Master of Science

Mechanical Properties of the Rubber Material Used in Elastomeric Bridge Bearing Considering the Effects of Aging.

The Graduate School

Of the University of Ulsan

Department of Civil and Environmental Engineering

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Mechanical Properties of the Rubber Material Used in Elastomeric Bridge Bearing Considering the Effects of Aging.

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Dedication

...In memory of Armah Quona Taylor and

Appreciation to Victoria Herbert Wollie

Preface

First and foremost, my utmost gratitude is expressed God-ward for His unwavering grace, mercy and provision throughout my study period.

I owe a debt of gratitude to the Korean people and their government for their financial support through the Korean Government Scholarship Program (KGSP).

Next, I would like to extend my gratitude to Professor Kim Ick Hyun upon whose intellectual capital and vast experience this paper came into fruition. He provided support where I was lacking, direction when I was lost and was particularly patient when I did not know. So much so that I mere mention of him in the acknowledgement greatly underscores his impact on this paper.

I would be remise if I were not to mention the unbending support from our lab manager Dr. Sun Chang Ho and my lab colleagues. Their unwaveringness to assist in matters relating to school as well as general livelihood has been remarkable and is certainly not unnoticed.

As a final note of Acknowledgement, I would love to thank my church for providing the desperately needed spiritual support in guiding me during these times. Immeasurable gratitude is also expressed to my mother, Victoria Herbert Wollie, my siblings, family and friends for the emotionally love and support they showed me during these times.

요약

노화의 영향을 고려한 교량 탄성받침의 고무 재료의 기계적 성질

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핸리 쿠오나 테일러

교량의 교각은 지진하중에 의해 큰 외력(모멘트 및 전단력)을 받게 된다. 이러한 지진력에 의한 에너지를 효과적으로 소산시켜서 원치 않는 부재력(응력)이 집중되지 않도록 하는 것이 중요하다. 이를 위하여 고무재료를 기반으로 하는 탄성받침이나 지진보호받침을 적용하는 경우가 점차 증가하고 있다. 교량의 공용수명이 약 100 년 정도임을 감안하면 교량의 고무받침의 성능은 시간이 경과함에 따라 역학적 거동 특성에 변화가 생긴다.

이 연구에서는 노화(열화)에 따른 탄성받침의 거동을 이해하기 위해 탄성받침에 사용되는 천연고무와 합성고무의 역학적 특성 변화를 실험을 통하여 분석하였으며, 이들 재료를 기반으로 하는 탄성받침의 부재 수준의 역학적 거동 특성변화를 해석을 수행하여 분석, 평가하였다.

이 연구를 통해, 합성고무가 천연고무에 비해 인장(tension) 및 전단(shear)의 물리적 변화가 훨씬 크다는 것을 알았으며, 또한 전단에 비해 인장의 역학적 특성이 노화에 크게 영향을 받는 것을 확인하였다.

노후화에 의한 강성의 변화는 천연고무에서는 최대 전단 강성이 18.73% 증가했고 합성고무는 2.89%로 증가하였다. 또한, 파단시의 최대 연신율은 감소하였다.

이러한 교량 받침의 역학적 특성 변화는 교량의 진동주기를 작게하여 교량에 발생하는 지진력을 증가시키기때문에 시간 경과에 따른 고무받침의 노후화가 교량의 내진성능을 악화시킬 수 있다는 것을 알 수 있다.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

1. INTRODUCTION

All concrete or steel bridge structures are subject to certain movements such as those caused by the change in temperature, traffic, wind, external loading or even by the movements as a result of their weight. This necessitates the need for support devices that absorb or transmit the loading from the superstructure through the substructure to the underlying soil. These devices, bearings, are considered the mechanical components of the bridge system. The types of bearings are primarily differentiated by their make-up materials and the degrees of freedoms they permit. Elastomeric bearings are quickly becoming the bearing of choice amongst several designers and engineers due to its superiority with respect to function, cost and maintenance.

1.1. Elastomeric bearings VS other types of bearings

Elastomeric bearing allows for translational and rotational displacement and the absorption of horizontal loads as well as vertical loads. An advantage of the elastomeric bearings is that they have no moving parts, making them superior to the traditional pin and balls mechanical bridge bearings in terms of repairs. As seen in figure 1-1 the factors that influence the selection of a bearing type by designers the most are ease of maintenance, repair or replacement, degrees of rotation and the cost of production. Cost as factor for selection of bearings favours the elastomeric bearing as it is more economical than most of the principle bearing types.

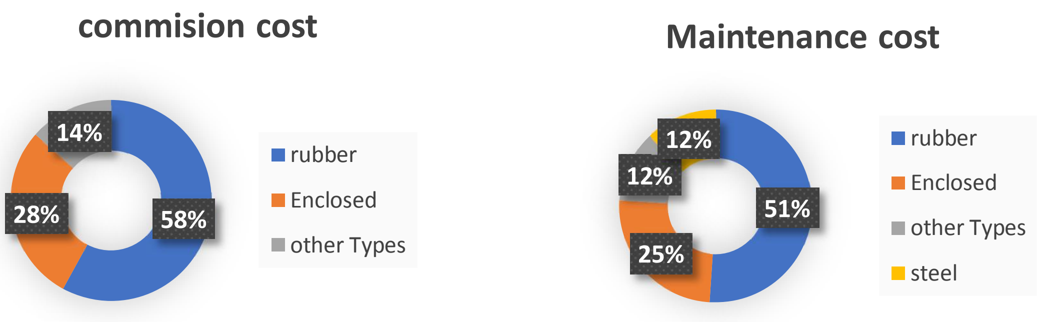


Fig.1-1. The cost of production and maintenance of the various types of bearings

Elastomeric bearings, when compared with other bearings were ranked best in terms of flexibility and durability requirements the most frequent cause of bearing replacement has been associated with problems originating from the degradation of the materials or corrosion. Degradation and the inability to further withstand external forces, thermal action, live and dead loads, weather condition air moisture changes and other environmental effects accounts for the problems affecting the durability of the bearings (Fasheyi, A, O).

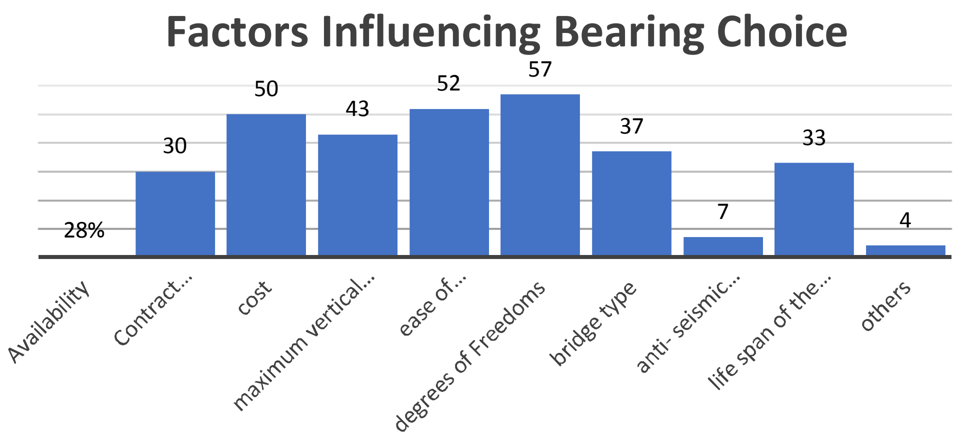


Fig1-.2. Factors influencing the selection of bearings

As a final note of introduction, it is important to realize that although the basic qualitative processes involved in degradation of common polymers are reasonably well determined, the present quantitative understanding, in general, is insufficiently advanced in order that quantitative predictions can be made of the extent to which degradation diminishes the physical properties of bearing.

This may be due to the relative recency of the innovation of these bearings and the cost and time associated with accelerated aging explements. This study investigates the mechanical behaviour of the most important material used in elastomeric bearing whilst taking into consideration the deteriorative effects of the environment. Bearing takes up 5% to 10% of the total cost of bridge construction therefore a clear understanding of their lifetime behaviours must be established to avoid repairs and replacement. In order to do this with the bridge bearing the behaviour of two types (Natural rubber and Neoprene) of the principal composite material, rubber, when subjected to the aging environment was investigated.

CHAPTER TWO

2. Background and Literature Review

2.1. Brief History of Bearing

The development of Bridge bearings into an essential bridge construction device has a history that spans about two centuries. The underlying factors responsible for this development are the ever-increasing sizes of constructions and the required solutions to those new engineering demands. The first generation of bearings had a simpler responsibility — to keep the superstructure, which were usually wooden, dry, absorb impact and to distribute loads evenly to the substructure. As cast-iron and steel became the predominant construction material for bridges, iron and steel bearings became the replacements to the structurally inferior wooden laths. This was the introduction of what has been termed as second-generation bridge bearings. The unique material characteristics of steel and iron allowed for the construction of bigger bridges with longer spans. However, the movement in the iron superstructure, mostly temperature induced, created a new engineering problem. Bridges could no longer be perceived as rigid unmovable structures but rather as mechanical systems that allow specified movements. Within no time rollers, balls and pins became indispensable components in bearings as they provided latitude for specified movements in longitudinal and traverse directions. These were the primary technological advancement in bridge bearings for the latter part of the nineteenth century and the earlier part of the twentieth century. There were, however, other innovations and modifications during this period, but none could permanently establish itself as they were only fuelled by the desire to acquire superior or cheaper materials for existing bearings. The application of synthetic materials like rubber and Teflon gave birth to the third and current generation of bridge bearings. The previous generations of bearings were either fixed or only capable of movements such as rolling, sliding, and or rocking, but rubber and Teflon gave bearings a newer dimension of movement— deformation. Hence, these forms of bearings are generally referred to as deformation bearings. This became a revolutionary advancement for bearings as the deformation bearings' energy dissipating capabilities would become pivotal in seismic resistance and base isolation engineering.

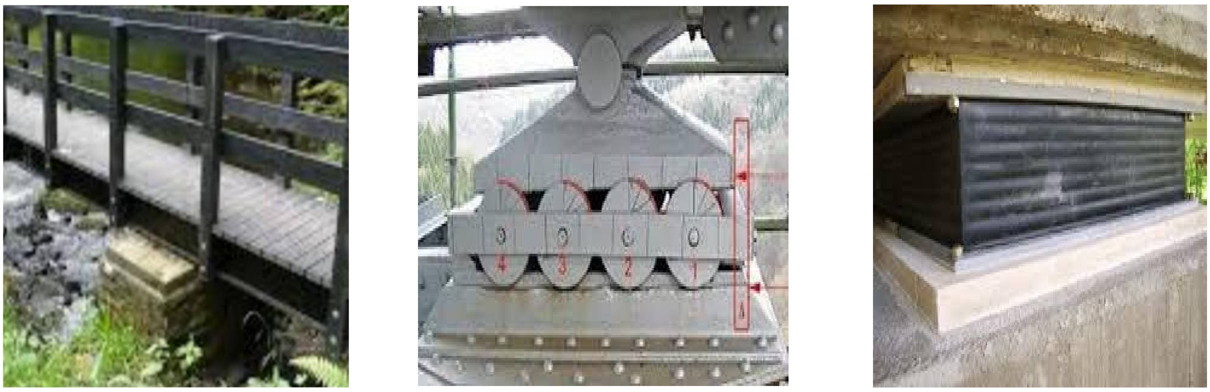


Fig.2-1. *From left to right. The wooden lath (1st Generation), the mechanical bearing (2nd generation) and the deformation bearing (3rd generation)*

2.2. Brief History of Isolation Devices

For most part of history seismic resistance was accounted for by massive and stiff construction. The stiffness and rigidity of these structures left them vulnerable to sudden and brittle failures. It would later become apparent that the most efficient approach is to reduce the seismic demands on the structure rather than stiffening the structure to increase its earthquake resistance capabilities. This approach is considered as seismic isolation. The concept of seismic isolation has been in application for as far back as 1892 as can be seen with the pads supporting the railway viaduct constructed in Melbourne, Australia; but the first recognized application of it was in 1969 at the Pestalozzi School in Skopje, Macedonia. (Itoh et al, 2006) The elastomeric pad used in Skopje had a major flaw; the vertical stiffness was only slightly larger than the horizontal stiffness leading to vertical movements in the system under horizontal loading. The remedy to this defect was the introduction of metal shims placed interchangeably between rubber layers to increase the vertical stiffness. (Wu, G et al) These bearings are known as elastomeric bearings. In other to add energy dissipation to the already existing flexibility, the lead rubber bearing (LRB) was invented in the 1970's.(In the early 1980's development in rubber technology led to new rubber compounds, which were termed as high damping rubber (HDR). These elastomeric bearings have been used widely and with much success as seen in the Northbridge earthquake 1994 and Kobe earthquake 1995. (Naeim, F et. Al. 1999). Isolation devices are usually characterized by three designed concepts.

i) Flexible mounting to lengthen the period of vibration in the total system

ii) Energy dissipation to control the deflection between the substructure and the superstructure

iii) Provision of rigidity under service loading such as wind and seismic load.

2.3. Problems associated with Elastomeric Bearings

Since the introduction of rubber as a material in bridge bearings, it has proven to be a more viable alternative to the traditional steel mechanical bearing systems in terms of functionality, cost and maintenance (D.E. Tonias and J.J Zhao). Whilst elastomeric bearings are not susceptive to corrosion and other related metallic deteriorative mechanisms like steel or iron, they are also prone to age related deteriorative complications. Frequent problems that have been observed through numerous feasibility studies are as follows.

2.3.1. Bearing slip

Bearing slippage is a serious serviceability issue as it leads to several structural problems like deflection, spreading of the pad, and concerns with the integrity of the sub structure. Pad slippage originating from designed failure has been found to occur when the shear stress exceeds one fifth of the compressive stress acting on the pad. Du Pont de Nemours and co. (design 1995). Another factor that significantly influences the bearing resistance to pad slippage is the shape factor of the bearing. Bakirzis and Lindley (1970). The cause of bearing slippage has largely been accredited to thermal movements within the bridge girder. Other cases like insufficient allowance for shrinkage and creep of prestressed concrete girders, girder placement at extreme temperatures and construction misalignment are also responsible for slippage. However, the cause of bearing slippage has not being solely structural related; it has been discovered through Spectro analysis that antiozonants, added to curb the deteriorative effects of ozone on rubber, moves to the surface of the rubber and creates a slippery surface that reduces the frictional resistance of the bearing. This causes the bearing to slip even when the loading satisfies the designed requirements specified by Du Pont de Nemours and co. Although a single slip is unlikely to do damage, cyclic slip deteriorates the outside of the rubber and may precipitate cracking earlier than would otherwise be the case. In extreme cases the bearing might slip out of position. In extreme cases the bearing might slip out of position. Slipping may be prevented by introducing lips, stops, or dowels or by using external steel plates that have a reliable coefficient of friction against concrete and can be directly connected to steel girders. Other positive connections can be made with sole plates that are bonded to the bearing and positively attached to the bridge piers or girders.

Fig.2-2. *Bearing slippage*

2.3.2. Delamination

Delamination between the elastomer and the steel reinforcement used in laminated bearings occurs as a result high shear stresses that causes the bearing to split and eventually delaminate. Delamination is usually not initiated by the failure of the bonds between the elastomer and the steel shim but by the splitting of the elastomer due to an inconsistency in the elastomer's profile. The ensuing crack propagates near the surface of the steel shim causing delamination. Older and brittle pads are more susceptible to these kinds of failure.

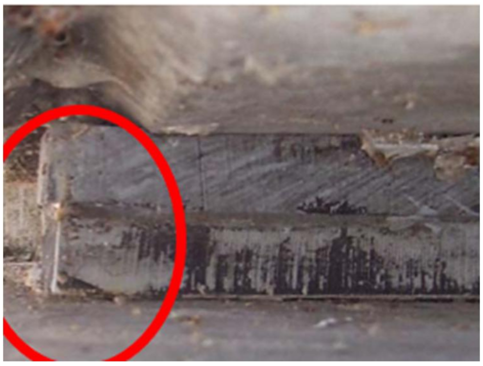


Fig.2-3. Delamination of bearing

2.3.3. Bulging and creep

The molecular structure of elastomers renders them vulnerable to time dependant deformation under constant loading. The ratio of creep strain to elastic strain is independent of stress, depending only on time and material hardness. Creep is caused mostly by compressive forces and moments in the bearing, as these will cause the bearing to bulge. The edges which are bulging will experience the highest shear stresses. Stress relaxation will be highest at the edges as well. The magnitude of the "bulge" in a bearing will be dependent on the temperature as well as the hardness of the bearing. The softer the bearing, at ambient temperature, the more the bearing will bulge and eventually creep. As the temperature decreases the bearing will become stiffer and bulge less and vice versa for increasing temperature. (Fu C.C and Angelilli C 2007).

