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Circular Elastomeric Bearings

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Submitted by

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16. Abstract

Reinforced and unreinforced elastomeric bearing pads have been used for bridges in NJ for about five years. The shape of these bearings is square or rectangular and their orientation is generally in the direction of thermal movements. Although the direction of thermal movement for straight bridges can be reasonably predicted, the direction of displacements of skewed and curved bridges may not be well defined. For rectangular bearings, if the direction of movement is not oriented along one of the principal axes of the bearing, distortion of the bearing may occur. The problem gets worse if the fatigue loading is significant which could cause delamination at the elastomer-steel shim interface. For very wide bridges, circular bearings have a better performance than square or rectangular bearings because transverse as well as longitudinal movement need to be considered and the direction of movement is not along the centerline of the beam. Moreover, rectangular bearings often need to be notched to provide edge clearance for certain capital geometries, which increases the cost of the bearing and adds more corners to its shape. Also in some instances, these bearings may not be properly oriented in the field as required by the contract drawings. Circular elastomeric bearings are not direction dependent and they exhibit the same behavior in all directions. The circular shape, moreover, does not have edge corners, which eliminates stress concentrations and the possibility of distortions. These bearings are less likely to be notched compared to the rectangular bearings and their orientation in the field is simple. Their advantages on skewed, curved, and wide bridges make them an attractive alternative to rectangular bearings, however, their behavior needs to be studied and evaluated. A nationwide survey has been conducted to evaluate state DOT's experience with circular elastomeric bearings and a finite element investigation was conducted to compare various bearing geometries. Survey results showed circular elastomeric bearings are being used in several states and more states are willing to consider them. Results from the analytical investigation showed that circular bearings have higher translational and rotational stiffness compared to square and rectangular bearings. The analysis also showed non-linear distribution of normal stresses across the bearing and the existence of tensile stresses at the interface between the elastomer top layer and the steel shim under compressive and shear loads.

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SUMMARY

Reinforced and unreinforced elastomeric bearing pads have been used for bridges in NJ for about five years. The shape of these bearings is square or rectangular and their orientation is generally in the direction of thermal movements. Although, the direction of thermal movement for straight bridges can be reasonably predicted, the direction of displacements of skewed and curved bridges may not be well defined. For rectangular bearings, if the direction of movement is not oriented along one of the principal axes of the bearing, distortion of the bearing may occur. The problem gets worse if the fatigue loading is significant which could cause delamination at the elastomer-steel shim interface bond. For very wide bridges, circular bearings have a better performance than square or rectangular bearings because transverse as well as longitudinal movement need to be considered and the direction of movement is not along the centerline of the beam. Moreover, rectangular bearings often need to be notched to provide edge clearance for certain capital geometries, which increases the cost of the bearing and adds more corners to its shape. Also in some instances, these bearings may not be properly oriented in the field as required by the contract drawings. Circular elastomeric bearings are not direction dependent and they generally exhibit the same behavior in all directions. The circular shape, moreover, does not have edge corners, which eliminates stress concentrations and the possibility of distortions. These bearings are less likely to be notched compared to the rectangular bearings and their orientation in the field is simple. Circular elastomeric bearings have been used on several projects in several states. Their advantages on skewed, curved, and wide bridges make them an attractive alternative to rectangular bearings, however, their behavior needs to be studied and evaluated. A nationwide survey has been conducted to evaluate state DOT's experience with circular elastomeric bearings. A similar survey was sent to bridge consultants in the New York/New Jersey area. Bearing manufacturers and suppliers were contacted by phone and electronic mail. The results of the surveys and results from an analytical investigation of circular and square bearings are presented with conclusions and recommendations.

INTRODUCTION

Elastomeric bearings have been used with increasing frequency in highway bridges during the last 30 years. These bearings, which are economical and require less maintenance, can support heavy gravity loads while accommodating large deformations of the elastomer. The early use of those bearings was limited to the unreinforced elastomeric pads. Today, steel-laminated elastomeric pads are often used for situations requiring higher bearing stress and stiffness. More recently, fiberglass reinforced elastomeric pads and fabric reinforced elastomeric pads have been used. AASHTO Standard Specifications allow the use of fiberglass reinforcement in elastomeric bearings. Other materials such as polyester have proven to be too flexible and both, polyester and cotton are not strong or stiff enough. The strength of the fabric reinforcement governs the compressive strength of the bearing when minimum reinforcement is used. If a stronger fabric with acceptable bond properties is used, the stress limits given in AASHTO [7,20] Section 14.4.1 (AASHTO Method A) may be increased. However, thorough testing over a wide range of conditions, including fatigue will be needed before being accepted. While elastomeric bearings have been used successfully for the last 30 years, there have been some instances of performance problems in the past. These problems included bearing slip or bearing “walking out “, a phenomenon, which was more evident in natural rubber pads more than in neoprene pads. Another problem was delamination due to the separation of the elastomer-steel bond. Delamination could happen due to poor bond between steel and the elastomer and due to overstressing of the bearing.

Reinforced and unreinforced elastomeric bearing pads have been used for bridges in NJ for about five years. The shape of these bearings is square or rectangular and their orientation is generally in the direction of thermal movements. Although, the direction of thermal movement for straight bridges can be reasonably predicted, the direction of displacements of skewed and curved bridges may not be well defined. For rectangular bearings, if the direction of movement is not oriented along one of the principal axes of the bearing, distortion of the bearing may occur. The problem gets worse if the fatigue loading is significant which could cause delamination of the elastomer-steel bond. Moreover, rectangular bearings often need to be notched to provide edge clearance, which increases the cost of the bearing and adds more corners to its shape. Also in some instances, these bearings may not be properly oriented in the field as required by the analysis.

Circular elastomeric bearings are not direction dependent and they generally exhibit the same behavior in all directions. The circular shape, moreover, does not have edge corners, which eliminates stress concentrations and the possibility of distortions. These bearings are less likely to be notched compared to the rectangular bearings and their orientation in the field is simple. Circular elastomeric bearings have been used on several projects in several states. Their advantages make them an attractive alternative to rectangular bearings, however, their behavior needs to be studied and evaluated.

The purpose of this study is to evaluate the performance of circular and rectangular bearings in regard to the factors that most affect their cost and behavior. These factors include compressive stress; shear strains, rotations, movements, geometry, and laminates. The study will include a survey of State DOT's experience with elastomeric bearings, in particular, circular bearings. Based on literature review and the results of this survey, and the results of an analytical investigation, and information from manufacturers, recommendations will be made to the NJDOT on the appropriateness of utilizing circular bearings in bridges in New Jersey. The study will also evaluate the use of composite laminates between elastomer pads in terms of strength and stiffness and make recommendations to the NJDOT on the potential of these composite materials in bridge bearings.

RESEARCH OBJECTIVES

The objective of this research to evaluate and compare the behavior and performance of circular and square and rectangular bearings with regard to critical parameters and for overall cost. Evaluate the thermal movements of circular elastomeric bearings already installed in bridge structures and compare these movements to design values and to determine whether using circular bearings can result in cost savings over square and rectangular elastomeric bearings. The objective also is to make recommendations based on the comparison of performance and cost on whether to allow the use of circular bearings in bridges in New Jersey and to evaluate the use of high performance composites instead of steel between elastomer pads in terms of strength, stiffness, durability, and cost. In order to achieve these objectives, two studies will be conducted: The first is a survey of current DOT experience in circular elastomeric bearings as well as area consultants and manufacturers, and the second is a comprehensive finite element investigation of circular versus square and rectangular elastomeric bearings.

LITERATURE SURVEY

The survey of literature given here includes an overall review of all research work done on bridge elastomeric bearings. Up-to-date experimental and analytical research, as well as current State DOT 's and design code specifications are reviewed.
Movements in bridge structures are caused by joint expansion and contraction, deflection, earth pressures, and other forces, and usually are accommodated by bearings. A variety of bearing devices has been used, including sliding plates, small and large-diameter roller nests, large single rollers, rockers, isolation bearings, and elastomeric bearings. Bearing components are generally specified by an AASHTO or ASTM designation that includes material and inspection requirements to assure quality and performance. In search for more satisfactory bridge bearings, the desire is to have bearings with no moving parts that could freeze, corrode, or deteriorate, easy to install and maintain, and aesthetically pleasing. Elastomeric bearings satisfy many of these desired features. Elastomeric bearings have been used with increasing frequency in highway bridges during the last 30 years. These bearings, which are economical and require less maintenance, can support heavy gravity loads while accommodating large deformations of the elastomer. The early use of those bearings was limited to the unreinforced elastomeric pads. Today, steel-laminated elastomeric pads are often used for situations requiring higher bearing stress and stiffness. More recently, fiberglass

reinforced elastomeric pads and fabric reinforced elastomeric pads have been used. AASHTO Standard Specifications allow the use of fiberglass reinforcement in elastomeric bearings. Other materials such as polyester have proven to be too flexible and both, polyester and cotton are not strong or stiff enough. The strength of the fabric reinforcement governs the compressive strength of the bearing when minimum reinforcement is used. If a stronger fabric with acceptable bond properties is used, the stress limits given in AASHTO(7,17) Section 14.4.1 (AASHTO Method A) may be increased. However, thorough testing over a wide range of conditions, including fatigue will be needed before being accepted.

While elastomeric bearings have been used successfully for the last 30 years, there have been some instances of performance problems in the past. These problems included bearing slip or bearing "walking out ", a phenomenon, which was more evident in natural rubber pads more than in neoprene pads. Another problem was delamination due to the separation of the elastomer-steel bond. Delamination could happen due to poor bond between steel and the elastomer and due to overstressing of the bearing. The performance of elastomeric bearings has been also questioned under low temperatures because the natural rubber and neoprene both become stiffer once subjected to extreme cold temperatures.

Minor and Egen(13) (1970) produced the most comprehensive study to date (NCHRP Report 109) on elastomeric bearings. They tested a wide range of neoprene, natural rubber, neoprene-dacron, and ethylene-propylene dimonomer elastomers. They introduced the shear modulus as a design parameter and they pointed out that quality control during fabrication is important. NCHRP Report 248, " *Elastomeric Bearing Design, Construction, and Materials*" by Roeder and Stanton(21) (1982) concentrated on the development of improved specifications (Method A) for unconfined, plain, and reinforced elastomeric bridge bearings. The recommendations of this report were adopted in the AASHTO *Standard Specifications for Highway Bridges* in 1985. Roeder and Stanton(18) (1987) in NCHRP Report 298, " *Performance of Elastomeric Bearings"* included laboratory testing of actual bridge bearings to correlate bearing performance and test data with the theories upon which Method A specifications were based. The research was performed on bearings of natural rubber and neoprene with different shape factors, different thickness and number of laminates, different bearing shapes (rectangular, circular, and square). Both steel and fiberglass reinforced specimens were tested. The report also included the development of special specifications for special applications (Method B). It also gave more rational bearing specifications that would allow bearing pressures as high as 1600 psi under some design conditions.

In their third NCHRP study, Report 325 in 1989, Roeder and Stanton(17) performed a study to develop recommendations for low temperature behavior and acceptance test procedures of elastomeric bearings. They concluded that low temperatures might cause dramatic increases in the stiffness of the bearing, which may result in significant forces transmitted by the bearing to the substructure. Neoprene pads in their study showed more increase in stiffness compared to natural rubber. Muscarella and Yura(18) (1995) conducted an experimental study for the Texas DOT on elastomeric bridge bearings. Their research showed that tapered elastomeric bearings performed equally as well as flat bearings and that manufacturing tapered bearings with the steel laminates parallel to each other offers several benefits over spacing shims radially. They also concluded that elastomers with lower hardness has some advantages over harder elastomers in terms of the additional rotational capacity they provide and that highly reinforced bearings performed better in compression and fatigue tests. The effects of square and rectangular elastomeric bearing pads on performance AASHTO precast I-beams were reported by Yazdani, Eddy, and Cai(24) (2000). Their study showed that the performance characteristics of precast bridge I-beams are slightly enhanced by the effects of restraints from laminated neoprene bearing pads. McDonald, Hemysfield, and Avent(10) (2000) studied the slippage of neoprene pad bridge bearings. In particular, they were interested in why those pads tend to slip of “ walk” out-of-place. Their study showed the slope of the bottom of the girder in contact with the bearing remains relatively constant and that slippage in bearings occurs on a daily basis due to thermal movements.

An analytical investigation using the finite element analysis by Hamzeh, Tassoulas, and Becker[5] (1998) of square and rectangular elastomeric bearings showed higher stresses and strains at the elastomer-steel shim interface. They also observed tensile stresses in the cover elastomer layers particularly near the tips of the steel shims.

The use of the finite element method in the analysis of elastomeric bearings began about twenty years ago. Lindley[8,9] (1971, 1975) first developed a large deformation plane stress finite element computer program, which was later modified to include bulk compression and plain strain. This program was than used to compute effective compression moduli (at small strains) for infinite long strips with different shape factors and material properties. Analytical investigations by Herrmann, Hamidi, Safigh-Nobari, and Ramaswamy[6] (1988) has resulted in the development of a composite three dimensional finite element procedure based on an equivalent homogeneous continuum. Seki [19] (1987) investigated multiplayer elastic bearings at the Technical Research Laboratory of the Bridgestone Corporation. Strip biaxial testing provided details of the strain energy function used to define the elastomer material properties. A five-layer bearing was analyzed and it was claimed that the analyses agree well with experimental results. Takayama et al. [22] (Takayama 1990) have fitted five material constants from biaxial elongation tests and have successfully analyzed a full-scale 500 mm (19.7 inches) diameter bearing. Their 3D model contained 4136 elements and 7120 nodes. The model was compressed to 100Mpa (14.5ksi) and it achieved a shear deformation of 380%. Billing[3] (1992) performed extensive finite element analysis regarding the elastomeric bearings. He studied low shape-factor and Malaysian Rubber Producer's Research Association twelve layers test bearings by two-dimensional and three dimensional models, and made some comparison with test results. But his work was concentrated on the performance of elastomeric bearing as base isolation for the buildings.

STATE DOT'S SURVEYS

A general survey was conducted of bridge state engineers at different DOT's across the United States. The main purpose of the survey was to learn which states use circular elastomeric bearings, for which bridge types it was specified, cost comparison with square and rectangular bearings, and their experiences and comments. An example of circular elastomeric bearings is shown in Fig. 1. The survey also investigated which states are willing to consider circular bearings in the future. Other information obtained from the survey was related to bearing design methods, bearing inspection and maintenance, and bearing failure. Surveys were sent out to forty-nine states and responses were received from thirty-nine states, about 80% participation ratio.

Figure 1. Circular elastomeric bearings used in concrete box girders in Massachusetts.

Results of the survey showing states already using circular bearings and the states that are willing to consider these bearings are summarized in Table 1. Eight states out of the thirty-nine states (21%) that participated in the survey have used circular bearings. Eighteen states (46%) said they are willing to consider circular elastomeric bearings for their bridges. Ohio stated that they will consider bearings but they thought they are more expensive than square and rectangular bearings. Other states such as South Dakota, Oregon, and Hawaii, mentioned that their willingness to consider them will be based on what advantages they offer over square or rectangular bearings. The states that used circular bearings gave the following information about circular bearings:

Table 1. Survey of State DOT's - Circular versus Square and Rectangular Elastomeric Bearings.

STATE DOT	Use circular elast. bearings	Willing to consider using circular elastomeric bearings	Additional State DOT comments
Alabama			
Alaska		Yes	
Arizona		No	
Arkansas		No	
California			
Colorado		Yes	
Connecticut	Yes		
Delaware	Yes		
Florida			
Georgia		Yes	
Hawaii		Yes	If their use is justified
Idaho	Yes		
Illinois		Yes	
Indiana		No	
Iowa		No	There is no reason to use them
Kansas		No	
Kentucky		Yes	
Louisiana			
Maine	Yes		
Maryland			
Massachusetts	Yes		
Michigan		No	
Minnesota		Yes	
Mississipi		Yes	
Missouri		Yes	
Montana		Yes	
Nebraska			
Nevada		No	
New Hampshire	Yes		
New Mexico		Yes	
New York	Yes		
North Carolina		No	
North Dakota		No	
Ohio		Yes	Though they think they are expensive
Oklahoma		No	
Oregon		Yes	Would consider them but right now
Pennsylvania		No	do not see any reason to use them
Rhode Island			

South Carolina		Yes	
South Dakota		No	Unless convinced there was an advantage for circular bearings
Tennesseee		Yes	
Texas	Yes		
Utah			
Vermont		Yes	
Virginia		No	
Washington		Yes	
West Virginia			
Wisconsin		Yes	
Wyoming			

Most of these states used 12 in to 24 in diameter bearings; only New Hampshire has used diameters less than 12 in. The thickness of the bearings varied from 2 in to 4 in with Connecticut using less than 2 in thickness and New Hampshire using more than 4 in thick bearings. None of the states have used the circular bearings for straight bridges. The survey results also showed that 29% of the circular bearings were used for mild skew bridges, 50% for larger skew, and 21% for curved bridges. As for bridge length and type, most of the bridges with circular bearings have short spans (less than 100 ft long) and two-thirds of these bridges were precast concrete girder bridges while the remaining third were steel bridges.

Table 2 shows circular elastomeric data reported by various states. Standard bearing drawings available on the website of the Texas Department of Transportation shows typical dimension for various bearing geometries based on location, beam type, and end clip angle. The drawing specifies circular bearings for Type IV and Type 72 beams with beam clip angles ranging from 30 degrees to 60 degrees. The New Hampshire Department of Transportation provides standard bearing drawings for circular bearings as well as design guidelines and specifications for bridge shoes. The New Hampshire DOT specifies circular elastomeric bearings for all concrete girder structures. For steel girders, they recommend circular bearings for skewed structures; however, they do not recommend round bearings for steel girders with high live load rotations.

More than 50% the states using circular elastomeric bearings specify neoprene for the elastomer layers. The remaining states specify natural rubber (20%) and polychloroprene (20%). The steel shims used by most states are mild steel with the exception of Delaware, which reported the use of stainless steel shims in their bearings. On the question of maintenance of circular bearings, Texas, New York, and Connecticut reported no difference in maintenance requirements for circular bearings versus square or rectangular bearings. The remaining states stated that not enough data available to compare maintenance requirements. Cost comparisons between circular and square bearings showed that most states did not have enough data to make such comparison. Texas reported a 10% increase when using the circular bearings and Connecticut saying the cost is about the same. Overall, these states reported that circular bearings in their state comprised less than 10% of the total elastomeric bearings in the state. In New York, New Hampshire, and Texas the percentage was between 10% and 30%. The remaining questions in the survey were related to bearing design methods, inspection, maintenance, and damage rather than to comparisons between circular and square bearings. However, information obtained from responses to these questions is applicable to all elastomeric bearings and will be presented and discussed in the following paragraph.

Table 2. Survey of State DOTs circular elastomeric bearing data

STATE DOT	Diameter	Thickness	Elastomer Type	Shim Type	Maintenance vs. square bearings	Cost vs. square bearings	Bridge Type
Connecticut	21"-24"	2"- 3"	Neoprene	Mild Steel	Similar	Minor differences	Mild and large skews; less than 100 ft and from 100 - 150 ft
Delaware	12"- 24"	< 2", 2"- 3"	Neoprene	Stain. Steel	Not enough info	Not enough info	-
Idaho	12"- 24"		Neoprene	Mild Steel	Not enough info	Not enough info	Large skew bridges
Maine	12"- 24"	2"- 4"	Neoprene	Mild Steel	Not enough info	Not enough info	PPC girders; large skew and curved;less than 100 ft
Massachusetts	12"- 24"	3"- 4"	Polychloroprene	Mild Steel	Not enough info	Not enough info	PPC girders; Large skew; less than 100 ft
New Hampshire	12"- 36"	2"- 4"	Natural Rubber	Mild Steel	Not enough info	Not enough info	PPC and steel girders; mild and large skew; less than 100 ft and 100-150 ft
New York	12"- 24"	-	Neoprene and Natural Rubber	Mild Steel	Similar	Not enough info	Steel girders; Large skew and curved; less than 100 ft
Texas	12"-24"	2"-3"	Neoprene and Polychloroprene	Mild Steel	Similar	More expensive by about 10%	PPC girders; Mild and large skew and curved less than 100 ft, 100-150 ft

On the question of the design methods used in practice, AASHTO standard specification Method A is used by 50% of the states compared to 12% using LRFD AASHTO Method A and 12% using LRFD Method B. In-house design methods are used by 8% of the participating states. Only the state of Texas has instrumented and monitored elastomeric bearings for longitudinal displacements, however, 35% of the states said that they would be interested in instrumentation and monitoring elastomeric bearings in the future. On the question of bearing replacement due to failure, 28% of the states stated that they have replaced a bearing due to failure. The common mode of failure observed in elastomeric bearings was bearing movement – bearing walking out- and excessive rotation with 50% of the states reporting this type of problem with elastomeric bearings. Other reported failure modes included: bulging of elastomer layers (29%), delamination at the elastomer-shim interface (10%), and material deterioration with age (12%).

COMMENTS FROM DOT'S SURVEY

Some states provided additional comments on circular bearings and elastomeric bearings in general. Washington State commented that load versus rotation could be an issue with circular bearings and design criteria will be needed for designers. Another issue they pointed out was top and bottom attachment details saying it is easier to fabricate these attachments for rectangular bearing, but they added this can be overcome with experience. Massachusetts said that design Method B is too conservative and results in very tall bearings due to rotation limits. They said that these limits are too restrictive due to insufficient rotational tests. Iowa DOT added more comments to the issue of rotation limits. Information provide by Iowa DOT bridge office showed that using rubber layer thickness rather than the total rubber thickness in Method A is better than Method B in predicting realistic bearing rotations. Minnesota DOT reported they have been using a curved plate bearing detail for almost twenty years that eliminated any consideration for rotation in their elastomeric bearing design. The Minnesota DOT details for the curved plate bearing assembly are shown in Fig. 2. Alaska DOT only allows natural rubber for elastomers due to cold weather concerns.

