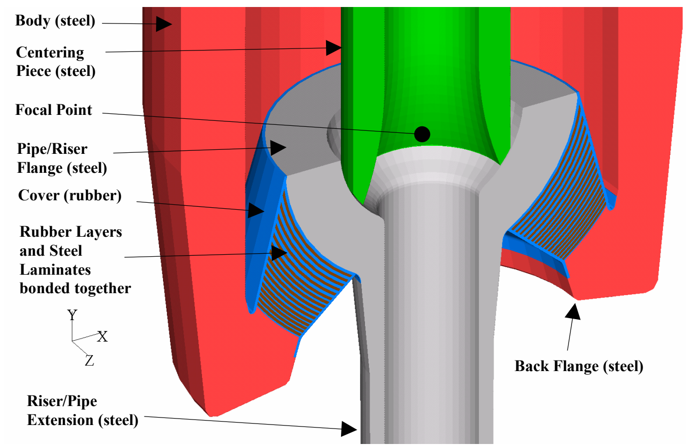

Figure 3: Cross-section of a Spherical Flex Element

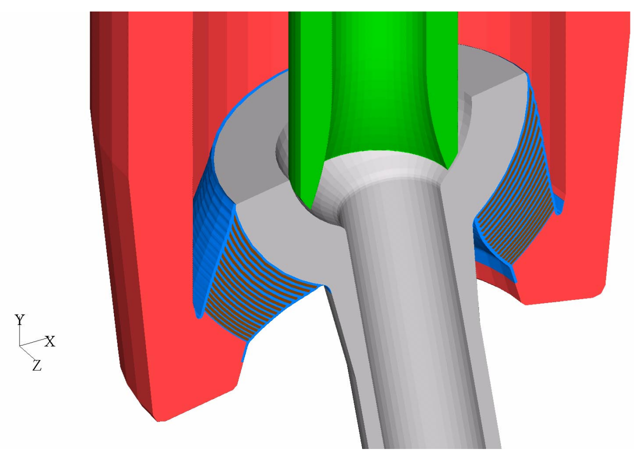

Figure 4: Deformed Configuration of a Spherical Flex Element

EFFECTS OF NON-LINEAR MECHANICAL RESPONSE

Rubber is isotropic and linearly elastic only in a very small deformation range. Due to the geometric constraints of the structural system, the rubber layers of some of the flex elements are designed to undergo over 120 percent direct shear strains under maximum operating conditions and over 200 percent direct shear strains under extreme conditions. Under cyclic loading, the rubber layers may experience shear strain amplitudes ranging from 0.01 to 50 percent. Succinctly, the rubber layers of a flex element undergoes direct shear strains ranging from -250 to 250 percent and indirect shear strains ranging from 0 to 800 percent during their design life. Figure 5 shows the shear stress-strain curves at room temperature while Figure 6 shows the shear modulus versus shear strain curves for five types of rubber studied in recent research. In these Figures NR, CR and NBR refer to natural rubber, neoprene and nitrile respectively. The numbers 50, 70 and 80 refer to the Shore A durometer reading which is a measure of hardness. The following points are noteworthy:

- The stress-strain curves are non-linear for all type of rubbers, however, the higher-hardness rubbers (CR and NBR) show higher non-linearity in comparison with the NR.
- The shear modulus of NR studied does not change with strain as much as that of the CR and NBR compounds. The CR's shear modulus is high at large strains while the NBR's shear modulus is high at low strains. It is clear that the non-linearities can be controlled by careful elastomer compounding.
- A single shear modulus does not represent the entire elastic stress-strain behavior as in the case of metals and therefore most of the evaluation criteria for rubber are based on strains rather than stresses.