Fig.2-4. Bulging and creep

2.3.4. Crushing

Crushing of an elastomeric bearing is usually an indication of compressive failure. Poor or under design of the pad is the primary cause of this kind of failure. Pad crushing has been resolved by tougher restrictions on the thicker unreinforced pads. This is not a reccurring problem as most newer bearing designs use steel laminated bearings which have higher compressive strength. In the instances where the bearing is crushed, the forces in the superstructure become directly transferred to the substructure leading to failures in the girders as well as the abutment or pier.

Fig.2.5. Crushing of bearing

2.4. Structural Behaviour of Elastomeric Bearings

2.4.1. Rubber Elasticity

The behaviour of elastomeric bearing under loading is mostly dependent on the material properties of the rubber material. Rubber materials are nearly incompressible materials with an approximate Poisson ratio of 0.5, which is flexible in uniaxial compression with large strains and very little changes in volume. Elastomers can be reinforced with steel plates or other stiffer (e.g. fiber) material that compels the elastomer to develop only out of plane shear strains. A simple shear deformation with little to no bulging is produced when the bearings are laterally translated. Bulging in elastomeric bearings is a function of the geometry and the material properties of the elastomer in use. In terms of geometry, the thicker the rubber the less it bulges, while with respect to material properties the stiffer the elastomer the lesser the bulging. However, while increasing the stiffness by the introducing of a harder elastomer may reduce bulging and the shear strain, it also reduces the elasticity, hence effectiveness of the bearing to accommodate required structural movements is degraded. Therefore, the adjustment of the geometry to suit a problem is a more effective method of controlling the behaviour of the elastomer. The key geometry characteristics use to control the behaviour of the bearing is the shape factor. The shape factor of a bearing, can be mathematically defined as follows

$$shape\ factor(\ S) = \frac{load\ area}{free\ area} \qquad \text{eq.1}$$

From the aforementioned mathematical definition of shape factor, we gather that more layers of reinforcement produce a larger shape factor, which evidently means a reduction in bulging and shear strains, an increase in the compressive stiffness of the bearing and with no significant changes in the resistance of structural movement. The shear stress in the elastomer produces tensile stress in the reinforcement, and both are proportional to the mean compressive stress. Failures occurring as a result of this tension are negligible because if the high tensile resistance of steel. However, design should take into consideration tensile resistance when alternative reinforcement like fiberglass et. al with lesser tensile strength are used. Unreinforced pads are also applicable, in those instances the design criteria for them a usually over conservative. Unreinforced pads are therefore prone to bulging and their bulging is as a result of the friction developed between the bearing and load surfaces. These types of bearings are therefore the most susceptible to slippage.

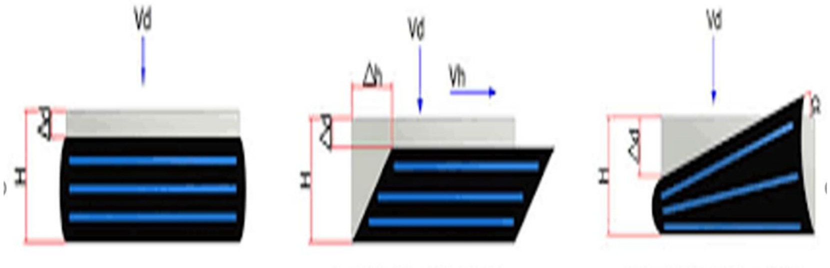


Fig.2.6. *From Left to Right. Vertical Deflection, combined vertical and horizontal deflection and combined # rotation and deflection*

2.4.2. Failure Modes

The major types of bearing failures occurring in elastomeric bearings as a result of design are as follows

(1) Fatigue

Fatigue in the rubber material occurs as a result of a variation of stresses that reduces the strength of the material. Fatigue of the elastomer is widely accepted as a prime concern in the design of bridge bearings, but there is disagreement over how fatigue is controlled. Most tests to date have attempted to find suitable fatigue or endurance limits for bearings under various loadings, but the results of these tests are contradictory and inconclusive.

(2) Failure of the reinforcement

The failure as a result of yielding of the reinforcement under monotonic loading or cyclic loading is a severe structural problem. This is usually a material-oriented problem resulting from either hole in the reinforcement or discontinuity in the material's molecular structure. This is not a very common cause of failure in elastomeric bearings.

(3) Stability

Instability in the bearing is usually dependant on the height to length ratio of the bearing. Ironically, stability failures occur in shorter bearings more frequently due to the low shear stiffness of rubber found in those bearings.

(4) Excessively Stiff Bearings

The stiffness of bearing is a very important criterion in elastomeric bearing design. Elastomers were as aforementioned were introduced into bridges because of their flexibility. Excessively stiff elastomers induce large expansions in the bridge and could lead to stress concentration in the superstructure or substructure.

(5) Bond failure

Bond failure in elastomeric bearings was once prevalent but the change in the manufacturing methodology has largely eliminated this problem. The reinforcement is now bonded to the elastomers before vulcanization under a stricter standard of cleanliness and quality control.

(6) Internal rupture and tension cracking

Internal rupture or tension cracking of the internal elastomer may occur as a result of tensile stresses and strain developed in the elastomer due to high magnitudes of loadings and deformation. Internal rupture can be as a result of poor rubber matrix or as a result of the placement error.

(7) Hydrostatic compression

Rubber incompressible characteristic makes rubber a superior resistor to hydrostatic compression. However, environmental conditions that lead to the change in the rubber properties could affect the response of rubber to hydrostatic compression.

2.5. Literature Review

The aging phenomena of rubber are of concern to several different fields of study. Therefore, a series of study has been done on the aging of rubber for different purposes. The engineering concern with this phenomenon, however, is with the changes it has on the material's mechanical properties. There are two approaches to determining the long-term properties changes in rubber. Investigation and testing of an in-service bearing can be carried out or an accelerated aging test that imitates the aging behaviour of rubber can be conducted. Investigation of actual bearings that has naturally aged are limited since elastomeric bearings have been around for barely a century. That emphasizes the importance of the accelerated aging tests which takes comparatively lesser time. The findings of researches using both approaches are presented below.

Investigation into the effects of aging on the mechanical properties of rubber has been done in two folds. Old rubber bearings used in older bridges could be replaced with newer bearings and the older ones tested against their original properties or a series of accelerated test along with some simulations could be conducted where such samples are not available. The preceding reviews consist of literary works covering both methodologies.

2.5.1. Pelham Bridge Bearing 1996 (Watanabe Y et al)

This research evaluated the changes in characteristics due to the aging of a 40year old laminated rubber bearings extracted from the Pelham bridge, in England. Tests conducted on the bearing included Hardness test, the tensile test, the peeling test and the mixture analysis test. The evidence suggested that physical properties change in the bearing as the result of air occurred at 50cm from the surface with the interior region remaining unchanged. Changes in horizontal stiffness were purported to be less than predicted as the change was a meagre 10%.

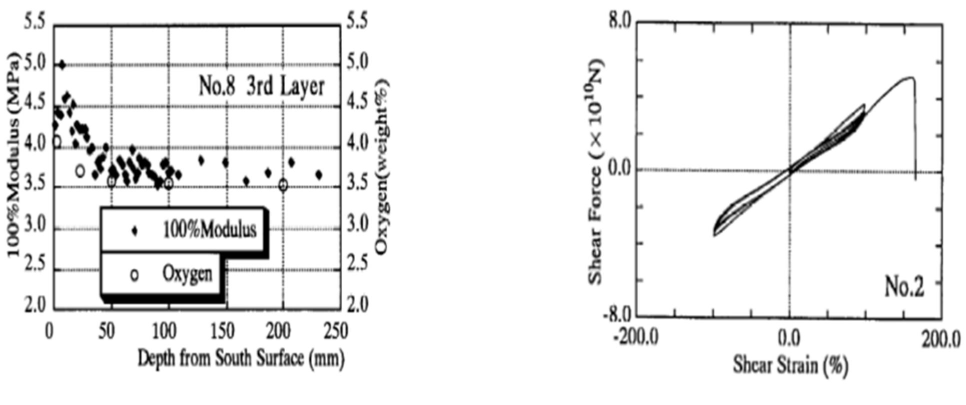


Fig.2-7. *From Left to Right. Physical Properties changes as a result of aging and Hysteresis curve of the bearing property*

2.5.2. Twenty years on rubber bearing (Hamaguchi H 2009)

The authors surveyed by means physical experiments the compressive creep, vertical stiffness and horizontal stiffness of 10 to 20years old aged rubber bearings alongside the various rubber material characteristics like hardness, strength and adhesion to metal plates. The results of the testings conclude that the creep corresponded with the predictions while the vertical and horizontal increased by less than 20 percent and about 10 percent respectively. The rubber material showed no clear changes with respect to adhesion to the metal plate. Hence it was concluded that after 20 years in use the natural rubber still has considerable durability. The experiments attribute a heterogenous profile of the physical properties as a result of the aging mechanism.

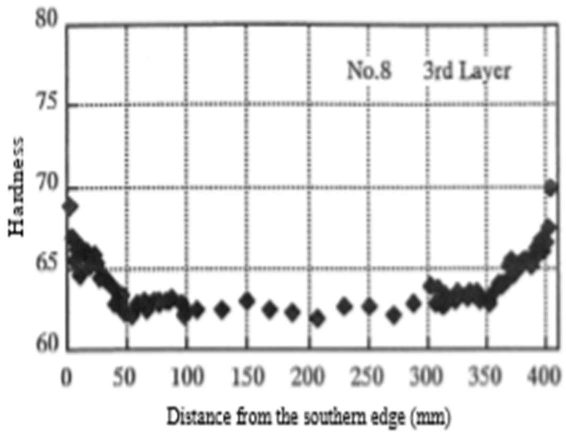


Fig.2-8. Hardness of Rubber after 10 and 22 years

2.5.3. Study of The Ultimate Performance of Elastomeric Bearings in Korea (Yoon H et al. 2013)

The research was intended to carry out experiments to ascertain the validity of the ultimate loads of the design allowable values of KS F 4420 as stipulated for elastomeric bearings in Korea. Tests conducted included the ultimate compression test, ultimate shear test and the shear failure test. The test results showed failure in the allowable compression test occurring at loads 16 to 26 times more the KS F4420 specified designed loading. However, the results from the shear performance shows failure at loads larger the design loads, but the performance was seen to fluctuate depending on fabrication conditions, with significant degradation in performance being noticed whenever the inner layers were not fabricated with a single rubber material. The authors concluded that the fabrication of rubber bearings by stacking of rubber pads degraded the performance of the elastomeric bearings.

2.5.4. Study on the Environmental Durability of Rubber Bearing for Bridges (Itoh Y)

This research sought to obtain the fundamental data for the life cycle of seismic isolation bearing considering atmospheric corrosion resistance performance. Accelerated exposure tests were conducted under the proceeding conditions;

Deterioration factor	Environment	Time (hour)
Sunlight	Irradiation and water spray	360,720
Ozone	Ozone 50pphm, 40° C	96,192,384,768,1536
Low temperature ozone	Ozone 50pphm, –30° C	96,192,384,768,1536
Heat	70° C	96,192,384,768,1536
Saltwater spray	Cycle of spray and dryness	720,1440
Acid rain spray	Cycle of spray and dryness	720,1440

Table 2-1. Testing Condition applied by Itoh et al.

Once the accelerated exposure tests were concluded with the physical properties of the deteriorated rubber by means of the hardness test and the tensile test (JIS Standard) were performed.

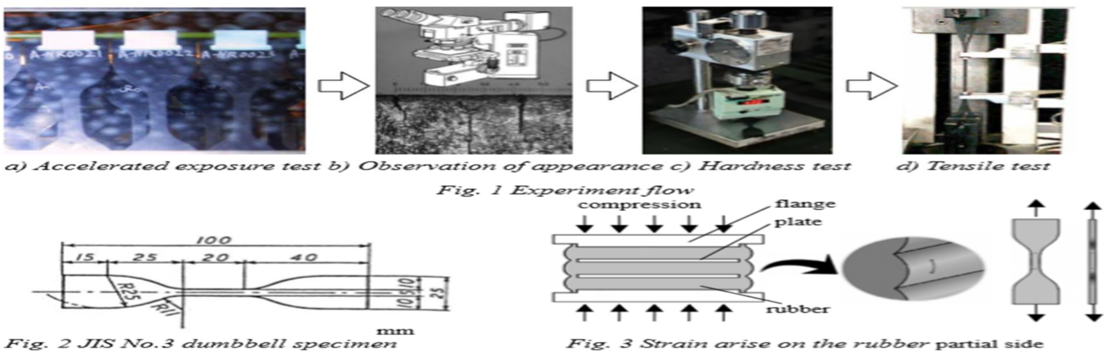


Fig.2-9. *Processes of the Accelerated Aging test*

The test pieces were made of natural rubber (NR) and chloroprene rubber (CR).

- Experiments of 720hrs conducted in NR and CR showed a decrease of 27% and 25% respectively, confirming the great influence of sunlight irradiation in the deterioration of rubber.
- The results also show that the influence of low temperature ozone on the deterioration of rubber is minimum. The influence caused by saltwater mist and acid rain mist were also found to be minute.

For the effects of heat deterioration, the accelerated exposure test was conducted for 1536hrs and when the Arrhenius equations were applied to the experiments results the performance of NR after 26 years was inferred, and the performance of CR after 79 years could also be known.

- The breaking stress fell about 10% and the hardness rose 10%.

It was observed that many cracks of 0.4mm long appeared at the edge.

2.5.5. Long Term Performance of Rubber in Seismic and Non-seismic Bearings: A LITERATURE REVIEW (Martin J W 1991)

The review was conducted to determine the limitation on the long-term seismic and non-seismic bearing and the gaps that necessitates further research. The primal objectives of this compilation were the determination of performance requirements for the rubbers used in seismic bearings, the description of materials and manufacturing processes used in the fabrication of seismic and no-seismic bearings, the identification of available field performance and laboratory data for assessing the performance of rubber and the identification of factors which may limit the service life of rubber.

Performance and Requirements for Seismic Rubber Bearings

Seismic Bearings functions by decoupling the structure from the ground motion during earthquakes by increasing the fundamental period of the structure. This results in the reduction of the magnitude of seismic forces by factors of 5% to 10%. They must have high vertical stiffness to support vertical loadings and high horizontal stiffness to provide a rigid support against low level lateral forces like winds. Small earthquakes and winds are not expected to induce large horizontal deflections, therefore lead plugs, frictional elements or rubber of high shear stiffness at small deflections and allow stiffness at large deflection are used to mitigate their effects on horizontal deflections. The high vertical stiffness is reliant on the interlaced steel plates and essentially dependent on the horizontal stiffness with the ratio between the two normally in the range of 500 to 1000. Bearings are also expected to meet requirements that include maximum allowable shear and compressive strain, stability, heat deterioration during repetitive cycling, and a capacity to withstand a specified minimum number of cycles.

Materials and Fabrication

The performance of elastomer bearings is largely reliant on the rubber material. Rubbers manufactured for engineering purposes must be vulcanised to denature the wobbly liquid-like thermo plastic mass into a strong, elastic tough material by forging a three-dimensional network of covalent sulfur crosslinks. The vulcanizate is composed of elastomers, fillers, oils, accelerators, antioxidants and retarders. The complexity of sulphur into covalent sulfur linkages and the residual sulfur and accelerators in always present in rubber may lead further crosslinking under micro-climatic conditions. The crosslinks density, crosslinks per macromolecule, is directed related to the rubber hardness, modulus of elasticity and Elongation at break (uncoiling). The Uncoiling of macromolecules of gives-rise to the rubber like elasticity

2.6. Research Goals

Rubber material used for bridge bearing is expected to maintain near design capabilities throughout its lifespan. It is, therefore, obligatory to understand the behaviour and characteristics of the material over a long period. Therefore, this research seeks to;

1. To determine the effects of aging on the material properties of the rubber used in elastomeric bearings considering Natural Rubber and Neoprene.
2. To conduct a member level simulation of the elastomeric bearing block and determine the changes in stiffness of the aged rubber bearing.
3. To evaluate the effects of the different assumptions surrounding the mode aging on the behaviour of aged rubber bearing.