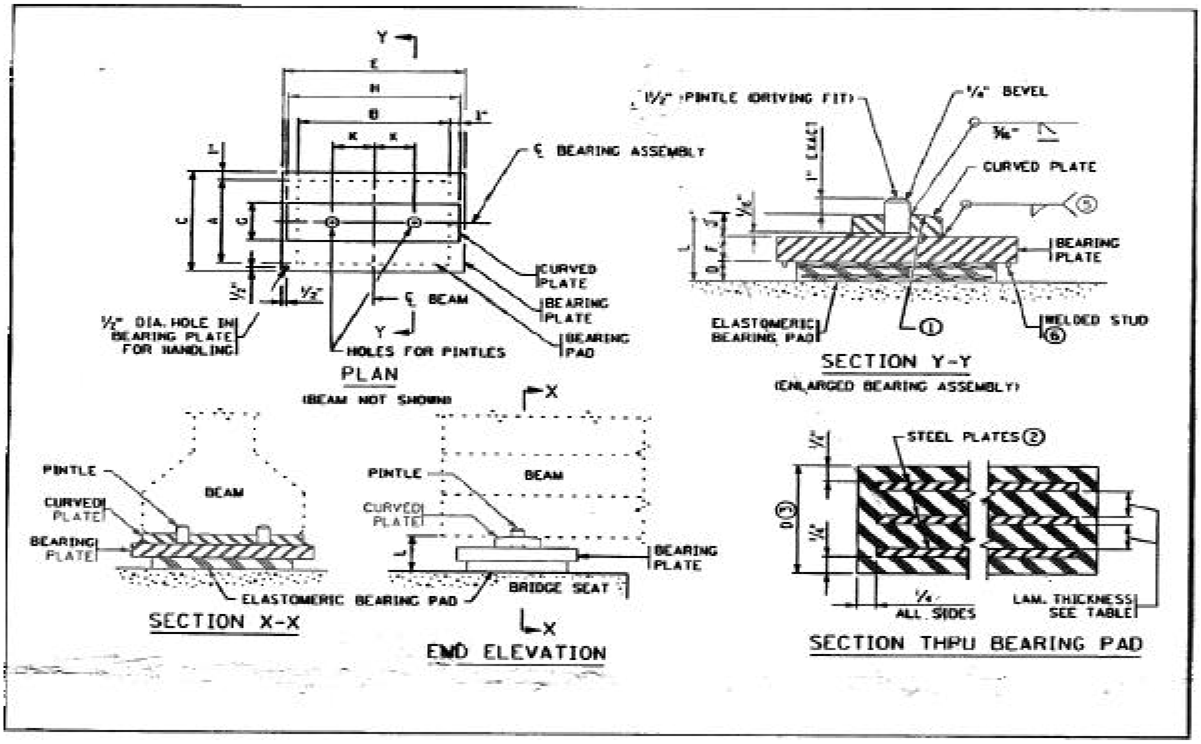


Figure 2. Minnesota DOT detail for curved bearing assembly.

Oregon DOT indicated that their bearing supplier informed them it is much easier and cheaper to manufacture rectangular bearings compared to round bearings and that is why they did not them. Texas DOT mentioned that they might discontinue use of circular bearings because higher stress rectangular pads could satisfy bearing seat room limitations in skewed conditions. Finally, Connecticut DOT added that excessive rotations are most critical and installation tolerances to prevent overstressing one edge.

CONSULTANTS AND SUPPLIERS SURVEYS

A second survey was conducted of bridge designers and consultants in the New York/New Jersey area on whether they have designed circular elastomeric bearings and what experience they had with these types of bearings relating to their use, cost, and other considerations associated with them. Questionnaires were sent to seventeen consultants and only seven responded to our survey. Three consultants (42%) said they have designed circular elastomeric bearings for bridges. Among those who designed circular bearings, (66%) stated that there are only minor differences in cost between circular and square bearings. Two consultants out of the seven who participated in the survey said they would be willing to consider circular elastomeric bearings in certain cases. On the question of design methods, most respondents said they use standard AASHTO method A in their design. Some of them also use method B, however, only one consultant stated that they use the LRFD AASHTO methods for bearing design. On the question of using carbon or glass fiber composite laminates instead of steel shims between elastomer layers, more than 50% of consultants who participated in the survey believe this material can be used fro low-stress elastomeric bearings. Finally, only one consultant reported they have done instrumentation and monitoring of bearing horizontal movements.

A third survey was conducted of bearing manufacturers in the United States to compare cost between circular and square bearings and determine whether composite laminates have been used in place of steel shims between elastomer layers. This survey was conducted by phone and by electronic mail. Table 3 shows cost comparison between circular and square bearings for the same area, thickness, and number of steel plates. The results of this survey showed minor differences in cost between the circular and the square bearings. Most manufacturers/suppliers indicated that there is no significant difference in molding and compressing circular bearings compared to square or rectangular bearings. Only two manufacturers reported that they have been involved in research type work involving using composite laminates to replace steel shims between elastomers in elastomeric bearings but they said do not produce these type of bearings on a commercial scale. They cited difficulty in compressing and vulcanizing the bearing because the composite laminates are flexible and cannot remain straight during the formation process. Others cited concerns with proper bonding between the elastomer and the composite. No cost estimates were given for elastomeric bearings using composite laminates. However, a couple of manufacturers suggested that the price of an elastomeric bearing with composite laminates may be higher than those with steel shims.

Table 3. Cost comparison of circular versus square elastomeric bearings from manufacturer/supplier survey.

Manufacturer	Square 12"x12"x3"	Circular ?14"x3"
Seismic Energy Products, TX	$225	$245
AMSCOT Company, NJ	$175-$200	$225-$250
Granor Rubber Inc.	$100	$130
Tobi Engineering, IL	$70	$75
Scougal Rubber Inc.	$400	$425

INSTRUMENTED ELASTOMERIC BEARINGS

The Ohio DOT did a study in 2000 on instrumented elastomeric bearings. There study was published in Report No. FHWA/OH-2000/010. One of the goals of their study was to assess the feasibility of using instrumented elastomeric bridge bearings as monitoring and condition assessment devices during the life of the bridge. This was based on the assumption that due to loading and changes in bridge conditions, the loads and deformations of the bearings would vary in a way that when measured could be related to the changes and the conditions of the bridge. In their study, bearing deformations was measured in the field for a three-span slab-girder bridge near Cincinnati. The bridge had continuous rolled beams and integral abutments. Measurements were made during deck concrete pour and static truck load-test. They reported that instrumenting bearings for short-term deformations is more practical and can be easily measured in the field and can provide useful information about bridge movement and overall bridge service behavior. Long-term assessment measurements and accurate bearing force prediction is not practical. Because of the non-linear behavior of the bearing and the effects of creep and thermal effects, and the variation of bearing stiffness with time, it was difficult to predict the force associated with measured displacements. Even in the laboratory, there was no unique force associated with a given bearing displacement. At deck-pour the maximum measured bearing deformations were 0.07 in (1.78 mm) horizontal and 0.02 in (51 mm) vertical and 0.003 radian rotation. The maximum measured horizontal deformations during static truckload test were 0.012 in (0.3 mm) horizontal. The variation of bearing properties over time makes these measurements difficult and not practical. They also found the bearings in the field developed a permanent shear offset prior to live load application. To study whether this initial offset would lead to premature failure, they ran fatigue tests in the lab on bearings with 25% and 50% initial shear offset and cyclic shear displacement +-50% up to 2000 cycles. The results showed that bearings did not have a substantial loss of vertical or shear stiffness and did not fail and that bearing in the field would serve their intended function. From the DOT survey, only the state of Texas reported monitoring and instrumentation of elastomeric bearings. They collected longitudinal thermal movements at few locations in the state. In their response to our questionnaire, they did not indicate any specific comments on thermal movements or whether measured data agreed with predicted data.

EVALUATION OF COST SAVINGS

From the response of the State DOT, Consultants, and Manufacturer's/Suppliers, the cost differentials between circular and square and rectangular bearings is less than 10%. A shown in Table3 in the survey section, the average cost of a circular elastomeric bearing with the same area, thickness, ad number of layers is approximately 10% higher than square bearing. The cost of the circular bearing was about $ 225 compared to $ 200 for square bearings. Since the cost of the bearings is only a small part of te overall cost of the bridge, the impact of this cost differential on the overall cost of the bridge is insignificant. Cost comparison of plain bearings showed that a circular plain bearing cost about $ 25 compared to $ 20 for square plain bearing. Although the cost difference is higher (about 20%) for plain bearings, it is not considered significant because of the lower cost of plain bearings.

EVALUATE EFFECT OF COMPOSITE LAMINATES ON BEARING BEHAVIOR

The advantages of using an elastomeric bearing with carbon-fiber or glass-fiber composite laminates is to eliminate corrosion in bearings and extend their service life as well as reducing their weight. On the other hand, the lower stiffness of the composite materials compared to steel, would reduce the vertical stiffness of the bearing and reduces its allowable vertical stress. Therefore, the use of these bearings may be limited to locations on the bridge where loads are small or for shorter span bridge. Because of very limited research work was reported on elastomeric bearings with carbon-fiber or glass-fiber composite laminates, an analytical investigation of these types of bearings was initiated to compare them to steel laminated bearings. The use of composite laminates to replace steel shims between elastomer layers was evaluated using the ABAQUS finite element analysis as explained in details in the next section. As reported earlier in the survey section, manufacturers and suppliers commented that elastomeric bearings with composite laminates, although possible, is not a commercially available product. The results of the finite element analysis showed lower stiffness for the bearings with composite laminates for the same bearing shape as shown in Figure 41 and 42 . Comparing circular and square bearings with composite laminates, the circular bearing showed more vertical stiffness as it did in the bearings with steel laminates. This comparison is shown in Figure 43**.**

FINITE ELEMENT ANALYSIS

Description Of Computer Model

The purpose of the finite element investigation is to evaluate the behavior of circular, square, and rectangular elastomeric bearings under various loading conditions. The types of bearings evaluated included plain elastomeric bearings and layered (laminated) elastomeric bearings. The loading conditions investigated were the following:

compression only, compression and shear, and compression and rotation. The bearing parameters included: bearing geometry, stiffness, thickness, and bearing contact area. The analysis program used was ABAQUS version 5.8-15. The program is multipurpose non-linear analysis program that can handle material and geometrical non-linearities. The elastomer layers and the steel and composite shims were modeled using three-dimensional eight-node solid elements as shown in Fig. 3. Boundary conditions at the top and bottom of the bearing were modeled assuming rigid plates for all cases.

To obtain a better understanding of elastomeric bearings' behavior, two set of models were developed; one set for the analysis of the plain elastomeric bearings and the other set for the analysis of laminated elastomeric bearings

In order to achieve this comparison, computer models with similar parameters such as surface area, total bearing thickness, internal elastomer layer thickness, and steel layer thickness were generated so that the only difference between these models would be the difference in their geometric shapes. The dimensions of the square bearing was set up to a typical value of 16 inches which gave a surface area of 256 in^2. Based on this value, the rectangular bearing with the same surface had dimensions of 12 inch by 21.33 inch, and the circular bearing had a diameter of 18.05 inches. In order to maintain ease of modeling and finite element generation the generated rectangular model had 12 inch by 21.5 inch dimensions which resulted in a slightly higher area (258 in^2) and the circular model had a diameter of 18 inches which resulted in a slightly lower surface area (254.47 in^2). These differences in surface areas were taken into consideration when lateral loads were determined. However, in general this adjustment of dimensions was very small and did not have an impact on the comparison of the bearing behavior.

The Neo-Hookean and the Mooney-Rivlin material models for rubber were used to model the elastomer. The elastomer was modeled as non-linear elastic material. These two model are modifications of the general material model studied by James, Green, and Simpson (1975). The model studied by James is based on a strain-energy function W given by:

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{11}(I_1 - 3)(I_2 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_2 - 3)^2 \qquad (1)$$

This potential function W is expressed as a function of I1 and I2. The accuracy of the model depends on the C constants. To simplify the general model, the constant C_{01}, C_{11}, C_{20}, and C_{30} were set equal to zero. The remaining constant C_{10} was obtained from tests on compressive tests on rubber made by Rubber Producers. Test data from Malaysian Rubber Producer's Research Association. The model then is known as Neo-Hookean model given by:

$$W(I_1, I_2) = C_{10}(I_1 - 3) \tag{2}$$

and

$$C_{10} = \frac{G}{2} \tag{3}$$

When only constants C_{10} and C_{01} are retained, the model is known the Mooney-Rivlin model given by the following equation:

$$W(I_1, I_2) = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \tag{4}$$

The steel shims were modeled using bilinear stress-strain model for low-carbon A36 structural steel. The material models for neoprene and steel shims are shown in Figs. 4 and 5 respectively. The properties of neoprene and steel materials were as follows:

Properties of the elastomer (neoprene):	Properties of the steel :
Hardness: 55±5	Mild steel, F_y=36 ksi
Shear modulus ≅ 200 psi (at -10°C)	Elastic modulus ≅ 29000 ksi

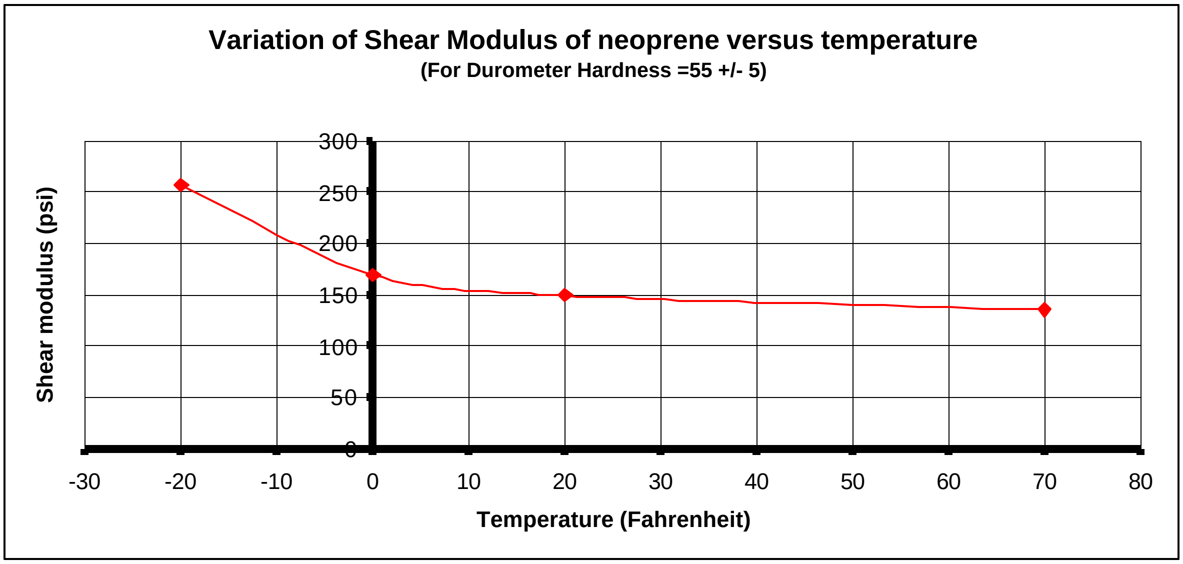


Figure 3. Variation of shear modulus with temperature.

The variation of neoprene shear modulus with temperature is shown in Figure 3. A spreadsheet was prepared in order to establish the geometry and the loading data used in the FE model. Model data are shown in table 4. Eight node brick elements were used in the modeling of the bearings (Hybrid elements were used to take into account the incompressible nature of the elastomer). The loading was applied incrementally and the geometric non-linearity of the material was included in the generation of the model.

Table 4. Bearing geometry and loading data for the finite element analysis.

SQUARE

Length (in)	Width (in)	Thickness (in)	Area (in2)	Load (psi)	Total vertical load (lb)	Lateral load percentage	Lateral load (lb)	Angle with the bearing (°)	Lateral load components (lb) Length	Lateral load components (lb) Width	Number of nodes Length	Number of nodes Width	Load per node (lb) Length	Load per node (lb) Width
16.0	16.0	3.0	256.0	1000	256000	0.2	51200	45.0	36204	36204	19	19	100.3	100.3

Number of steel layers	Steel thickness (in)	Edge layer thickness (in)	Intermediate layer thicknesses (in)	Shape Factor (S)
5	0.075	0.25	0.531	7.5

$$\text{Shape Factor} = S = \frac{W.L}{2x(W+L)x\text{LayerThickness}}$$

Note: No holes within the plate.

RECTANGLE

Length (in)	Width (in)	Thickness (in)	Area (in2)	Load (psi)	Total vertical load (lb)	Lateral load percentage	Lateral load (lb)	Angle with the bearing (°)	Lateral load components (lb) Length	Lateral load components (lb) Width	Number of nodes Length	Number of nodes Width	Load per node (lb) Length	Load per node (lb) Width
21.5	12.0	3.0	258.0	1000	258000	0.2	51600	29.2	45057	25148	19	19	124.8	69.7

Number of steel layers	Steel thickness (in)	Edge layer thickness (in)	Intermediate layer thicknesses (in)	Shape Factor (S)
5	0.075	0.25	0.531	7.2

$$\text{Shape Factor} = S = \frac{W.L}{2x(W+L)x\text{LayerThickness}}$$

Note: No holes within the plate.

CIRCULAR

Diameter (in)	Thickness (in)	Area (in2)	Load (psi)	Total vertical load (lb)	Lateral load percentage	Lateral load (lb)
18.0	3.0	254.5	1000	3E+05	0.2	50894

Number of steel layers	Steel thickness (in)	Edge layer thickness (in)	Intermediate layer thicknesses (in)	Shape Factor (S)
5	0.075	0.25	0.531	8.5

$$\text{ShapeFactor} = S = \frac{D^2}{4x\text{LayerThickness } xD}$$

Note: No holes within the plate.

BEHAVIOR OF PLAIN BEARINGS UNDER COMPRESSION

In order to clearly visualize the behavior of the elastomeric bearings under the loadings, 3-D models were generated by ABAQUS 5.8 using three-dimensional brick elements. The analytical investigation included two bearing groups: plain elastomeric bearings and steel reinforced elastomeric bearings. Each set or group had three different bearing shapes: circular, square, and rectangular. For the first set of bearings, the total thickness of the bearing was pure elastomer (neoprene) material and material properties at an ambient temperature of –10°C were used. For the second set of bearings, the bearing had both elastomer layers and steel shims (plates) rigidly attached to each other at the interface. Eight node hybrid brick elements are used in the model. In order to generate a realistic pressure distribution on the bearing, i.e. through the bottom flange of a girder, a distributed load is applied to the elastomer bearing through a rigid layer. The assumption was that the friction between the bearing and the rigid layer was infinite such that no slip occurred during the loading and also the bearing is supported such that no movement at the plane of support is allowed (later in the investigation, bearings with slip were evaluated). A distributed load of 1000 psi was applied according to the ASSHTO specifications for load limits on elastomeric bearings.

Deformations Of Plain Bearing

The undeformed and deformed shapes of square plain bearing are shown in Figures 4 and 5 respectively. Figures 6 and 7 show the undeformed and deformed shapes for a rectangular plain bearing while Figures 8 and 9 show the undeformed and deformed shapes for a circular plain bearing. The deformed shapes under compressive loads show the effect of bearing geometries on bearing deformations. It can be observed that for circular bearing, there are no local deformations compared to deformations of square and rectangular bearings. Since the square and rectangular bearings lack the radial symmetry, there are excessive deformations at the corners.

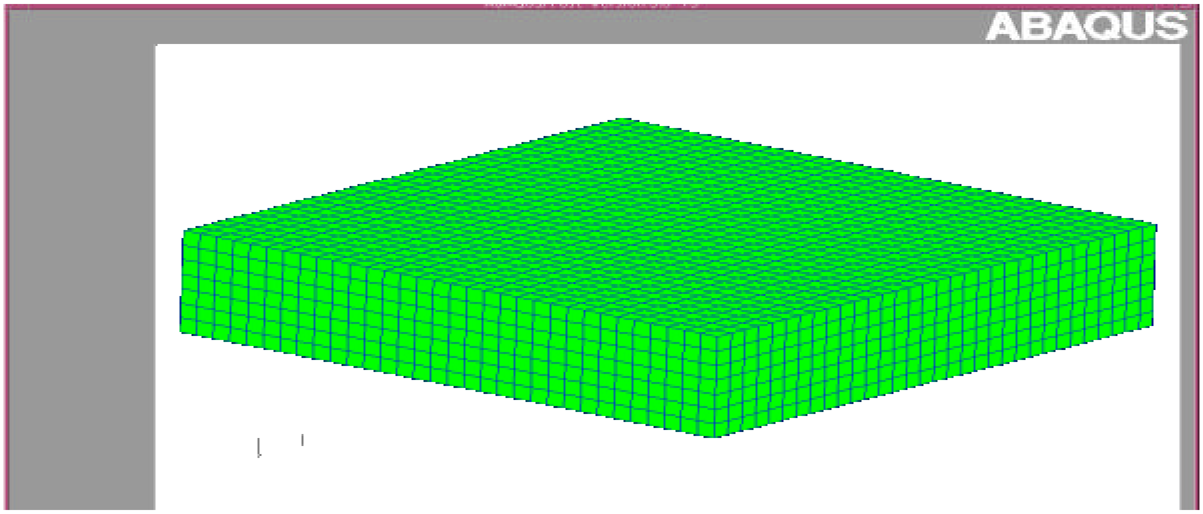


Figure 4. Finite element model of plain square bearing.

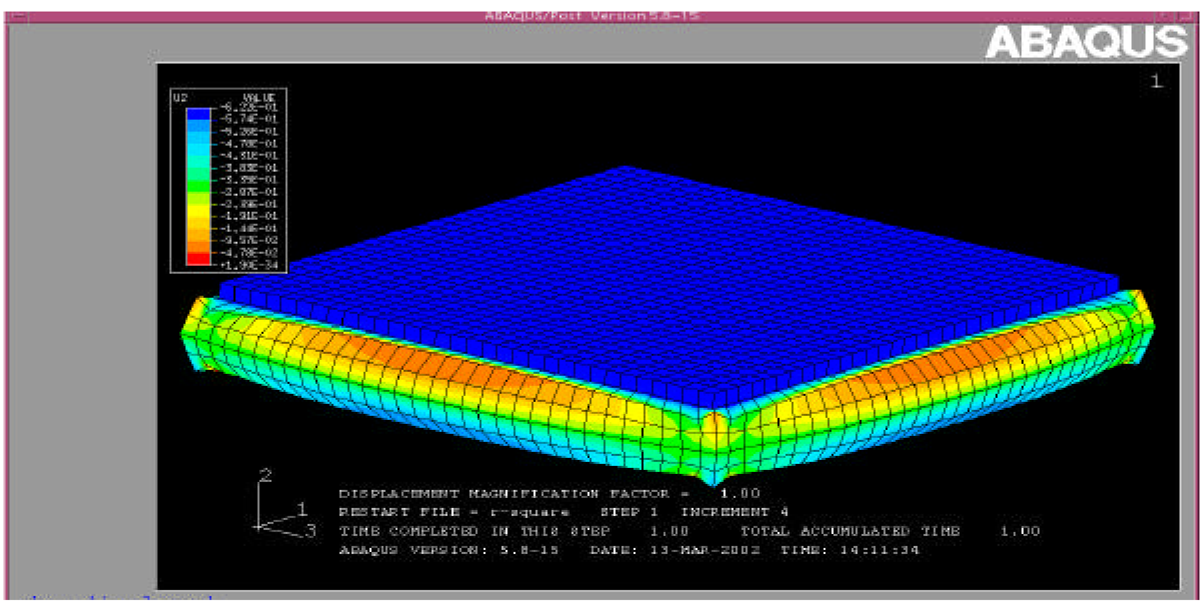


Figure 5. Displacements in the square bearing.