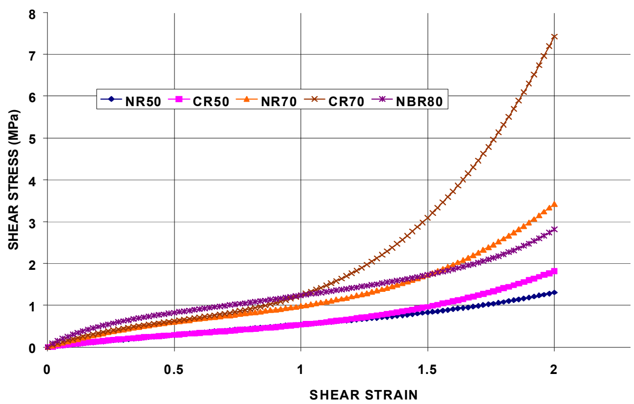

Figure 5: Stress-Strain Curve in Simple Shear for NR, CR and NBR

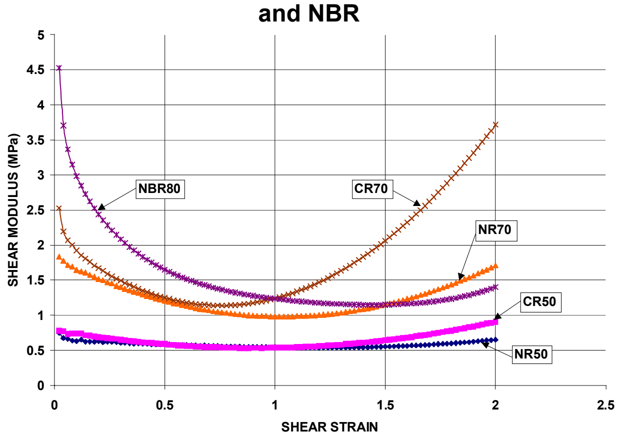

Figure 6: Variation of Shear Modulus with Shear Strain for NR, CR and NBR

The effects of non-linearity are more important in the fatigue evaluation of metal laminates and metal riser/pipe. The bending stresses in the riser/pipe are directly proportional to the cocking stiffness of a flex joint. As mentioned earlier, the cocking stiffness (shear stiffness) is directly proportional to the shear modulus of the elastomer. The same strain fluctuations at different mean strain levels can result in very different stress ranges in the steel laminates and connected risers/pipelines. This is particularly important in the small strain region, where most of the cyclic loading occur, the cocking stiffness can be 10 times higher than the design cocking stiffness. Depending on the mean angle, the variable stiffness of flex element can significantly affect the durability of the metal components in the vicinity of the flex joint, if not properly considered.

EFFECTS OF STRESS-SOFTENING

Rubber, especially when filled with reinforcing carbon black, softens when deformed. This phenomenon is often called the Mullins effect [2]. There has been considerable controversy about the causes of stress softening and it appears that more than one mechanism may contribute to the effect. One of these is simply incomplete elastic recovery. When a filled rubber is extended to a strain ε_1, returned to zero strain and stretched again, the second stress-strain curve lies below the first one, but rejoins it at ε_1. This happens even if the specimen is retested after the first extension for an extended period of time in an attempt to ensure full recovery. Figure 7 shows the first six cycles of stress-strain behavior in shear for CR70 rubber.

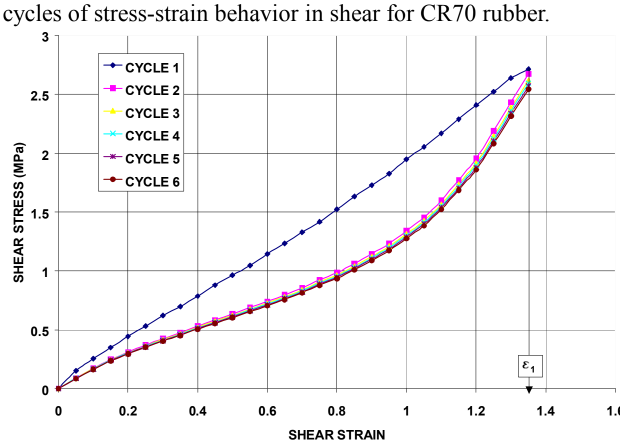

Figure 7: Stress Softening of CR70 in Shear

Note that most of the change occurs during the first deformation, but small changes may still be detectable after many cycles. Since the laminate stresses increase as the shear modulus decreases, the effects of stress softening are more important in fatigue evaluation of laminates in flex joints subjected to cyclic loading. To incorporate this behavior in the design of flex joints, the shear modulus is calculated from the sixth cycle data. This usually gives a softer material but one on which results are reproducible. The flex joint generally undergoes cyclic motions at low strains and the shear modulus obtained from the sixth cycle data at low strains is representative of the actual shear modulus of the rubber layers. However, at large cocking angles, that occur occasionally during maximum operating or extreme loading conditions, the actual cocking stiffness of the flex joint can be 1.2 to 1.5 times higher than the reported design stiffness based on the sixth cycle data due to the recovery (cross-linking of broken long chain molecules), mentioned earlier.

EFFECTS OF CREEP AND STRESS RELAXATION

All rubbers exhibit the characteristics of creep, or continuing time dependent deformation under constant load; and stress relaxation, or time dependent decay in stress at constant deformation. These phenomena occur whenever rubber is subjected to force or deformation of any magnitude, which differentiates creep and stress relaxation in rubber from that in metal, where they only seem to occur under relatively large stresses and at high temperatures. This time dependent phenomenon makes the shear modulus time dependent. Figure 8 shows the relaxation of shear modulus with time at 50 percent strain for CR50 rubber. Notice that most of the relaxation occurs in the first few minutes of loading but small changes in shear modulus continue to occur with time.