2.7. Scope of Research

This research which seeks to provide further and precise elucidation on the adverse effects that degradation has on the mechanical properties of rubber, it shall comprise of physical experimentations and computer aided simulations to determine the changes in the mechanical properties as a result of aging. The physical experimentations would include a series of accelerated aging tests to replicate the natural degradation process but within a shorter period and at elevated temperature. Accelerated aging test shall be conducted in an aging oven for a period of 28days on Natural Rubber and Neoprene specimens .After the completion of the accelerated aging tests, uniaxial tension and quad shear tests will be executed to determine the mechanical properties of the rubber material like elongation at break, ultimate tensile and shear strains. The results thereof shall be compared to determine the effects of aging on the vulcanizates. Subsequently, modelling of a full bearing will be executed by means of a computer program (ANSYS) and analysed to determine and compare the physical properties derived thereof.

2.8. Organization of Thesis

The thesis seeks to evaluate the property changes of rubber used in elastomeric bearings as a result of aging and then investigates the influence of those changes on the performance of the bearing. This thesis is thus partitioned into five parts.

Chapter three discusses the experimental testing of the rubber material. Two types of testing were conducted on the rubber specimen. Mechanical testing was conducted to determine the properties of the material and accelerated aging experiments were also conducted to simulate the deteriorative conditions. Tension and quad shear experiments are the mechanical experiments considered. Accelerated aging tests were conducted in an aging oven for 28 days at an elevated temperature of 70^0C.

Chapter four captures the modelling of and elastomeric bearings. The chapter captures the concept of finite element modelling and the modelling of the material properties attained from the aforementioned experiments. The finite element modeller ANSYS Mechanical apdl is used to determine the stiffness of the rubber material.

Chapter five discusses the findings of the study. This would include results from the accelerated aging experiments and that of the finite element modelling.

CHAPTER 3

Experiments to Determine the Mechanical Properties of the Rubber

In this chapter an extensive theoretical and experimental study is conducted on two of the most frequently used rubber materials in elastomeric bridge bearing— Natural Rubber (NR) and Neoprene (Cr). The chemistry involved in the aging of rubber, the process of accelerated aging, and physical properties tests are discussed herein.

3.1. The Chemistry of Rubber

Any material which can undergo large deformations and recover almost completely and instantaneously on the release of the deforming forces. This property is known as the elasticity of rubber. The degree to which the rubber material can remain elastic is dependent on the macromolecular structure and molecular weight of the rubber material; but generally, rubber materials used for engineering purposes can achieve elastic deformation ranging from 200% to 1000%. The stress strain relation of elastomers does not conform to Hooke's law — that is the stress-strain curve is nonlinear. At higher stress rubber exhibit entropic characteristics as the rubber macromolecules inhabits more ordered forms under stress and reverts to their statistically random configurations upon the removal of stress. The entropy reduction at unchanged free energy of the stressed system must relate to the enthalpy reduction, which results in a temperature increase in the sample.

$$\Delta G^o = \Delta H^o - T\Delta S^o = 0 \qquad \text{Eq. 2}$$

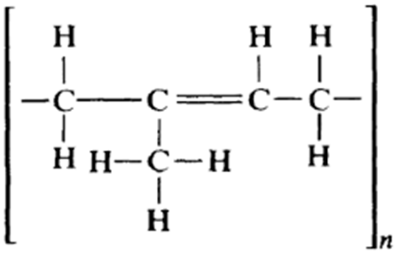
Where, ΔG^o the energy requires to do work (Gibbs free energy)

ΔH^o the enthalpy,

ΔS^o the entropy and

T the temperature.

Under Ideal circumstances, the macromolecules revert to its original position after the removal of load and the temperature of the stressed samples drops back to the original temperature. Rubbers naturally have long and regular hydrocarbon chains with spatially oriented structural units as seen below. The molecular formula for rubber is $(C_5H_8)_{20000}$, which is generally composed of a large number of simple repeating units attached to each other in long chains.



Eq. 3

where n represents the value of about 20,000.

The temperature behaviour of polymers is governed by two extremes temperature limits. The glass transition temperature (Tg) for the lower extremes and the melting point for the higher extremes. At glass transition temperature or crystallization temperature the rubber material crystallizes and exhibits characteristics resembling plastomers while at the higher temperature extreme the rubber changes from elastic to viscoelastic state and at above softening temperatures they flow. It is advantageous when rubbers at normal temperature crystallize only under stress and their glass transition temperature (Tg) is significantly lower than their usage temperature. The rubbers gain optimum properties of engineering materials only in the form of vulcanizates. It is possible to transfer them into this form by means of vulcanization.

3.1.1. The Compounding and Vulcanization of Rubber

The compounding of rubber material is usually based on different recipes which are mostly kept as trade secrets by the manufacturers. However, the ingredients of the rubbers used for engineering properties can be categorized into nine groups as seen in *table 1.* After compounding of the rubber material, it goes through a phase to enhance its mechanical properties. This phase is known as vulcanization. During vulcanization the long chains of the rubber molecules become crosslinked by reactions with the vulcanization agent to form three-dimensional chain structures, effectively transforming the rubber material from a weak plastic-like material into a stronger, more elastic product. The rubber also losses its tackiness and its solubility to solvents, becoming more resistant to environmental deteriorations. There are two basic types of vulcanization system— Efficicient and conventional system. (see ref.)

Satisfactory properties can be obtained only by proper compounding of elastomers with chemicals and additives, and by subsequent vulcanization in appropriate conditions.

Ingredient	Purpose
Elastomers	This is the fundamental material of the rubber compound. This rubber could be used alone or with other combinations (e.g. Rubber oil or rubber carbon black). Carefully selecting the elastomer is important in specifying the physical properties of the end product.
Processing Aids	Use to modify the rubber during mixing by aiding in extrusion, calendaring and moulding.
Vulcanization Agents	These ingredients, except thermoplastic, initiates crosslinking reactions between the agents and the rubber chains leading to improvement in the physical properties.
Accelerator	Reduces the curing time and in some cases improves the physical properties
Accelerator Activators	Form chemical complexes with accelerators and enhance the function of the accelerator.
Anti-degradants	They function by retarding the deterioration rate by preventing the reaction of material with deteriorative catalyses like oxygen, ozone, ultraviolet radiation and so forth. (antiozonants, antioxidants)
Fillers	Use as reinforcements to either improve physical properties of reduce cost (carbon black)
Softeners	Any material added to improve workability, elasticity, without limiting the physical properties
Miscellaneous Ingredients	Material that is added to produce specific mechanical properties but are not normally added for general purposes.

Table 3-1. Compounding of Rubber

3.2. Natural rubber

Natural Rubber (NR) can be tapped from more than 200 different species of plants. However, the commercially substantial source of natural rubber is the Hevea Brasiliensis, a member of the spurge family, Euphorbiaceae. This species is prefers because it grows well under cultivation. A properly managed tree responds to wounding by producing more latex for several years. Natural rubber is obtained from latex, which is the emulsion of cis-1,4-polyisoprene and water. Latex is obtained from the tree by tapping the inner bark and collecting the latex in cups. Anticoagulants are added to the fresh rubber sap to prevent early coagulation.

Fig.14. latex dripping from a wounded Hevea Brasiliensis plant

The Latex is then concentrated by centrifuging or creaming and sold as concentrated latex. Latex can be coagulated with hydrogen carboxylic acid, formed in sheets or granulated and then dried to a solid raw rubber. Natural rubber also contains a few percent of non-rubber constituents such as resins, proteins, sugars and fatty acids, which can function as weak antioxidants and accelerators in the natural rubber. The primary vulcanizing agent of Natural rubber is sulphur. The biggest producer countries of natural rubber are Liberia, Thailand, Indonesia, Malaysia and India. (Rubber Engineering, Indian Rubber Institute, McGraw-Hill, 2000).

3.3. Neoprene

Neoprene was created in 1930 by DuPont as an air and oil resistant alternatives to for natural rubber. It was the first of what will be a large family of synthetic rubber (Dupont and co). The first chloroprene monomers were prepared from acetylene. Neoprene is known for the large range of multipurpose properties it poses. It provides good resistance to moderate exposure to ozone, sunlight, oxidation, weather, oils, gasoline, greases, solvents, petroleum oils, animal and vegetable oils, compression set, silicone oil, refrigerants, ammonia, carbon dioxide, water, and steam. Certain compounds of neoprene are flame resistant and does not support combustion.

ASTM designation	NATURAL RUBBER(NR)	NEOPRENE(CR)
Durometer range	30-90	30-95
Tensile max	4500	4000
Elongation max%	650	600
Compression set	A	B
Creep	A	B
Resilience	High	High
Abrasion resistance	A	A

Tear resistance	A	B
Heat aging at 212° F	C-B	B
T_g °C	-73	-43
Weather resistance	D-B	B
Oxidation resistance	B	A
Ozone resistance	NR-C	A
Solvent resistance		
Water	A	B
Ketones	B	C
Chlorohydrocarbons	NR	D
Koreosene	NR	B
Benzol	NR	C-D
Alcohol	B-A	A
Water glycol	B-A	B
Lubricating oils	NR	B=C

A=excellent B-good, C-fair, D=use with caution, NR = not recommended

Table 3-2. general characteristic: natural Rubber versus Neoprene. (source seals eastern inc)

3.4. Construction of Elastomeric Bearing

Over the years the technology and methodology used in the production has changed considerably. These changes have been geared towards increasing the efficiency of the production process whilst enhancing the bearings durability. For instance, the reinforcements used in the bearings are now vulcanised with the bearing effectively reducing the probability of delamination occurring. The process of the production of bearing is in figure 3-2

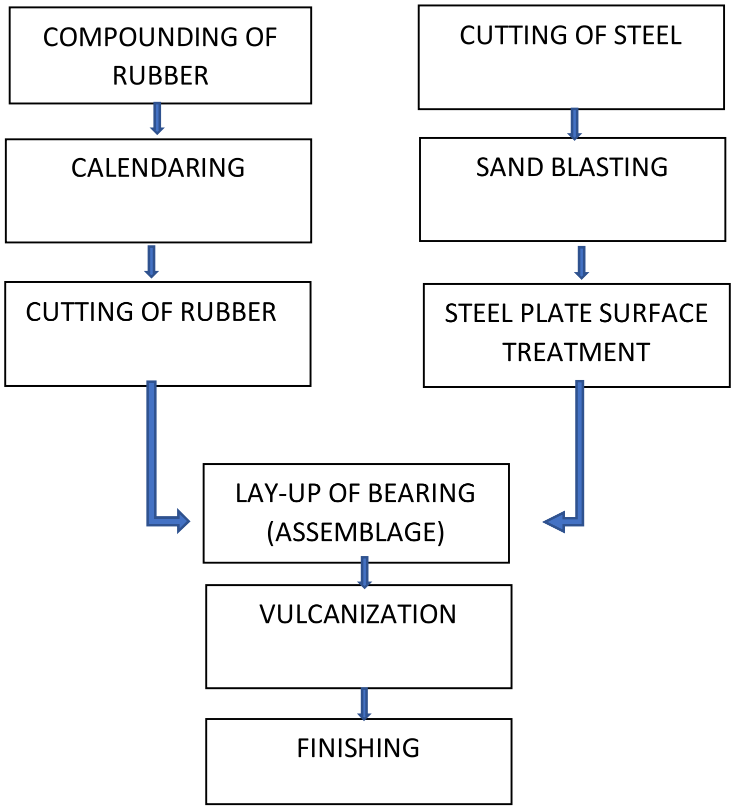


Fig.3-2. *Flow chart of the construction of rubber bearing*

3.5. Deterioration Mechanism

An understanding of the chemical mechanism occurring at the macromolecular during the degradation of polymer of paramount importance. The degradation of polymeric materials may be initiated in a couple of ways. While polymers may be affected by several deteriorative factors, at the macromolecular level the mechanism of deterioration is controlled by either Thermal or photooxidative degradation,

3.5.1. Thermal Aging

Thermal aging is formed when free radicals found in the polymer reacts with oxygen to form peroxide radicals.

$$P^{*} + O_2 \rightarrow POO^{*} \qquad \text{Eq. 4}$$

The number of free radicals is increased by light, ionizing radiation or the presence of trans metals. The peroxide radical undergoes a period of slow propagation and little to no physical degradation known as the induction period. The length of the induction periods, which is essential the service life, is temperature dependant. At higher temperatures the period of induction decreases and is much lengthier at lower temperatures. High temperature can therefore be view is a catalyst in the propagation on free radicals. Thermal cycles, low and high temperatures, leaves behind a mismatch of fibre known as Thermo mechanical degradation. Thermal spiking a sudden brief rise in the temperature of polymers. (Allara L.D. 1978)

3.5.2. Photooxidation

Photo degradation is the absorption of solar radiation ultraviolet chromophores and in the activation of excited states in macromolecules. When polymer is exposed to solar radiation free radical is formed by the dissociation of C—H bonds in the polymer chains.

$$PH \rightarrow P^{*} + H^{*} \qquad \text{Eq. 5}$$

When the free radical is produced, they react with oxygen to produce hydroperoxide (POOH).

$$P^{*} + O_2 \rightarrow POO^{*} \qquad \text{Eq. 6}$$

$$POO^{*} + PH \rightarrow POOH + P^{*} \qquad \text{Eq. 7}$$

This propagation continue as free radicals continues to react even after the UV exposure propagations. The propagation is then retarded when free radicals runs out of elements to react and then pairs with other free radicals, reducing the number of free radicals.

3.5.3. Hydrolysis

Polymers In usage goes through a circle of charging, wetting and darkness which assist in the recovery and the ingression of oxygen. The reaction of the fluid to polymers results in a chemical process known as hydrolysis. Hydrolysis leads to chain scission which enhances the amount of fluid intake. The reduction in the weight due to chain scission leads to a reduction in the molecular weight.

3.6. Accelerated aging experiments

The principles governing the relationship between real time aging and the accelerated aging were propounded by Nobel laureate Svante August Arrhenius. Accelerated Aging tests are performed on polymeric materials to understand their service life. These tests help material designers, engineers and quality control personnel in their selection of materials that will maintain admissible properties throughout its design lifespan. Elevation of test temperatures or the decrease in the activation energy by the addition of catalyst accelerates the loss of physical properties or chemical changes caused by oxidative and thermal aging. This relationship is captured in the Arrhenius equation.

$$k = Ae^{-E_a}/RT \qquad \text{Eq. 8}$$

Where K, the number of collisions that result in a reaction per second;

A, the total number of collisions per second and

e^{-E_a}/RT the probability that ant given collision will result in a reaction.

3.6.1. The relationship between the Arrhenius Equation and Aging

Firstly, the relationship between the rate of reaction and temperature is combined into two first-order Arrhenius equations

$$k_1 = Ae^{-E_a}/RT_1 \qquad \text{Eq. 9}$$

$$k_2 = Ae^{-E_a}/RT_2 \qquad \text{Eq. 10}$$

Then, the natural log is taken on both sides of the equations

$$\ln(k_1) = \ln(Ae^{\frac{-E_a}{RT_1}}) \qquad \text{Eq. 11}$$

$$\ln(k_2) = \ln(Ae^{\frac{-E_a}{RT_2}}) \qquad \text{Eq. 12}$$

Then, the natural log product rule is applied

$$\ln(k_1) = \ln(\mathrm{A}) + ln(e^{\frac{-E_a}{RT_1}}) \qquad \text{Eq. 13}$$

$$\ln(k_2) = \ln(\mathrm{A}) + ln(e^{\frac{-E_a}{RT_2}}) \qquad \text{Eq. 14}$$

Since $\ln(e^x)=X$

$$\ln(k_1) = \ln(\mathrm{A}) + \frac{E_a}{RT_1} \qquad \text{Eq. 15}$$

$$\ln(k_2) = \ln(\mathrm{A}) + \frac{E_a}{RT_2} \qquad \text{Eq. 16}$$

Then, both equations are equated to ln(A)

$$\ln(\mathrm{A}) = ln(k_1) + \frac{E_a}{RT_1} \qquad \text{Eq. 17}$$

$$\ln(\mathrm{A}) = ln(k_2) + \frac{E_a}{RT_2} \qquad \text{Eq. 18}$$

Then equation X is substituted into equation Y

$$ln(k_1) + \frac{E_a}{RT_1} = \ ln(k_2) + \frac{E_a}{RT_2} \qquad \text{Eq. 19}$$

$$ln(k_1) + ln(k_2) = \ \frac{E_a}{RT_1} + \frac{E_a}{RT_2} \qquad \text{Eq. 20}$$

By means of the quotient rule

$$ln\left(\frac{k_2}{k_1}\right) = \frac{E_a}{RT_1} + \frac{E_a}{RT_2} \qquad \text{Eq. 21}$$

$$ln\left(\frac{k_2}{k_1}\right) = \frac{E_a}{R}(\frac{1}{T_1} = \frac{1}{T_2}) \qquad \text{Eq. 22}$$

3.6.2. Conversion to Real Time

According to ASTM F1980

$$AAF = {Q_n}^{(T_{AA} - T_{RT})/n} \qquad \text{Eq. 23}$$

Where,

AAF= accelerated aging factor

Q_n= An aging factor for 10^0Cincrease or decrease in temperature

T_{AA}= Accelerated aging, temperature in Celsius

T_{RT}= ambient temperature (^{0}C)

The accelerated aging time (AAT) needed to establish to real time agin is determined by the dividing of the required shelf life (RT) by the AAF.

$$AAT = \frac{RT}{AAF} \quad \text{Eq. 24}$$

It should be noted that, for each 10°C increase in temperature, the rate of oxidation may be approximately double.

