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Long Term Performance of Rubber in Seismic and Non-Seismic Bearings: A Literature Review

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ABSTRACT

The use of seismic isolation bearings to decouple buildings and lifeline structures from strong ground motion has received an increased amount of attention in recent years. While several types of seismic isolation bearings have been developed and proposed for use, the most common type is the laminated rubber (elastomeric) bearing. Because the design lifetime of these bearings is expected to be on the order of 50 to 100 years, the long-term performance of the rubber must be addressed. Therefore, a literature review was conducted to identify potential limits on the long-term performance of rubbers used in bearings. Several issues, including the need for consensus performance standards and for additional research on the effects of creep, aging, temperature, and high-energy radiation on the properties of rubber, were identified.

KEY WORDS: elastomeric bearings; isolation bearings; long-term performance; materials; rubber bearings; seismic isolator

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1. INTRODUCTION

Reinforced rubber[1] base-isolation bearings have been used in the United States in non-seismic applications, such as bridge bearings and anti-vibration mounts, for over 50 years [Long, 1974; Stanton, Roeder, 1982]. The general acceptance of these bearings (hereinafter called non-seismic bearings) has largely been due to their excellent in-service performance [Long, 1974] and the fact that they are more economical, efficient, and maintenance-free than other types of bearings, such as steel springs, steel roller bearings, and steel rocker bearings [Long, 1974; Roeder, et al., 1987].

Within the last decade, rubber bearings have been used in seismic applications. These bearings (hereinafter called seismic isolation bearings) have been installed in over 100 engineered structures worldwide, including 5 bridges, 4 buildings, and 4 major pieces of equipment in the United States [Mayes, Buckle, and Jones, 1988]. Because the number of buildings equipped with seismic isolation bearings is increasing [Kelly, 1986], and since the service life of most structures is normally considered to be on the order of 50 to 60 years [Buckle, 1987; Mayes, Buckle and Jones, 1988], it is important to investigate the long-term performance of seismic bearings.

A reinforced rubber bearing is a columnar, composite structure comprised of alternating layers of rubber and steel. A schematic diagram of one type of rubber seismic isolation bearing is shown in Figure 1. The materials and fabrication techniques used in manufacturing seismic and non-seismic bearings are essentially the same. The major difference is the required performance: seismic isolation bearings must be capable of sustaining large earthquake-induced lateral deformations at some time during the life of a structure. Because seismic isolation bearings might be pushed to the limits of their performance capabilities at some time during their service life, it is necessary to understand the behavior of the materials that comprise the bearing. The properties of a rubber change with time, and are highly dependent on the environmental conditions in the vicinity of the rubber bearing at the time when the earthquake-induced ground motions occur. It appears that little recognition has been given in the base isolation literature to the effects of aging and environment.

For this reason, the literature was reviewed with these objectives:

1. Determine performance requirements for the rubbers used in seismic bearings.

2. Describe materials and manufacturing processes used in fabricating seismic and non-seismic bearings.

3. Identify available field performance and laboratory data for assessing the performance of rubber bearings.

4. Identify factors which may limit the service life of rubber bearings.

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[1] The words rubber and elastomer are used interchangeably in the literature in referring to the broad class of natural and synthetic materials exhibiting high elastic extensibility. In the present work, the term rubber has been selected in referring to these materials.

Although all of these objectives are addressed, the emphasis of this review is to identify and discuss, from the perspective of materials science, the factors that affect the long-term performance of rubber bearings.