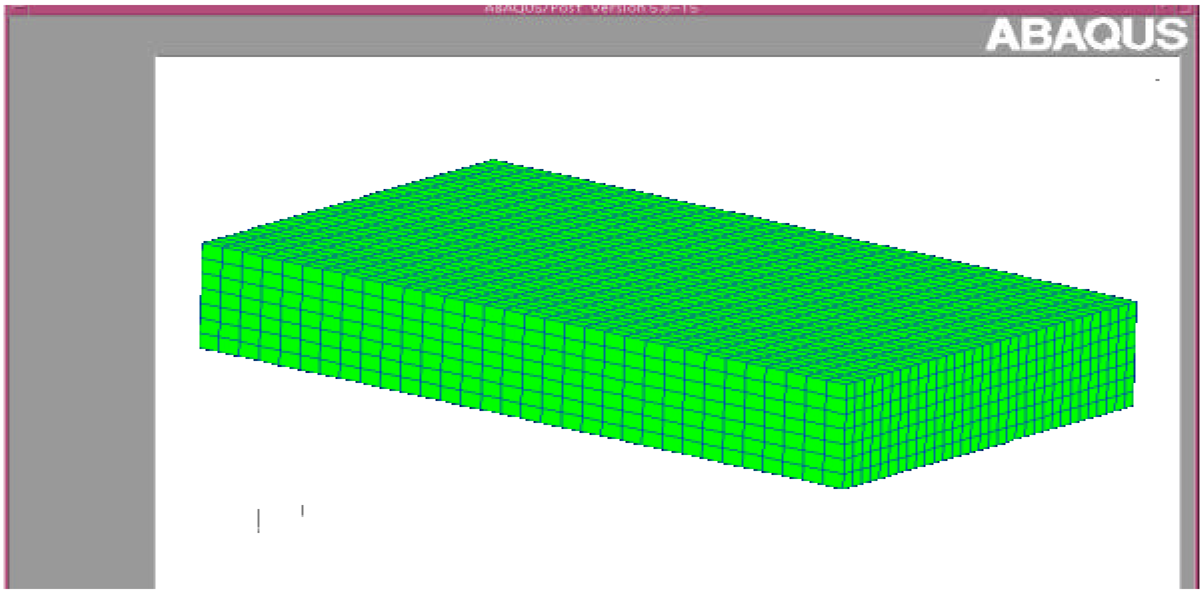


Figure 6. Finite element model of the rectangular bearing.

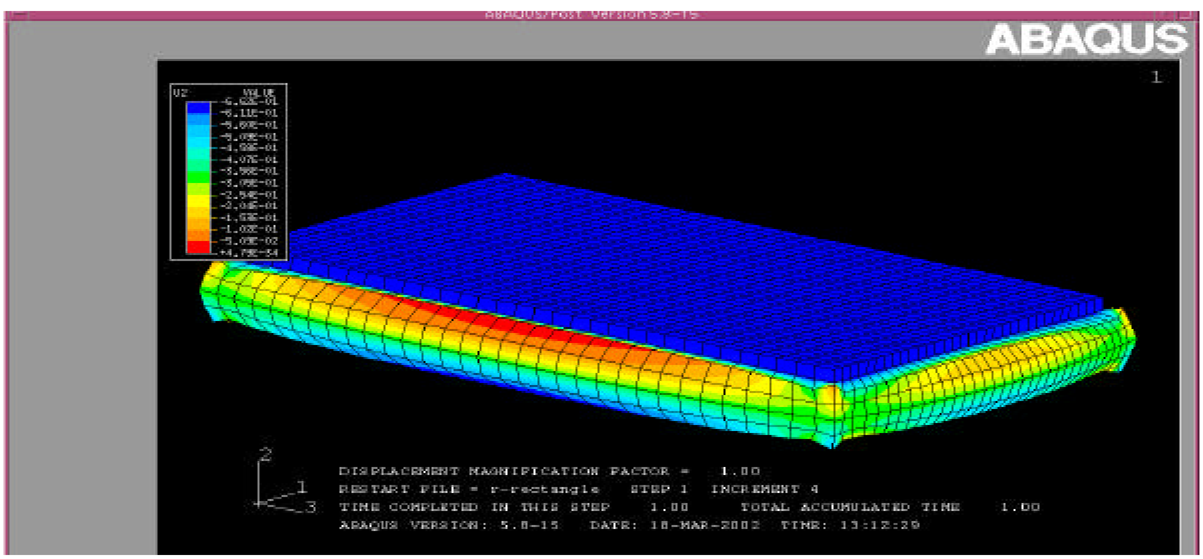


Figure 7. Displacements in the rectangular bearing.

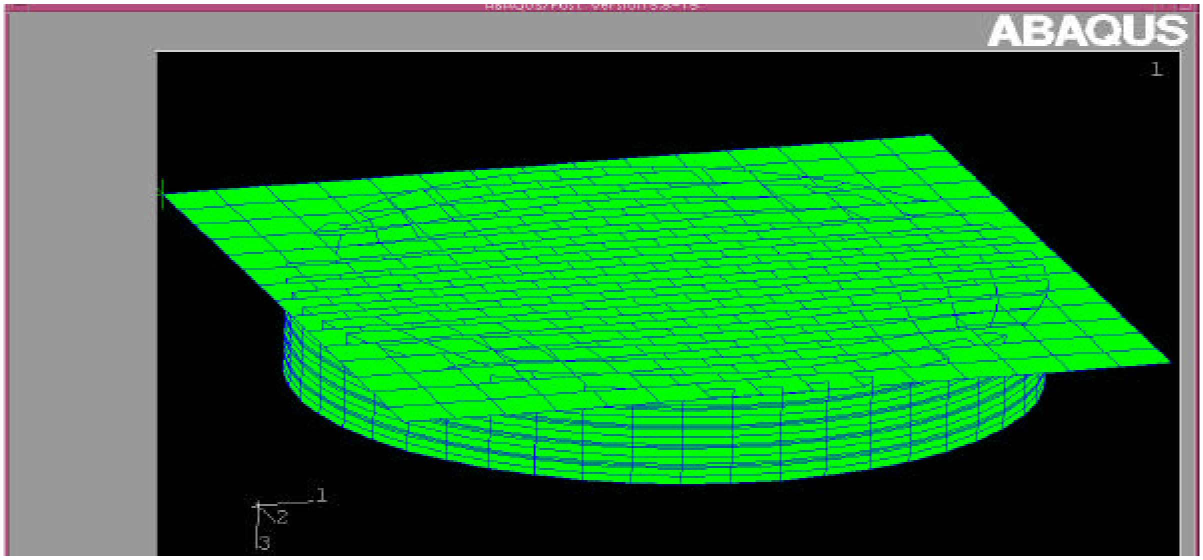


Figure 8. Finite element model of the circular bearing.

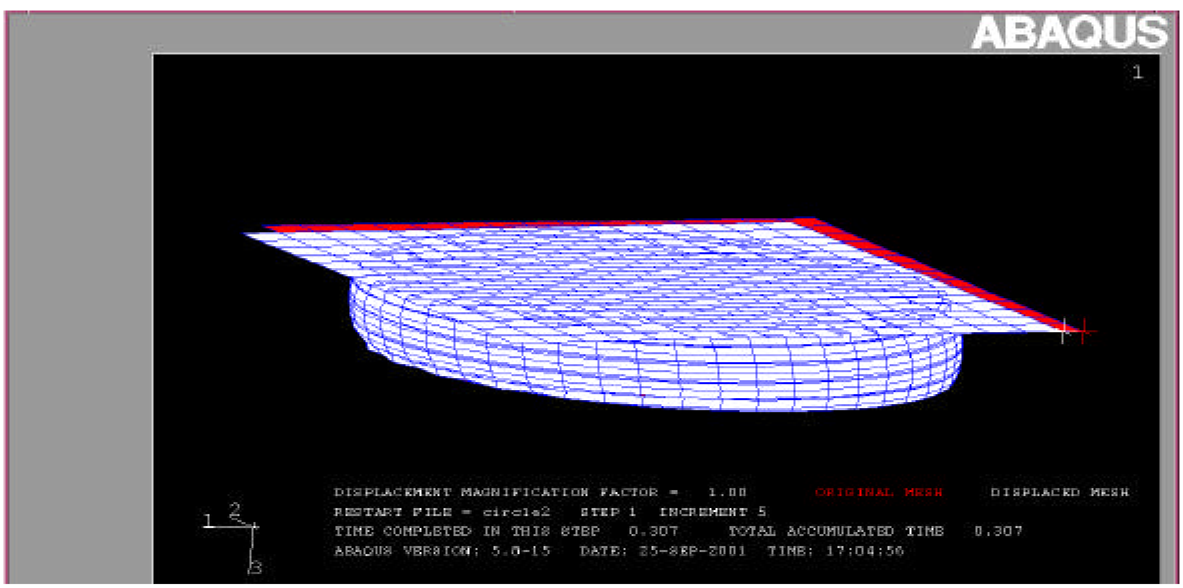


Figure 9. Deformed shape of circular bearing.

BEHAVIOR OF LAMINATED BEARINGS UNDER COMPRESSION

In bridge bearings, laminates such as steel or fiber reinforced composite plates are provided in order to make the plain elastomeric bearing stiffer. There are two factors for this increase in stiffness:

1. When a laminate with a higher translational stiffness than the elastomer is introduced within a bearing, it replaces a hypothetical layer of elastomer with a lower translational stiffness, which increases the overall stiffness of the bearing.
2. When a plain elastomeric bearing is compressed, it bulges. When laminates are introduced to the bearing, available surface to bulge is reduced and the remaining surfaces that are free to bulge are confined. This confining effect is caused by the tensional stresses induced in the laminates.

The following is a brief discussion of these factors:

Assume that a plain elastomer bearing is sliced into three hypothetical layers. Each of these layers has a translation stiffness of K_e. Total stiffness of the plain elastomeric bearing K_T can be represented in the form:

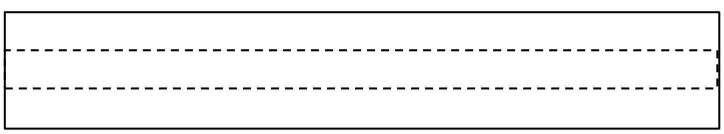


Figure 10. Representation of plain elastomeric bearing.

$$\frac{1}{K_T} = \frac{1}{K_{e1}} + \frac{1}{K_{e2}} + \frac{1}{K_{e3}} \Rightarrow K_T = \frac{K_{e1}.K_{e2}.K_{e3}}{K_{e2}K_{e3} + K_{e1}K_{e3} + K_{e1}K_{e2}} \qquad (5)$$

Now lets assume that one of these layers is replaced by another layer such as steel or fiberglass, which has a larger stiffness than the elastomer layer denoted by K_S

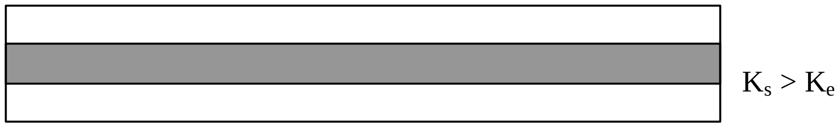


Figure 11. Representation of layered elastomeric bearing.

The total stiffness of the laminated elastomeric bearing K_P can be represented in the form:

$$\frac{1}{K_L} = \frac{1}{K_{e1}} + \frac{1}{K_S} + \frac{1}{K_{e2}} \Rightarrow K_L = \frac{K_{e1}.K_S.K_{e2}}{K_S K_{e2} + K_{e1}K_{e2} + K_{e1}K_S} \qquad (6)$$

If these two equations are compared, it seen observed that in the second equation, the rate of increase in the numerator is higher than the rate of increase in the denominator. Therefore the total stiffness of the laminated bearing K_L is higher than the total stiffness of the plain bearing K_T

On the other hand, when a plain elastomeric bearing is held under compression, the free exterior surfaces bulge and the cross section of the deformed shape takes the form in figure.

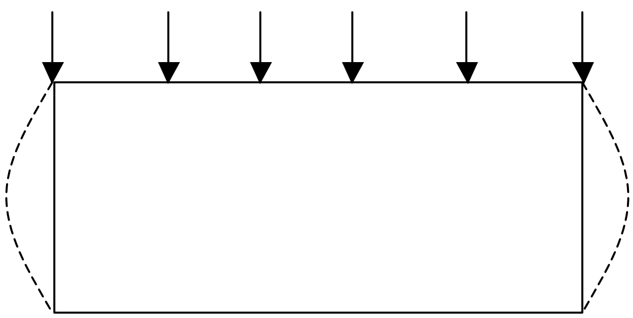


Figure 12. Representation of plain elastomeric bearing deformation.

Here it is assumed that the top and the bottom surfaces are rigidly supported, such that no movement is allowed on these surfaces.

The deformed shape of a laminated bearing is shown in Figure 13.

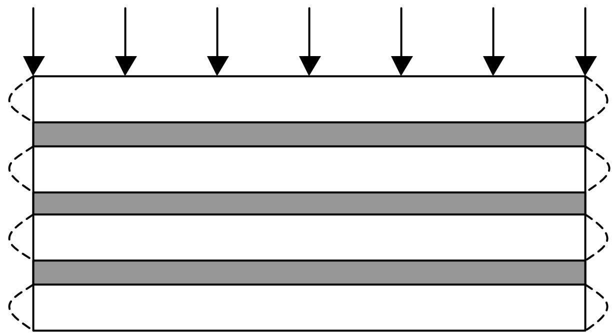


Figure 13. Representation of layered elastomeric bearing deformation.

Since the laminates are bonded to the elastomer layers above and below, they provide confinement. As the free elastomer layer surfaces tend to bulge under compression, they are confined by the friction between the laminate and the elastomer interface, which in return causes tension within the laminates.

Variation of Local Stiffness Within The Elastomer

Another important property that must be discussed is the stiffness distribution within the elastomeric material. Stiffness of a material depends on the confinement of the material as well as the properties of the material. Inside a layer of elastomer the interior regions are more confined than the outer regions, which in return causes the stiffness to be higher at the interior regions. On the other hand, another factor that effects this spatial stiffness variance is the material property of the elastomer. Elastomers are incompressible materials such that the volume of the elastomer remains constant under any type of loading. Unlike other materials such as metals, this fluid like behavior prevents the elastomer from deforming by loosing it’s volume. The elastomer reacts to the loading by deforming and thereby dissipating the energy that has been induced on it. This dissipation of energy also relieves the stresses that have been induced. However, when the ability to deform is prevented by confinement, the stresses build up within the elastomer. Since elastomers are incompressible materials, by preventing the elastomer from deforming, the only means of dissipating energy has also been prevented. Therefore, as the degree of the confinement increases, the local stiffness is also increased.

The models that were generated were loaded such that the loads were transmitted to the elastomer through a rigid plate that was rigidly attached to the bearing. The physical outcome of this procedure is that all the points along a bearing surface are forced to move the same amount. Since the interior regions within an elastomer are stiffer than the exterior regions, the stresses that are developed are also higher at interior locations.

Laminated square bearing

Figures 14, 15, and 16 show bearing model, vertical deformations, and stress distribution in a typical layer in a steel reinforced square bearing. The plots in these figures show that 1) the radial rate of change of stiffness is not equal within a square bearing, and 2) local stiffness depends on the local degree of confinement, with the highest stiffness at the center and lower stiffness near the edges and the lowest stiffness at the corners. It is seen that there is a tendency towards circular distribution of the stress, however because of the geometry of the bearing, stress distribution near the edges become discontinuous.

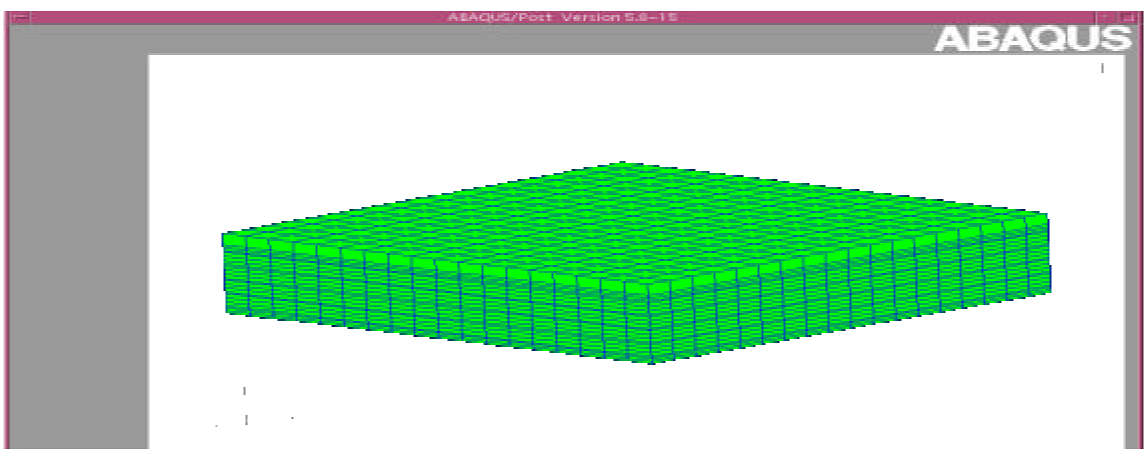


Figure 14. Finite element model of laminated square bearing.

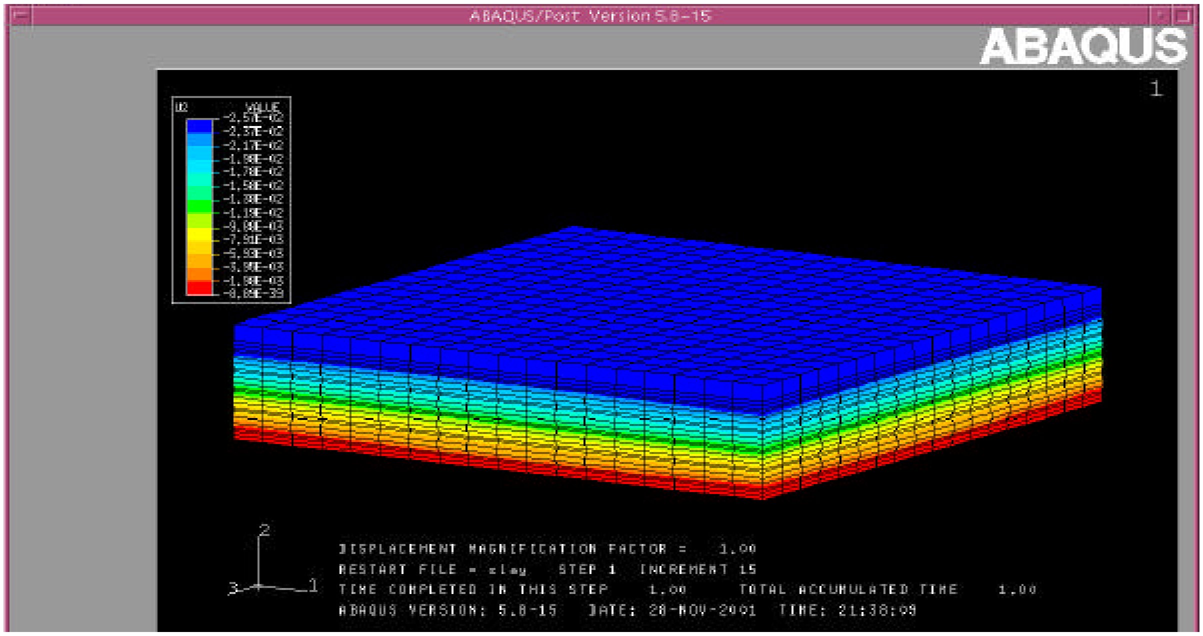


Figure 15. Displacements in laminated square bearing.

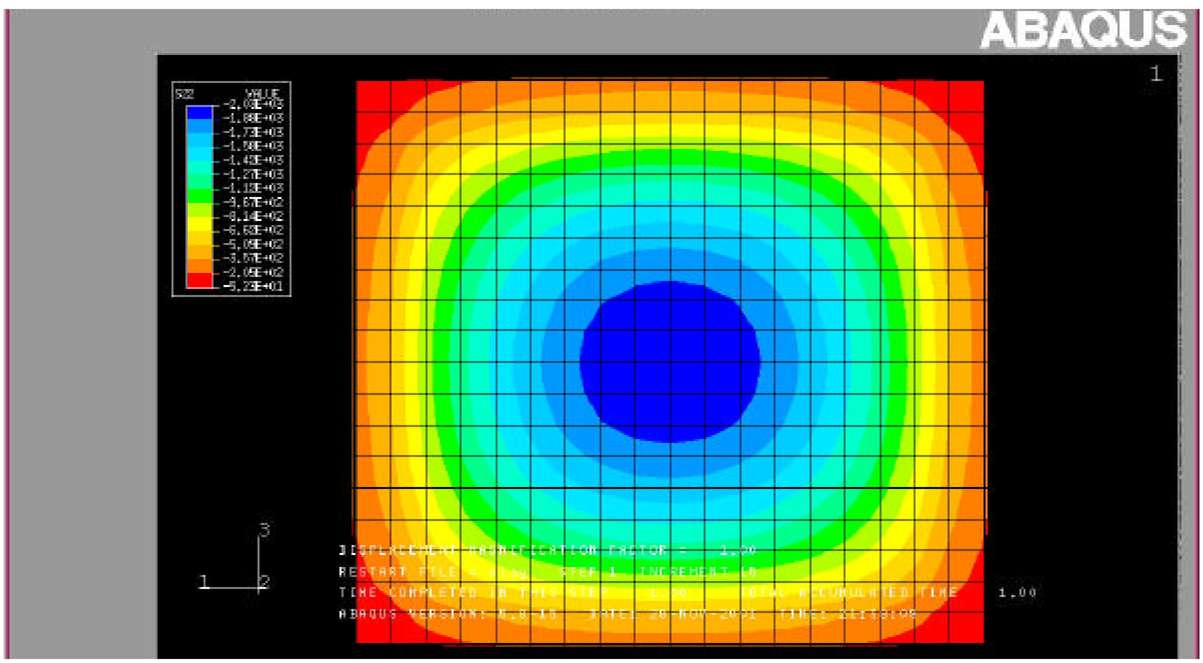


Figure 16. Stress distribution within a typical elastomer layer.

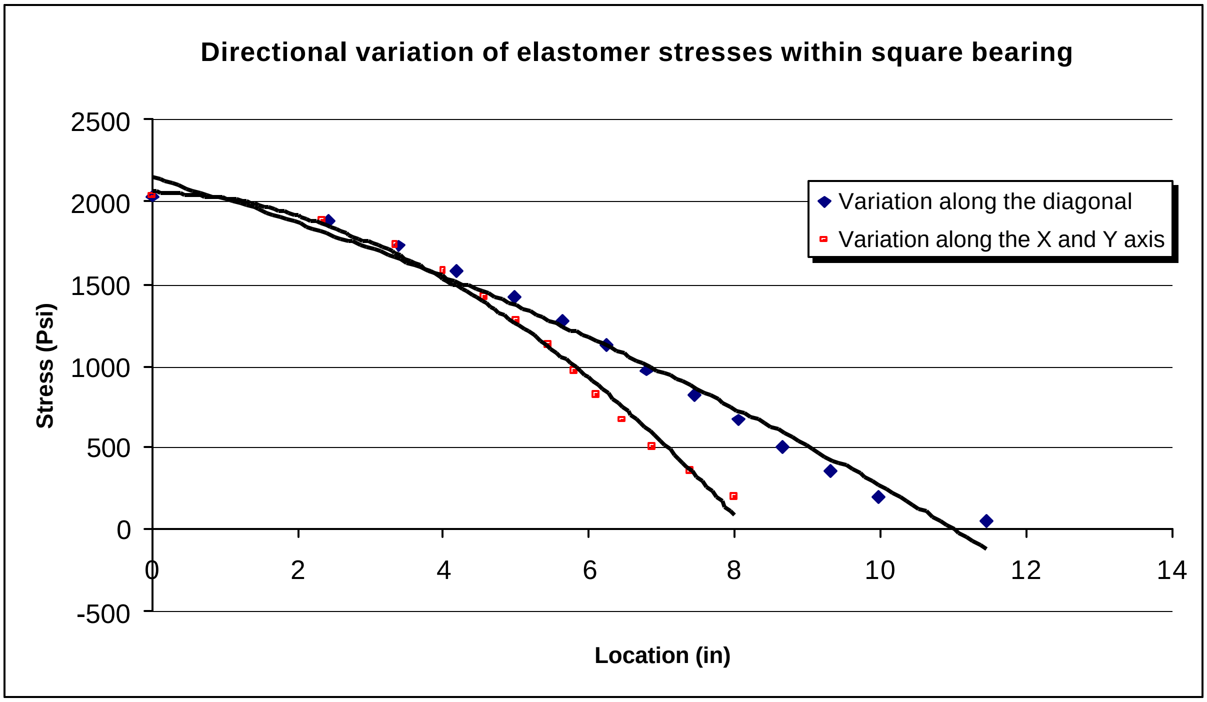


Figure 17. Directional variation of elastomer stresses within the square bearing.