3.7. The Experimental methodology

3.7.1. Accelerated aging Experiment

Rubber must resist the deterioration of its mechanical properties with time caused by oxidative and thermal aging.

(1) Apparatus

Type IIB ovens specified in ASTM Test Method E145 are satisfactory for use through 70°C. The interior size the air oven was 450mm ×450mm in width and ×500mm in Height. The specimens were placed vertically in the oven with caution taken to avoid contact between each other or the sides of the aging chambers. The oven was heated by circulating air within the chamber at atmospheric pressure.

Automatic temperature control by means of thermostatic regulation was used and special precautions shall be taken in order that accurate, uniform heating is obtained in all parts of the aging chamber. Baffles were used as required to prevent local overheating and dead spots. Uniformity of temperature was insured by the verifying the temperature at b=various part of the oven

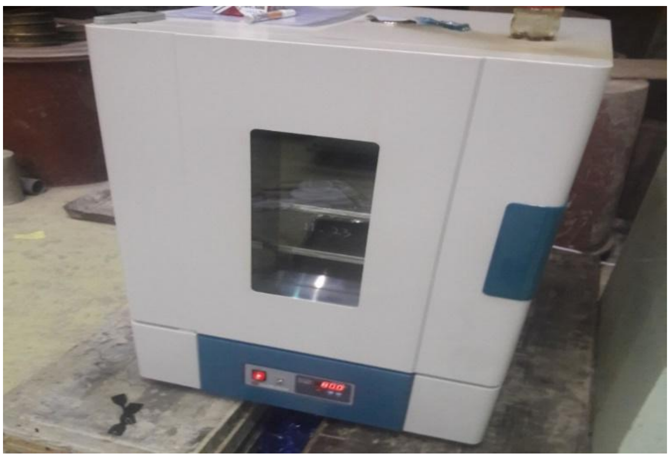


Fig.3-3. Aging Oven

(2) **Sampling**

The sample size was such that they were sufficient to allow for the determination of the original properties on three specimens and also on three or more specimens for each exposure period of the test.

For every test, four dumbbells were considered. In cases where the results of either of these tests be below the specified requirements. At least three test specimens were used to determine the original physical properties of each sample and also three or more specimens of the same material for each exposure period of the test.

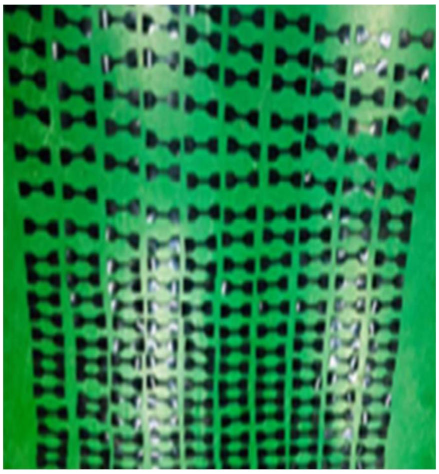


Fig.3-4. Tensile specimen sampling

(3) Test Specimens

The Dumbbell-shaped specimens were prepared in accordance with the geometric requirements as described in Test Methods D412. The cross-sectional dimensions of test specimens for calculating the physical properties were measured prior to exposure in the aging chamber.

Loading Modes	**Specimen**	**No**	**Accelerated Aging time(hrs)**
Uniaxial Tension test	DW NR_T D0	4	0
	DW NR_T D3	4	72
	DW NR_T D7	4	168
	DW NR_T D14	4	336
	DW NR_T D28	4	672
	DW CR_T D0	4	0
	DW CR_T D3	4	72
	DW CR_T D7	4	168
	DW CR_T D14	4	336
	DW CR_T D28	4	672

Table 3-3. Tensile test specimens

(4) Procedure for Accelerated Aging

The specimens were placed for aging in an air aging oven after the oven has been preheated to the operating temperature of 70^{0}C.The aging interval starts at the time the specimens are placed in the oven and continue for a measured time interval as stated in figure.19.

The aging intervals used was such that the deterioration will not be so great as to prevent determination of the final physical properties. At the end of the aging interval, specimens were removed from the oven, cooled to room temperature, and allow to rest not less than 16 h nor more than 96 h before the determination of the physical properties.

3.7.2. Physical Tests of Aged Specimens

The tensile strength and ultimate elongation or the stress-strain properties of the specimens aged for different intervals was determined as the intervals terminate in the progress of aging, disregarding the fact that more specimens may still be aging. In determining the physical properties after aging, the final values shall be the median of results from three specimens.

(1) Tensile testing

The tensile properties of the rubber specimens where tested using ASTM D412 Method A. This method is the guideline for evaluating the tensile properties of dumbbell samples of vulcanized thermoset rubbers and thermoplastic elastomers.

Type	Middle section measurements			
	width	length	thickness	Scale length
KS dumbbell type 3	5	20	≤3	20

Table 3-4. geometric specification for tensile test specimens (source: Korean Standard)

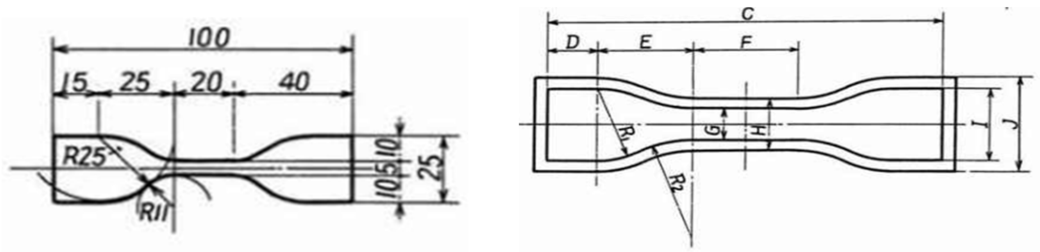


Fig.3-5. Geometry of tensile specimen (a, left and b, right)

specimen type	Measurements per position mm (fig.21. b)											
	A	B	C	D	E	F	G	H	I	J	R_1	R_2
KS type3	107	34	100	15	25	20–22	5.0±0.5	12	25.0±0.5	32	25	11

Table 3-5. detail geometric measurement of tensile specimens (Source: Korean Standard)

The test sought to determine mechanical properties like tensile stress, tensile stress at a given elongation, tensile strength, yield point and ultimate elongation. Tensile stress, yield point, and tensile strength are based on the original cross-sectional area of a uniform cross-section of the specimen. The tests were performed using a universal testing machine capable of constant rate of extension (CRE) control. To determine tensile stress, tensile strength and yield point, the dumbbell-shaped sample was placed grips. (see fig 3-6.). At the start the machine the distance between the benchmarks was noted and the force at the elongation specified for the test and at the time of rupture was recorded. The elongation at the point was the specimen broke was also measured and recorded. Separation of the grips was done at a uniform rate of speed.

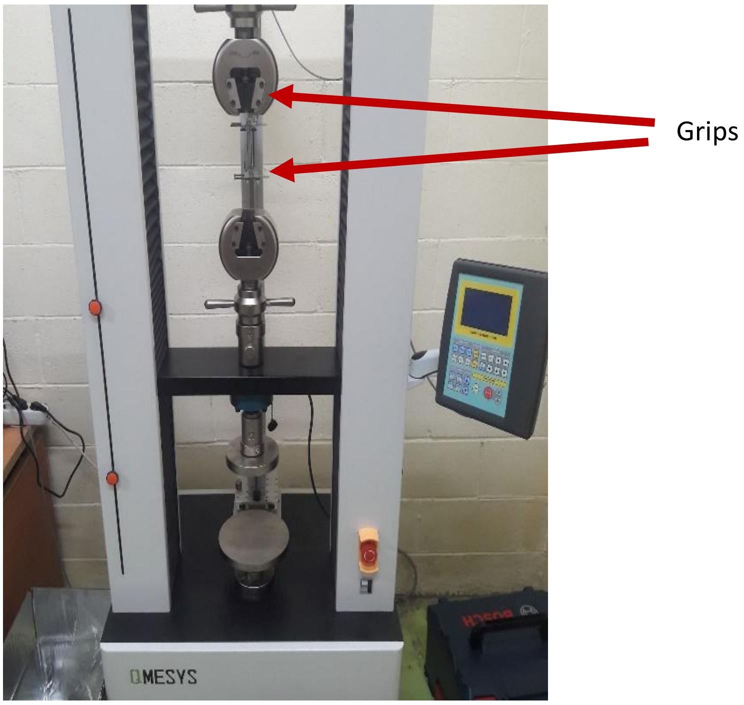


Fig. 3-6. Tensile testing machine

(2) The shear testing

This results in a compact test piece for exposure to prescribed environments elevated temperature. Specimens were sampled as can be seen in fig 3-7.

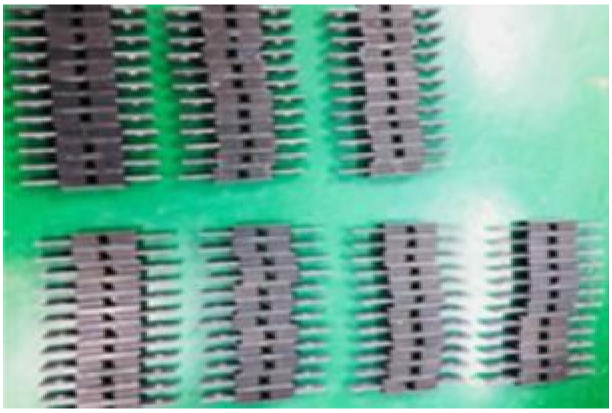


Fig.3-7. Shear test specimen

The test piece consists of four identical rubber elements as seen in table 3-6. The rubber is bonded to rigid plates of the same width and appropriate lengths to obtain a symmetrical double sandwich arrangement. The central plates may have a hole at each protruding end to accommodate pins to fixture the assembly to the test machine. (See Fig. 3-8.)

	Accelerated aging time(hrs)	**Number**	**temperature**	**width**	**length**	**thickness**
DW NR_Sh D0	0	4	70^0C	20mm±5mm	25 mm±5mm	4mm±1mm
DW NR_Sh D3	72	4				
DW NR_Sh D7	168	4				
DW NR_Sh D14	336	4				
DW NR_Sh D28	672	4				
DW CR_Sh D0	0	4				
DW CR_Sh D3	72	4				
DW CR_Sh D7	168	4				
DW CR_Sh D14	336	4				
DW CR_Sh D28	672	4				

Table 3-6. shear specimens and their aging specifications

The shape of the block was such that there is no contact between the block and the strained rubber elements (see Fig. 22).

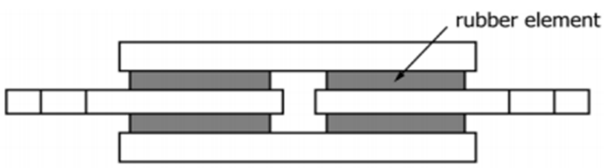


Fig 3-8

. Shear test Assemblage

(i) Testing machine:

To test the adhesion before/after an immersion test, a power-driven test machine equipped to produce a uniform rate of grip separation was used for measuring the strength of adhesion. The head of the machine shall travel at the uniform rate of 0.83 ± 0.08 mm/s. (2 6 0.2 in./min.). The machine was equipped with a recording device that provided the force in Newtons at the conclusion of the test.

(ii) Laboratory Preparation of Test Specimens

Masking is required to ensure that the bonding agent is applied only to the portion of the plates where bonding is required. The bonding was done using compression molding of the rubber into a suitable mold holding the adhesive coated samples.

A minimum of two replicates (eight interfaces) was used for each condition and environmental condition, plus two control replicates for each prestrain. In addition, one test piece of each batch shall be prepared as a quality control for the bonding procedure.

(iii) Procedure

A quality control test piece was pulled from each molded batch to determine that 100 % adhesion (100R) is obtained prior to environmental exposure or laboratory storage with a pre-strain.

After a predetermined period of time, pull to failure each test piece which remains sufficiently intact, including those exposed to the chosen environmental conditions and the control test pieces, and record the peak force required to do this. 77.6 Measure the amount of de-bond in mm and classify the loci of failure according to Section 74. Note that the loci may be different according to whether the failure took place during the environmental exposure or during the pull to failure.

CHAPTER FOUR

FEM MODELLING OF BEARING BLOCK

A finite element analysis is performed on five full bearing models. Two different approaches are taken to model the aging phenomena of the rubber material. The first approach assumes homogenous aging across the rubber profile while the second approach assumes aging by progression or a heterogenous profile.

In bridges, movement within the system is persistent as the superstructure is prone to movement emanating from dynamic loads, temperature fluctuations, seismic excitation, concrete creep, shrinkage etc. Isolation devices are therefore essential in these systems so as to prevent large horizontal forces developing in the bridge pier. Elastomeric bearing's rubber material makes it a good buffer that dissipates some of energy coming from the girder, effectively reducing the impacts on the pier.

4.1. Methods of analysis

The nonlinear techniques required for the analyses of multi-layered elastomeric bearings are very complex, but a simplify model originating from elastic theory has proven valid and has been verified by both laboratory and FEM analysis. The horizontal stiffness of the bearing is the most important property considered by designers and engineers in relation to elastomeric bearings. The horizontal stiffness is given as

$$K_H = \frac{GA}{t_r} \qquad \text{Eq. 25}$$

Where G is given as shear modulus

A Full cross-sectional area

t_r total thickness of the rubber

Max horizontal displacement D is related to the maximum shear strain γ by

$$\gamma = \frac{D}{t_r} \qquad \text{Eq. 26}$$

In the vertical direction the vertical stiffness k_v is expressed as the rigidity (EI) in accordance with the beam theory and is mathematically expressed as

$$K_V = \frac{E_c A}{t_r} \qquad \text{Eq. 27}$$

Where A is given as the cross-sectional area

t_r total thickness of rubber in the bearing

E_c the instantaneous compression modulus of the rubber steel composite under specific load.

The instantaneous compressive modulus is dependent on a dimensionless aspect ratio of the single layer of an elastomer known as the shape factor which can be given as follows

4.2. The Models

In other to determine the changes in the behaviour of the rubber material over time, five elastomeric bearings were modelled using the Finite Element software ANSYS. All the models considered in this research share the same geometrical identities as seen table 4-1 and figure 4-1. We Assume that the bearing Is flat no grade and laminated with 5 laminates. All rubber layers were taken with the same thickness as seen in. Also, all steel laminates are of the same thickness. Fig 4-2.

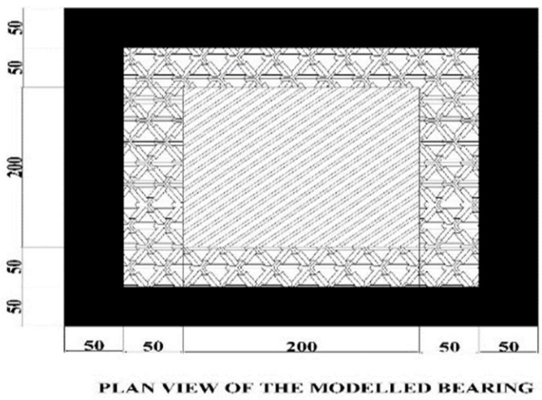


Fig.4-1. Plan of rubber model profile

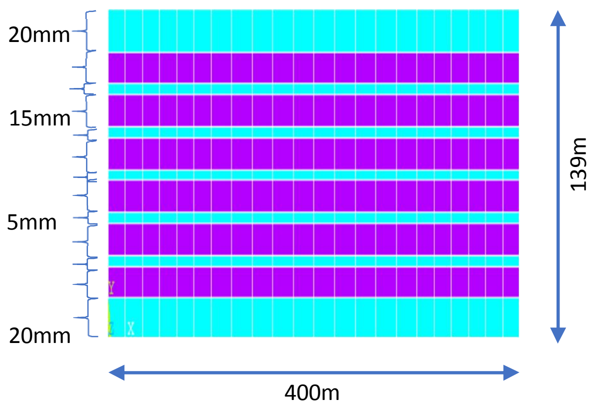


Fig.4-2. Cross-section of the models

BEARING GEOMETRY			
BEARING PART	AREA (mm^2)	THICKNESS (mm)	NUMBER OF PARTS
BASE PLATE	460×460	20	2
STEEL SHIMS	380×380	5	5
RUBBER LAYERS	400×400	15	6

Table 4-1. Table Bearing Geometry

Steel laminates are placed interchangeably between the rubber layers to provide vertical reinforcement. The mechanical properties of the steel were constant in all the models. The steel properties used in the model were as can be seen in table 4-3.

property	value	Units
Poisson ratio	0.3	
Young modulus	210	GPa

Table 4-2. Table of Steel Material Property

4.2.1. Model 1_NR_F55.6411 and Model 2_CR_F

These models are representative of a new elastomeric bearing with no deterioration of the rubber. These models represent the design mechanical properties of the bearing and are used as the reference model to which all other models will be compared. Rubber material properties used in this model are that of the Day 0 tensile and shear test were DW NR_T D0 and DW NR_Sh D0, for Model 1_NR_F and DW CR_T D0 and DW CR_Sh D0 for Model 2_CR_F.