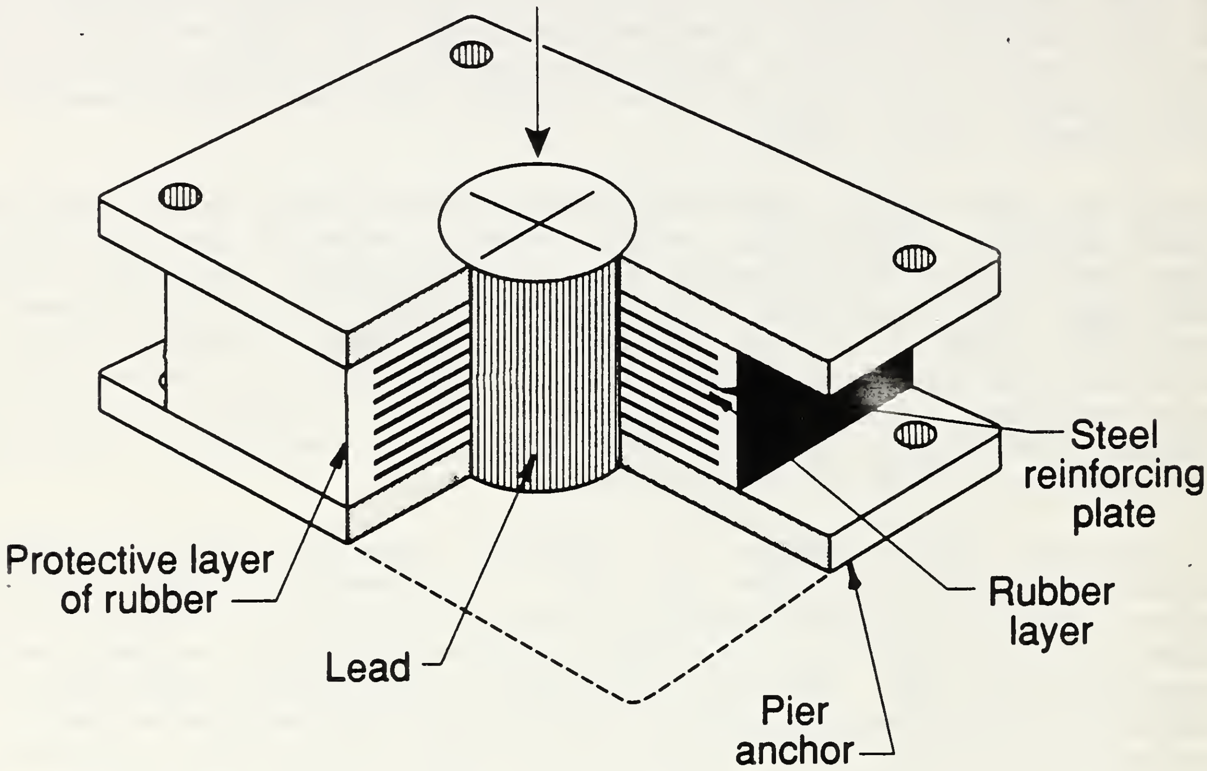

Figure 1: Schematic diagram of rubber seismic isolation bearing.

2. PERFORMANCE REQUIREMENTS FOR SEISMIC RUBBER BEARINGS

Seismic bearings decouple the motion of a structure from the motion of its foundation and, thereby, greatly reduce the forces induced in a structure when large, potentially damaging, earthquake-induced ground motions occur [Derham, et al., 1975; Kelly, 1986; Mayes, et al., 1988; Derham, et al., 1977]. Decoupling is achieved by increasing the fundamental period of the structure to a value beyond the range containing the principal earthquake energies [Robinson, 1982; Mayes, et al, 1988; Buckle, 1987]. This can reduce the magnitude of the earthquake-induced forces by a factor of 5 to 10 [Mayes, et al. 1988] and the damage to the structure's occupants, contents, and facade [Mayes, et al. 1988].

Seismic and non-seismic bearings must also have high vertical stiffness to support the vertical load, and high horizontal stiffness at small displacements to provide rigid support at low levels of lateral force, that, for example, might be generated by high winds. High vertical stiffness results from the restricted lateral deformation of the rubber layers which are constrained by the steel plates. The vertical stiffness of a bearing is essentially independent of its horizontal stiffness [Gent, 1964; Stanton and Roeder, 1982]. The ratio of the vertical- to horizontal-stiffness is nominally in the range of 500 to 1000.

Wind loads and small earthquakes should not induce large horizontal deflections [Buckle, 1986]. To minimize these small deflections, seismic isolation bearings may be equipped with lead plugs [Skinner, 1975; Robinson, 1982; Kelly, Hodder, 1981], frictional elements [Kelly, 1986], or be composed of a rubber having a high shear stiffness at small deflections and a low stiffness at large deflections [Kelly, 1986].

Other requirements which must be satisfied include maximum allowable shear and compressive strains, stability, heat dissipation during repetitive cycling, and a capability to withstand a specified minimum number of cycles. Research on establishing acceptable performance values for these factors is underway at several research centers and these efforts are discussed by Kelly [1986].

3. MATERIALS AND FABRICATION

The field performance of a rubber bearing depends on the materials (steel, rubber, and adhesive) and techniques used in its fabrication.

3.1 Properties of Rubbers

Commercial rubbers are complex materials composed of the elastomer, fillers, oils, accelerators, antiozonants, and retarders which must be blended and vulcanized [Alliger and Sjothun, 1964]. At the molecular level, the unvulcanized rubber can be viewed as a large number of non-polar, long-chain, highly-coiled macromolecules in a random, amorphous microstructure [Treloar, 1975]. The properties of unvulcanized rubbers, however, have little engineering interest, however, since the macromolecules in the unvulcanized rubber easily flow past one another whenever a stress is applied; that is, unvulcanized rubber exhibits liquid-like flow when stressed. Vulcanization transforms this weak, liquid-like, thermoplastic mass into a strong, elastic, tough material by creating a three-dimensional network of covalent sulfur crosslinks between the previously independent macromolecular chains [Billmeyer, 1971; Hertz, 1988]. However, the conversion of sulfur into covalent sulfur linkages is never complete [Sjothun and Alliger, 1964] and residual sulfur and accelerator are always present in vulcanized rubber. These residual constituents may, under suitable micro-climatic conditions, cause further crosslinking as the rubber ages.

The number of crosslinks formed per macromolecule (the crosslink density) is directly related to a rubber's hardness, modulus of elasticity, and the amount of uncoiling (elongation to break). At the low crosslink densities typical of the rubbers used in bearings, localized uncoiling of the macromolecules provides the properties normally associated with rubber-like elasticity. At high tensile or compressive strains, however, the macromolecules strain crystallize; that is, they become parallel with each other and taut, such that a substantial increase in the applied stress is required to cause any additional strain in the rubber [Smith, 1972]. When the stress is removed, the rubber returns quickly to its original, random coiled conformation by an entropic mechanism where the macromolecular chains adopt a conformation of maximum randomness [Gent, 1978].