Figure 17 shows the difference in stresses at a certain radial distance from the center of the bearing. This change in stress distribution is an indication of the radial rate of change of stiffness within the bearing. Since the material is not stressed the same amount, this change of radial stiffness may create delamination problems.

Stresses within the laminates in square bearing

Under compression, tension stresses are induced within the laminates in order to prevent bulging. Figures 18 and 19 show tensile stress distribution within the steel laminates along the horizontal and vertical axis. From these figures it is observed that, since the bulging at the midpoints of the edges are the highest, the tensile stresses, which are dir related to displacements are also higher.

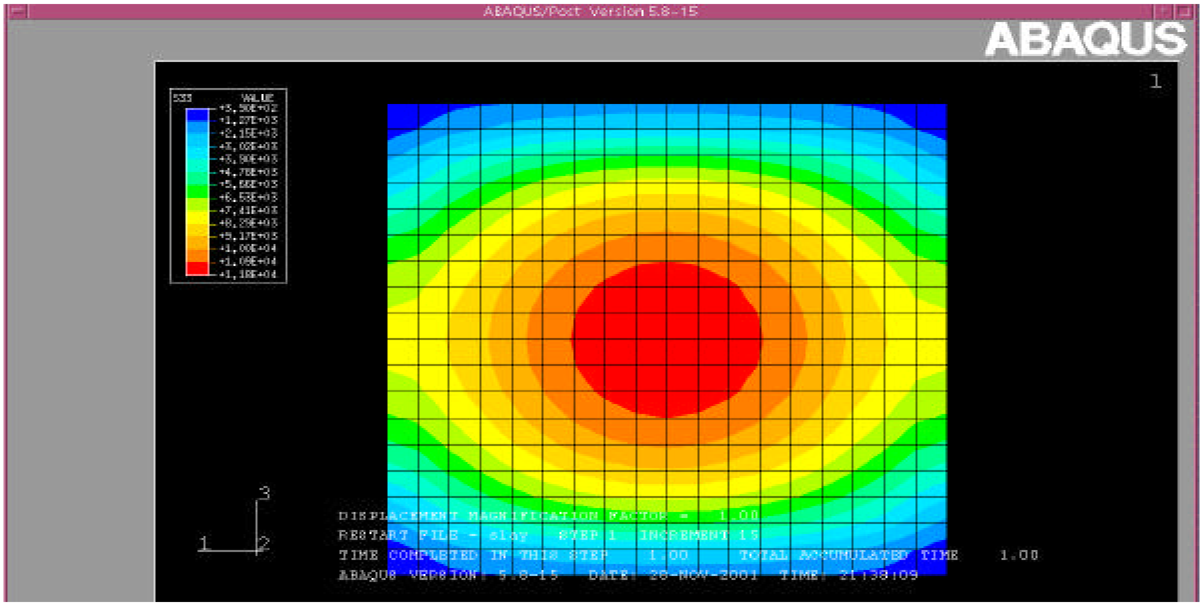


Figure 18. Tension along the horizontal axis.

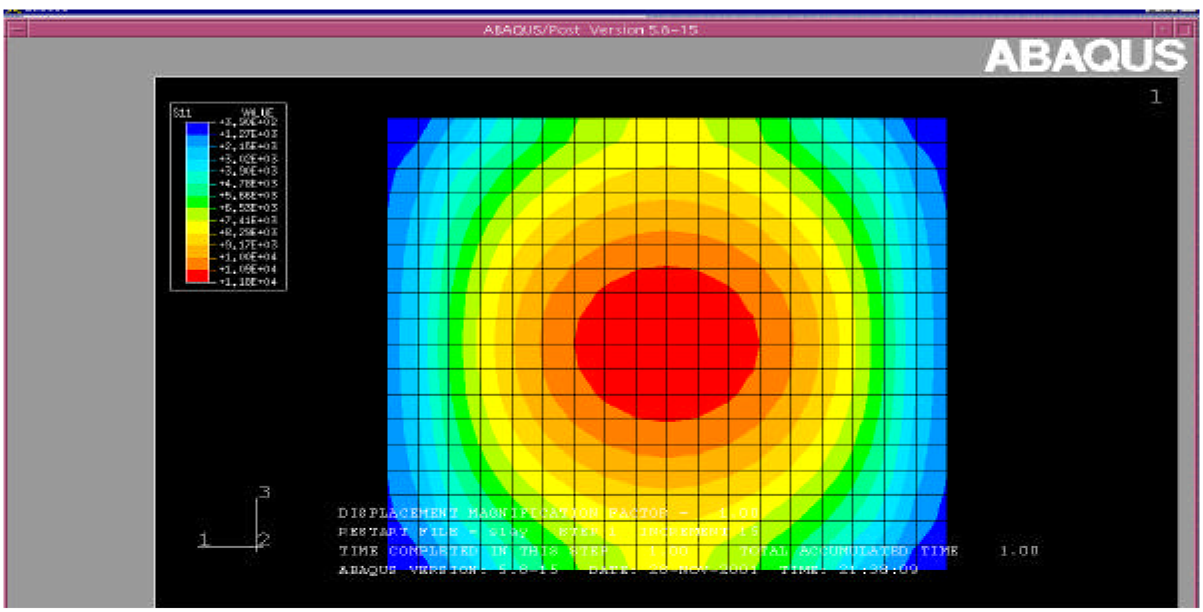


Figure 19. Tension along the vertical axis.

Laminated rectangular bearing

The deformations and stress distribution in a rectangular bearing are shown in Figures 21 and 22 respectively. Compared to the displacement values for the square bearing shown in Figure 15, the deflections of rectangular bearings in Figure 21 are approximately 14% higher. The increase in the vertical deflection in a rectangular bearing is due to a lower shape factor than the square bearing which lead to a lower bearing stiffness. Shape factor is a measure of the ability of the bearing to deform. In layered elastomeric bearings, the ability deform is proportional to the amount of free-to-bulge surface area which is provided by the free surfaces of the intermediate elastomer layers. As this free-to-bulge surface area gets higher, the bearing becomes less stiff and more deformable. Note that the radial rate of change of stiffness is also not constant due to rectangular shape of the bearing (Figure 22). Figures 22 and 23 show the stresses and the directional stress profile within elastomer layer. Figure 23 shows that the rate of change of radial stiffness is not the same along 3 directions, which may create delamination problems.

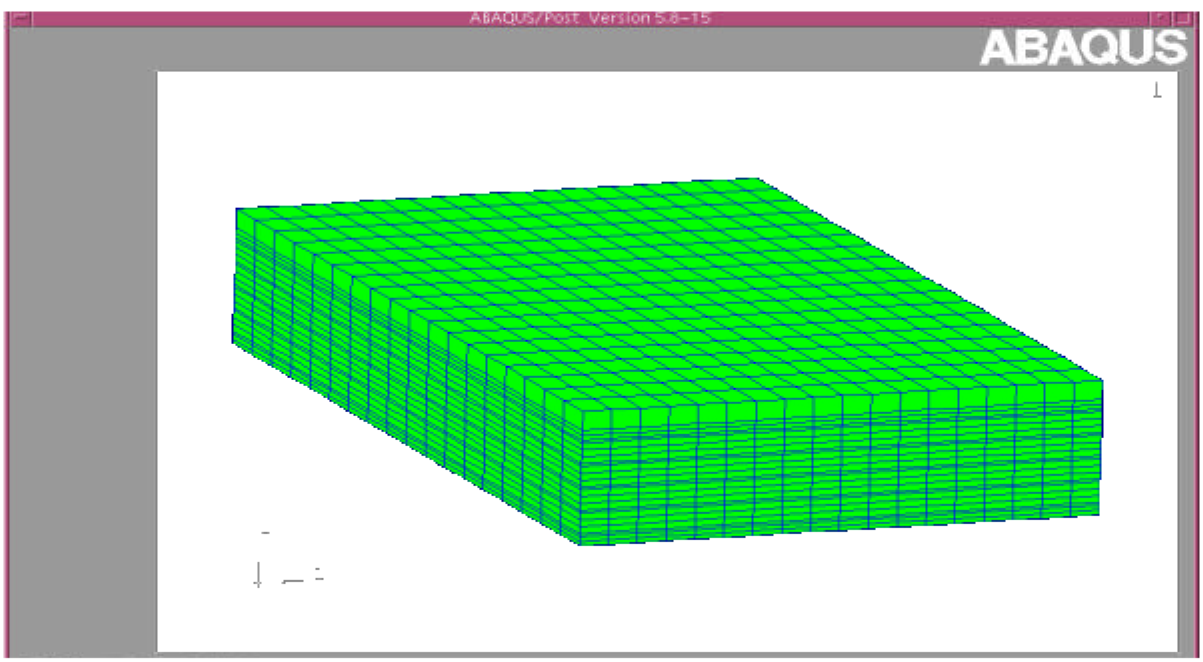


Figure 20. Finite element model of rectangular bearing.

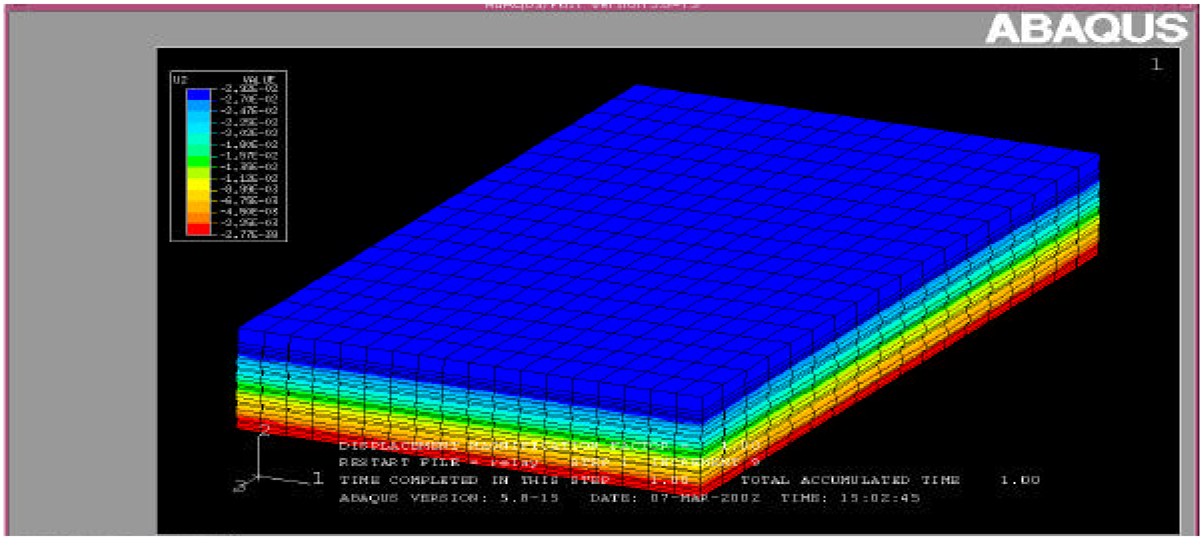


Figure 21. Displacement in rectangular bearing.

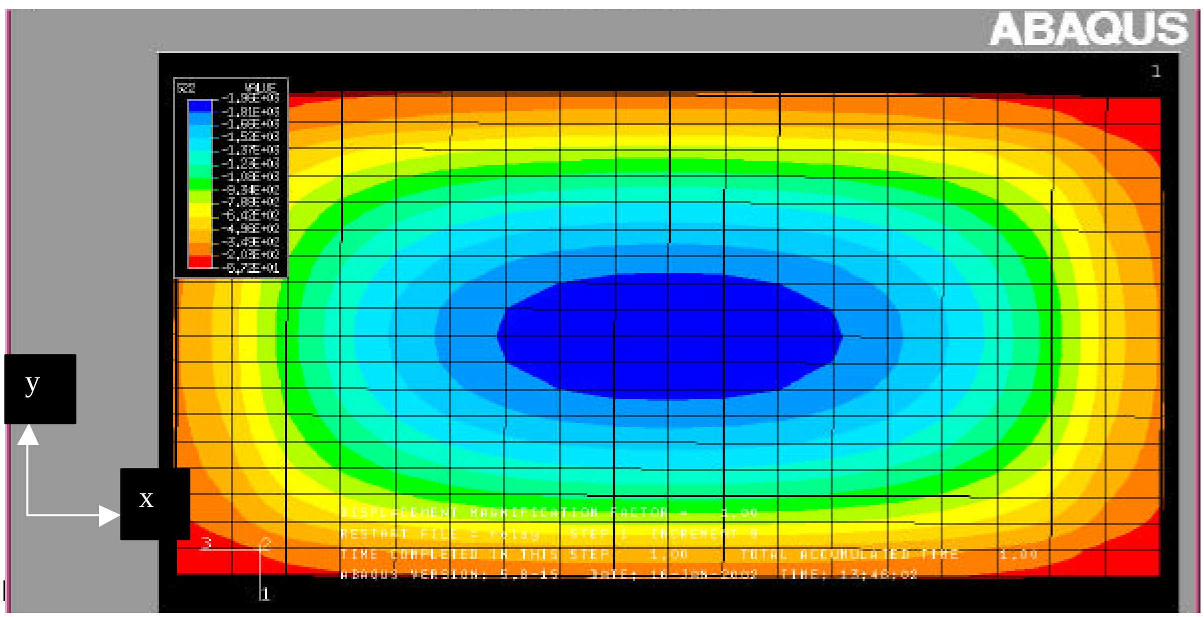


Figure 22. Stress distribution in a typical elastomer layer.

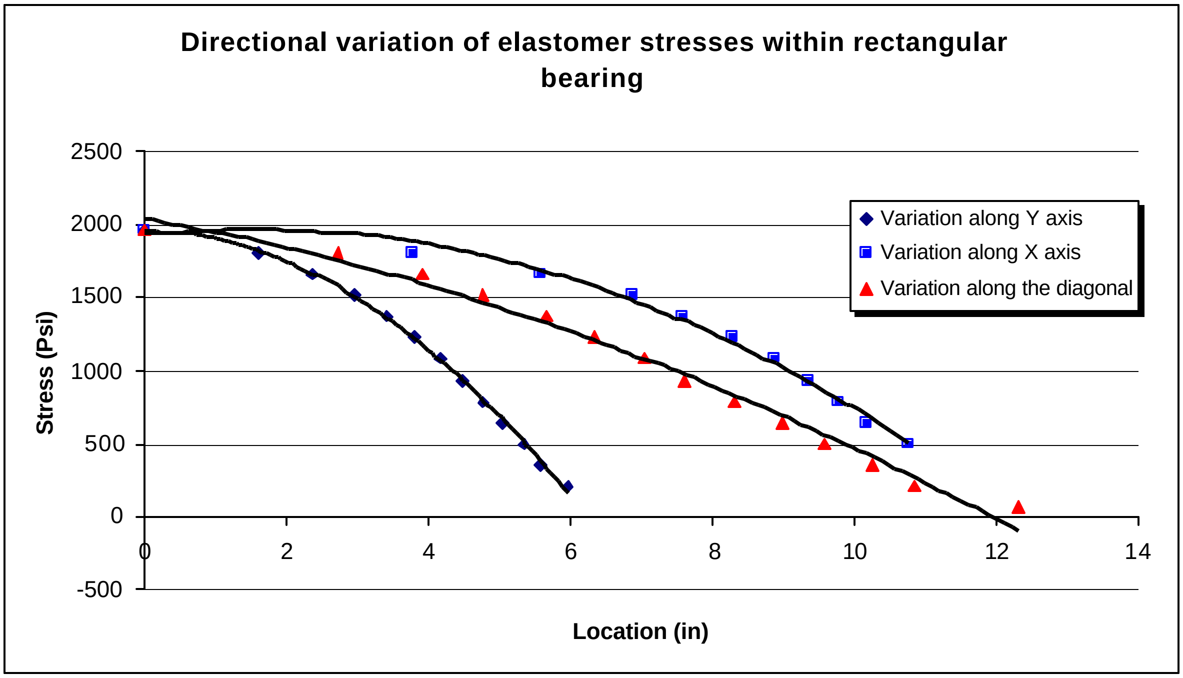


Figure 23. Directional variation of elastomer stresses within the rectangular bearing.

Stresses in laminates in rectangular bearing

Since the free to bulge surface is higher at the longer sides than the shorter sides, the amount of bulging is also higher at longer sides. Since the amount of bulging is higher, the tensile stresses are also higher as seen from the stress contours of the steel laminates in Figures 24 and 25.

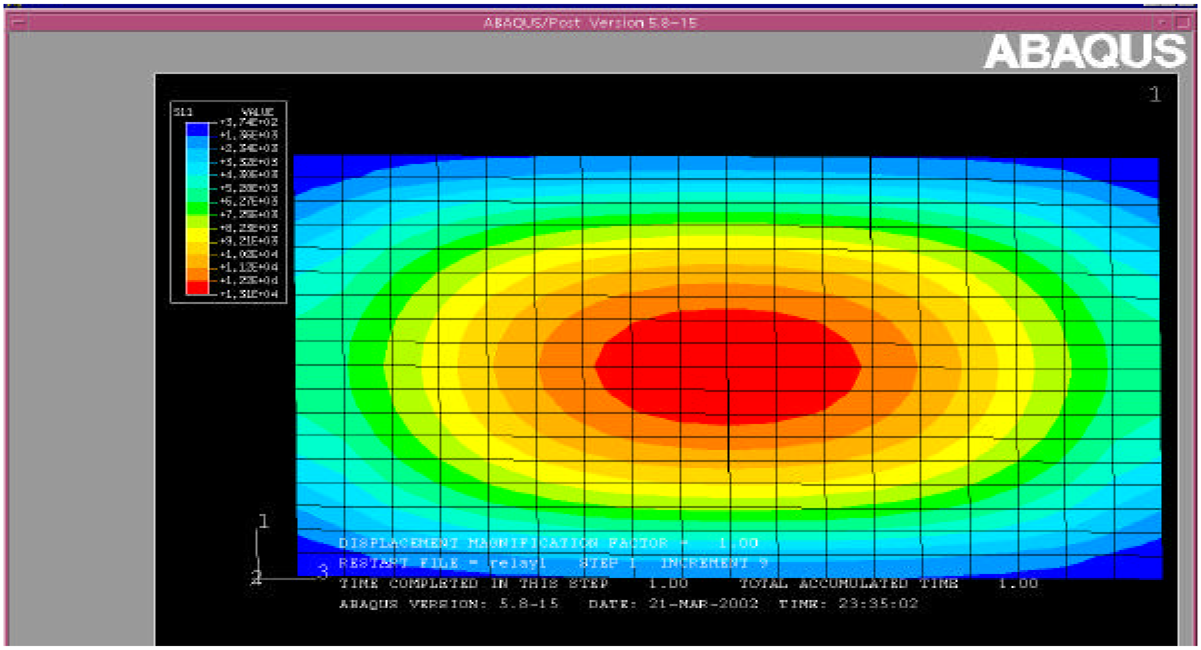


Figure 24. Tension along horizontal axis.

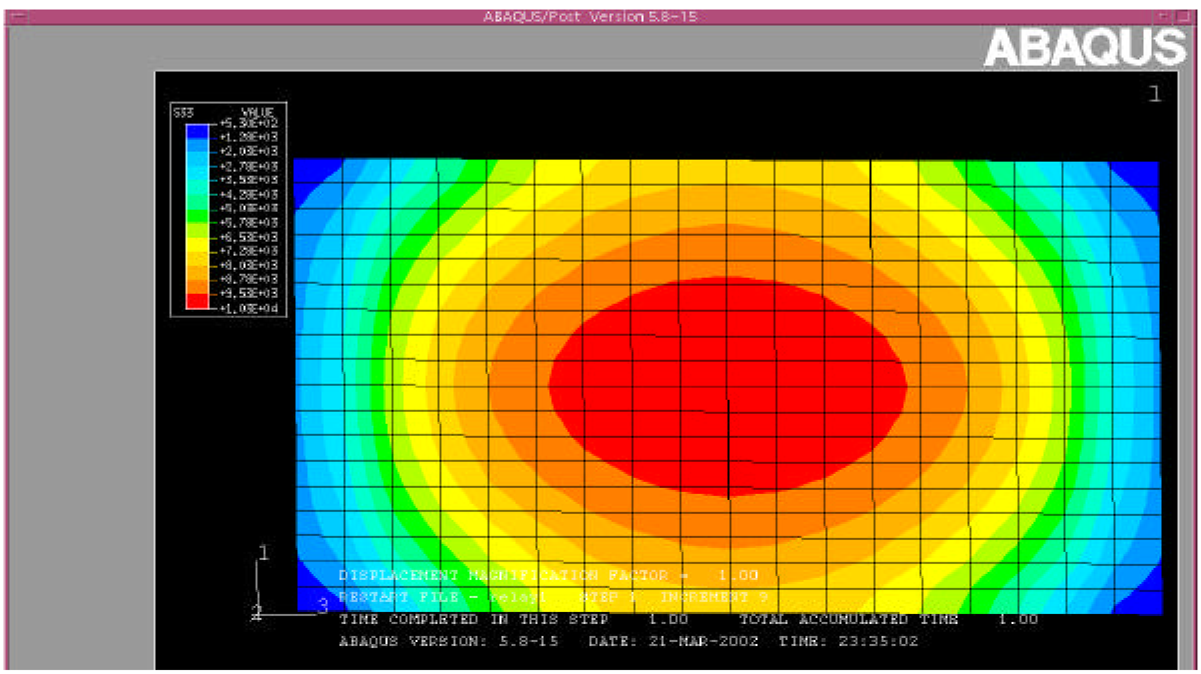


Figure 25 . Tension along vertical axis.