4.2.2. Model 3_NR_Mp and Model 4_CR_Mp

These models provide an approximation of a mildly deteriorated bearing. This model assumes that the deterioration is present across the entire rubber profile. These models while they might not precisely simulate the aging phenomena, might come in handy due to their simplicity. The detailed profiling and the material's shear and tensile properties, acquired from the experiments from the previous chapter are seen in the figure 4-4

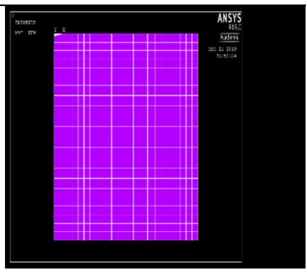
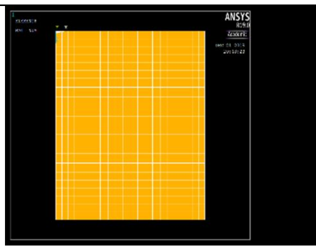
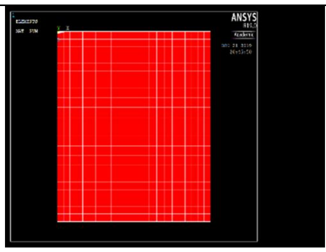
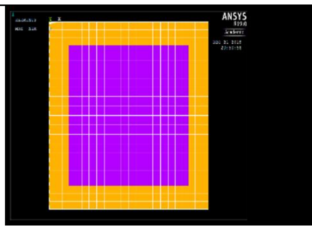
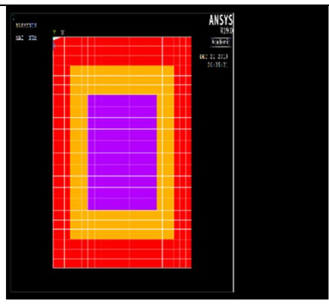
Model	Material		profile
Model 3_NR_Mp	DW NR_T D0 DW NR_Sh D0	100%	
Model 2_CR_F	DW CR_T D0 DW CR_Sh D0		
Model 3_NR_Mp	DW NR_T D7	100%	
Model 4_CR_Mp	DW CR_T D7		
Model 5_NR_Sp	DW NR_T D28	100%	
Model 6_CR_Sp	DW CR_T D28		
Model 7_NR_Mmx	DW NR_T D0, DW NR_T D7	54.25% 43.75%	
Model 8_CR_Mmx	DW CR_T D0, DW CR_T D7		
Model 10_NR_Smx	DW NR_T D0, DW NR_T D7 DW NR_T D28	25% 31.3% 43.7	
Model 10_CR_Smx	DW CR_T D0, DW CR_T D0, DW CR_T D0		

Fig.31. Table of the model properties and profile

4.2.3. Model 5_NR_Sp and Model 6_CR_Sp

These models simulate a case of harsh deterioration. In these models the rubber vulcanizates with the most time of deterioration are used to simulate the rubber material model. A 100 percent deterioration is also assumed across the rubber material profile. The detailed profiling and the materials quad shear and tensile properties, acquired from the experiments from the previous chapter are seen in the figure

4.2.4. Model 7_NR_Mmx and Model 8_CR_Mmx

These models take into consideration the research results from the works of Watanabe Y. et al's experiments on the 20 year on elastomeric bearing from the Pelham bridge. Their research found a that the deterioration of the rubber material was progressive, and the physical properties degraded mostly on the outer surfaces while the innermost surfaces remained unchanged. The deterioration starts from the surface and through towards the center through chemical processes as explained in chapter 2. Therefore, in other to approximate that aging characteristic model consists of a rubber material with a varying profile consisting of mild deterioration and no deterioration.

4.2.5. Model 9_NR_Smx and Model 10_CR_Smx

Model a la model 4 adapts the same aging mechanism assumption but model five differs in that it simulates aging at a later time. At this time, it is assumed that aging has occurred much deeper into the rubber and much severe at the surface. Therefore, three different levels of deterioration are applied in the model.

4.3. Modelling Approaches

For modelling the rubber elements, the structural Solid 185 from the ANSYS APDL libraries is used. This element processes nodes and degree of freedoms suitable for the three-dimensional modelling required here. The element is defined by eight nodes with each node having three degrees of: translations in the nodal x, y, and z directions. The element has plasticity, stress stiffening, large deflection, and large strain capabilities

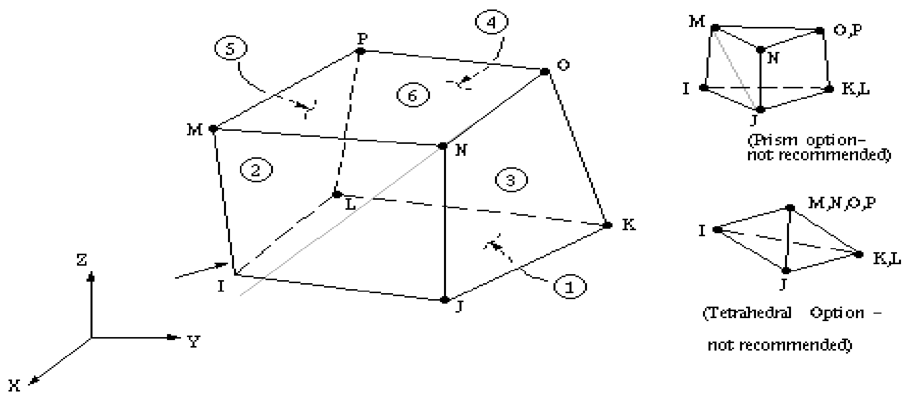


Fig.4-3. *degrees of freedom for Solid 185*

4.2.1. The material Model

In order to model the material rubber, the FEM software ANSYS provides series of nonlinear hyper elastic of model. Amongst these models this study utilized the model known as the yeoh model. This option follows a reduced polynomial form of strain energy potential. This form can be given as:

$$W = \sum_{i=1}^{N} c_{i0} (\bar{I}_1 - 3)^i + \sum_{k=1}^{N} \frac{1}{d_k} (J-1)^{2k} \qquad \text{Eq. 28}$$

where:

W = strain energy potential

J = determinant of the elastic deformation gradient

N, c_{i0}, and d_k = material constants

The fundamental idea of the model is the assumption that stored energy function (SEF) of incompressible rubber-like materials is a regular function with respect to isochoric deformation tensors$\mu = 2_{C_{10}}$

The initial bulk modulus K is defined as:

$$K = \frac{2}{d_1} \qquad \text{Eq. 29}$$

The hyper elastic material are characterised by the strain energy function W. For isotropic hyperelastic material, W can be written as a function of the principal invariants C

$$w = w(I_1, I_2, I_3) \qquad \text{Eq. 30}$$

The Yeoh strain -energy density function is written in terms of the first, I_1, of the green deformation tensor

$$W = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3 \qquad \text{Eq. 31}$$

C_{10}, C_{20} and C_{30} being the material constants. The following values of theses constants derived from scaling the are used

model	C_{10}	C_{20}	C_{20}	residual
Fresh(NR)	4.5538e+06	1.2279e+07	-9.5189e+06	26.736
Mild(NR)	5.6411e+06	1.2983e+07	-7.7753e+06	24.413
Severe(5.5588e+064.)	6.345e+06	1.3251e+07	-1.0673e+07	35.48
Fresh cr	5.004e+06	1.0916e+07	-9.3914e+06	18.951
MILD (cr)	5.341e+06	7.6298e+06	-2.9942e+06	12.914
SEVERE	5.5577e+06	7.9858e+06	-1.7172e+06	14.018

Fig.33. Material Constant of the models according to the Yeoh Model

4.2.2. Discretization

The model's domain was discretized or meshed into smaller elements and the meshing properties were as seen in figure 31. Perfect bonding is assumed between elements as the adhesive behavior of the bearing is not in the slope of this research. The p-version method of discretization was adapted in the models. A global mesh with hexagonal meshed of 2 elements per line was adopted using mapped meshing.

4.2.3. Loading

The study seeks to compare the results from all the models. Ergo, consistency across all ten models was prioritized when loading conditions were applied. Fixed boundary conditions were adopted at the base of the models. The constant compressive pressure of 550MPa was applied at across the top layer of the bearing. The constant pressure imitates the weight of the superstructure. Progressive horizotal displacement of $1.5t_r$ was applied in the X axis in 40 load steps of the models.

4.3.4. Modelling process as with the program ANSYS

PREFERENCE

Structural

PREPROCESSING

ELEMENT TYPE

- For Rubber Solid 185
- For steel Shims Solid 185
- For baseplate solid 185

MATERIAL MODEL

- For Steel linear isotropic
- For rubber
  Nonlinear Hyperelastic 3rd order Yeoh model

MODELLING

- As specified in geometry

MESHING

- Volume mesh, Hexagonal mapped meshed

SOLUTION

Analysis type

- Static Analysis

Loading

- Boundaries Conditions
- Vertical force
- Horizontal Displacement

Solution
Solve LS

POST PROCESSING

General Post Processing

- Read Results

Fig.4-4. Modelling of the Bearing in ANSYS APDL

CHAPTER 5

RESULTS AND DISCUSSION

This chapter discusses the findings gathered form both the experimental and analytical studies. Consequently, The chapter has two parts. Part one discusses the experiments comparing two rubber types used and their behaviors as they age, while part two discusses the behavior of the bearing and its properties changes as it ages.

5.1. Experimental Results

5.1.1. Tensile test

(1) Natural rubber (NR)

Natural rubber aged by means of the accelerated aging experiments as explained in chapter three of this thesis has shown to be degraded over time. It can be seen in figure 5-1 that the slope(stiffness) of the force-displacemnet curve grows steeper as the aging time increases, implying a stiffness increase corresponding to aging time. Consequently, this degradation of the elasticity of the rubber material inturn affects the extent to which elongation is possible. The elongation at break degraded from 234.54mm at day 0 to a 45% lesser capacity by day 28 of the accelerated aging.In addition the ultimate tensile strength was degraded by 16 % by the 28th day of the aging experiment.

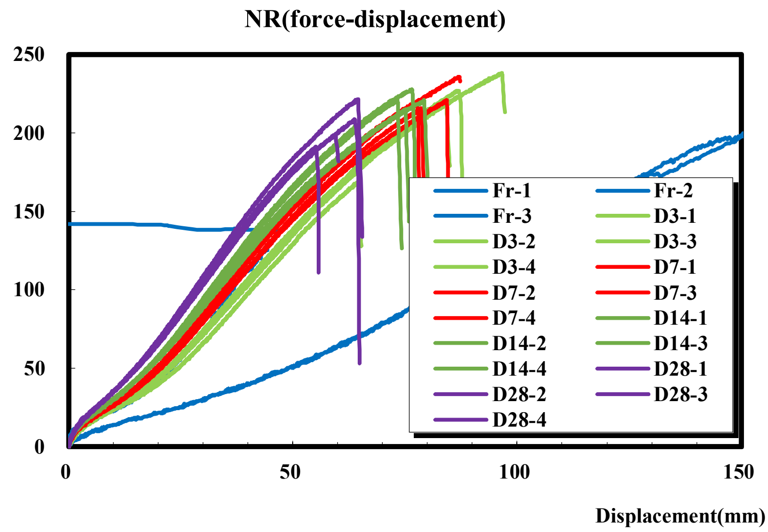


Fig.5-1. NR Force Displacement Compilation

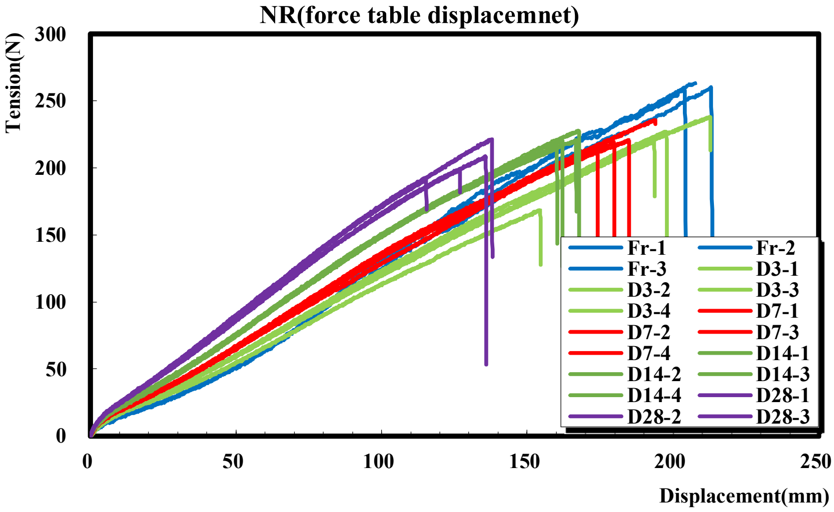


Fig.5-2. NR Force- table Displacement Compilation

As seen in fig 5-3 the ultimate tensile force decreases form day one to day six. This is evidence of the degradation of the force bearing capacities of the vulcanizates. This is evident of the thermal oxidative processes that promotes crosslink formation hence reducing the elasticity and elongation at break.The sample can be seen for the displacement and table displacemnets as they also decreases relative to aging time.

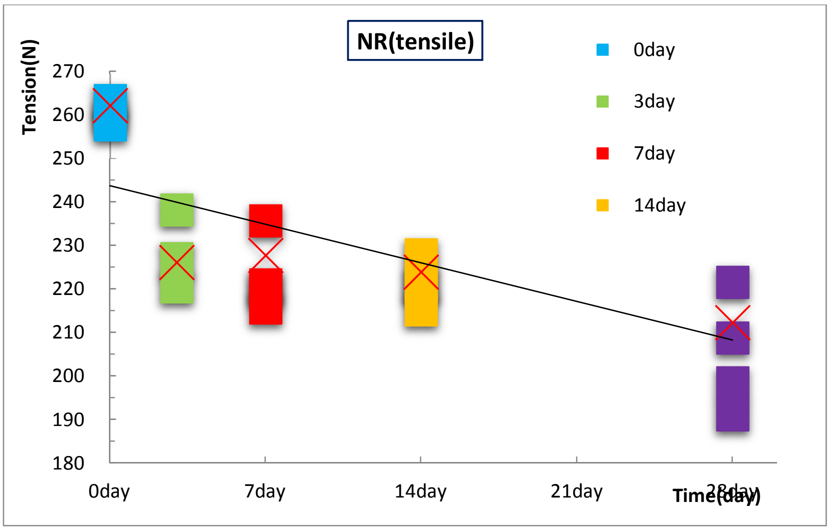


Fig.5-3. NR Force Time relation

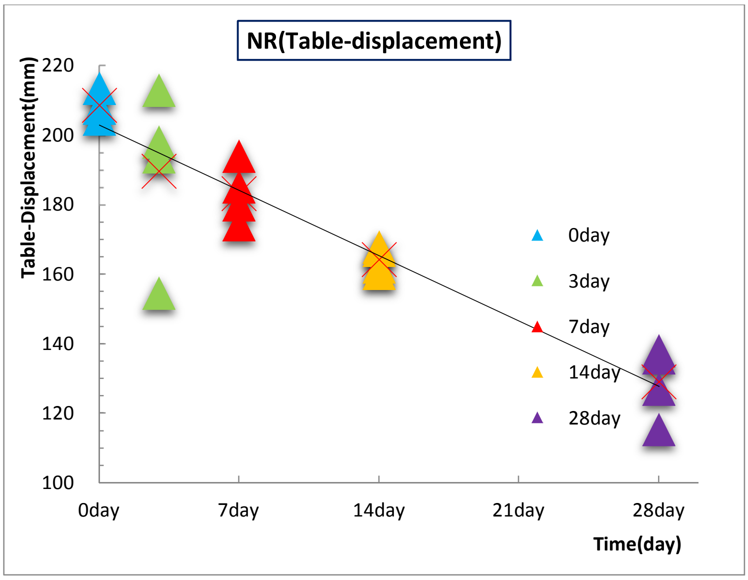


Fig.5-4. NR Table Displacement time Relation

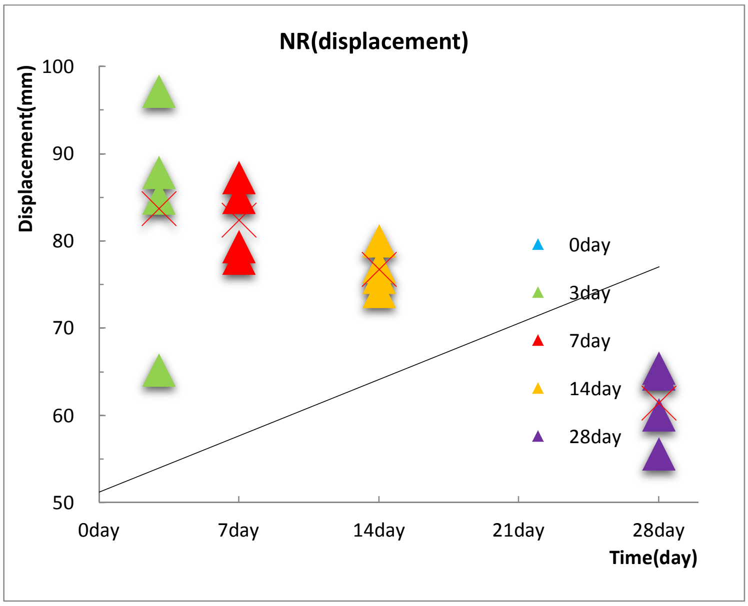


Fig.5-5. NR Displacement time relation

(2) Neoprene (Cr)

The behaviour of the neoprene rubber over the duration of the accelerated aging process showed a behaviour the mirrors that of Natural rubber. The Changes in the physical properties are more favourable than that of the Natural Rubber. The Elongation at break for vulcanizate specimens tested on day 28^{th} of aging was 9% lesser than those tested on original specimens. Ultimate strength also varied by 8% less on than 28^{th} day from that of the original specimens.