In engineering applications, rubbers are often specified by their hardness and low temperature properties. The hardness of a rubber is highly correlated with a number of other physical properties including modulus of elasticity and elongation to break. (See Table 1 for other properties). Vulcanized natural rubber can be compounded for IRHD (<u>I</u>nternational <u>R</u>ubber <u>H</u>ardness <u>D</u>egree) hardnesses ranging from 20 to 100 [Teo and Pond, 1977]. A pencil eraser has an IRHD hardness of 30, while an automobile tire has an IRHD hardness of 60. Rubbers used in seismic and non-seismic bearings typically have hardness values of 50 to 60 IRHD. IRHD is highly correlated with both durometer hardness measurements [ASTM D2240] and Young's modulus over most of the hardness range [Gent, 1958]. Decreasing the hardness of the rubber yields a more flexible bearing with greater rotational capacity, while increasing the hardness provides a stiffer bearing with a reduced maximum elongation to break [Long, 1974].

Another significant property is the behavior of a rubber at low temperature. The temperatures (actually temperature bands) of interest are a rubber's cold crystallization temperature and its glass transition temperature.

TABLE 1. TYPICAL PROPERTIES OF BEARING RUBBERS

Property	Natural rubber	Neoprene	Butyl	Silicon	Nitrile
Max Extension %	500	450	500	500	450
Glass Transition Temperature (°C)	-65	-40	-65	-120	-60
Crystallization Temperature (°C)	-25	-10	N/A	N/A	N/A
Creep Deflection	30	30	35	40	N/A
Regional Preference	G. Britain Australia	Germany	cold climates		offshore oil rigs

N/A Not available

Cold crystallization is a first order, time- and stress-dependent, crystal nucleation and growth process which causes changes in the microstructure of the rubber resulting from the formation of locally-ordered regions of the macromolecules [Bruzzone and Sorta, 1978]. In the unstressed state, natural rubber crystallizes over a broad range of temperatures, +5 to -40°C, where the maximum rate of crystallization occurs at -25°C [Wood, et al., 1946]. Designers should be concerned with the increase in the rate of crystallization and the crystallization melting temperature [Bekkedahl, et al., 1941; Smith, 1972; Dow, 1939; Wood, et al., 1945; Treloar, 1975], that occurs when rubber is stressed.

Many properties change when cold crystallization occurs, including increases in the hardness and shear stiffness, and a decrease in its maximum elongation to break [Wood, et al., 1945, 1946; Smith, 1972; Sharples, 1972; Treloar, 1975]. The effects of cold crystallization are quickly reversed when the rubber is heated above its crystalline melting temperature, which is approximately +15°C. As an example of the effect of cold crystallization on the properties of a rubber, Leitner [1955] observed a one-hundred-fold increase in the Young's modulus for unvulcanized natural rubber when it was cooled for 300 hours at 0°C. This research was conducted on unvulcanized rubber, but it is known that vulcanized rubber exhibits all of the main features of crystallization which are observed in unvulcanized rubber [Bekkedahl and Wood, 1941; Wood et al., 1945, 1946].

Rubber loses its elastic properties and assumes glasslike properties below the glass transition temperature. At the glass transition temperature, the shear modulus of the rubber increases by a factor of about 10000 and its maximum elongation to break is greatly reduced. Glass transition differs from cold crystallization because it is not a time-dependent process, and it does not change the amorphous microstructure of the rubber. Instead, the mechanical properties change suddenly after the rubber reaches its glass transition temperature. These changes are approximately an order of magnitude greater than those occurring from cold crystallization; that is, the modulus of an unvulcanized rubber at the glass transition temperature can increase by a factor of 10000 [Roeder, et al., 1987], as opposed to a factor of 1000 during cold crystallization. Like cold crystallization, however, these effects are quickly reversed when the rubber is heated above its glass transition temperature.

Rubbers formulated for use in bearings have low glass transition temperatures (less than -40°C). However, glass transition temperature is not an intrinsic material property, but is highly dependent on the rate of mechanical loading, the rate of cooling, the measurement technique, the loss of plasticizers, and the aging characteristics of the rubber. Deterioration processes such as crosslinking, loss of plasticizers, and aging [Struik, 1978] increase the glass transition temperature and must be considered.

3.2 Rubbers used in Bearings

The most common rubbers used in seismic and non-seismic bearings are natural rubber, polychloroprene (neoprene), polyisobutylene (butyl), and butadiene-acrylonitrile (nitrile) rubber. All of these rubbers strain-crystallize, an important attribute in the selection of rubbers used in bearings [Cadwell, et al., 1940; verStrate, 1978]. It should be noted that not all rubbers are capable of strain crystallizing. Styrene Butadiene Rubber (SBR), for example, is not capable of strain crystallizing and should not be considered for use in bearings.

The mechanical (tear strength, high strain fatigue resistance, and creep resistance) and low temperature (cold crystallization) [Dutt, 1984] properties of natural rubber are superior to those of most synthetic rubbers. Natural rubber, followed by neoprene, is the most frequently specified material for use in rubber bearings. Butyl rubbers have the best low temperature properties of the hydrocarbon rubbers and they are often substituted for neoprene in low temperature applications; nitrile rubbers have limited application in offshore oil structures [Dutt, 1984]. Practices vary around the world; for example, natural rubber is preferred in Great Britain and Australia while neoprene is preferred in Germany.