The consequences of creep and relaxation on the overall performance of a flex joint include: (a) significant shift of the center of reaction (focal point) from its original position resulting in second order bending stresses in the connected riser/pipes, (b) reduction in restoring forces or bending moment in the riser/pipe under displacement controlled loading and (c) increase in indirect shear strains and laminate stresses. Proper consideration of stress relaxation is very important for flex joints that are laid on seabed for extended period of time prior to installation. As discussed elsewhere in this paper, a state of tri-axial tension develops when a flex joint is laid on seabed in deep water. Due to stress relaxation the effective shear modulus reduces with time thereby increasing the susceptibility to cavitation failure of small pores left during vulcanization.

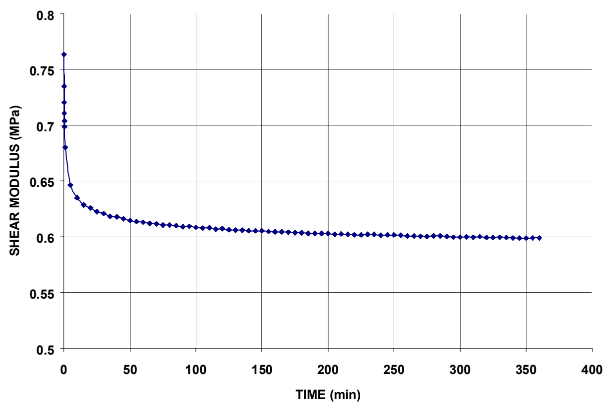

Figure 8: Relaxation of Shear Modulus at 50% Shear Strain for CR50

EFFECTS OF TRI-AXIAL TENSION

Rubber is commonly found to undergo internal cavitation when subjected to excessive tri-axial tension. This phenomenon is a consequence of an elastic instability known as "an unbounded elastic expansion of preexisting cavities, too small to be readily detected." This situation generally occurs when the flex joint is laid down on seabed for extended period of time during installation phase. The seabed temperature is generally 20^{o}C to 30^{o}C lower than the factory temperature where the flex joint is manufactured. As shown in Table 1, the coefficient of volume expansion/contraction of rubber is 20 times higher than that of steel. Due to stress relaxation and thermal contraction of the rubber layers the constraint imposed by centering ball is released causing a state of tri-axial tension in rubber layers induced by external hydrostatic pressure.

The critical stress depends on the non-linear elastic behavior of the rubber and varies from 2.5G - 10G depending on the type of rubber, where G is the average shear modulus. Figure 9 shows the behavior of a cylindrical rubber pad (40 mm OD x 3 mm thick NBR80) pulled to failure. The shear modulus versus shear strain curve for the same rubber (NBR80) is shown in Figure 6. Notice in Figure 9, the onset of cavitation occurs at an axial tension of 5 KN that corresponds to 4 MPa average tensile stress (critical stress) on the specimen. The 4 MPa critical stress is approximately 5 times the nominal shear modulus, that is much less than the simple tensile stress at failure (~ 30 MPa). Thus, a flex joint is extremely vulnerable to failure when the rubber layers experience tri-axial tension. Under normal operating conditions, the centering piece controls the tri-axial tension, however, when the flex joint is laid on the seabed under deep water, a specially designed device may be necessary to control the effects of tri-axial tension.

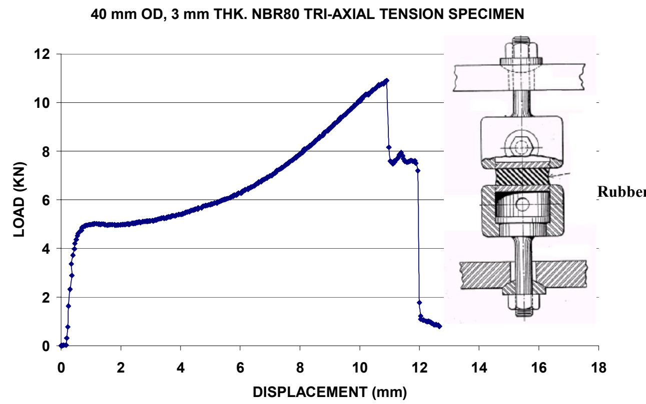

Figure 9: Results of Tri-axial Tension Test (NBR80)

EFFECTS OF CHEMICAL ATTACK AND EXPLOSIVE DECOMPRESSION

Almost all elastomers are prone to chemical and physical effects arising from contact with fluids and gases, however, the extent of susceptibility varies. When immersed in an inert solvent, a cross-linked rubber does not dissolve, but becomes distended isotropically by imbibing the solvent into the network (swelling). Thus swelling is a three dimensional form of deformation. The shear modulus of rubber decreases with increasing degree of swelling. Chemical attack due to a reactive chemical can cause further deterioration.

In the offshore environment, rubber can be exposed to two type of solvents. (a) sea water and (b) a mixture of oil and gas that may be chemically reactive or passive. The absorption of sea water may reduce the shear modulus slightly, however, it does not affect the strength of the rubber. Exposure to sea water may also reduce the fatigue resistance of rubbers containing compounding ingredients soluble in water (such as antioxidants added to the NR to increase its fatigue resistance) by dissolving these ingredients. Generally, NBR rubbers used in offshore flex elements do not contain anioxidants or other ingredients that are soluble in water and therefore are not susceptible to this type of chemical attack.