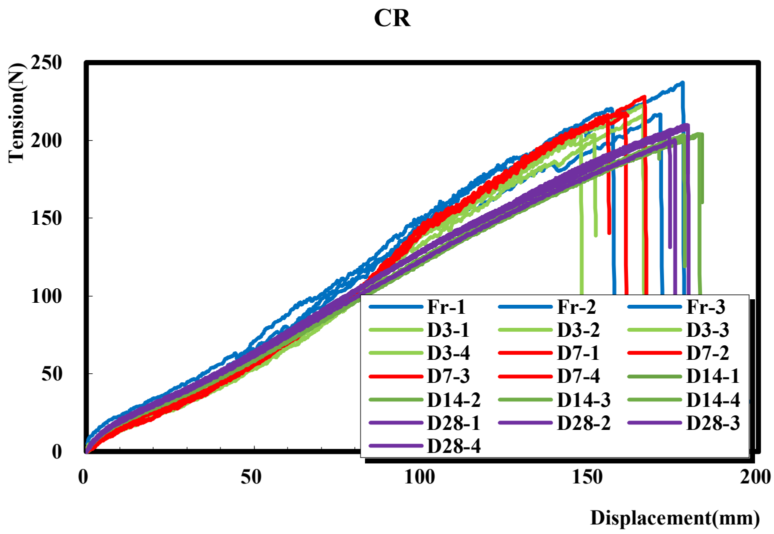


Fig.5-6. CR Force Displacement Compilation

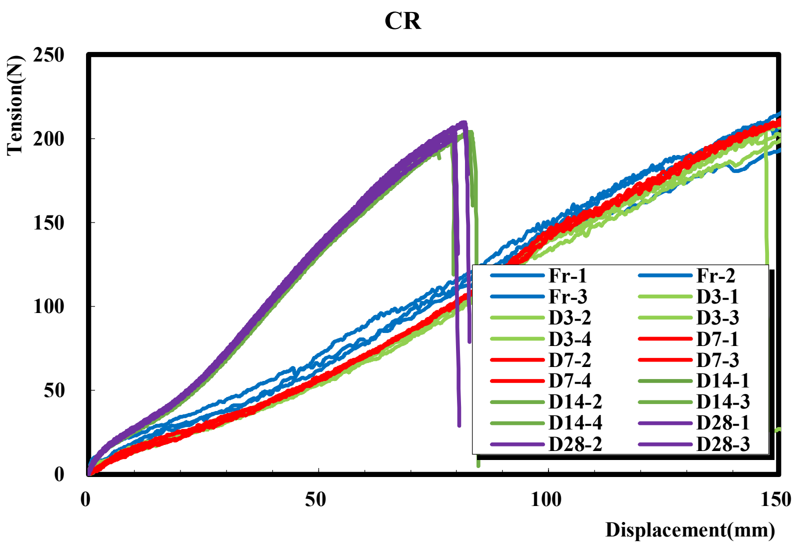


Fig.5-7. CR Force table Displacement Compilation

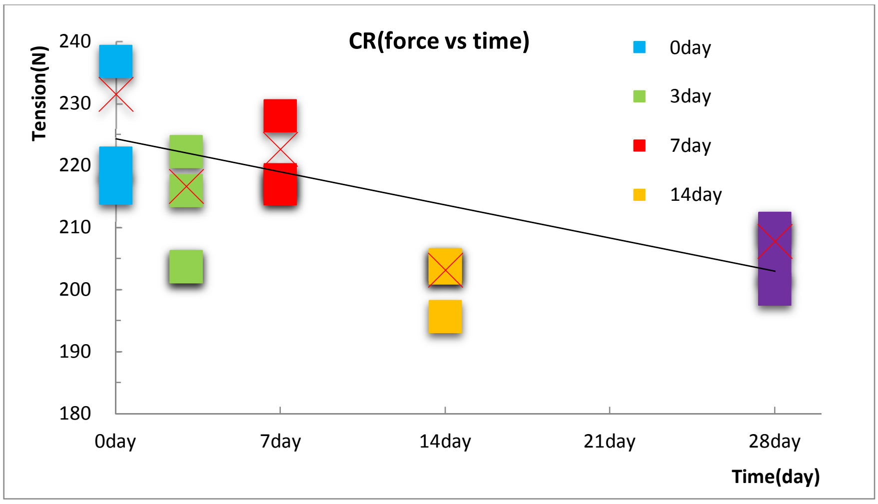


Fig.5-8. CR Force Time Relationship

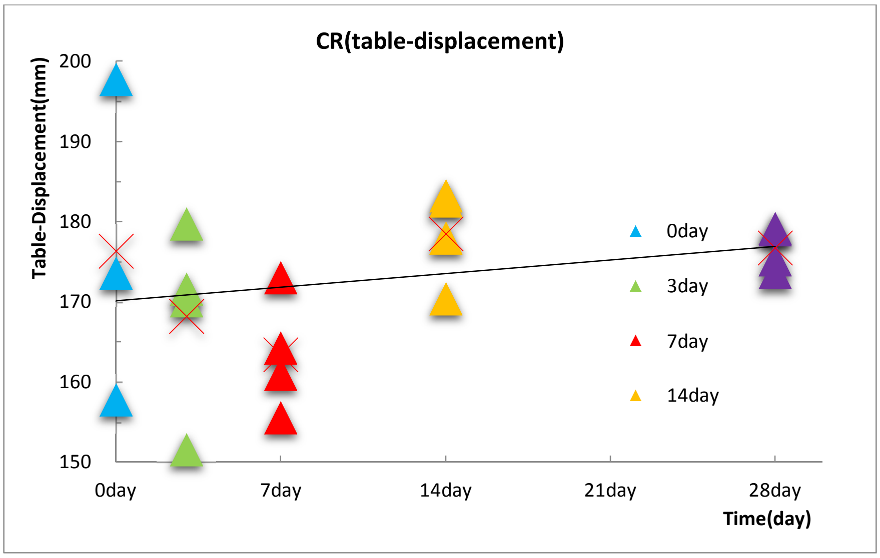


Fig.5-9. CR table Displacement time relationship

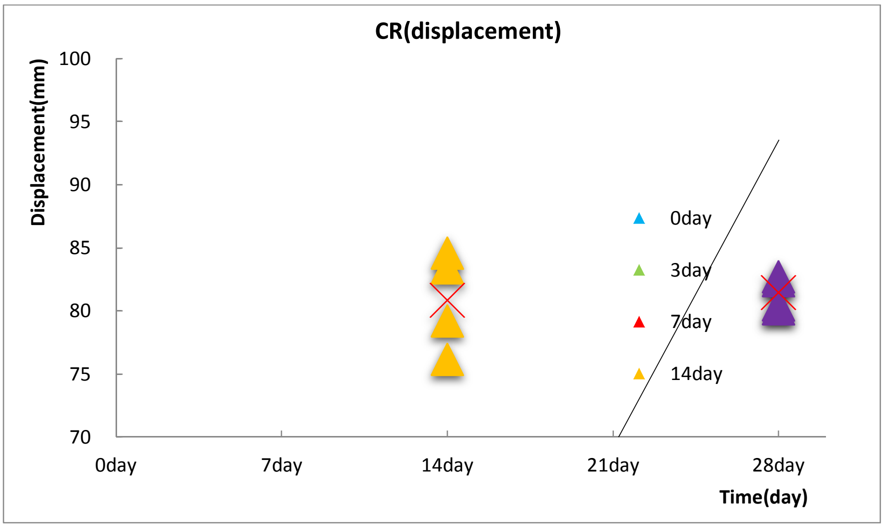


Fig.5-10. CR Displacement Time Relationship

5.1.2. Shear

(1) Natural Rubber

The effects of aging on the shear properties of the natural rubber vulcanizates were not as severe as they were on the tensile properties. Essential physical properties like Elongation at break and ultimate strength deteriorated by 21% and 10% from the original test specimens respectively. An assemblage of the results can be seen from figure 5-11 to figure 5-11.

	ULTIMATE STRENGHT	STRAIN	FORCE	DISPLACEMENT	STRESS %	STRAIN%	FORCE%	DISP%
0	28.92	425.44	18077.25	34.04	0%	0%	0%	0%
3	27.49	395.16	17178.75	31.6	-5%	-7%	-5%	-7%
7	27.78	382.97	17362.5	30.64	-4%	-10%	-4%	-10%
14	26.85	363.72	16779	29.1	-7%	-15%	-7%	-15%
28	25.97	352.91	16231.67	27.02	-10%	-17%	-10%	-21%

Table 5-1. Shear properties of Natural Rubber

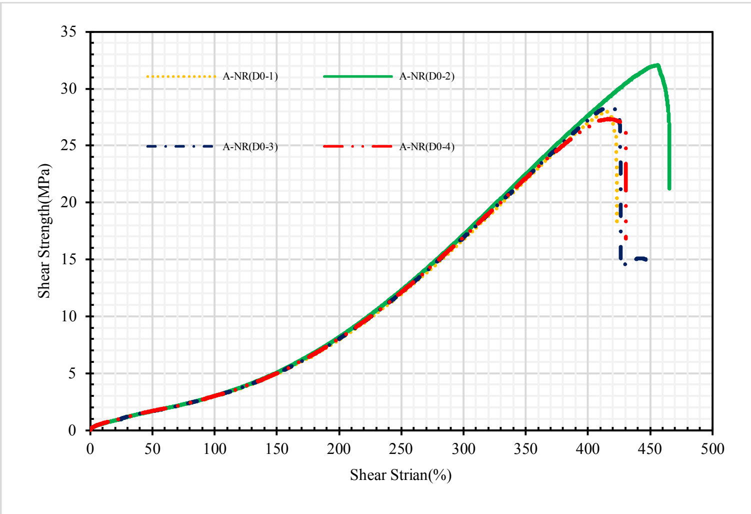


Fig.5-10.. Day 0

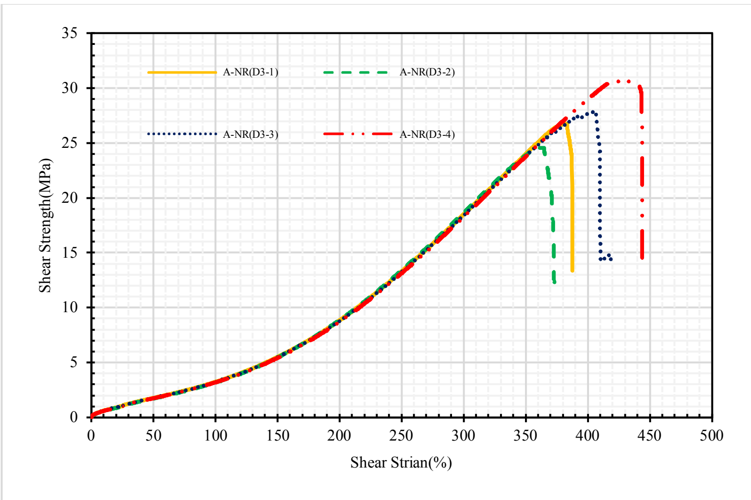


Fig.5-10.. Day 3

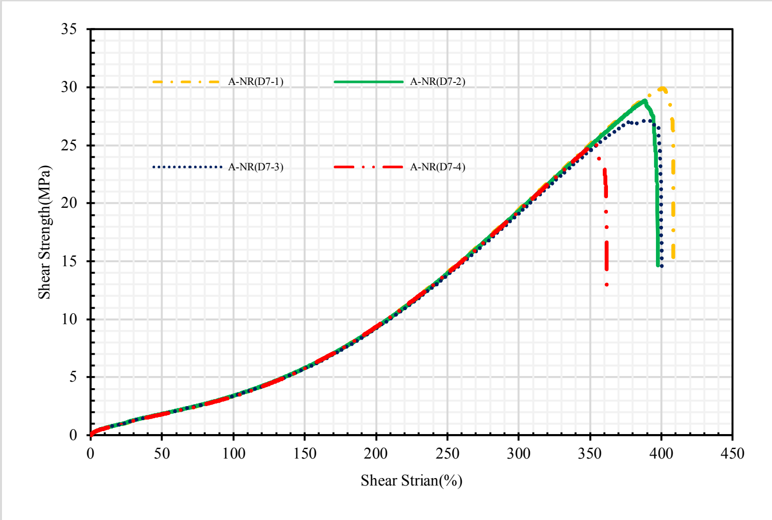


Fig.5-10.c. Day 7

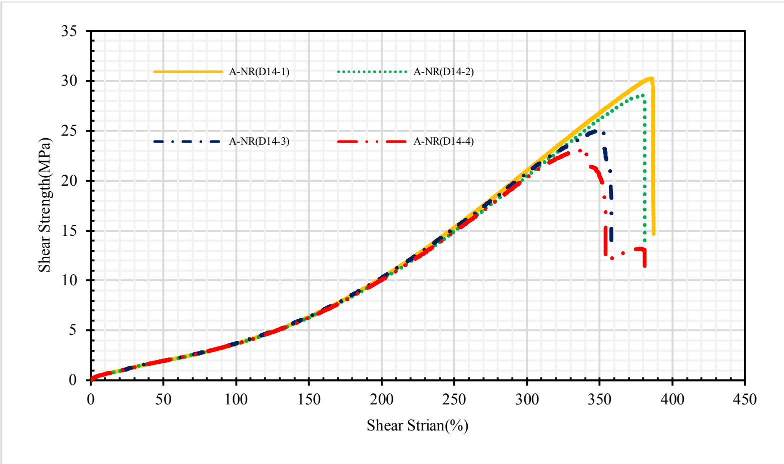


Fig.5-10.d. Day 14

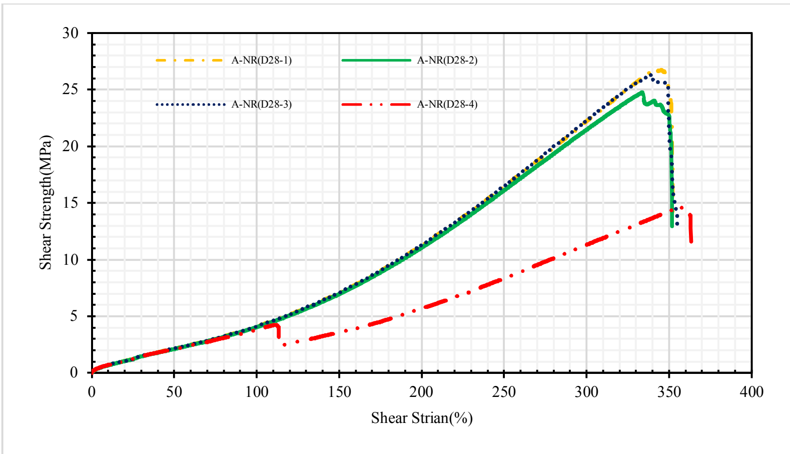


Fig.5-10..e. Day 28

Fig.5-10.Shear properties of Natural Rubber

(2) Neoprene (CR)

The shear physical testing of the neoprene specimens yielded results that differ from that of the natural rubber sharply. Neoprene through these test results exhibits behaviour that suggests softening of the vulcanizates. Elongation at break and ultimate tensile strength derived from the 28th day of testing were 5% and 16% more than that of the original specimens.