Other rubbers [Aldridge, et al, 1968; Clark and Moultrop, 1963], can also be used in seismic isolation bearings. These include polydimethyl siloxane (silicone), ethylene propylene diene terpolymer (EPDM), chlorobutyl, and chlorosulfonated polyethylene (Hypalon). Silicone rubber has an excellent working temperature range (see Table 1), but like EPDM, is difficult to cold bond [Long, 1974]. Alternative rubbers have not been used widely in bearings because, in comparison, natural rubber and neoprene are less expensive, have extensive performance histories, and have performed well in the field. Given the advantages of the mainstream materials, it is difficult to justify the use of the alternative rubbers.

3.3. Fabrication Processes

Base isolation systems are fabricated by either a cold-bonding or a fully-vulcanized process [Long, 1974; Ting, 1984]. In cold-bonding, sheets of fully-vulcanized rubber are bonded to interleaving steel plates with adhesive, and cured at room temperature or at an elevated temperature in an oven or autoclave. After the adhesive has cured, another layer of rubber is bonded around the periphery of the bearing to protect the steel reinforcing plates from corrosion. The adhesive used to adhere this protective layer of rubber must be cured separately.

In the fully-vulcanized process, unvulcanized rubber in a semi-liquid or plastic condition is molded or extruded, onto cleaned and adhesively-primed steel plates. The spacing between the steel plates is accurately maintained with dowels, pins, or wedges. The assembly is then heated and pressed in a mold, which vulcanizes the rubber and cures the adhesive. The result is an integral rubber bearing containing no joints.

The advantages of the cold-bonding process are; (a) it provides complete freedom in the size and geometry of the plan section of the bearing; (b) it is not a capital intensive process; and (c) it readily permits inspection of the fully-vulcanized bearing prior to applying the protective layer of rubber [Long, 1974]. Disadvantages include (a) long cure times, (b) the inability to effectively monitor and control the quality of the adhesive bonds between the steel and the rubber sheets [Minor and Egan, 1970], (c) the need for two curing steps in the manufacturing process, the (d) greater waste of materials, and (e) the excessive number of debondments experienced in service.

The fully-vulcanized process is the more common process for manufacturing rubber bearings in the United States. The advantage of the fully-vulcanized process is that it is a one-step process with a short curing time. The disadvantage of the process are the difficulties experienced in monitoring and controlling the vulcanization process, and in the inspection and quality assurance of the finished bearing.

4. PERFORMANCE DATA FOR RUBBER BEARINGS

The most useful data for evaluating the performance of seismic isolation bearings would result from the inspection of these bearings after an isolation-bearing-equipped structure has experienced a design-level earthquake. Such data are not available, however, because no isolation-bearing-equipped structure has yet been subjected to an earthquake of sufficient intensity. In lieu of this prototype response data, the best data can be obtained from observing the field performance of non-seismic bearings and from laboratory tests.

The field performance of non-seismic rubber bearings has generally been satisfactory, although a few bearings have failed [Stanton and Roeder, 1982]. Accurate data on the number and causes of bearing failures are difficult to obtain, however, due to the litigious risks of revealing failure data, reservations on the part of the engineer responsible for a failure, and difficulties in defining rubber bearing failures [Stanton and Roeder, 1982].

Bearing failures are seldom catastrophic. Instead, bearing failures are often attributed to excessive creep, splitting, debonding, overstressing, and loss of vertical alignment [Stanton and Roeder, 1982]. Debonding is the most frequently reported failure mode. Detecting debondments and the other failure modes are important, because these defects may act as initiation sites for crack propagation when the bearing is subjected to large earthquake-induced shear loads [Gent, 1978].

Although the exact cause of a failure is often difficult to determine, failures have been associated with the following: (a) choice of material, (b) design and manufacture of the bearing, (c) installation of the bearing, and (d) environmental conditions. The effect of each of these factors will be considered in the following sections.

4.1 Materials:

Most laboratory studies and theoretical analyses have been performed on newly-manufactured rubber bearings subjected to static or dynamic stress conditions. The research on the static properties of rubber bearings has led to a greater understanding of the mechanics of bearings, but many questions remain. This is particularly true for studies related to the static and dynamic properties of aged rubber bearings, since the ability of a rubber bearing to sustain large horizontal earthquake-induced deformations 60 years after installation must be taken into account.

4.1.1 Short-term Static Loads:

The mechanics and strength properties of un-aged, statically-loaded bearings have been studied by a large number of investigators including DuPont [1959]; Minor and Egan [1970]; the Union Internationale [1962]; Crozier, Stoker, Martin, and Nordlin [1979]; Bell, Schloss, and Subramanian [1981]; Sanpaolesi and Angotti [1972]; Roeder and Stanton [1982]; and Roeder, et al [1978]. When a rubber bearing is compressed, the steel reinforcing plates are subjected to lateral tension while the rubber layers are compressed, except along the edges of the reinforcing plates where the rubber is in tension.