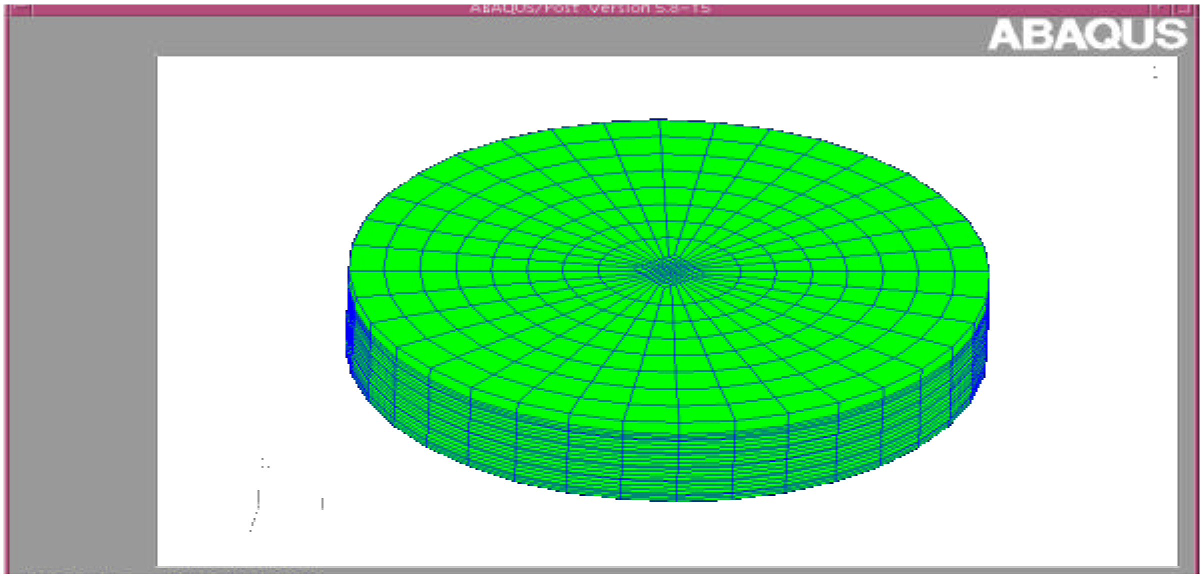


Figure 26. Finite element model of circular bearing.

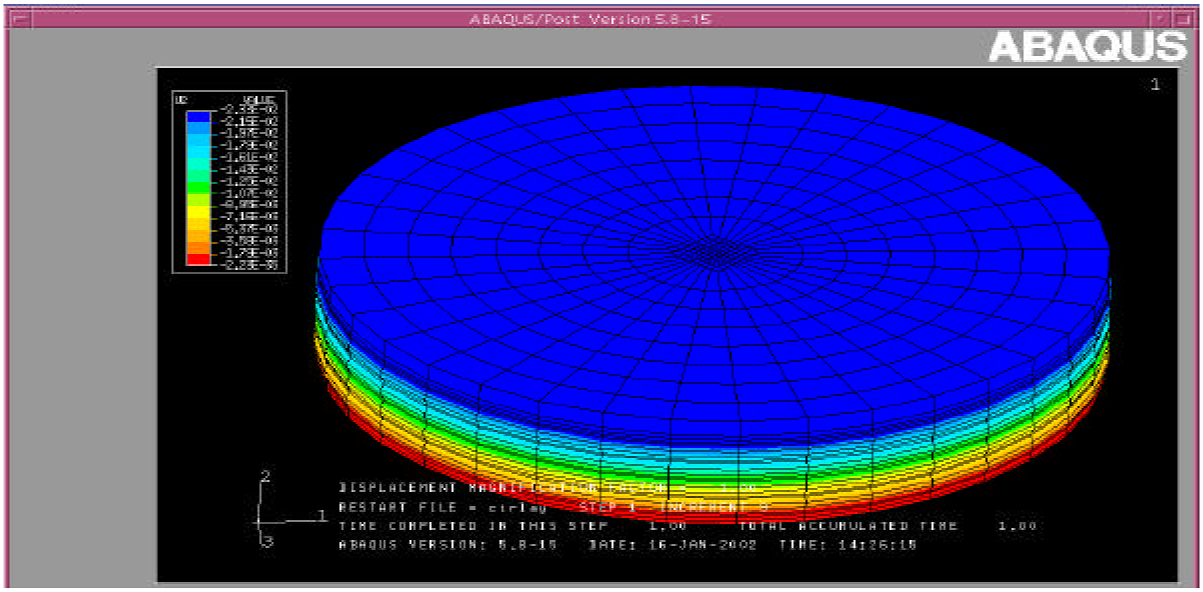


Figure 27. Displacement in circular bearing.

Laminated circular bearing

Note that the total vertical deflection in the circular bearing is approximately 10% lower than the vertical deflection in square bearing. The decrease in the vertical deflection in a circular bearing is due to a higher shape factor than the square bearing.

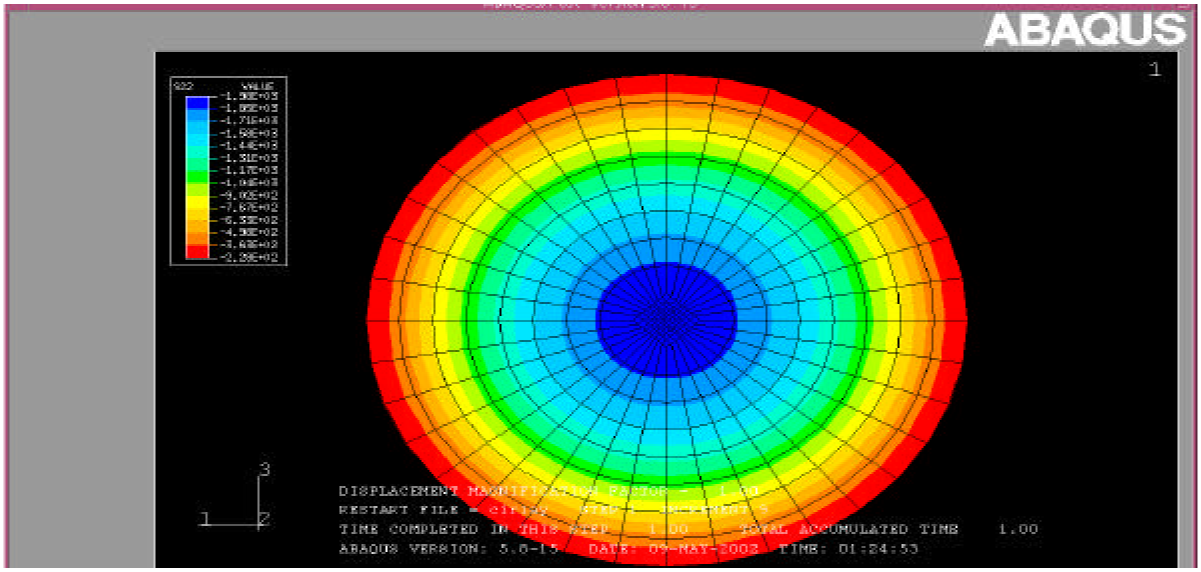


Figure 28 . Stress distribution in a typical elastomer layer.

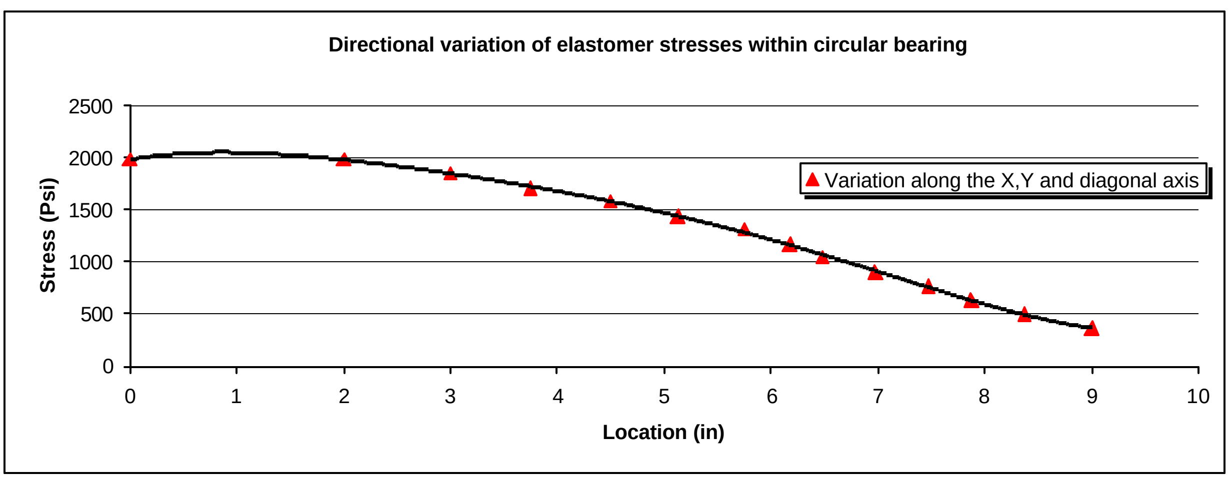


Figure 29. Directional variation of elastomer stresses within circular bearing

From Figure 28 and Figure 29 it seen that unlike square and rectangular bearings, the geometry of the bearing enable the equivalent radial stress distribution within the bearing, and the radial rate of change of stiffness is the same in all directions. The stress contours are homogeneously distributed along the bearing.

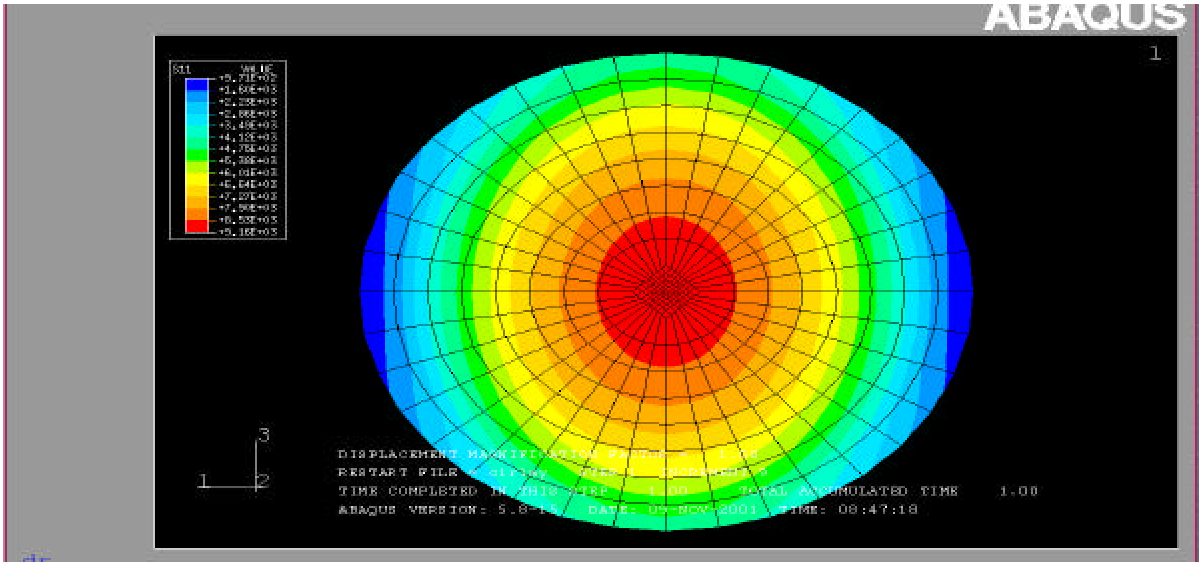


Figure 30. Tension along the vertical axis.

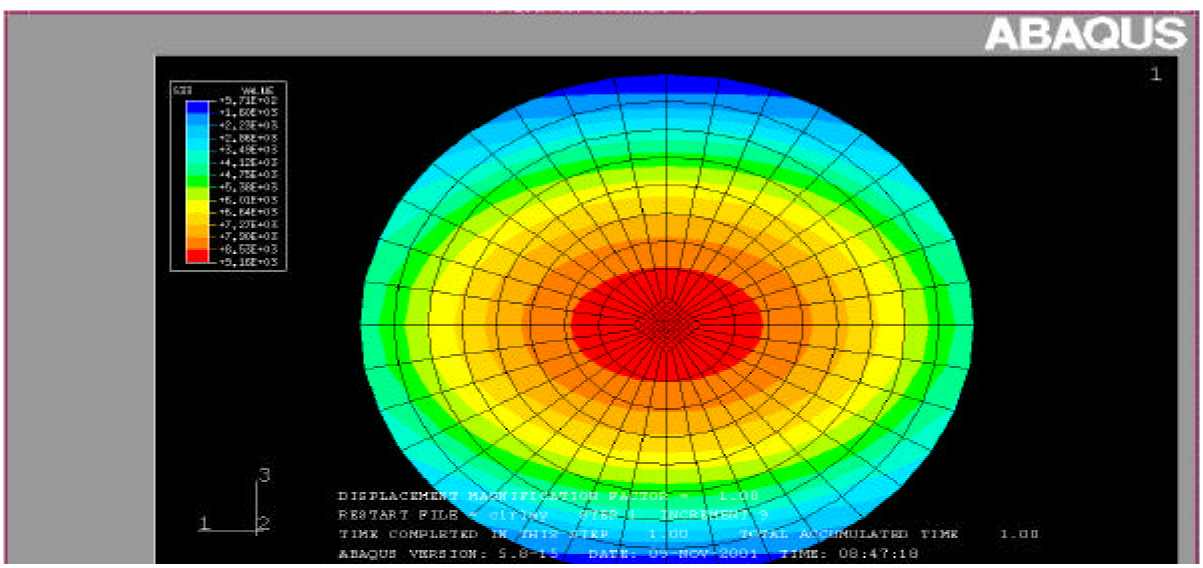


Figure 31. Tension along the horizontal axis.

Stresses in Laminated Elastomeric Bearings

From Figures 30 and 31 it is seen that there are no directional variances regarding the tensile stresses, meaning that the plate is tensioned equally in all directions. However, in square and rectangular bearings, the stress distribution is not equal. Also note that the value of the tensile stresses is also lower than the stresses in the square and rectangular bearings. Since the surface are that is free to bulge is lower (higher shape factor) than either square of rectangular bearings, the amount of bulging is lower, which in return causes lower tensile stresses. In square bearings, the diagonal stress distribution is less than the stress distribution along primary axis, due to the fact that bulging occurs along the primary axis. In the rectangular bearing, the laminate is tensioned the highest amount along the vertical axis, due to the fact that bulging occurs the most along the longer sides of the bearing. Since the bulging along the shorter sides is relatively lower, the horizontal stresses are also lower. However, the laminate in the circular bearing is tensioned equally, meaning that due to it's circular shape the laminate material is better made use of.

BEHAVIOR OF BEARINGS UNDER COMPRESSION

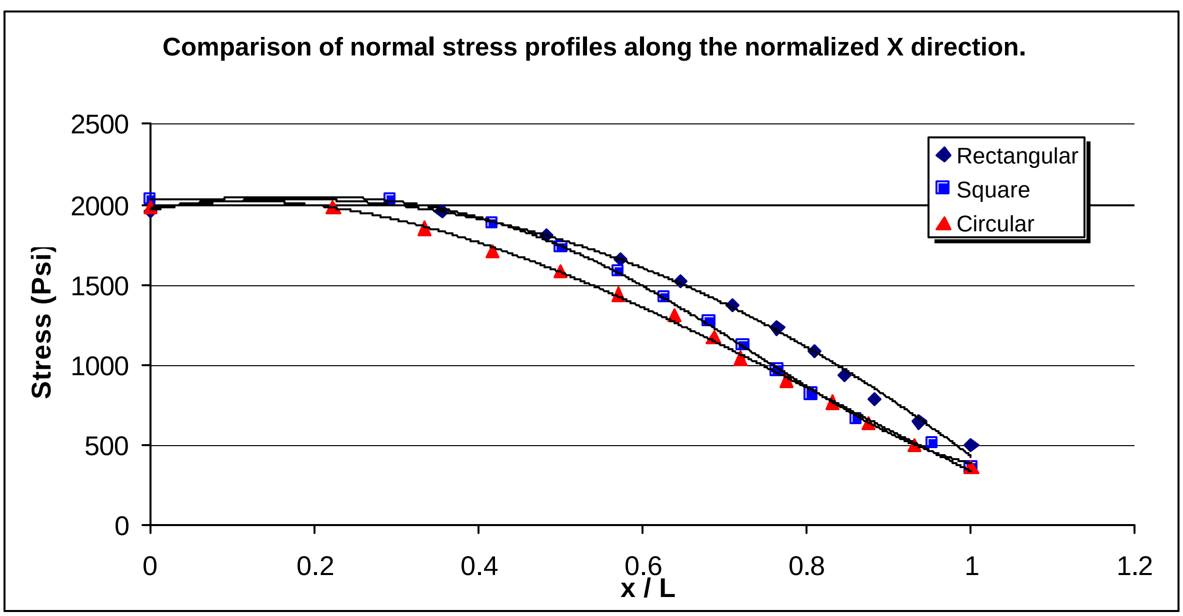


Figure 32. Comparison of normal stress profiles along the normalized X direction.

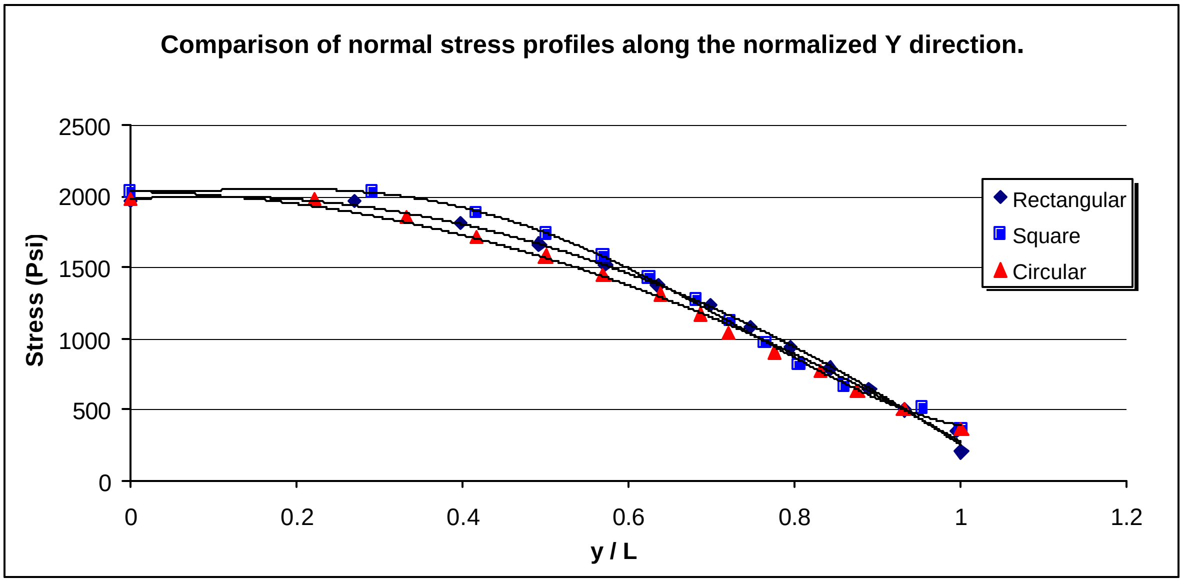


Figure 33. Comparison of normal stress profiles along the normalized Y direction.

Figures 32 and 33 are proportional representations of the behavior of the bearings under the same loading conditions. In these graphs, the locations along X and Y axis of the bearings are normalized with respect to the total length (L) along the corresponding axis. It is observed that, the stress values within the circular bearing at proportional distances are less than the square and the rectangular bearings.

BEARINGS SUBJECTED TO COMPRESSION AND SHEAR

In order to analyze the effect of the lateral loads on bearings, which are subjected to vertical loads, the bearings have been simultaneously subjected to a distributed load of 1000 psi and a lateral load that equals to 20 percent of the total vertical load.
The lateral loads have been applied along the diagonal for the square and rectangular bearings in order to take into consideration the effect of skew and multi-directional movements.

Table 5. Combined data for compression and shear.

	Square	Rectangular	Circular
Distributed load (psi)	1000	1000	1000
Surface area (in^2)	256	258	254.5
Total vertical load (lb)	256000	258000	254500
Lateral load (20% of vertical) (lb)	51200	51600	50900
Maximum deflection (x-axis) (in)	1.86	1.29	1.86
Maximum deflection (y-axis) (in)	1.86	2.3	1.86
Total deflection along the diagonal (in)	2.63	2.64	2.63

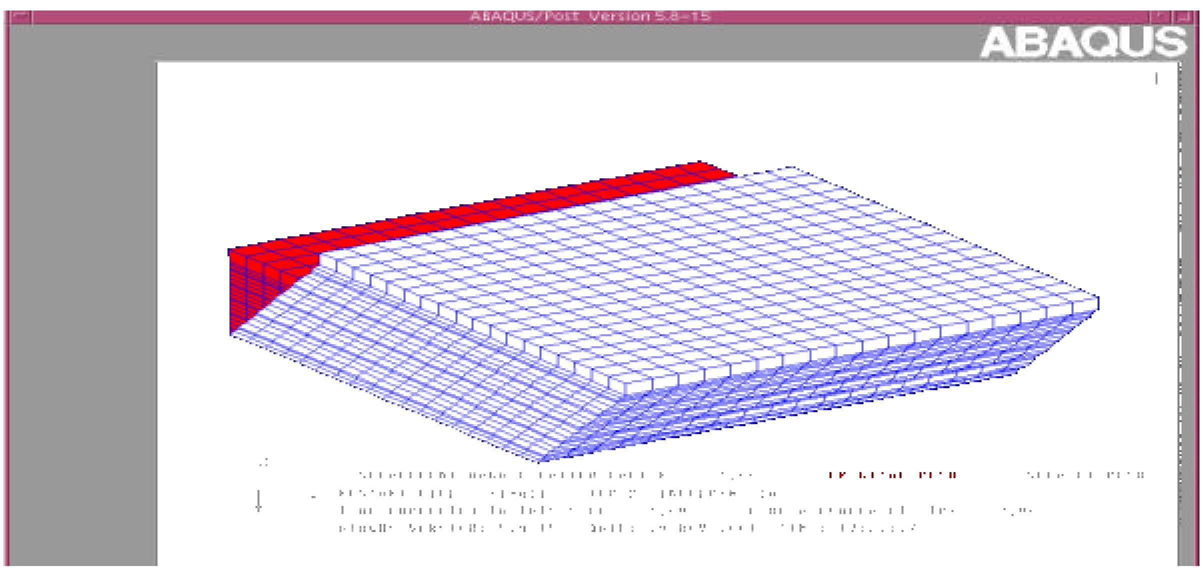


Figure 34. Displaced shape of the square bearing.

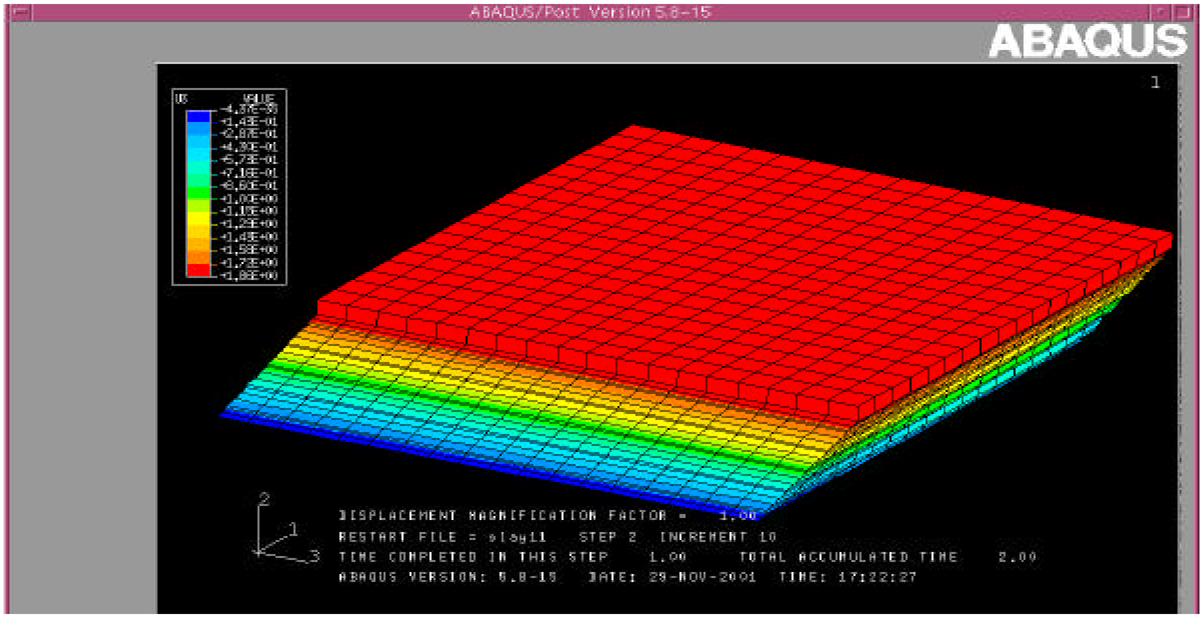


Figure 35. Displacements in the square bearing.