	STRESS	STRAIN	FORCE	DISPLACEMENT	STRESS	STRAIN	FORCES	DISPLACEMENT
0	22.59	374.96	14121.67	30	0%	0%	0%	0%
3	23.18	379.56	14489.25	30.37	3%	1%	3%	1%
7	24.31	389	15195.5	31.14	8%	4%	8%	4%
14	23.52	377.5	14701.02	30.2	4%	1%	4%	1%
28	26.1	411.25	15938.25	31.36	16%	10%	13%	5%

Table 5-2. Shear Properties of Neoprene

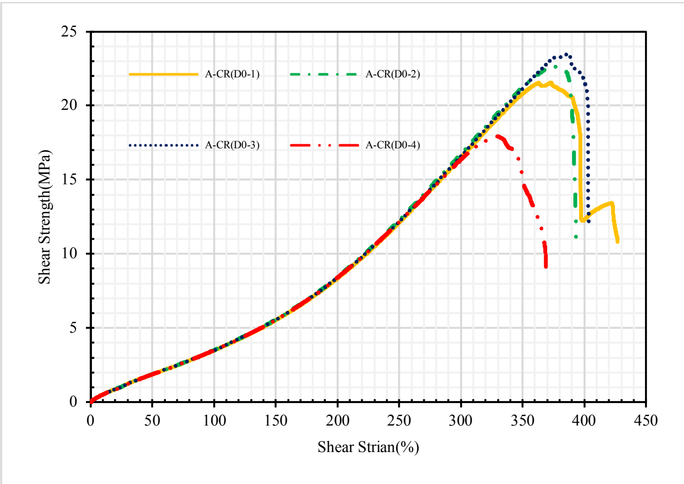


Fig.5-11. Day 0

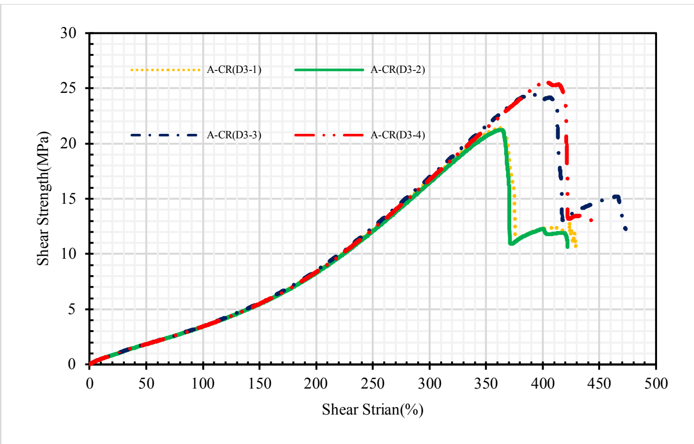


Fig.5-11. Day 3

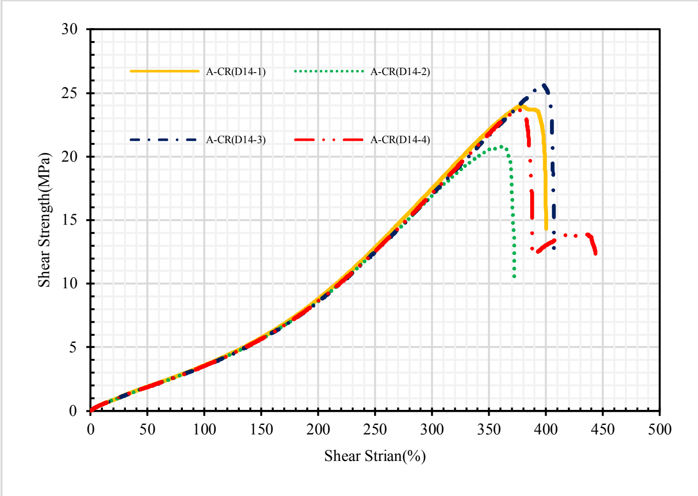


Fig.5-11.d. Day 14

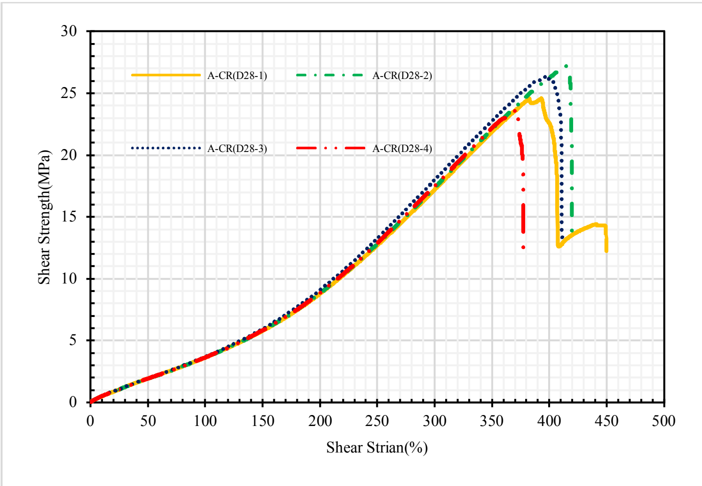


Fig.5-11. e. Day 28

Fig.5-11. Shear Properties of Neoprene

5.2. Experimental results

The modelling and analysis of ten elastomeric bearing models were conducted with specifications and under loading conditions as mentioned in chapter 4. The models are compared based on their horizontal stiffnesses and are compared in relation to their profile type as well as their rubber type. Type A bearings represents homogeneously aged bearings and type B denotes heterogeneously aged bearings. The classifications of the various models are presented in Table 5-3.

Rubber Type	Type A	Type B	Reference Bearing
Natural Rubber (NR)	Model 3_NR_Mp	Model 7_NR_Mmx	Model 1_NR_F
	Model 5_NR_Sp	Model 9_NR_Smx	
Neoprene (CR)	Model 4_CR_Mp	Model 8_CR_Mmx	Model 2_CR_F
	Model 6_CR_Sp	Model 10_CR_Smx	

Table5-3. Table of Bearing Types and Material

5.2.1. Natural Rubber

Of the five models simulated with Natural Rubber changes in the horizontal stiffness was evident of Rubber hardening as the stiffness increase with aging time. Shear stiffness increases by 13.21% and 13.59% in the models Model 3_NR_Mp and Model 7_NR_Mmx respectively, More severely aged models, Model 5_NR_Sp and Model 9_NR_Smx, produced shear stiffness differences of 18.59.% and 18.73% respectively from the reference model.

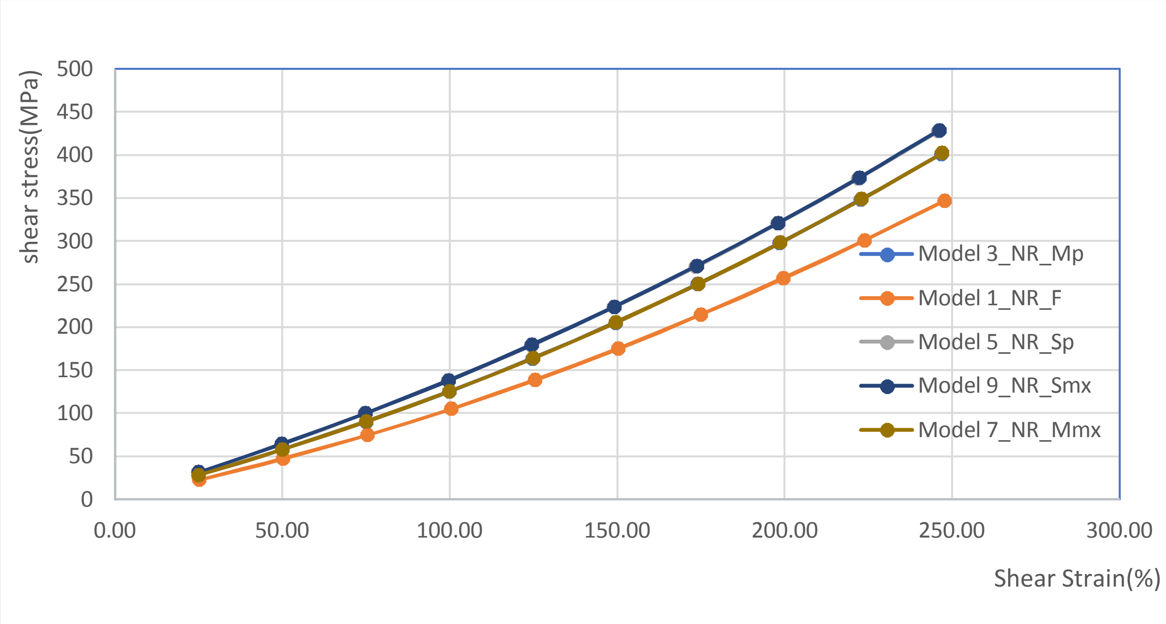


Fig.5-12. Shear strain Curve of Natural Rubber Models

Models	**Changes in Shear stiffness (%)**
Model 1_NR_F	0
Model 3_NR_Mp	13.21
Model 5_NR_Sp	18.60
Model 7_NR_Mmx	13.59
Model 9_NR_Smx	18.73

Table 5-4. Changes in stiffness of Natural Rubber Models

5.2.2. Neoprene (CR)

Similar to Natural Rubber Five models were simulated with the material properties of neoprene. However, the changes in the shear stiffness in the bearing models were in contrast. For mildly deteriorated models, Model 4_CR_Mp and Model 10_CR_Smx, the shear stiffness were 2.89% and 2.90% lesser than the reference model whilst the more severely models, Model 6_CR_Sp and Model 10_CR_Smx produced a positive increase in stiffnesses of 2.30% and 2.34% respectively.

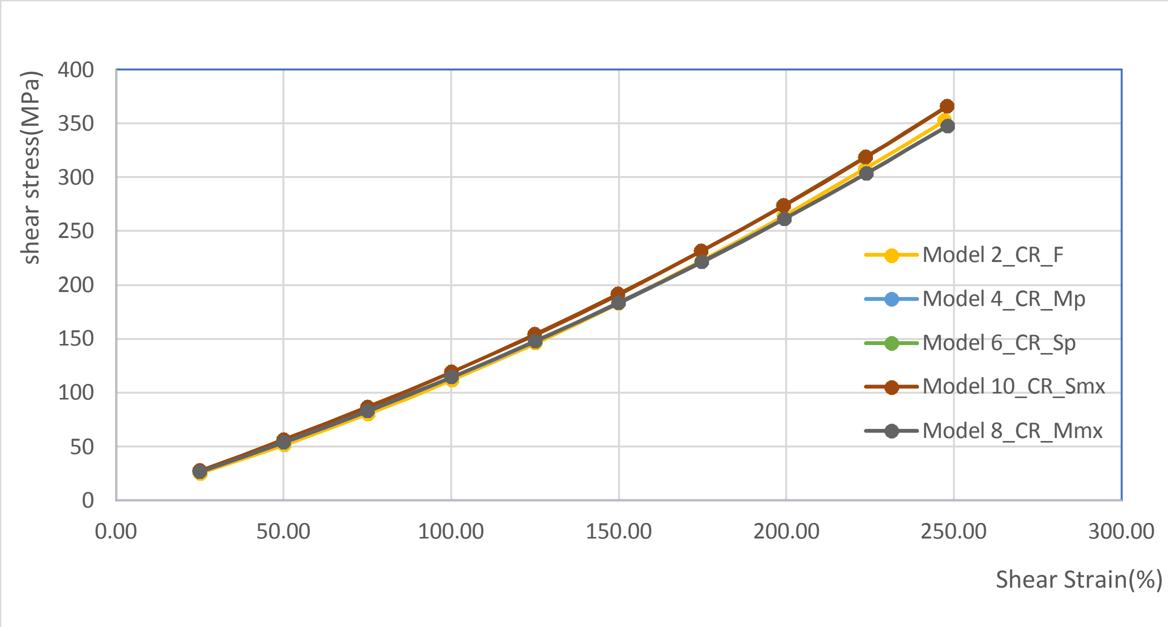


Fig.5-13. shear strain curve of Neoprene

Model 2_CR_F	**0**
Model 4_CR_Mp	-2.89
Model 6_CR_Sp	2.30
Model 8_CR_Mmx	-2.90
Model 10_CR_Smx	2.34

Table 5-5. Changes in shear Stiffness of Neoprene

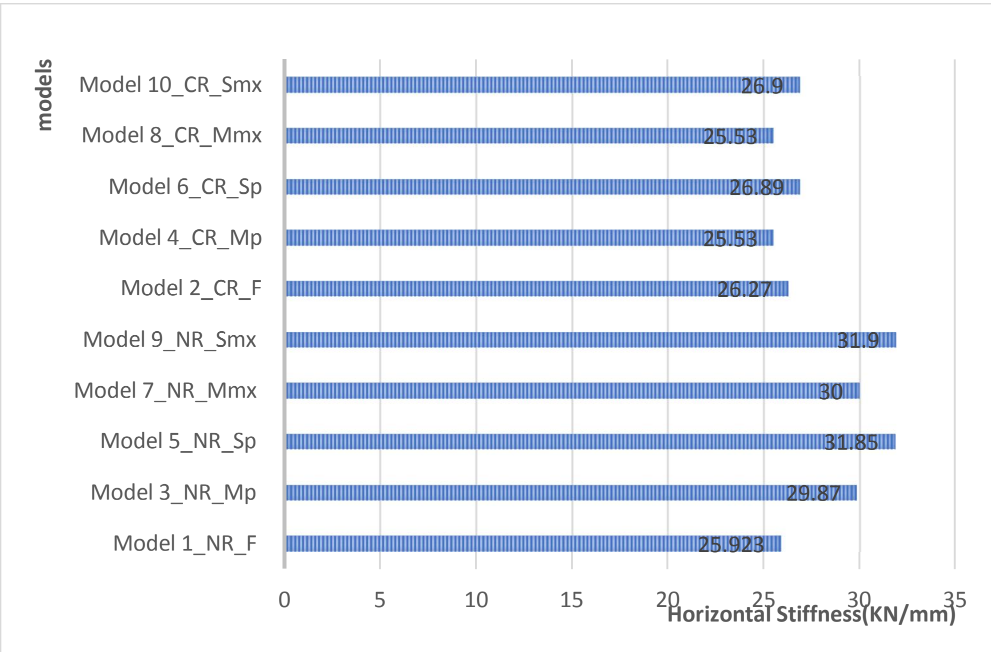


Fig.5-14. Compilation of the changes in shear stiffnesses of all Models

5.2.3. Behaviour of bearings

It was observed in the analysis of the behaviour of the elastomeric bearing models that under combined loading of compression and shear that the maximum stresses were developed at the interface between the rubber layer and the steel plate. The contour of the vertical stress component was characteristic of rotation developing in the bearings.

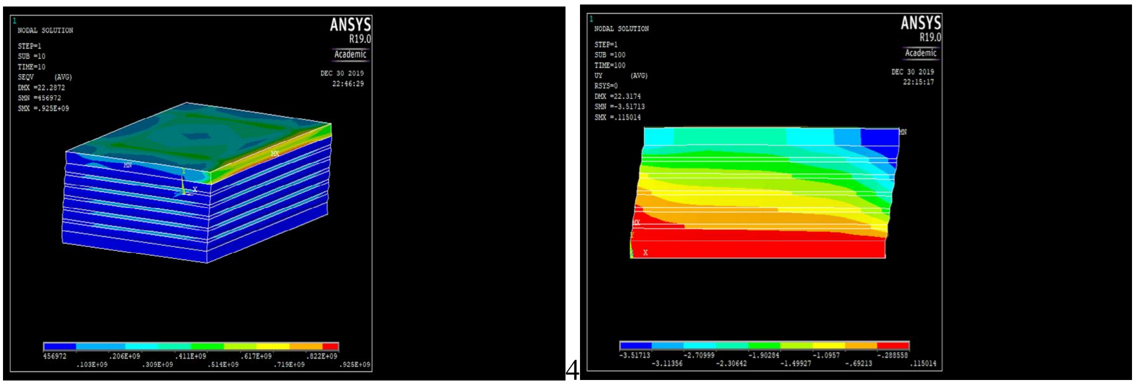


Fig.5-15. Von-Misces stress concentration in the models.