From a materials perspective, rubber bearings take advantage of many of the properties of rubber. For example, the strength of rubber in compression is excellent, the shear properties of compressively-loaded rubbers are good [Cadwell, et al., 1940]. The only apparent weakness occurs along the periphery of the reinforcing plates where the rubber is loaded in tension. Rubber is weak in tension and is highly susceptible to degradation by ozone and other air pollutants [Schnabel, 1981; Andrews, 1968], when loaded in tension.

If the compressive load is sufficiently high, rubber bearings can fail in compression. Common compression failure modes include debonding [Stanton and Roeder, 1982 and Minor and Egan, 1970], yielding of the reinforcing plates [Bell, et al., 1981; Roeder and Stanton, 1982; and Sanpaolesi and Angotti, 1972], buckling [Schapery and Skala, 1976; Buckle and Kelly, 1986; Derham and Thomas, 1983; Minor and Egan, 1970; Roeder and Stanton, 1982; Gent, 1964; and Gent and Lindley, 1959], and curling of the rubber membranes at the corners of rectangular bearings [Stanton and Roeder, 1982; Gent, Henry, and Roxbury, 1974]. Yielding of the reinforcing plates is no longer common, because thicker reinforcing plates are used in newer bearings. Debondment of the rubber from the steel plates, however, remains a problem. The compressive stress at which debondment occurs exhibits high statistical scatter, which has been attributed [Roeder, et al, 1987] to variables associated with the manufacturing process.

4.1.2 Short-term Combined Stresses and Dynamic Loading:

The effect of combined stresses (e.g., compression and shear [Cadwell, et al., 1940; Roeder, et al., 1987; Fujita, 1989] and compression, rotation, and shear) and dynamic compressive shear fatigue and compressive fatigue loading [Cadwell, et al., 1940; Roeder, et al., 1987; the Union Internationale, 1963] are important in seismic applications. As shown in Table 2, few studies of these effects have been conducted to date.

TABLE 2. AVAILABILITY OF DATA.

Failure Mode	Short-term Compress.	Combined Short-Term Loading			Creep	Cyclic loading			
		Compress + Shear	Compress + Rotation	Compress + Shear + Rotation		Shear	Compress	Shear of aged rubber	
								Room Temp	Low Temp
Tensile crack	A	C	C	C	B	B	B	C	C
Yielding of steel reinforce-ment	A	C	C	C	C	C	C	C	C
Debonding	A	B	C	C	C	B	B	C	C
Buckling	A	C	C	C	C	C	C	C	C
Rotation	A	B	C	C	C	C	C	C	C

Notes:
A. Several data sources, good theory
B. One data source, theory in doubt
C. No data, no theory.

Roeder et al. [1987] found that the shear stiffness of a rubber bearing loaded in combined compression and shear is almost identical to the shear stiffness of an uncompressed rubber bearings. Hence, the shear stiffness of a rubber bearing might be the most reliable measure of its elastic properties. Fujita [1989] believes that rubber bearings loaded in combined compression and shear fail through buckling.

For compressed bearings loaded in dynamic shear, the dynamic shear modulus of vulcanized rubber depends on the frequency and amplitude of the imposed oscillations [Roeder, et al., 1987; Minor and Egan, 1970], the rubber compounding ingredients, the temperature, the magnitude of the compressive load [Cadwell, et al., 1940; Roeder, et al., 1987], and the hardness of the rubber [Cadwell, et al., 1940; Roeder et al., 1987]. In general, the fatigue life in shear decreases with increasing rubber hardness, loading rate, magnitude of the shear strain, and magnitude of the compressive load. In all cases of combined compressive and cyclic shear loading, the dominant failure mode was by debonding [Roeder, et al., 1987]. Of the rubbers tested, the strain crystallizing rubbers performed best [Cadwell, et al., 1940; Studebaker and Beatty, 1978] and natural rubber tended to outperform neoprene which in turn tended to outperform butyl rubbers.

The fatigue life of rubber bearings loaded in cyclic compression is affected by the magnitude of the compressive load, the type of elastomer, and the presence of ozone. The compressive fatigue life of rubbers decreased with an increase in compressive load [Roeder, et al., 1987], especially if ozone was present [Lindley and Teo, 1977; Lindley, 1978; Lake and Lindley, 1964]. The compressive fatigue life, however, was not greatly affected by the rate of loading [Roeder, et al., 1987]. In all cases, debondment and losses in Young's modulus were the primary failure modes.

4.1.3 Creep:

Rubbers are viscoelastic materials and exhibit creep. Compressive creep is regarded as an undesirable effect in bridges because of the need to maintain the vertical alignment of these structures. It is common, therefore, to limit the maximum allowable creep deflection in bridge bearings to 20 to 40% of the instantaneous, elastic deformation. For buildings, the limit on maximum compressive creep deflection is less stringent, since creep deflections are not such a significant concern. For this reason, maximum creep deflections equal to 100% of the instantaneous deflection have been allowed [Anderson, 1990].

Only a few studies have been performed on the creep behavior of rubbers. Stanton and Roeder [1982], Derham, et al. [1970], and Crozier, et al. [1989] found that the maximum creep deflection limitations of 20 to 40% could easily be met by current natural rubber formulations. DuPont [1959] found that the ratio of the creep strain to the instantaneous elastic strain only depends on the duration of the stress and the hardness of the rubber, and not the magnitude of the stress. Minor and Egan [1970] observed that hard rubbers tended to creep more than soft rubbers and that the maximum creep deflections increased by 14 to 73% when a compressed rubber was subjected to a few cycles in shear, an effect which has been observed in many polymers [Struik, 1978].