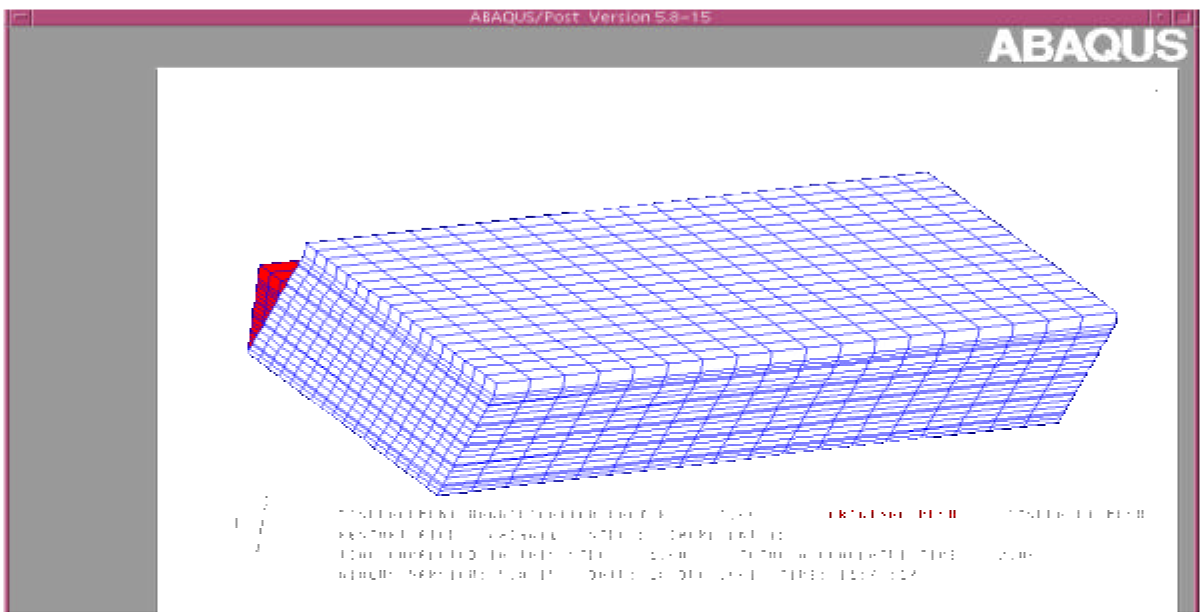


Figure 36. Displaced shape of the rectangular bearing.

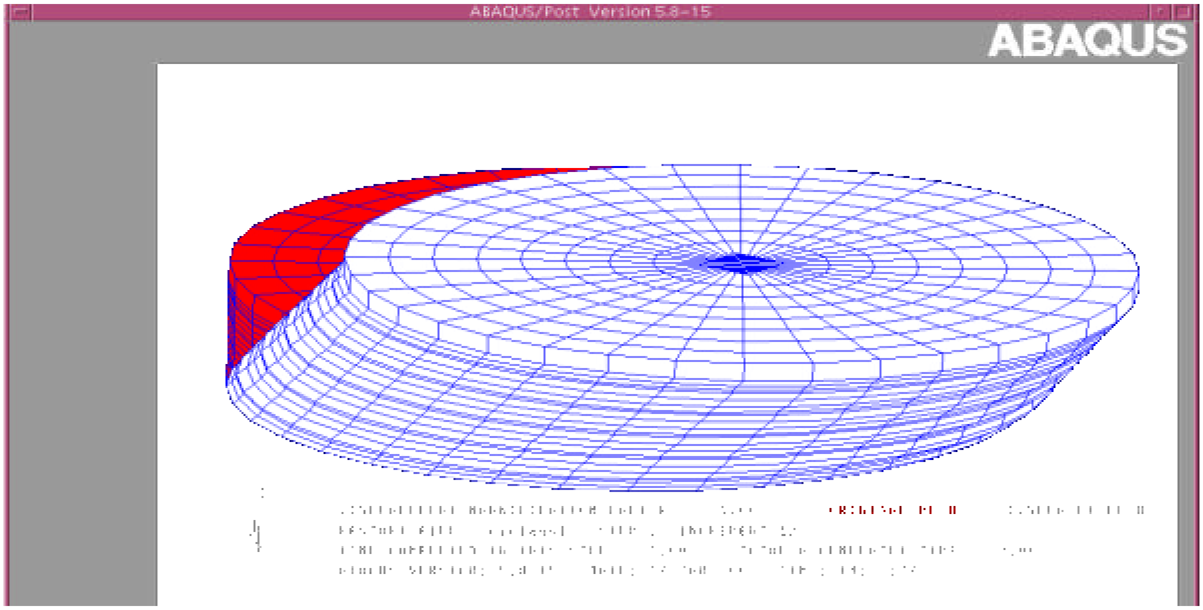


Figure 37. Displaced shape of the circular bearing.

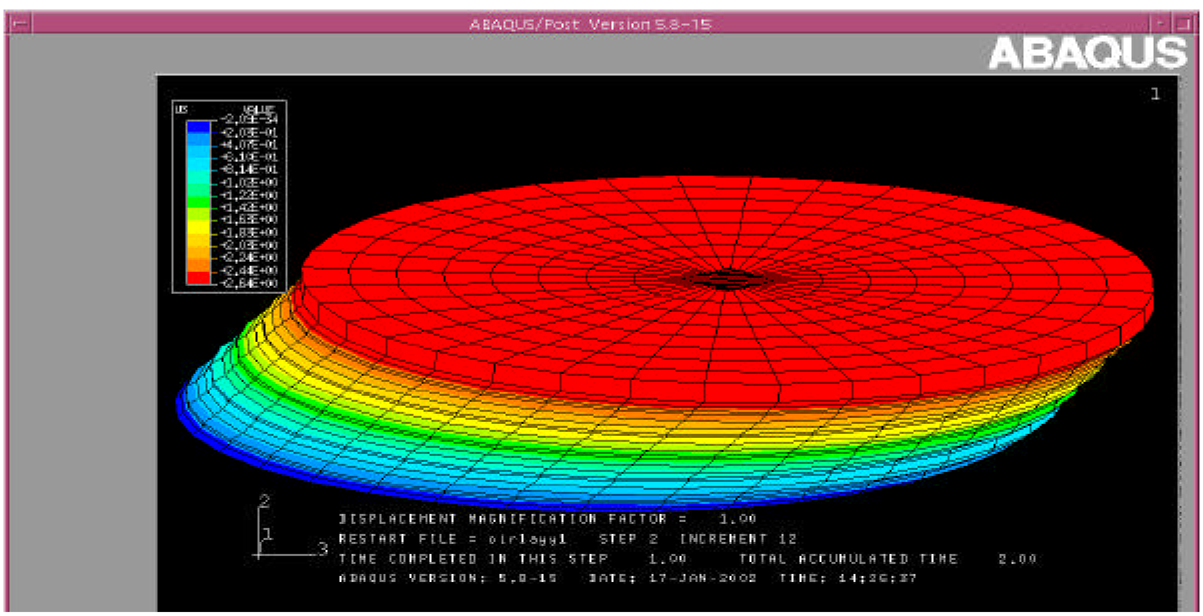


Figure 38. Displacements in circular bearing under compression and shear.

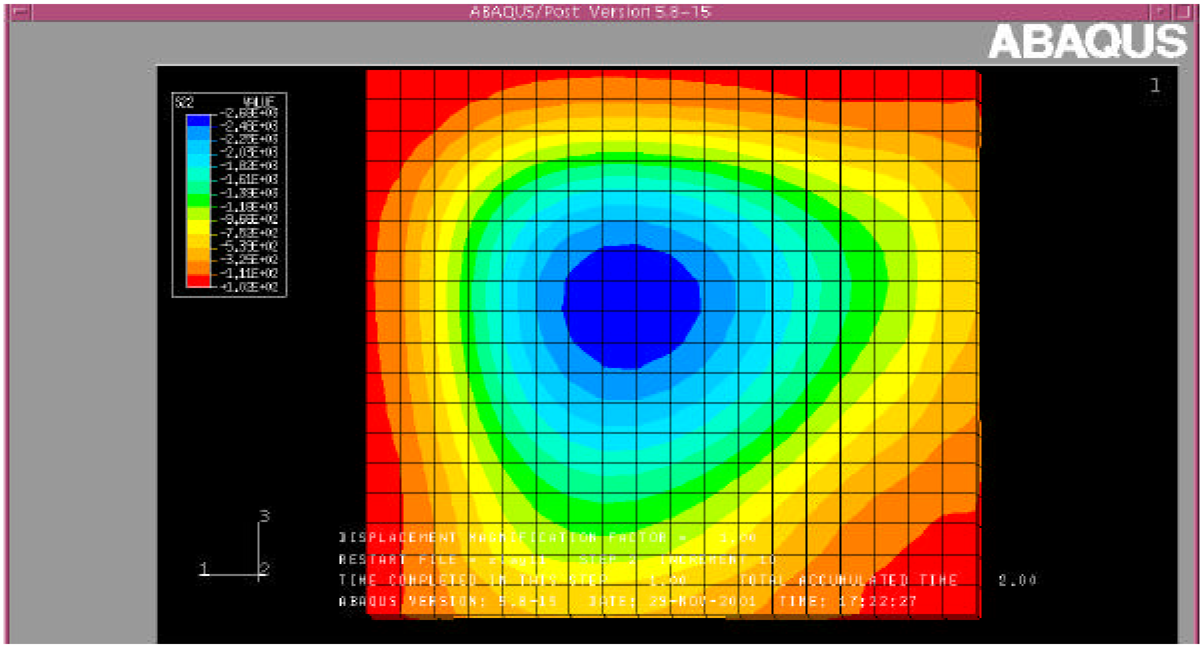


Figure 39. Stress distribution in a typical elastomer layer under shear and compression.

Along the lower and right vertical edges of the bearing, the stresses are not continuous and vary along the length. Under repetitive loadings, the elastomer will be under different loadings. Since the material properties change with loadings in the long run, the change will be different locally due to the variation of stresses along an edge.

It is important to note that the radial variation of the stress away from the center of the bearing depends on the amount of friction between the interface of the bearing and the top platen, however the variation of the stress along a certain cross section, such as along the edges of the bearing is a result of the geometry of the bearing.

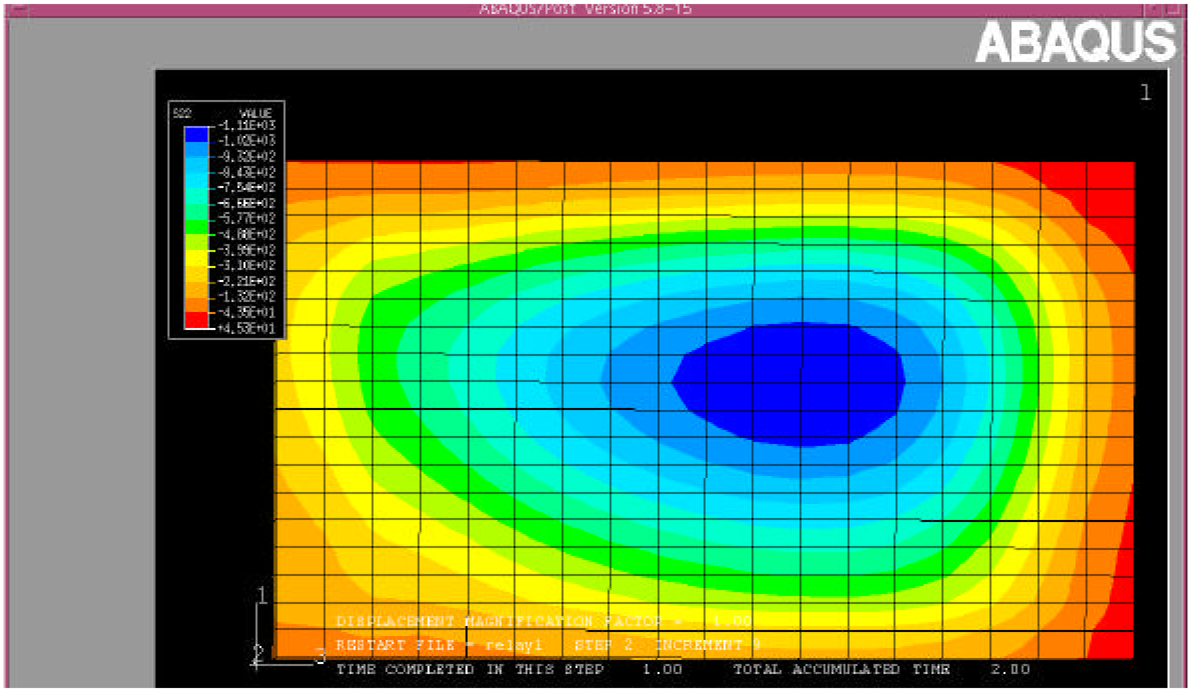


Figure 40. Stress distribution in a typical elastomer layer under shear and compression.

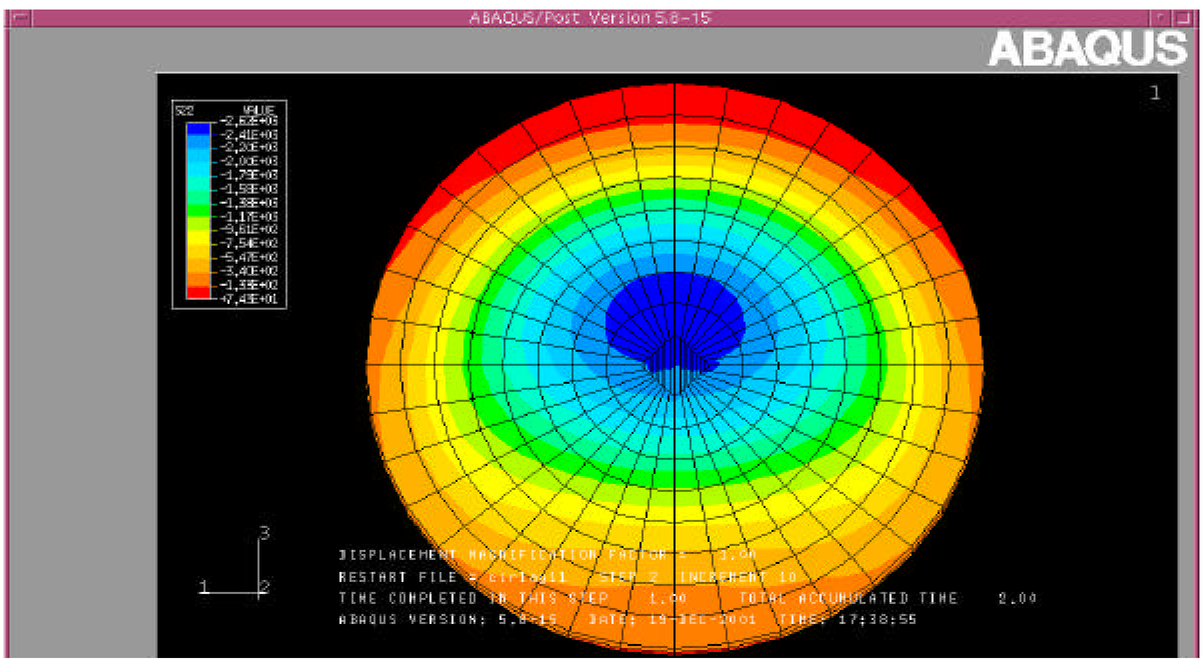


Figure 41. Stress distribution in a typical elastomer layer under shear and compression.

From Figure 41 it seen that the stress contours are tangent to the along the edges, and the geometry of the bearing allows the radial dispersion of the stresses along the bearing, keeping the local stresses at a certain radial distance the same. There are no discontinuities of the stresses along a certain radial distance away from the center.

BEARINGS SUBJECTED TO COMPRESSION AND ROTATION

Square Bearings

Circular and square bearings were compared under compression and rotation. In order to achieve rotation, variable distributed loads along the surface were applied in order to create an eccentricity of the resultant load with the center of gravity of the bearing. Varying distributed loads in the shape of a trapezoid was applied to the square bearing. Five different loading values have been applied. The average height of the profile has been set to be 2000 psi, in order to generate measurable rotations.

Table 6. Generation of pressure profile on the square bearing.

c (x=0 in) (psi)	a (x=16 in) (psi)	Slope	Edge Distance (E) (in)	Datum (in)	Eccentricity (e) (in)	Resultant (R) (kips)	Moment (in-kips)
2000	1500	31.25	48	64	0.3814	448	170.88
2250	1250	62.5	20	36	0.7629	448	341.76
2500	1000	93.75	10.67	26.67	1.1443	448	512.64
2750	750	125	6	22	1.5257	448	683.52
3000	500	156.25	3.2	19.2	1.9071	448	854.40

The following figure refers to the pressure profile on the bearing and the parameters that are used to devise the moment and the total force.

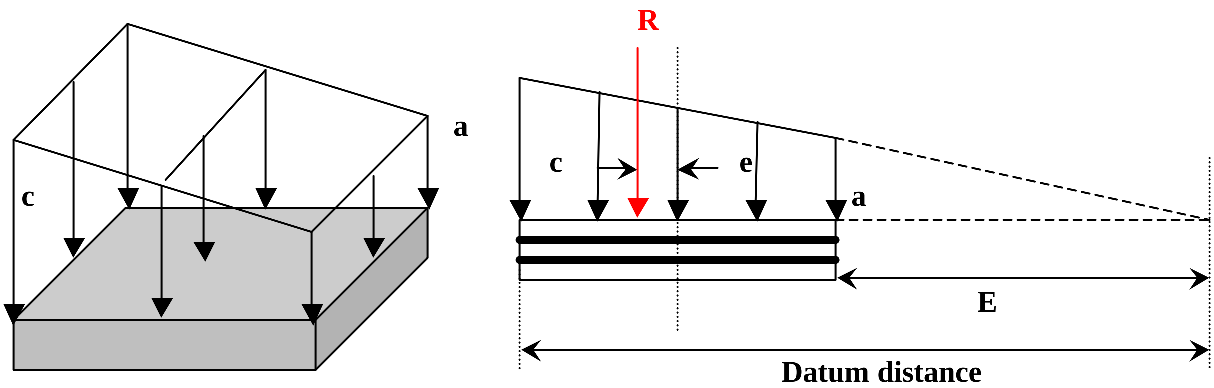


Figure 42. Pressure profile on the square bearing.

By consecutive application of these loads, the rotation has been calculated from the measured deflections at the ends of the bearing.

Table 7. Deflection data for the square bearing under rotation.

M (in-kip)=	170.88		M (in-kip)=	341.76	
location (in)	**deflection (in)**	**strain**	**location (in)**	**deflection (in)**	**strain**
0	-0.0602	-0.020	0	-0.0763	-0.025
15.9999	-0.0232	-0.008	15.95	-0.0117	-0.004
tan (f) =	0.0023		tan (f) =	0.0040	
(f) (rad)=	0.0023		(f) (rad)=	0.0040	
(f) (deg)=	0.1325		(f) (deg)=	0.2313	

M (in-kip)=	512.64		M (in-kip)=	683.52	
location (in)	**deflection (in)**	**strain**	**location (in)**	**deflection (in)**	**strain**
0.00	-0.09220	-0.031	0	-0.1080	-0.036
14.77	0.00121	0.0004	16.003	0.0264	0.009
tan (f) =	0.0063		tan (f) =	0.0084	
(f) (rad)=	0.0063		(f) (rad)=	0.0084	
(f) (deg)=	0.3634		(f) (deg)=	0.4813	

M (in-kip)=	854.4	
location (in)	**deflection (in)**	**strain**
0	-0.124	-0.041
16.003	0.0404	0.013
tan (f) =	0.0103	
(f) (rad)=	0.0103	
(f) (deg)=	0.5887	

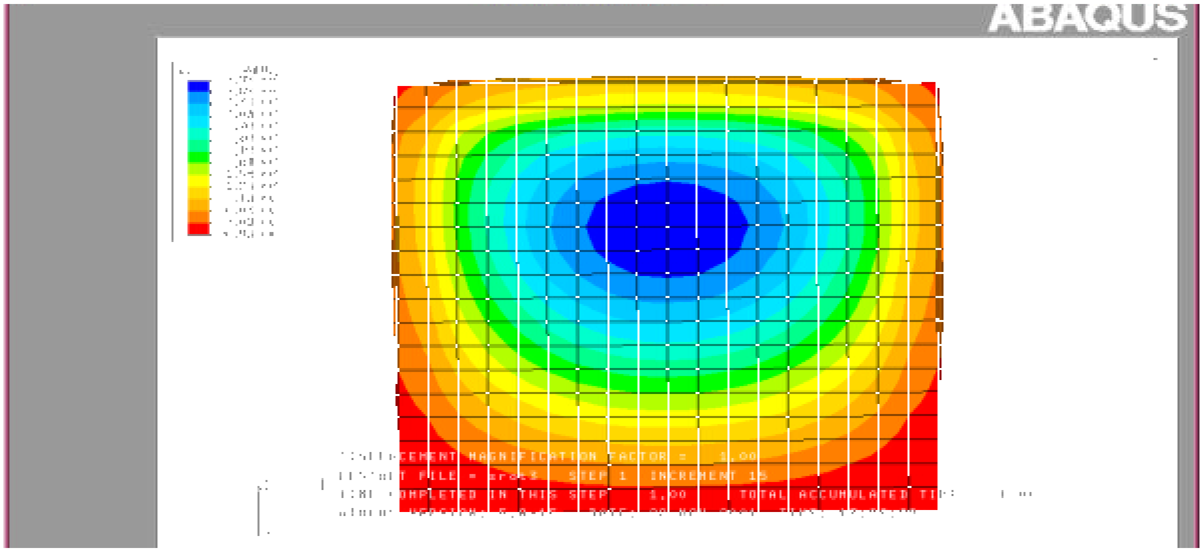


Figure 43. Typical stress distribution in an elastomer layer under an applied moment.

Note that the maximum stress region has shifted due to the shifting of the resultant force.