Absorption of hydrocarbon liquids and gases can deteriorate the flex joint performance in two ways: (a) chemical reaction between hydrocarbon and elastomer matrix can reduce the shear stiffness of the rubber, and (b) absorbed gas can cause explosive decompression damage to the rubber surfaces that may gradually effect the load carrying capacity of the flex element.

Deterioration due to chemical reaction can be controlled by using the appropriate rubber that is resistant to thermal and chemical degradation. Explosive decompression on the other hand requires special design considerations for flex elements subjected to high internal pressure.

The explosive decompression failure of rubber is an extremely complex problem and depends on several factors. The primary damage occurs due to rapid inflation of small spherical voids, initially present at the time of cross-linking either in the form of submicroscopic bubbles of air trapped in rubber processing or in the form of badly wetted particles of dirt or dust. Gent and Tompkins [3], estimated the size of these voids on the order of 10-5 cm or larger in radius. When a rubber layer is subjected to a sustained high-pressure in a gas environment, gas permeates inside these small spherical voids. The permeation of gas through an elastomer takes place in two steps, the gas dissolves in the elastomer and the dissolved gas diffuses through the elastomer. When the elastomer is fully saturated with gas, a steady state condition is reached. After a certain duration of sustained pressure in steady state condition, an equilibrium is reached between the internal pore pressures and the external compressive pressure. When the external pressure is suddenly released, the initially compressed spherical voids experience a mechanical shock caused by a disruption in the above mentioned equilibrium. Due to the low permeability of the rubber, the compressed gas inside the voids cannot escape instantaneously. Consequently, the voids are subjected to a high-pressure differential and sudden volume expansion. The voids will not expand indefinitely because the supply of gas is limited due to the limited solubility. Depending on the magnitude of the pressure differential, the inside spherical surface of the void stretches until one of the following takes place: (a) the pressure inside the void drops in accordance with the increased volume and equilibrium is reached between the tri-axial internal and external stresses without fracture, or (b) energy is dissipated due to rupture of the interior surface of the void, and the system attains its original energy state.

By the virtue of high shape factors of the rubber layers in elastomeric flex elements (necessary to support high axial load caused by high-pressure) the explosive decompression damage is generally restricted to the cover rubber or generally noticed in areas where the confinement of rubber is minimum. In a typical rubber layer of a high-pressure elastomeric flex element, the top and bottom surfaces are bonded to steel reinforcements and it has been observed that the bond provides adequate confinement of these surfaces. The side surfaces, however, are free to bulge and therefore most susceptible to explosive decompression damage.

The variables that potentially influence the EDD in an elastomeric flex element include: (a) type of rubber (b) thickness of the rubber layer, (c) thickness of cover, (d) axial compression of rubber layer, (e) decompression pressure, (f) type of gas, (g) exposure temperature, (h) exposure time (i) rate of decompression and (j) number of compression-decompression cycles. From a structural designer's point of view, most of these variables are constant, except the type of rubber, thickness of rubber layers and cover rubber. Based on Explosive Decompression Damage (EDD) tests conducted on specially designed small-scale test specimens that replicate the bulge region of full scale flex elements, the following conclusion can be drawn [4]:

- The explosive decompression damage can severely affect the performance of a flex joint and must be considered in the design of flex joints that are exposed to fluid/gas environment in conjunction with precipitous changes in pressure.
- Under similar environmental and loading conditions, thicker rubber layers are more susceptible to explosive decompression damage. All specimens tested showed blisters in the covered regions (refer to side 1 and side 3 in Figures 10 through 12) and extrusion of rubber in uncovered regions (refer to side 2 and side 4 in Figures 10 through 12). Note that the extrusion is the phenomenon where the rubber layer is permanently damaged in the bulge region by sharp edges of the top and bottom surfaces, to which it is bonded, while it bulges out due to compression. The size of blisters and extent of extrusion increases with thickness of rubber layer. Note that the pictures shown in Figures 10 through 12 were taken right after the specimens were taken out of the pressure vessel. As the gas permeates out, the blisters decrease in size and eventually vanish. After a month of degassing, very few blisters were visually noticeable, however the structural damage was still there as observed in the load-deflection tests.