Stevenson [1985] conducted field investigations on the creep response of three rubber-bearing-equipped structures (an apartment building, a railroad bridge, and anti-vibration pads under a subway track). He found that the creep response of rubbers loaded for 20 years could be predicted from creep deflection data collected a short time after the bearing was loaded in compression. Derham, et al. [1975] had similar findings. Therefore, it has been assumed that the long-time creep response of seismic bearings is not of major concern, and rubbers that have been in service for 60 years will be able to sustain large earthquake-induced shear deformations. This assumption, however, may be incorrect.

Creep deflections decrease the entropy of crosslinked networks [Smith, 1972; Treloar, 1975], resulting in a broadening of the glass temperature range [Struik, 1978] and increasing the rate of crystallization and the crystalline melting temperature [Dow, 1939; Wood, et al., 1945]. For example, Dow [1939] found that the melting temperature of crystalline regions in unvulcanized rubbers increased from 16°C for unstressed rubber, to 77°C for rubber subjected to a 125 MPa (18,000 psi) hydrostatic compression stress. Wood, et al. [1945] observed an approximately linear increase in the crystalline melting temperature from 36 to 70°C for hydrostatically-compressed unvulcanized rubber as the stress increased from 0 to 120 Mpa (17,000 psi). Thus, rubbers which are continuously loaded in compression may crystallize at temperatures which are normal during most of the year over large segments of the country. Since rubber crystallization affects a wide-range of mechanical properties of a rubber, including hardness and shear modulus, the creep-induced cold crystallization effects deserve further study.

4.2 Design and Manufacturing Considerations:

Many of the early non-seismic bearing failures were associated with problems in the design and manufacture of bearings. The principal causes of failure included debondment, uneven thickness of elastomeric pads, non-uniform bulging of the rubber pads, slipping, and missing reinforcing plates [Minor and Egan, 1970; Stanton and Roeder, 1982]. The frequency of bearing failure has been reduced by (a) changing from unreinforced plain pads to reinforced rubber bearings, (b) changing from the cold-bonding process to the fully-vulcanized process, and (c) establishing better understanding between the bearing manufacturer, designer, and end user about the needs and requirements of a good rubber bearing. Debondment and, to a lesser extent, uneven rubber pad thickness and non-uniform bulging remain the most frequently reported problems. Many of these failures can be attributed to the lack of manufacturing and processing control in the production of the bearings [Long, 1974; Hindmarch, 1984; Ting, 1984].

Rubber compounding [Johnson, 1987; Kraus, 1978], cleaning and priming the metal reinforcing plates, extruding the rubber latex, curing the adhesive, and vulcanizing the rubber are highly complex manufacturing processes which should be controlled by consensus performance standards. This is especially important for equipment having a life-safety function, such as seismic isolation bearings. The establishment of performance standards has been hindered, however, by the proprietary nature of the rubber bearing manufacturing process [Stanton, et al., 1982; Tarics, Way, and Kelly, 1990]. Unable to ensure the quality of the manufacturing process, the end user is limited to checking the quality and performance of the finished product. These checks include measuring the dimensions of the rubber bearings and performing rudimentary mechanical tests. It is doubtful whether these tests on the finished bearing are sufficient and sensitive enough to detect any but the most gross defects. Clearly, the best way to ensure the quality, and the reliability of the rubber bearing, is to control the manufacturing process [Ting, 1984; Hindmarch, 1984; Burke, 1980; Fujita, 1989]. Current materials standards for rubbers and steel reinforcement in the United States are listed in Appendix A.

4.3 Installation:

Installation-related problems appear to be rare. Exceptions include cases where a rubber bearing was installed vertically, instead of horizontally, and where the bearing was installed on a non-parallel concrete foundation [Stanton and Roeder, 1982]. The lack of installation-related problems can be attributed to good field inspections, the finished nature of a rubber bearing, and the ease of its field installation.

4.4 Environmental Effects:

As mentioned in section 4.1.2, compressively-loaded rubber bearings take advantage of many of the physical and chemical properties of rubber. This is especially true with respect to the effect of solvents and air pollutants, which are often of major concern. In the following sections, the effects of ozone, corrosion, temperature, and high-energy radiation are reviewed.

4.4.1 Ozone:

Ozone attacks unsaturated double bonds in the molecular chain and can chemically degrade rubber through a free radical mechanism. Both of these degradation mechanisms result in an increase in crosslink density and, eventually, rubber embrittlement and cracking. The degradation effects of ozone are greatly accelerated, however, if a rubber is loaded in tension [Andrews, 1968; Braden and Gent, 1962; 1960a,b]. For this reason, it is not surprising that the degradation effects of ozone are probably the most extensively studied of the environmental effects [Lewis, 1972,1973].