Chapter Six

Conclusion and Limitation of the study

This study which included results from experiments as well as FEM simulation has conclude the following;

- Neoprene performs better than natural Rubber with respect to the physical changes, tensile and shear, in the vulcanizates. This can be attributed to the heat resistance capabilities of Neoprene, noting clearly that the only aging condition applied to specimens was an elevated temperature of 70^{0}C.
- The Effects of the aging conditions applied were more prominent in their tensile behaviour than it was with their shear.
- Hardening behaviour was evident in Natural Rubber as the stiffness increased while the Elongation at break decreased. This could be attributed the crosslinking as product of thermal oxidative aging.
- Neoprene rubber was shown to exhibit behaviour characteristics of softening. A chemical process of chain scission could be responsible for such behaviour. However, the statistical variability of the results as can be seen in the figure is inconclusive to be certain of such behaviour as the data domain of accelerated aging 28 day is approximately at the mean of the range of the data range of accelerated aging day 0. Therefore, further testing at a later aging time will be required to ascertain such behaviour.
- Concomitant with to material level physical testing, models with neoprene had lesser changes in the shear stiffness as they aged than did Natural Rubber. Natural rubber produced a maximum shear stiffness increase of 18.73% while neoprene produced a maximum shear difference of a meagre 2.89%.
- With respect to the mode of aging, this study has observed that while heterogenous (Type B) produces a more conservative results than the homogenous modes (Type A). Nevertheless, the difference in output as per the assumptions of this study were deemed neglected.
- The Bearing models under combined loading of compression and shear developed maximum shear at the interface between the rubber and steel plates. This behaviour could be evidence of adhesive failure between bearings and steel plate as has reported in from feasibility studies.

Chapter Seven

Future Research

Future research to enhance and validate the frontier of this study must include but not be limited to the following.

- A continuation of the accelerated aging test on the rubber vulcanizates is needed to further the understanding of the aging behaviour.
- Physical Aging experiments on bearing blocks must be conducted to corroborate with the simulation results presented herein.
- Investigation into the debonding behaviour at the rubber steel interface must be done either by physical examination or by means of FEM Analysis.

Abstract

Mechanical Properties of the Rubber Material Used in Elastomeric Bridge Bearing
Considering the Effects of Aging

University of Ulsan

Department of Civil and Environmental Engineering

Henry Quona Taylor

Bridge systems are subjected to certain movements, induced by external or dead loading, which has necessitated the inclusion of support devices with the capabilities to efficiently dissipate energy and protect the bridge pier from unwanted stress concentration. These criteria are effectively met by elastomeric bearings, whose primary material, rubber, has elasticity properties suitable for base isolation. The performance of these bearings whose service life is about 100years is dependent on the behaviour of the rubber material over time.

Pursuant with understanding the behaviour of elastomeric bearing overtime, this study sought to determine the effects of aging on the material properties of the rubber used in elastomeric bearings considering Natural Rubber and Neoprene; to conduct member level simulations of the elastomeric bearing blocks and determine the changes in stiffness of the aged rubber bearing and to evaluate the effects of the different assumptions surrounding the modes aging on the behaviour of aged rubber bearing.

In its pursuit, the Study discovered that neoprene performs better than natural Rubber with respect to the physical changes, tensile and shear, in the vulcanizates and that the effects of the aging conditions applied were more prominent in their tensile behaviour than it was with their shear. Also evident from the study was that the models with neoprene had lesser changes in the shear stiffness as they aged than did Natural Rubber. Natural rubber produced a maximum shear stiffness increase of 18.73% while neoprene produced a maximum shear difference of a meagre 2.89%. it was noticed that the Bearing models under combined loading of compression and shear developed maximum shear at the interface between the rubber and steel plates

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APPENDIX

Geometry, areas and meshing of the model

!Geometry

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k,2,50,0,0

k,3,100,0,0

k,4,300,0,0

k,5,350,0,0

k,6,400,0,0

k,7,0,0,50

k,8,50,0,50

k,9,100,0,50

k,10,300,0,50

k,11,350,0,50

k,12,400,0,50

k,13,0,0,100

k,14,50,0,100

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k,17,350,0,100

k,18,400,0,100

k,19,0,0,300

k,20,50,0,300

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k,23,350,0,300

k,24,400,0,300

k,25,0,0,350

k,26,50,0,350

k,27,100,0,350

k,28,300,0,350

k,29,350,0,350

k,30,400,0,350

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v,39,3,9,45,38,2,8,44
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v,64,28,34,70,63,27,33,69

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v,75,39,45,81,74,38,44,80

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v,77,41,47,83,76,40,46,82

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v,125,89,95,131,124,88,94,130

v,126,90,96,132,125,89,95,131

v,128,92,98,134,127,91,97,133

v,129,93,99,135,128,92,98,134

v,130,94,100,136,129,93,99,135

v,131,95,101,137,130,94,100,136

v,132,96,102,138,131,95,101,137

v,134,98,104,140,133,97,103,139

v,135,99,105,141,134,98,104,140

v,136,100,106,142,135,99,105,141

v,137,101,107,143,136,100,106,142

v,138,102,108,144,137,101,107,143

v,146,110,116,152,145,109,115,151

v,147,111,117,153,146,110,116,152

v,148,112,118,154,147,111,117,153

v,149,113,119,155,148,112,118,154

v,150,114,120,156,149,113,119,155

v,152,116,122,158,151,115,121,157

v,153,117,123,159,152,116,122,158

v,154,118,124,160,153,117,123,159

v,155,119,125,161,154,118,124,160

v,156,120,126,162,155,119,125,161

v,158,122,128,164,157,121,127,163

v,159,123,129,165,158,122,128,164

v,160,124,130,166,159,123,129,165

v,161,125,131,167,160,124,130,166

v,162,126,132,168,161,125,131,167

v,164,128,134,170,163,127,133,169

v,165,129,135,171,164,128,134,170

v,166,130,136,172,165,129,135,171

v,167,131,137,173,166,130,136,172
v,168,132,138,174,167,131,137,173
v,170,134,140,176,169,133,139,175
v,171,135,141,177,170,134,140,176
v,172,136,142,178,171,135,141,177
v,173,137,143,179,172,136,142,178
v,174,138,144,180,173,137,143,179

v,182,146,152,188,181,145,151,187
v,183,147,153,189,182,146,152,188
v,184,148,154,190,183,147,153,189
v,185,149,155,191,184,148,154,190
v,186,150,156,192,185,149,155,191
v,188,152,158,194,187,151,157,193
v,189,153,159,195,188,152,158,194
v,190,154,160,196,189,153,159,195
v,191,155,161,197,190,154,160,196
v,192,156,162,198,191,155,161,197
v,194,158,164,200,193,157,163,199
v,195,159,165,201,194,158,164,200
v,196,160,166,202,195,159,165,201
v,197,161,167,203,196,160,166,202
v,198,162,168,204,197,161,167,203
v,200,164,170,206,199,163,169,205
v,201,165,171,207,200,164,170,206
v,202,166,172,208,201,165,171,207
v,203,167,173,209,202,166,172,208
v,204,168,174,210,203,167,173,209
v,206,170,176,212,205,169,175,211
v,207,171,177,213,206,170,176,212
v,208,172,178,214,207,171,177,213
v,209,173,179,215,208,172,178,214
v,210,174,180,216,209,173,179,215

v,218,182,188,224,217,181,187,223
v,219,183,189,225,218,182,188,224
v,220,184,190,226,219,183,189,225
v,221,185,191,227,220,184,190,226
v,222,186,192,228,221,185,191,227
v,224,188,194,230,223,187,193,229
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v,226,190,196,232,225,189,195,231
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v,245,209,215,251,244,208,214,250
v,246,210,216,252,245,209,215,251

v,254,218,224,260,253,217,223,259
v,255,219,225,261,254,218,224,260
v,256,220,226,262,255,219,225,261
v,257,221,227,263,256,220,226,262
v,258,222,228,264,257,221,227,263
v,260,224,230,266,259,223,229,265
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v,263,227,233,269,262,226,232,268
v,264,228,234,270,263,227,233,269
v,266,230,236,272,265,229,235,271
v,267,231,237,273,266,230,236,272
v,268,232,238,274,267,231,237,273
v,269,233,239,275,268,232,238,274
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v,290,254,260,296,289,253,259,295
v,291,255,261,297,290,254,260,296
v,292,256,262,298,291,255,261,297
v,293,257,263,299,292,256,262,298
v,294,258,264,300,293,257,263,299
v,296,260,266,302,295,259,265,301
v,297,261,267,303,296,260,266,302
v,298,262,268,304,297,261,267,303
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v,302,266,272,308,301,265,271,307
v,303,267,273,309,302,266,272,308
v,304,268,274,310,303,267,273,309
v,305,269,275,311,304,268,274,310
v,306,270,276,312,305,269,275,311
v,308,272,278,314,307,271,277,313
v,309,273,279,315,308,272,278,314
v,310,274,280,316,309,273,279,315
v,311,275,281,317,310,274,280,316
v,312,276,282,318,311,275,281,317
v,314,278,284,320,313,277,283,319
v,315,279,285,321,314,278,284,320
v,316,280,286,322,315,279,285,321
v,317,281,287,323,316,280,286,322
v,318,282,288,324,317,281,287,323

v,326,290,296,332,325,289,295,331
v,327,291,297,333,326,290,296,332
v,328,292,298,334,327,291,297,333
v,329,293,299,335,328,292,298,334
v,330,294,300,336,329,293,299,335
v,332,296,302,338,331,295,301,337
v,333,297,303,339,332,296,302,338
v,334,298,304,340,333,297,303,339
v,335,299,305,341,334,298,304,340
v,336,300,306,342,335,299,305,341
v,338,302,308,344,337,301,307,343
v,339,303,309,345,338,302,308,344
v,340,304,310,346,339,303,309,345
v,341,305,311,347,340,304,310,346
v,342,306,312,348,341,305,311,347
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v,345,309,315,351,344,308,314,350
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v,347,311,317,353,346,310,316,352
v,348,312,318,354,347,311,317,353
v,350,314,320,356,349,313,319,355
v,351,315,321,357,350,314,320,356
v,352,316,322,358,351,315,321,357
v,353,317,323,359,352,316,322,358
v,354,318,324,360,353,317,323,359

v,362,326,332,368,361,325,331,367
v,363,327,333,369,362,326,332,368
v,364,328,334,370,363,327,333,369
v,365,329,335,371,364,328,334,370
v,366,330,336,372,365,329,335,371
v,368,332,338,374,367,331,337,373
v,369,333,339,375,368,332,338,374
v,370,334,340,376,369,333,339,375
v,371,335,341,377,370,334,340,376
v,372,336,342,378,371,335,341,377
v,374,338,344,380,373,337,343,379
v,375,339,345,381,374,338,344,380
v,376,340,346,382,375,339,345,381
v,377,341,347,383,376,340,346,382
v,378,342,348,384,377,341,347,383
v,380,344,350,386,379,343,349,385
v,381,345,351,387,380,344,350,386
v,382,346,352,388,381,345,351,387

v,383,347,353,389,382,346,352,388
v,384,348,354,390,383,347,353,389
v,386,350,356,392,385,349,355,391
v,387,351,357,393,386,350,356,392
v,388,352,358,394,387,351,357,393
v,389,353,359,395,388,352,358,394
v,390,354,360,396,389,353,359,395

v,398,362,368,404,397,361,367,403
v,399,363,369,405,398,362,368,404
v,400,364,370,406,399,363,369,405
v,401,365,371,407,400,364,370,406
v,402,366,372,408,401,365,371,407
v,404,368,374,410,403,367,373,409
v,405,369,375,411,404,368,374,410
v,406,370,376,412,405,369,375,411
v,407,371,377,413,406,370,376,412
v,408,372,378,414,407,371,377,413
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v,411,375,381,417,410,374,380,416
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v,413,377,383,419,412,376,382,418
v,414,378,384,420,413,377,383,419
v,416,380,386,422,415,379,385,421
v,417,381,387,423,416,380,386,422
v,418,382,388,424,417,381,387,423
v,419,383,389,425,418,382,388,424
v,420,384,390,426,419,383,389,425
v,422,386,392,428,421,385,391,427
v,423,387,393,429,422,386,392,428
v,424,388,394,430,423,387,393,429
v,425,389,395,431,424,388,394,430
v,426,390,396,432,425,389,395,431

v,434,398,404,440,433,397,403,439
v,435,399,405,441,434,398,404,440
v,436,400,406,442,435,399,405,441
v,437,401,407,443,436,400,406,442
v,438,402,408,444,437,401,407,443
v,440,404,410,446,439,403,409,445
v,441,405,411,447,440,404,410,446
v,442,406,412,448,441,405,411,447
v,443,407,413,449,442,406,412,448
v,444,408,414,450,443,407,413,449
v,446,410,416,452,445,409,415,451
v,447,411,417,453,446,410,416,452
v,448,412,418,454,447,411,417,453
v,449,413,419,455,448,412,418,454
v,450,414,420,456,449,413,419,455
v,452,416,422,458,451,415,421,457
v,453,417,423,459,452,416,422,458
v,454,418,424,460,453,417,423,459
v,455,419,425,461,454,418,424,460
v,456,420,426,462,455,419,425,461
v,458,422,428,464,457,421,427,463
v,459,423,429,465,458,422,428,464
v,460,424,430,466,459,423,429,465
v,461,425,431,467,460,424,430,466
v,462,426,432,468,461,425,431,467

v,470,434,440,476,469,433,439,475
v,471,435,441,477,470,434,440,476
v,472,436,442,478,471,435,441,477
v,473,437,443,479,472,436,442,478
v,474,438,444,480,473,437,443,479
v,476,440,446,482,475,439,445,481
v,477,441,447,483,476,440,446,482
v,478,442,448,484,477,441,447,483
v,479,443,449,485,478,442,448,484
v,480,444,450,486,479,443,449,485
v,482,446,452,488,481,445,451,487
v,483,447,453,489,482,446,452,488
v,484,448,454,490,483,447,453,489
v,485,449,455,491,484,448,454,490
v,486,450,456,492,485,449,455,491
v,488,452,458,494,487,451,457,493
v,489,453,459,495,488,452,458,494
v,490,454,460,496,489,453,459,495

v,491,455,461,497,490,454,460,496

v,492,456,462,498,491,455,461,497

v,494,458,464,500,493,457,463,499

v,495,459,465,501,494,458,464,500

v,496,460,466,502,495,459,465,501

v,497,461,467,503,496,460,466,502

v,498,462,468,504,497,461,467,503

!full bearing base

91,96,100,104,108,70,75,79,83,87,49,54,58,62,66,28,33,37,41,45,3,9,14,19,24

!top

1049,1054,1058,1062,1066,1069,1073,1076,1079,1082,1085,1089,1092,1095,1098,1101,1105,1108,1111,1114,1117,1121,1124,1127,1130

!side

1128,1112,1096,1080,1063

!outer

vmesh,26,31

vmesh,76,81

vmesh,126,131

vmesh,176,181

vmesh,226,231

vmesh,276,281

vmesh,35

vmesh,85

vmesh,135

vmesh,185

vmesh,235

vmesh,285

vmesh,36

vmesh,86

vmesh,136

vmesh,186

vmesh,236

vmesh,286

vmesh,40

vmesh,90

vmesh,140

vmesh,190

vmesh,240

vmesh,290

vmesh,41

vmesh,91

vmesh,141

vmesh,191

vmesh,241

vmesh,291

vmesh,45,50

vmesh,95,100

vmesh,145,150

vmesh,195,200

vmesh,245,250

vmesh,295,300

!inner

vmesh,32,34

vmesh,82,84

vmesh,132,134

vmesh,182,184

vmesh,232,234

vmesh,282,284

vmesh,37

vmesh,87

vmesh,137

vmesh,187

vmesh,237

vmesh,287

vmesh,39

vmesh,89

vmesh,139

vmesh,189

vmesh,239

vmesh,289

vmesh,42,44

vmesh,92,94

vmesh,142,144

vmesh,192,194

vmesh,242,244

vmesh,292,294

!center

```
vmesh,38
vmesh,88
vmesh,138
vmesh,188
vmesh,238
vmesh,288
!steel plates
vmesh,1,25
vmesh,301,325
!Steel shims
vmesh,51,75,
vmesh,101,125
vmesh,151,175
vmesh,201,225
vmesh,251,275
```