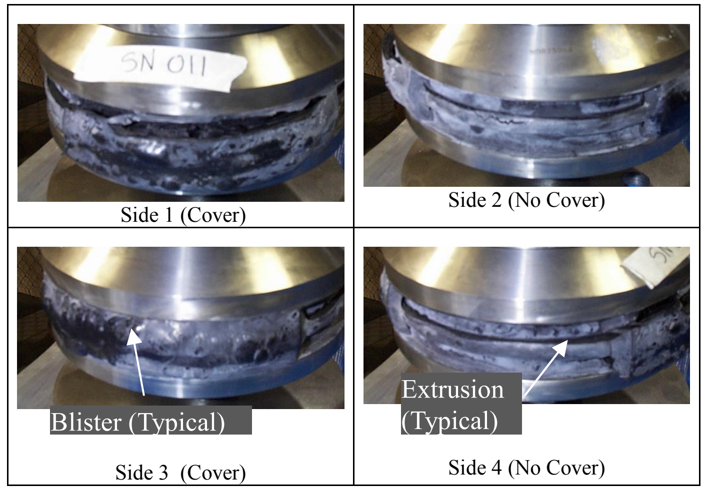

Figure 10: Explosive Decompression Damage in 8 mm Specimen (Typ.) – 21 MPa Decompression Pressure

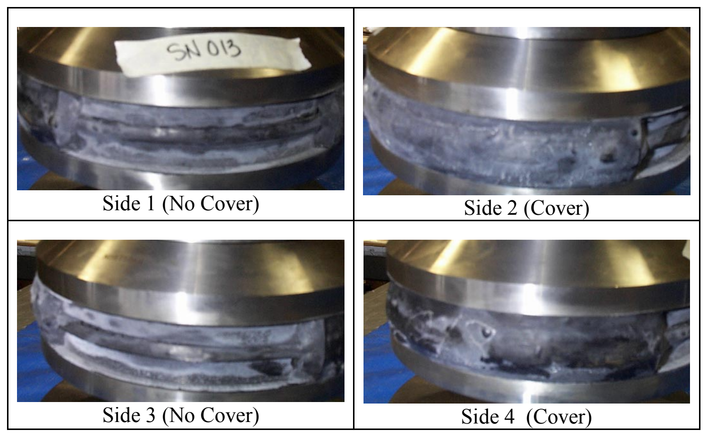

Figure 11: Explosive Decompression Damage in 5 mm Specimen (Typ.) – 21 MPa Decompression Pressure

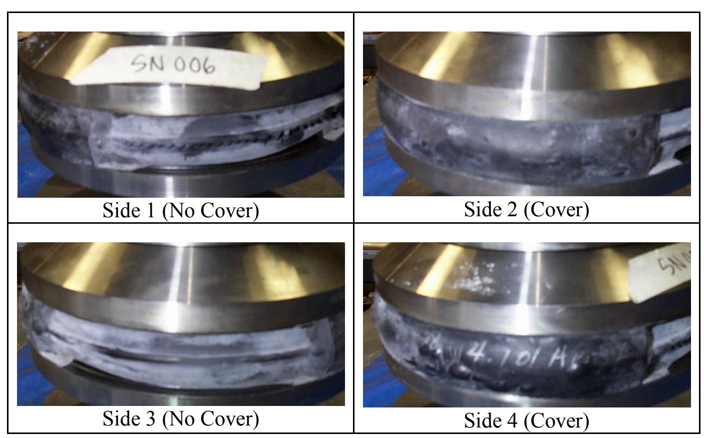

Figure 12: Explosive Decompression Damage in 2.5 mm Specimen (Typ.) – 21 MPa Decompression Pressure

- For thick rubber layers that experience EDD, the damage is not limited to the bulge region only. It propagates inside as more pressurization-depressurization cycles are applied.
- For thick rubber layers that are prone to EDD, a thick cover layer makes things worse.
- Reduction in axial stiffness correlates very well with the extent of explosive decompression damage, therefore comparison of axial stiffness before and after pressurization-depressurization cycles can be used as a measure of explosive decompression damage.
- The extrusion of rubber can be attributed to the localized tearing at sharp uncovered edges exasperated by high temperature to which the specimens were exposed In the present study, high temperature was needed to accelerate the diffusion rate, however, in real service the highest temperature seen is about half of what was used in this study.
- The presence of cover increased blisters, however, it helped to restrict extrusion at high temperatures. Therefore, cover is definitely needed, however more research is needed to determine the thickness of cover that will provide a compromise between the damage due to blisters and damage due to extrusion.
- With adequate confinement of rubber layers, the effects of EDD can be reduced to acceptable levels.
- As shown in Figure 13, the reduction in axial stiffness due to explosive decompression damage is directly proportional to the thickness of the rubber layer. The effect of EDD is almost negligible if the rubber layer thickness is less than 2.5 mm (0.1 inch).