The design of a rubber bearing greatly mitigates the effects of ozone. For example, several researchers have concluded that bearings should be able to withstand 50 years of exposure to ozone without major deterioration [Lindley, 1971; Derham et al., 1975; Lake and Lindley, 1964, 1967]. Ozone attacks and cracks the outer protective cover of a bearing, but this degradation should only affect the appearance of a bearing, and not its structural performance. A crack that extends into the interlaminar regions of a bearing, however, may reduce the fatigue life of a bearing loaded in shear [Minor and Egan, 1970; Stanton and Roeder, 1982; and Lewis, 1973], accelerate debonding of the adhesive from the metal plates [Lindley, 1971], and facilitate the corrosion of the reinforcing plates.

4.4.2 Corrosion:

Many of the early non-seismic bearings were manufactured without a protective rubber layer around the periphery of the bearing. As a result, the steel reinforcing plates often corroded. The steel plates in rubber bearings manufactured by the fully-vulcanized process, however, are protected by a layer of rubber and, to date, no corrosion in seismic isolation bearings manufactured by this process have been reported in the literature.

4.4.3 Temperature:

Rubbers do not perform well at either high temperatures (greater than 70°C) or low temperatures (temperatures below the crystalline melting temperature) in dynamic fatigue [Cadwell, et al., 1940], but do perform quite well at temperatures between these extremes [Stevenson, 1984]. Problems related to the low temperature response have been discussed in Sections 3.1 and 4.1.3. Problems associated with the high temperature performance of rubbers are discussed in this section.

At temperatures above 70°C, many rubbers degrade via a mechanism of crosslinking or reversion (breakage of crosslinks creating free radicals which reform into cyclic structures [Coran, 1978]). Both mechanisms increase the hardness and modulus of the rubber, resulting in embrittlement. For example, Barker [1988] observed an 80% reduction in the elongation to break in 170 days, and a doubling of the modulus in 50 days for a vulcanized natural rubber heated at 70°C. When this same rubber was heated to 100°C, the elongation at break was reduced by 80% in seven days and the modulus was doubled in seven days.

Bergstrom [1977 a,b] found that some rubbers perform better at high temperatures than others; for example, when heated in an air-circulating oven at 100°C, natural rubber outperformed neoprene rubber which, in turn, outperformed both nitrile and butyl rubbers.

4.4.4 High-Energy Radiation:

At least six nuclear power facilities in France and South Africa have been equipped with seismic rubber bearings and it is expected that, in the near future, the United States, Japan, and other European countries will equip their nuclear facilities with seismic bearings [Tajirian, Kelly, and Aiken, 1990]. Although shielded from the high-energy radiation flux by a concrete barrier [Coladant, 1989], seismic bearings are probably exposed to low fluxes of gamma, neutrons, X-rays, and fast electron radiation in nuclear facilities. Knowledge of the expected radiation dosages and other operating conditions must be well understood prior to the installation of these bearings, since rubbers are highly susceptible to radiation damage [King, et al., 1961].

High-energy radiation is absorbed through the interaction of high-energy particles with the atomic nucleus or the electron cloud surrounding the atomic nucleus [Schnabel, 1981]. Absorption of high-energy particles can rupture the macromolecular chains via ionization or through a free radical mechanism. The amount of damage sustained by a rubber is directly proportional to the absorbed radiation. After the free radicals are formed, the rubber degrades via either a chain scission or a crosslinking mechanism. Most rubbers degrade through crosslinking which increases both the modulus and hardness of the rubber while decreasing the maximum elongation to break [Sieron and Spain, 1968; Spinks and Woods, 1990; Gluekler, et al., 1989]. Butyl and polysulfide rubbers degrade through a chain scission mechanism causing the rubber to soften and, at extremely high dosages, to become liquid-like. Prior to becoming liquid-like, the modulus and hardness of these rubber will greatly decrease.

The amount of radiation which can be absorbed before the utility of a rubber is impaired depends on the thickness and composition of the rubber, including the type of curing agent, antioxidants, fillers, and other additives used in the formulation [King, et al., 1961]. The effect of three exposure levels are shown in Table 3. The threshold absorption is the maximum absorption below which no macroscopic damage is observed in the rubber; moderate damage signifies a 50% change in the mechanical properties of a rubber; while severe damage implies that the rubber has little or no remaining utility. For the rubbers used in bearings, an absorption value between the threshold and moderate damage seems like a reasonable upper limit. It should be noted, however, that the absorption values in Table 3 are for unstressed rubber. The radiation dosages yielding equivalent damage in compressed, dynamically-loaded rubbers are known to be substantially lower than these values. For example, King, et al. [1961] found that most rubbers acquire high compressive set when irradiated at slightly elevated temperatures (70°C) and irradiated with gamma photons.

TABLE 3. RADIATION DAMAGE TO UNSTRESSED VULCANIZED RUBBERS [Sieron and Spain, 1968].

ELASTOMER	THRESHOLD (Mrads)	MODERATE (Mrads)	SEVERE (Mrads)
Butadiene-styrene	40	40	400
Natural rubber	40	60	400
Hypalon	10	60	100
Neoprene	10	60	100
Butadiene acrylonitrile	10	60	100
Polysulfide	30	40	100
Silicone	10	40	70
Fluorocarbon	10	30	50
Butyl	1	3	5

5. SUMMARY

Rubber bearings have been successfully used in the United States in-non-seismic applications for over 50 years. In the past decade, rubber bearings have been designed for seismic applications. Worldwide, over 100 structures have been equipped with seismic rubber bearings and it appears that seismic bearings will be used increasingly to isolate structures from earthquake-induced ground motions.