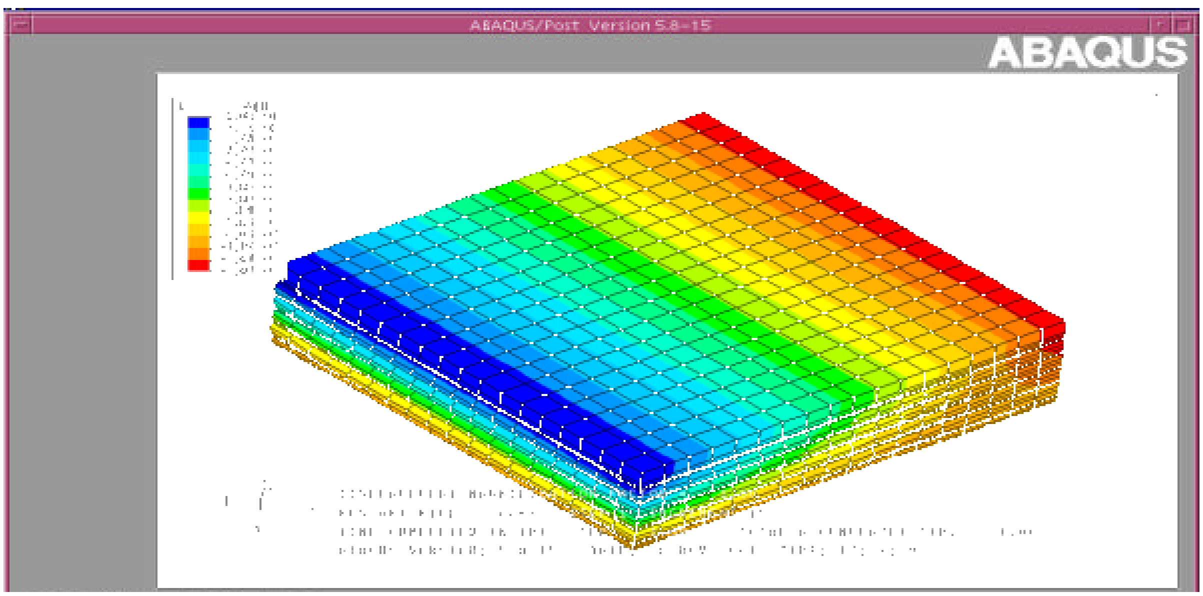


Figure 44. Deflections in square bearing under an applied moment.

Circular Bearings

In order to compare the behaviors of circular and square bearings under rotation the same total load and the moment must be applied on the circular bearing. However, this is not straightforward as it were in the case of square bearing. In the case of the square bearing, the cross section of the loading profile was a trapezoid and did not vary along the surface, however in the case of the circular bearing, the cross section of the loading profile changes along the surface, therefore an equation must be generated in order to keep the loadings equal to the ones in the case of the square bearing.
In order to achieve this, an analogy was established between the rotation inducing loading on the bearing, and the pressure profile on a circular plate submerged in a fluid.

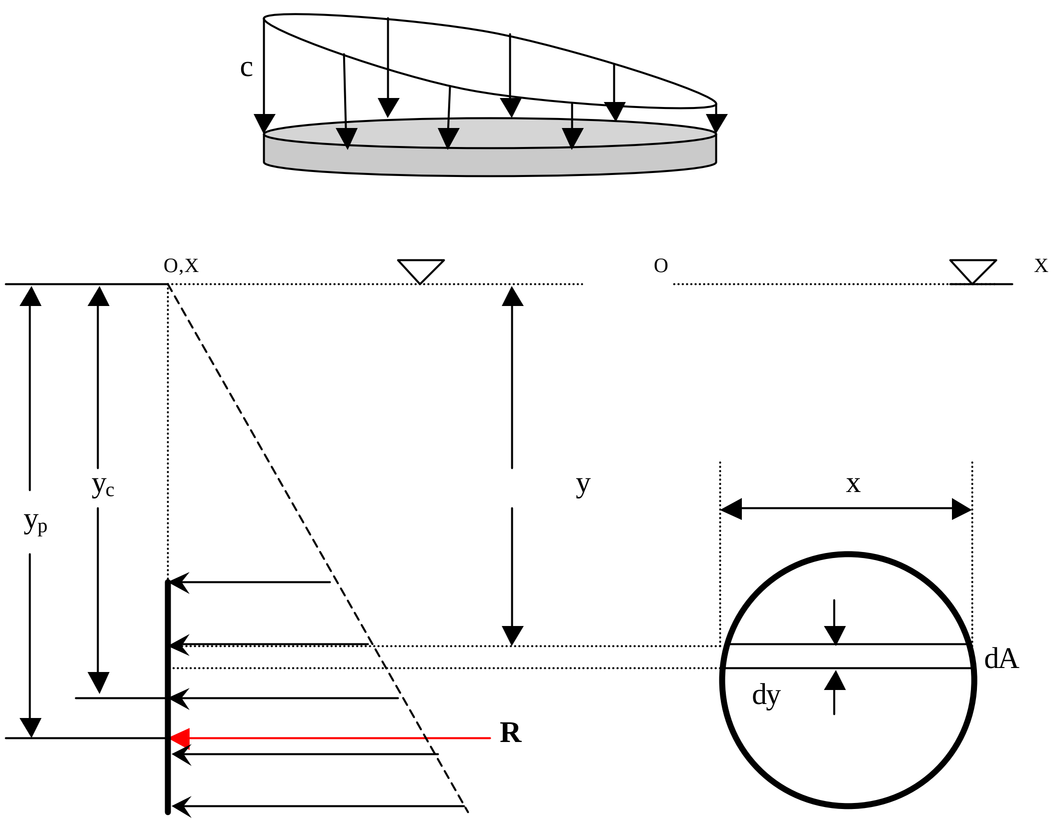


Figure 45. Pressure profile on the circular bearing.

Consider a strip of element dA (Figure 36), where the pressure distribution is uniform over it. The infinitesimal element $dA=x.dy$.

The pressure at depth y is : $P = \rho.h$ where ρ = unit weight of the fluid.

Therefore the force dF on the horizontal strip is: $dF=P.dA = \rho.y.dA$ and the force on the whole surface is $\int dF=\int\rho.y.dA$

$$\Rightarrow \quad F=\rho.y_c.A \tag{7}$$

where y_c is the distance from O,X to the centroid C of the circular area, and $y_c.A$ is the static moment of the area about the O,X axis.

The point of application of the resultant pressure force on a submerged area is called the "center of pressure".

If we take the moment of this elementary force dF around the O,X axis:

$y.dF=\rho.y^2.dA$ and integrate it: $\int y.dF = \int\rho.y^2.dA \Rightarrow y_p.F= \rho\int y^2.dA$ where y_p is the location of the center of pressure with respect to O,X axis and F is the total force acting on the circular submerged area. The quantity in the within the integration is the moment of inertia of the circular surface about the O,X axis, therefore this equation can be summarized as :

$$y_p.F= \rho.I_{O,X} \tag{8}$$

If equations 3 and 4 are combined we obtain: $y_p .(\rho.y_c.A) = \rho.I_{O,X} \Rightarrow y_p = \frac{I_{O,X}}{y_c.A}$

Noting that from the parallel axis theorem: $I_{O,X} = A.y_c^2+I_c$, where I_c is the moment of inertia of the are around it's centroidal axis.

Thus $y_p = \frac{A.y_c^2 + I_c}{y_c.A}$

In order to generate the loading profiles along the circular bearing, so that the force and the moment for each loading value is the same as that of the square bearing, equation 2 was reorganized in the form: $(y_c+e).F=\rho\ (I_c+A.y_c^2)$ where e is the eccentricity of the resultant force.

By varying the value of ρ and y_c , the force (F) and the moment (M) values were set equal to the values used for the square bearing.

Table 8. Generation of pressure profile on the circular bearing.

y_c (in)	e (in)	ρ (pci)	F (kips)	M (in-kips)	a (psi)	c (psi)
47	0.3814	37.416	448.00	170.88	1422	2095
35	0.7629	50.558	448.01	341.77	1315	2225
28	1.1443	63.793	448.00	512.64	1212	2360
21.5	1.5257	84.009	448.00	683.52	1050	2562
17	1.9071	107.63	448.01	854.41	861	2798

Table 9. Deflection data for the circular bearing under rotation.

M (in-kip)=	**170.88**		**M (in-kip)=**	**341.77**	
location (in)	**deflection (in)**	**strain**	**location (in)**	**deflection (in)**	**strain**
2	-0.0602	0.0201	1.6364	-0.0675	-0.0225
18	-0.0232	0.0077	18.0004	-0.0156	-0.0052
tan (f) =	0.0021		tan (f) =	0.0029	
(f) (rad)=	0.0021		(f) (rad)=	0.0029	
(f) (deg)=	0.1178		(f) (deg)=	0.1652	
M (in-kip)=	**512.64**		**M (in-kip)=**	**683.52**	
location (in)	**deflection (in)**	**strain**	**location (in)**	**deflection (in)**	**strain**
1.5	-0.0746	-0.0249	1.3846	-0.0853	-0.028433
18	-0.0057	-0.0019	17.9998	-0.00249	-0.00083
tan (f) =	0.0038		tan (f) =	0.0046	
(f) (rad)=	0.0038		(f) (rad)=	0.0046	
(f) (deg)=	0.2192		(f) (deg)=	0.2636	
M (in-kip)=	**854.41**				
location (in)	**deflection (in)**	**strain**			
1.38462	-0.0986	-0.0329			
18	0.00766	0.0026			
tan (f) =	0.0059				
(f) (rad)=	0.0059				
(f) (deg)=	0.3382				

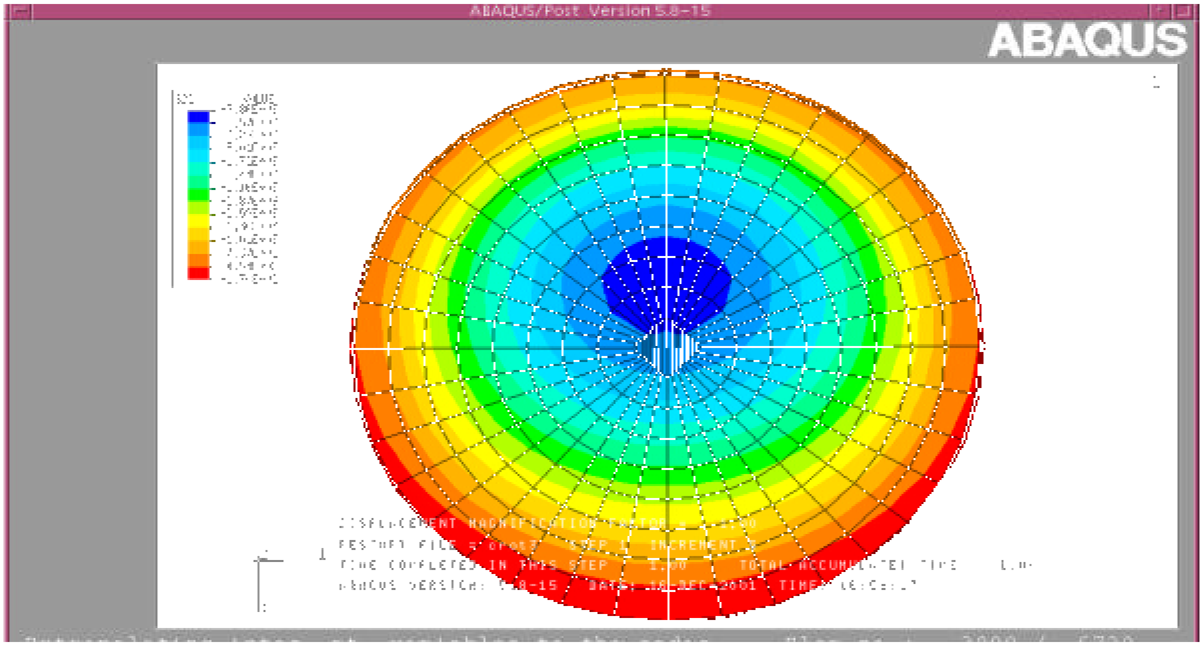


Figure 46. Typical stress distribution in an elastomer layer under an applied moment.

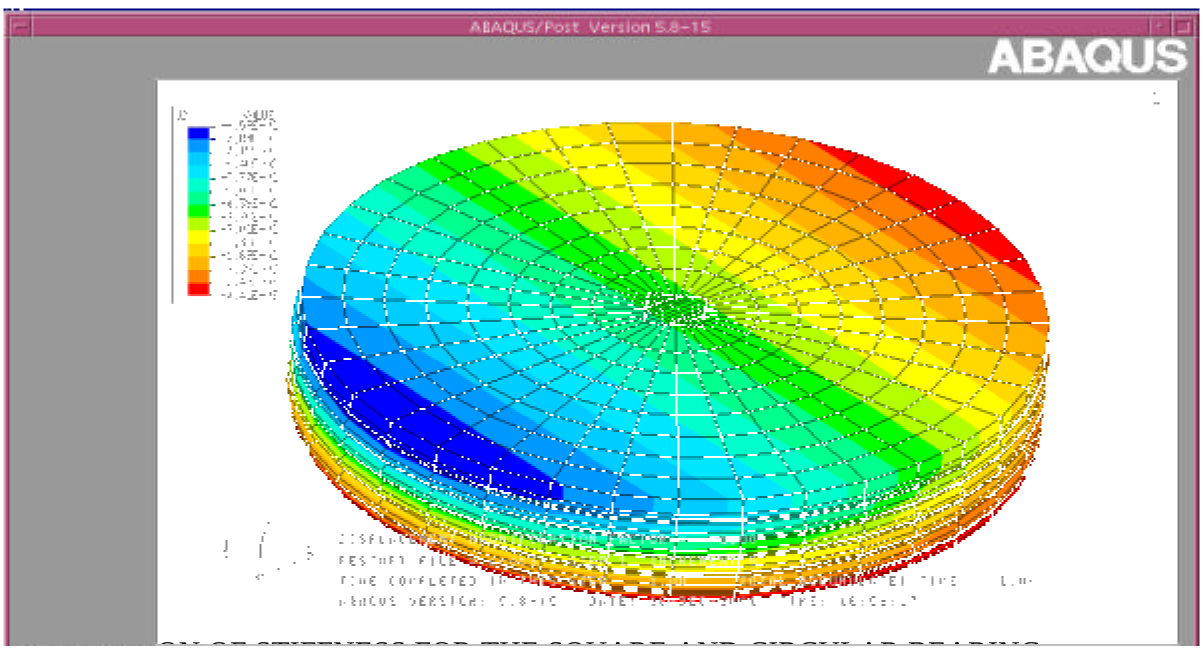


Figure 47. Deflections under an applied moment.

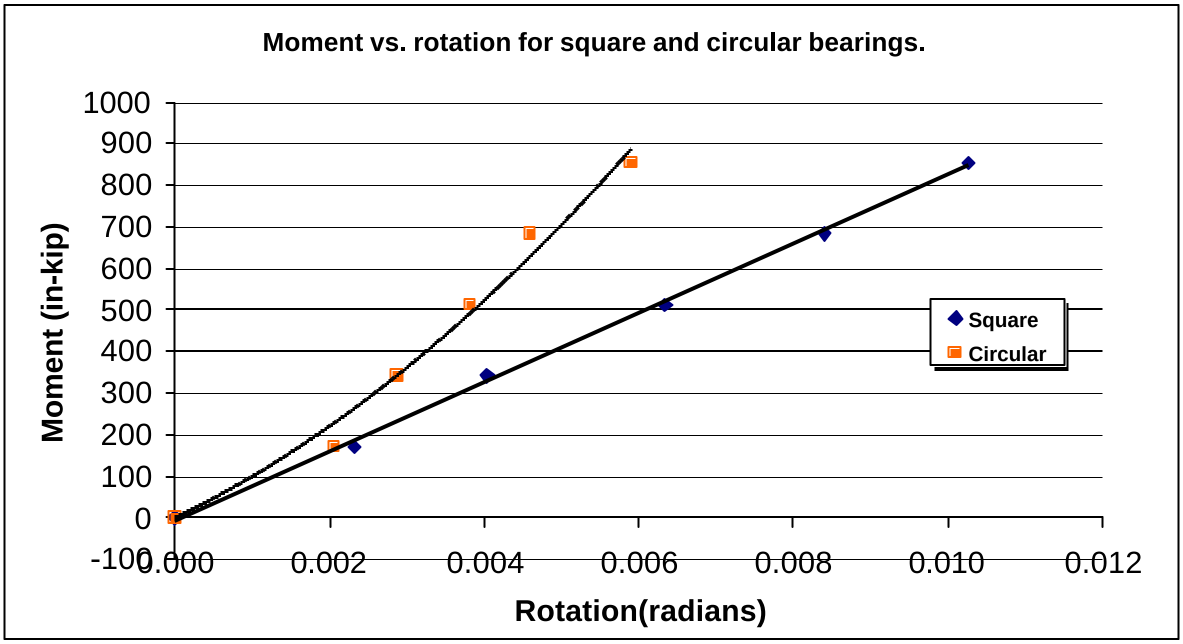


Figure 48. Moment versus rotation for square and circular bearings.

The moment-rotation relationships for square and circular bearings are seen in Figure 48. As we can see in this figure, the rotational stiffness of circular bearing is higher than that of square bearing. Moreover, the relationship for circular bearing is not linear whereas that of square bearing is linear. These relationships clearly show the effect of bearing geometry on rotational stiffness and magnitude.

EFFECT OF BEARING THICKNESS ON STIFFNESS OF THE BEARING

In order to observe the way the bearing stiffness changes with thickness, three sets of models were generated for square and circular bearing (Figure 50). Each set contained steel laminated bearings with three, five and seven laminates respectively. They were subjected to a distributed load of 1000 psi, and the deflections were observed which were then plotted versus bearing thickness as shown in Figure 51 for square bearing and in Figure 52 for circular bearing.

It was observed that as the number of layers increased the stiffness of the bearing decreased. The reason for this decrease in stiffness is briefly as follows:

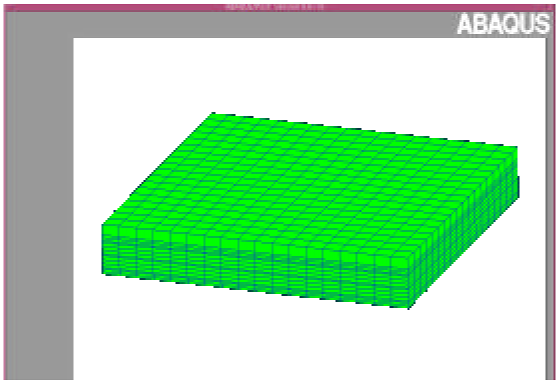
Consider two bearings, one with single laminate, and the other with two laminates. Each elastomeric layer has a stiffness K_1 and each laminate layer has a stiffness K_2.

Figure 49. Representation of single laminate and double laminate bearings.

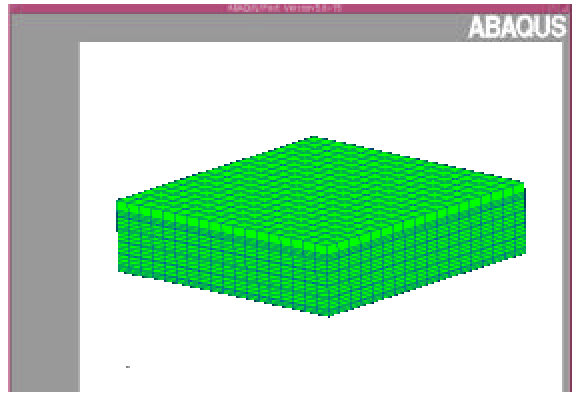
The total stiffness of the single laminate bearing is: $$K_{T1} = \frac{1}{\frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_1}} \quad (9)$$

The total stiffness of the two laminate bearing is: $$K_{T2} = \frac{1}{\frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_1}} \quad (10)$$

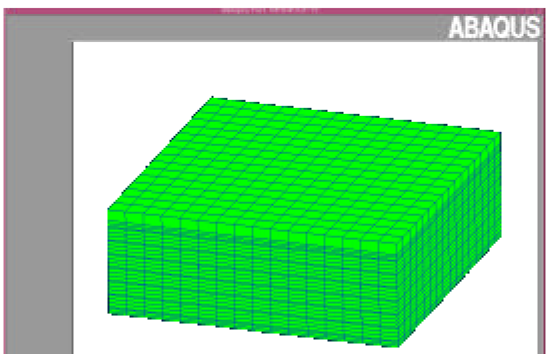
Everything else being the same, as the total thickness and the number of laminates increase, the denominator in the stiffness equations also increase, which in return decreases the total stiffness.



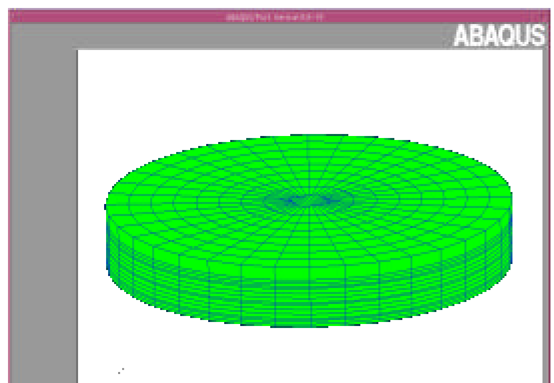
3 layer square bearing



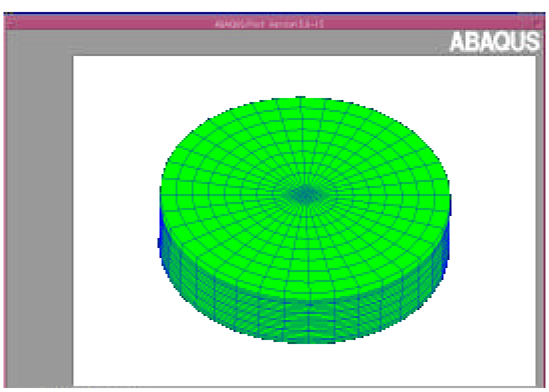
5 layer square bearing



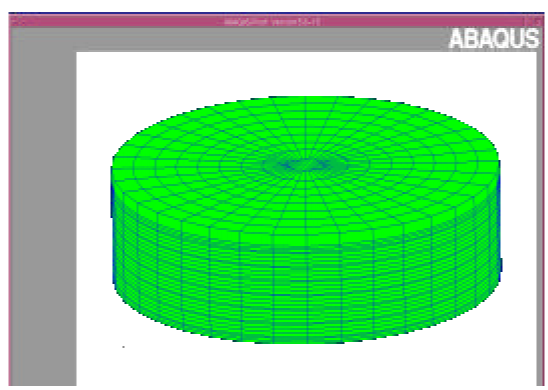
7 layer square bearing



3 layer circular bearing



5 layer circular bearing



7 layer circular bearing

Figure 50. Finite element models for square and circular bearings with various thickness'.

Table 10. Deflection data for variable bearing thickness.

Number of steel layer	Thickness (in)	Deflections (in)			
		Square		Circular	
		Steel	Fiber	Steel	Fiber
	0	0	0	0	0
3	1.787	0.0134	0.0152	0.0121	0.0139
5	3	0.0257	0.0291	0.0233	0.0267
7	4.211	0.0317	0.0356	0.0314	0.0354

EFFECT OF LAMINATE TYPE ON STIFFNESS OF ELASTOMERIC BEARINGS

In order to evaluate the effect of laminate type on bearing behavior, elastomeric bearings with steel laminates were compared to elastomeric bearings with glass fiber composite laminates. All other bearing parameters were kept the same. The material properties of the glass fiber composite were obtained from manufacturers specifications. These properties are the modulus of elasticity E, and Poisson's ratio μ .