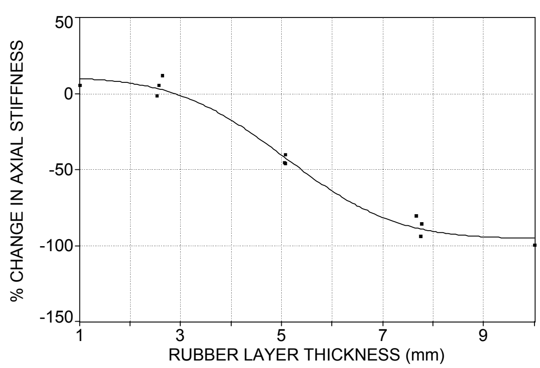

Figure 13: Percent Change in Axial Stiffness due to EDD v/s Rubber Layer Thickness

EFFECTS OF TEMPERATURE VARIATIONS

All physical characteristics (elastic modulus, density, coefficient of thermal expansion, thermal conductivity, specific heat, creep etc.) of elastomers change with temperature, some to greater extent than others. However, distinction must be made between short-term and long-term effects of temperature. Short-term effects are generally physical and reversible while long-term effects are chemical and irreversible.

The most important characteristic from the point of view of a structural engineer is the dependence of mechanical response of elastomer layers on temperature changes. According to the kinetic-molecular theory of rubber elasticity, the elastic modulus of rubber increases as its temperature is increased. This is only valid when elastic behavior predominates. The most commonly used elastomers in flex elements exhibit viscoelasticity and generally soften with an increase in temperature. Figure 14 shows the shear modulus versus shear strain curves for NR50 at various temperatures. Notice that the shear modulus in not as sensitive to temperature changes at higher temperatures as it is at lower temperatures. This phenomenon is more pronounced at low strains. At low temperatures the shear modulus of all types of rubber is very sensitive to temperature changes due to crystallization and vitrification, however, the change in modulus is higher in synthetic rubbers (CR and NBR) in comparison with NR.

At sufficiently elevated temperatures all types of rubber undergo degradation reactions leading to a loss of physical properties. Moderately elevated temperatures may cause the exchange of chains and a net formation of additional cross-links leading to some hardening of the rubber, described elsewhere in this paper. At higher temperatures the scission of cross-links may outweigh cross-link formation with breakdown of the main chain and then charring and embrittlement of rubber. The presence of oxygen is a very important factor in determining the resistance of rubber to elevated temperatures. In the absence of oxygen, most types of rubber (including natural rubber) can survive temperatures up to 180 ^{o}C when degradation would occur very rapidly in the presence of oxygen at this temperature.

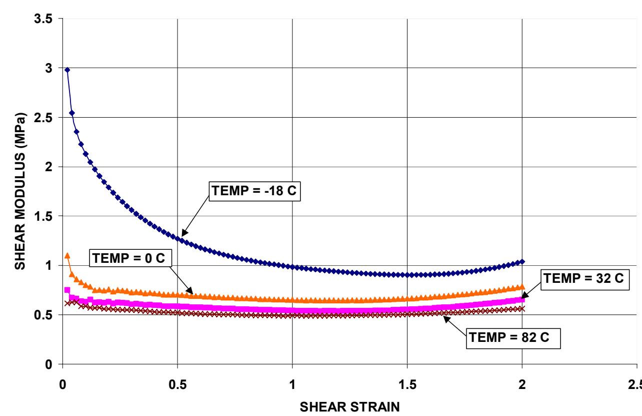

Figure 14: Shear Modulus v/s Shear Strain for NR50 at Various Temperatures

At low strains where most of the fatigue loading occurs, the cocking stiffness of a typical flex joint at 4 ^{o}C is approximately 60 percent higher while at 83 ^{o}C it is about 20 percent lower, in comparison to room temperature. The performance of a flex joint can deteriorate drastically below 4^{o} C or above 100^{o} C unless special design measures are taken.

EFFECTS OF AGING

All elastomers are attacked by oxygen even at room temperature and the reaction is accelerated by heat, light and presence of certain metallic impurities that catalyze the decomposition of peroxides to form free radicals. This process is called aging. Degradation of physical properties is observed in elastomers even at quite low levels of oxidation. The nature of the changes observed vary considerably depending upon the specified elastomer, and the aging conditions to which it is subjected. The net effect on the properties is the resultant of two competing processes of chain scission and crosslinking. If chain scission dominates, the elastomer softens and eventually become sticky with aging. Most elastomers, however, harden and eventually embrittle as a result of aging - a consequence of cross-linking dominance.

Since oxidation most often is involved in the rate-determining step in elastomer aging, the rate and extent of diffusion of oxygen through the elastomer governs the change in properties. The rate of diffusion is dependent on temperature, pressure, exposed surface area and permeability of elastomer. In the case of flex elements oxygen ingress is generally limited to a thin layer of exterior surface only because of small exposed surface area (relative to loaded area) and low permeability of elastomer.

For flex elements, the change in overall cocking stiffness (shear stiffness) due to aging is more relevant than the change in localized tensile properties represented by most of the accelerated aging tests specified in various codes and standards for rubber.