The materials and manufacturing processes for non-seismic and seismic bearings are basically the same. The major difference between the two bearings is in their performance requirements. Seismic bearings are expected to perform like non-seismic bearings for most or all of the life of a structure, and yet be capable of withstanding large earthquake-induced horizontal deformations. This additional performance requirement is a demanding one, since the chemical and physical properties of viscoelastic materials, like rubber, change over time; that is, rubbers age. The aim of this review was to identify possible factors affecting the ability of a seismic bearing to perform its intended life-safety function over the design life of a structure.

Rubbers are most commonly specified by their hardness and their low temperature properties. The most frequently specified rubbers for seismic and non-seismic bearings are natural rubber and neoprene, although butyl and nitrile rubbers also find some application. One of the primary requirements of a bearing rubber is that it must strain crystallize at large deformations.

The field performance of non-seismic bearings has generally been excellent. The few failures that have been reported have been attributed to inadequacies in the manufacture of the bearings. To improve the reliability of rubber bearings, consensus standards should be developed for compounding and mixing the rubber, cleaning the surface of the metal plates, curing the adhesive and vulcanizing the rubber, determining the uniformity of the cure, determining the strength of the bond between the steel and the elastomer, measuring the vertical alignment of the bearing, and measuring the performance characteristics of the finished bearing.

To date, most of the research on the mechanical properties of rubber bearings reported in the literature pertain to the strength and stiffness of rubber bearings. Limited data are available on the effects of combined loads (e.g., compression and shear loading) and dynamic loading, and no published data were found on the static strength and dynamic properties of statically compressed, aged rubber bearings. This lack of data should be of major concern in seismic bearings because compressive creep deflections can increase the cold crystallization temperature, the rate of cold crystallization, the crystalline melting temperature, and can broaden the range of temperatures within which the glass transition temperature falls. These changes could affect the mechanical properties of rubber bearings at temperatures which are common within the United States during most of the year. As such, the effects of creep on the low temperature properties of bearings deserve further study.

Ozone attacks the protective layer of rubber on the periphery of a rubber bearing. This deterioration is normally considered to be cosmetic in non-seismic bearings. In seismic bearings, however, these defects may act as initiation points for crack propagation during an earthquake, or they may facilitate the debondment of the rubber from the reinforcing plates resulting in the corrosion of the steel plates.

For seismic bearings installed in nuclear facilities, the rubber and adhesives in the rubber bearings will degrade if sufficiently high dosages of high energy radiation are absorbed. At high absorptions, rubbers embrittle or become liquid-like. The dosages reported in the literature are for unstressed rubbers, whereas bearings in service are continuously compressed. In the few published results in which rubbers were compressed, heated to 70°C, and irradiated with gamma radiation, the dosage required to reach an equivalent change in a physical properties were less than those observed in unstressed rubbers. For this reason, the effects of high-energy radiation on compressed rubbers deserve further study.

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APPENDIX A: Standards for Physical Testing of Rubbers and Steel

A large number of standard methods exist for measuring the physical properties of rubber [Brown, 1986] and for specifying steel. Few standards exist for insuring the performance of the materials (rubber, steel, and adhesives) comprising rubber bearings. A list of ASTM standards which have applicability to rubber bearings follows:

- ASTM A36, Specification for Structural Steel.
- ASTM A570, Specification for Hot-Rolled Carbon Steel Sheet and Strip, Structural Quality.
- ASTM D395, Test Methods for Rubber Property -- Compression Set.
- ASTM D412, Test Methods for Rubber in Tension.
- ASTM D429, Test Methods for Rubber Property -- Adhesion to Rigid Substrates.
- ASTM D518, Test Method for Rubber Deterioration -- Surface Cracking.
- ASTM D573, Test Method for Rubber Deterioration in an Air Oven
- ASTM D624, Test Methods for Rubber Property -- Tear Resistance.
- ASTM D1149, Test Methods for Rubber Deterioration -- Surface Ozone Cracking in a Chamber.
- ASTM D1229, Test Method for Rubber Property -- Compression Set at Low Temperatures
- ASTM D2137, Test Methods for Rubber and Rubber-Coated Fabrics -- Brittleness Temperature by Impact.
- ASTM D2240, Test Methods for Rubber Property -- Durometer Hardness.
- ASTM D4014, Specification for Plain and Steel-Laminated Elastomeric Bearings for Bridges with Annex (A1 -- Determination of Shear Modulus).

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The use of seismic isolation bearings to decouple buildings and lifeline structures from strong ground motion has received an increased amount of attention in recent years. While several types of seismic isolator bearings have been developed and proposed for use, the most common type is the laminated rubber (elastomeric) bearing. Because the design lifetime of these bearings is expected to be on the order of 50 to 100 years, the long-term performance of the rubber (elastomer) must be addressed. Therefore, a literature review was conducted to identify potential limits on the long-term performance of rubbers (elastomers) used in bearings. Several issues, including the need for consensus of performance standards and for additional research on the effects of creep, aging, temperature, and high-energy radiation on the properties of rubber.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

elastomeric bearings; isolation bearings; long-term performance; materials; rubber bearings; seismic isolator

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