Based on the results of recent research [5], wherein accelerated aging tests in shear mode were conducted in controlled environment (refer to Figure 15) on different sizes of specimens molded from NR, CR and NBR compounds typically used in elastomeric flexible connections, the following conclusions can be drawn (refer to Figures 16 and 17):

- The change in shear stiffness due to aging is dependent on the size of the specimen. As the size increases the percent change in shear stiffness decreases drastically. This can be attributed to the amount of rubber affected by oxidation process.

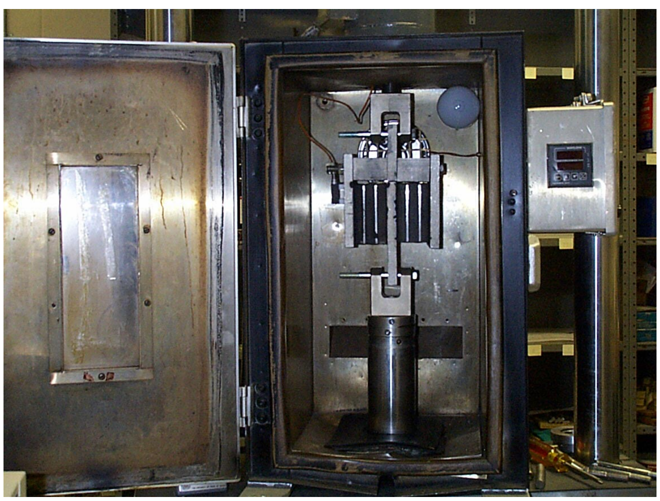

Figure 15: Test Setup for Accelerated Aging Tests in Shear Mode

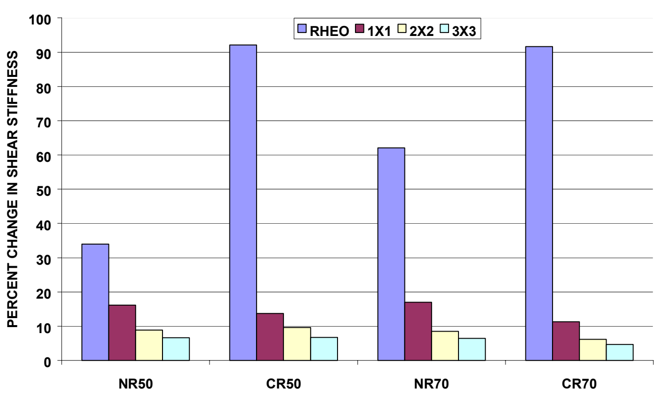

Figure 16: Results after 7 Weeks of Aging at 82° C

- At higher aging temperatures the stiffness change is higher. This is due to a higher oxygen diffusion rate at higher temperatures. The ingress of oxygen is faster and deeper at higher temperatures and therefore the percentage of affected zone to unaffected zone is higher.
- In general the effects of aging are higher in CR and NBR as compared to NR.
- The stiffer rubber compounds age faster.
- The effects of aging are more dominant at higher shear strains.
- Arrenhius based predictions from accelerated aging tests showed that the full size elastomeric flexible connections at ambient temperatures will experience insignificant change (less than 5 percent) in stiffness due to aging over their lifetime.
- Aging can have significant effect on the stiffness characteristics of flex elements exposed to high temperatures for long duration in the presence of oxygen. For such flex elements the effects of aging must be considered during the design phase.

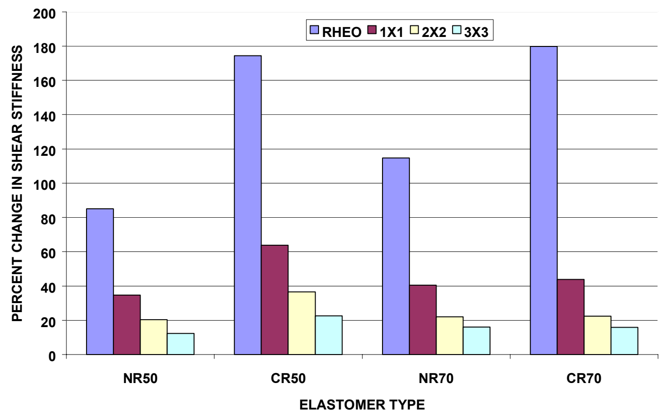

Figure 17: Results after 7 Weeks of Aging at 100° C

EFFECTS OF HYSTERESIS

A high frequency cyclic deformation of a flex joint can lead to a considerable amount of heat generation especially if the amplitude of deformation is large. A plot of load versus displacement for a single deformation cycle is called a hysteresis loop. The area within this closed loop is the amount of mechanical energy converted to heat during this cycle. If the operating conditions are such that hysteresis heat is generated faster than it can be dissipated, the rubber layers will get hot and the performance may deteriorate. In rubber, the viscous component, that is responsible for the heat generation, arises from molecular friction. Strain rate (frequency), strain magnitude and presence of reinforcing fillers (carbon black) increases the molecular friction.

Based on the cyclic tests conducted on a NBR80 shear specimen shown in Figure 18, the hysteresis loops under shear loading at two different frequencies (2 and 4 HZ) are shown in Figure 19. The corresponding temperature increase at ambient environmental temperature is shown in Figure 20.

An extrapolation of these results to full scale flex joints (by means of non-linear coupled thermal-structural finite element analyses) indicates that a cyclic loading at 2 HZ and 50 percent maximum shear strain will not deteriorate the performance, however, at higher frequencies, the effects of heat generation need to be considered during design phase.

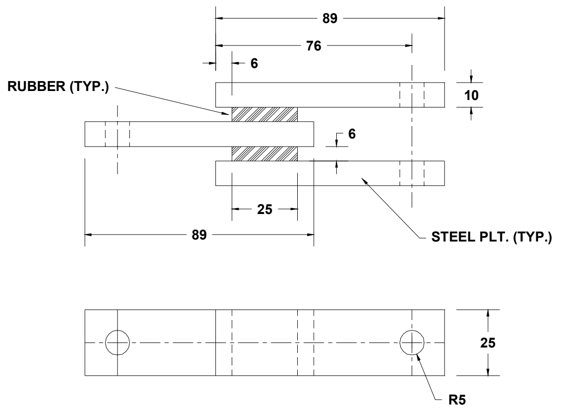

Figure 18: Configuration of Shear Specimen (mm)

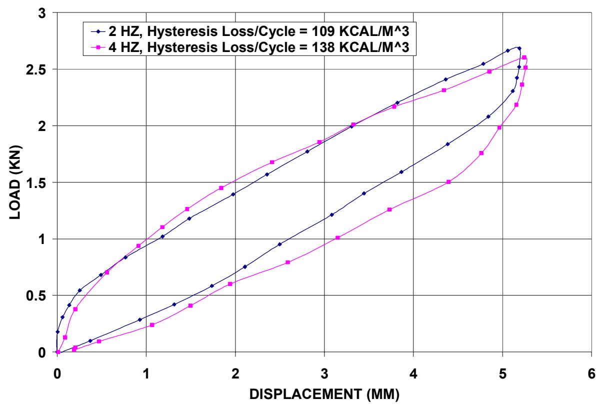

Figure 19: Hysteresis Loops for NBR80

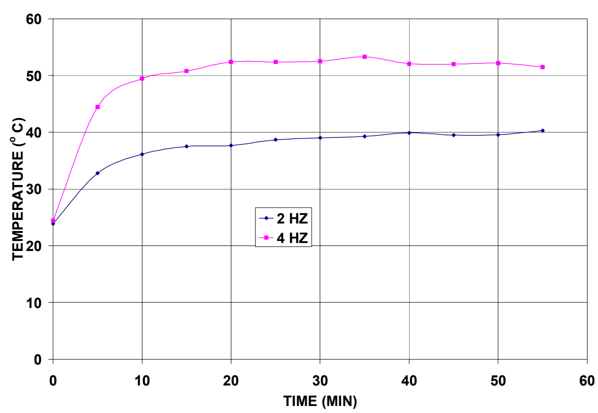

Figure 20: Change in Temperature of 25x25x6 mm Shear Specimen (NBR80)

CONCLUSIONS

Based on the recent research conducted to streamline the design and analysis of elastomeric flexible connections used in offshore oilfield applications, the characteristic properties of rubber that can adversely affect the structural performance of such connections must be properly accounted for in component design.

The most important parameter that governs the structural performance of an elastomeric connection is the effective shear moduli of its rubber layers. The cocking stiffness, that controls the bending stresses in the riser/pipes connected to the flex joint, is directly proportional to the shear moduli of rubber layers. Unlike metals, the shear modulus of rubber is highly dependent on the strain level, strain rate, loading history and temperature. At low and high strains it is high in comparison with moderate strains. At a constant strain, shear modulus decreases as the temperature increases and it relaxes with time. Most of the relaxation occurs in the first few minutes of loading but small changes in shear modulus continue to occur with time. At low temperatures (above glass transition temperature) the shear modulus of all types of rubber is very sensitive to temperature changes due to crystallization and vitrification. This phenomenon is more pronounced at low strains where most of the fatigue cycling occurs. Long-term exposure to high temperatures (below degradation temperature of rubber) in the presence of oxygen increases the shear modulus due to chemical aging. Under cyclic loads shear modulus decreases as more cycles are applied. Other characteristics that may affect the performance include the local damage in rubber layers under tri-axial tension and explosive decompression. Effects of heat generation need special consideration under high frequency cyclic deformation.

Notwithstanding the intricacy of rubber behavior, elastomeric flexible connections remain sine qua non in the flexible joint industrial applications. The flex joint performs as a "smart joint" with four independent nonlinear spring rates (axial, radial, cocking and torsion). The ability to control the stiffness of this four-in-one spring gives unique options to the designers in their development of a structural system with optimum performance.

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