Elastic modulus=7000 ksi
Poisson's ratio=0.2

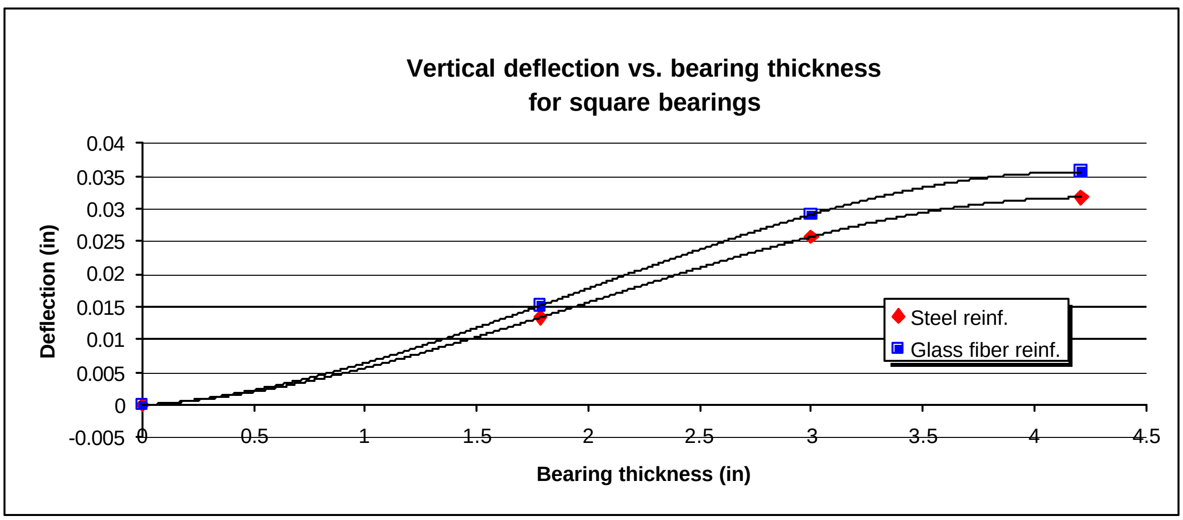


Figure 51. Vertical deflection versus bearing thickness for square bearings.

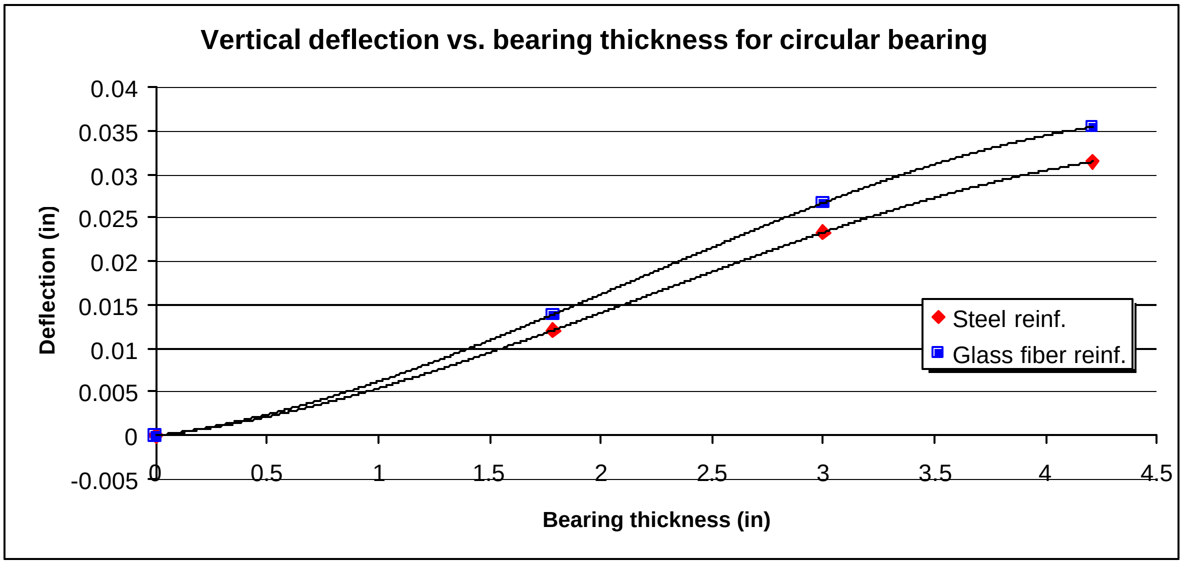


Figure 52. Vertical deflection versus bearing thickness for circular bearings.

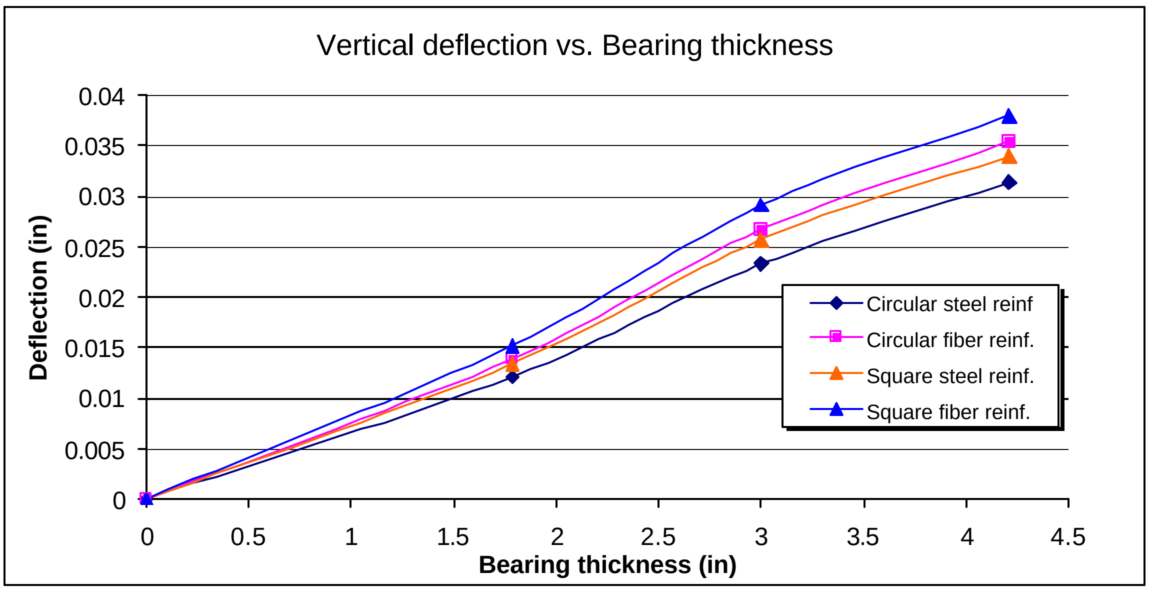


Figure 53. Vertical deflection versus bearing thickness.

The results of the analysis showed that the vertical deflection of bearings with composite laminates were about 15% higher than bearings with steel laminates (Figure 53). This is due to the fact that the composite laminate stiffness is smaller than that of steel. No effect on shear resistance has been observed.

From Figures 51, 52 and 53, it is observed that the trend of deflection versus bearing thickness is such that, as the thickness of the bearing increases, the deflection value approaches a limiting value. The reason for this type of behavior is that as the thickness increases, the slenderness of the bearing also increases, and bending effects start to control the behavior of the bearing due to it's column like behavior.

EFFECT OF TEMPERATURE CHANGES ON SHEAR MODULUS AND COMPRESSIVE STIFFNESS

In order to analyze the effect of temperature changes on compressive stiffness of layered elastomeric bearings, a 16" by 16" square elastomeric bearing with 5-steel layers and a 5 steel layered 18" diameter circular bearing was analyzed under a 1000 psi compressive load for 5 different values of shear modulus (G) for the elastomer which corresponded to 5 different temperatures values.

The data needed was obtained from a chart generated by CALTRANS, which showed the variation of shear modulus with temperature for neoprene (Figure 3).

The compressive stiffness of elastomeric bearings is directly related to the shear modulus (G) and the shape factor (S). This relationship is stated in an equation given by AASHTO, which relates the compressive modulus of the bearing to the mentioned parameters.

$$E_c = 3G(1+2kS^2) \qquad \textbf{(11)}$$

Where G is the shear modulus, S is the shape factor and k is a constant based on hardness.

Table 11. Variation of vertical deflections with temperature for square and circular bearings.

Temperature (C^o)	Shear modulus	Circular	Square
		Deflection (inch)	
20	150	0.0305	0.0336
10	170	0.0271	0.0299
-7	200	0.0233	0.0257
-10	220	0.0213	0.0235
-18	250	0.0189	0.0209

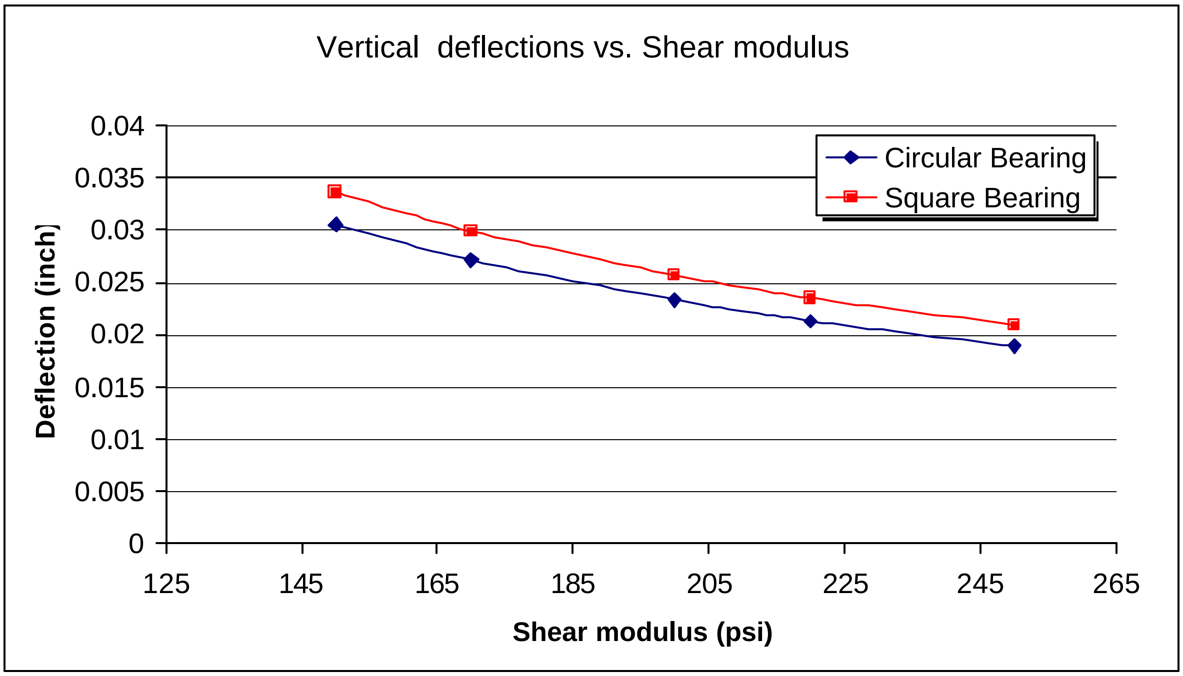


Figure 54. Vertical deflections versus shear modulus.

As can be seen from Figure 54, the variance of the compressive deflection with change in shear modulus reflects the relationship that was presented in equation (11). The slightly non-linear relationship that is observed in figure 54 arises from the fact that in equation (11), the compressive stiffness is not only related to shear modulus but also related to the hardness of the elastomer (k), which is in return related to the shear modulus. So, although it seems from equation (11) that compressive stiffness and the shear modulus are linearly related to each other, because of the k factor within the parentheses a non-linear relationship arises.

It is also seen from Figure 54 that due to the higher shape factor of the circular bearing, the compressive deflections are approximately 10 percent to 15 percent smaller than the deflections of the square bearing loaded under the same temperature conditions.

BEARING SLIP

There are instances of elastomeric bridge bearings slipping "walking out" from their position under bridge girders rather than remaining in their original location and responding to the bridge movement by elastomer deformation.

The walking out phenomena causes the area of contact between the bearing and the girder to decrease leading to higher stress on the remaining area. There are cases in which the bearing shifts with the girder thereby causing a reduction in the supported area of the bearing by the supporting structure or the girder shifts above the bearing, thereby causing a reduction in the bearing area between the elastomeric bearing and the supported beam or the girder.

The second mentioned case has been analyzed, considering a loss contact area. This loss was estimated at 10% of the original contact area for the square and circular bearings. Some portion of the rigid top plate which represents the bottom flange of the supported member is removed in order the model the partial loss of contact surface.

The bearing slip models were subjected to two types of loading: 1) a uniform compression of 1000 psi, and 2) a combined application of a uniform pressure of 1000

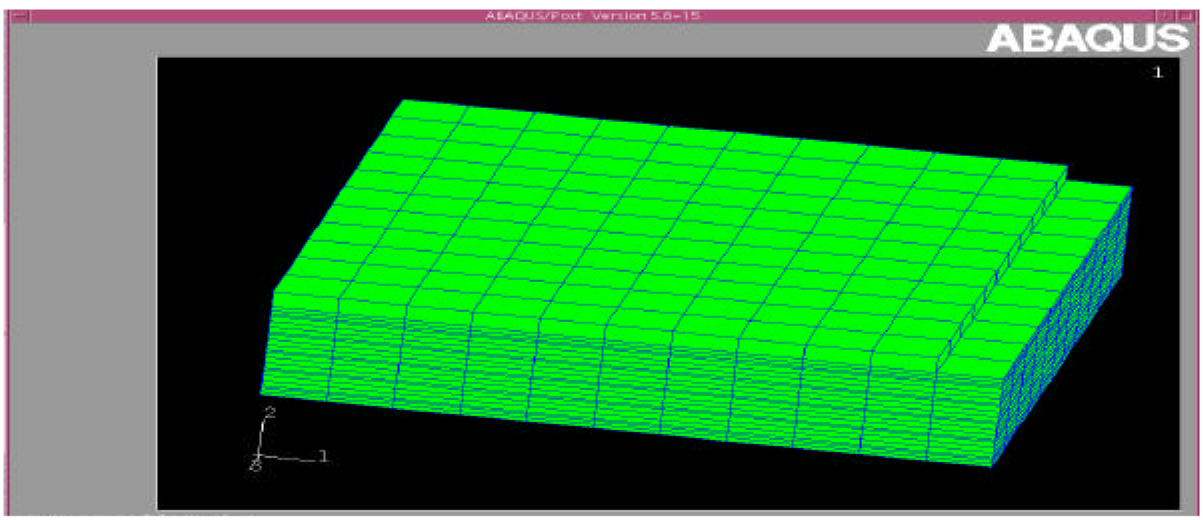


Figure 55. Laminated square bearing model with partial contact area loss.

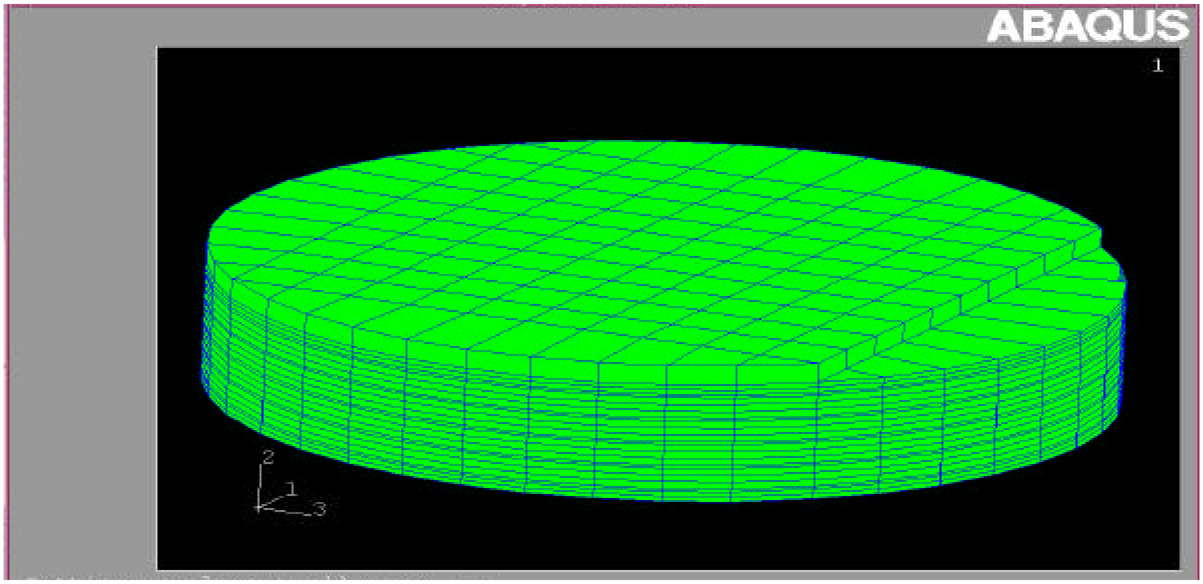


Figure 56. Laminated circular bearing model with partial contact area loss.

psi and a lateral load of 15 percent of the vertical load. Bearing models for square and circular bearings are shown in Figures 55 and 56 respectively. From the analysis it was observed that behavior of the bearings under lateral loads did not show a significant difference. It was also observed that due to the removal of a portion of the top plate, there are some distortions in the stress distribution in bearing layers for both the circular and the square bearings. The differences in the normal and shear stresses within the circular and the square bearing with and without slippage were small. The variations of normal stresses is shown in Figure 57 for square bearings and in Figure 58 for circular bearings.

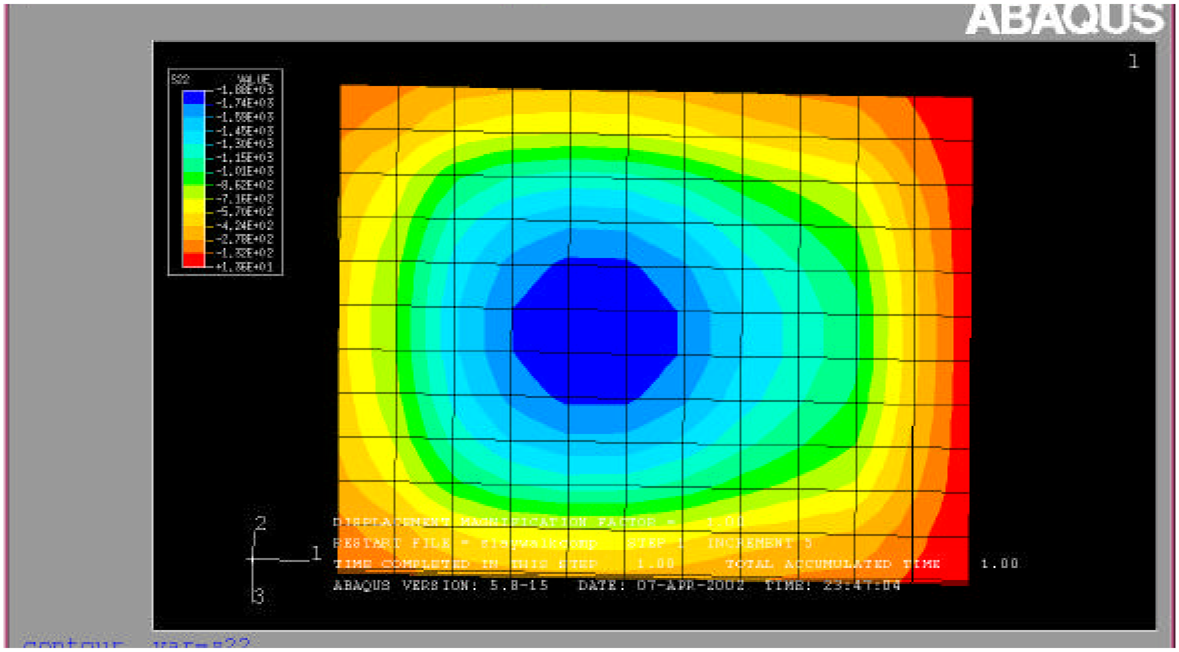


Figure 57. Normal stress distribution in an elastomer layer under compression.

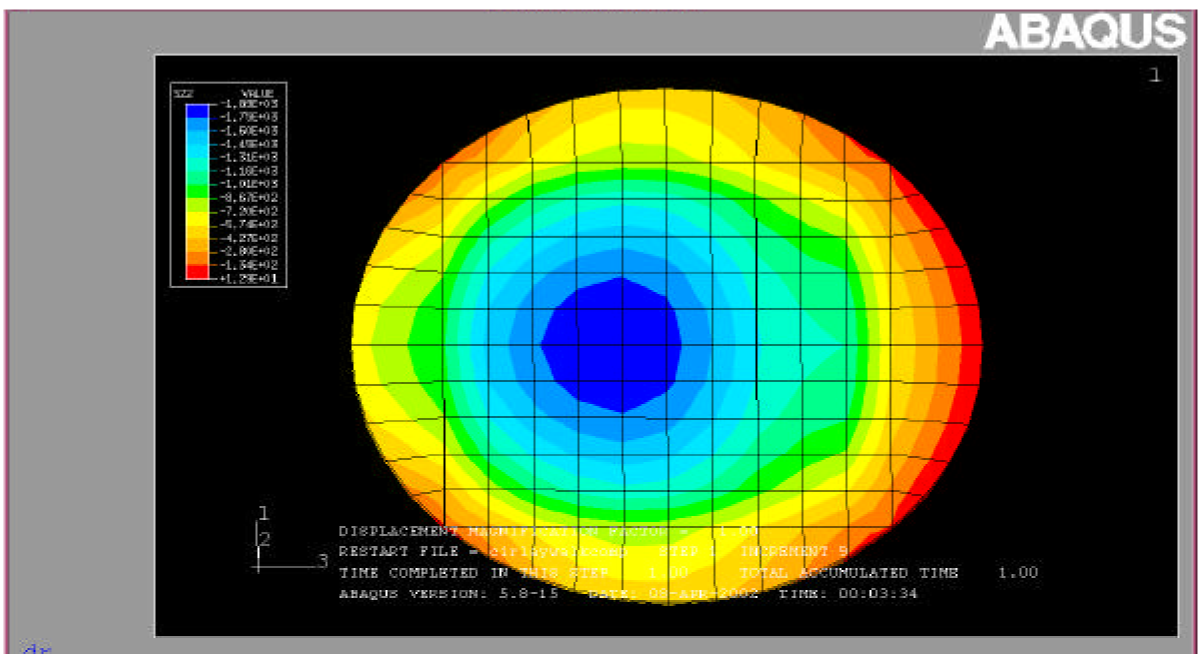


Figure 58. Normal stress distribution in an elastomer layer under compression.

Another difference that was observed is that the vertical deflections in the circular bearing are approximately 15 percent less than the deflections within the square bearing. This difference is due to higher shape factor of the circular bearing and does not seem to be affected by bearing slip or walking out. Vertical deformations for square and rectangular bearings are shown in Figures 59 and 60 respectively.

Also note that since a part of the plate is not loaded, the resultant force has shifted from the center of gravity of the bearing. This shift in the location of the resultant force has created a difference between the deflections of the ends of the bearing. However, the average deflection of the circular bearing is less than the square bearing which is similar to what was observed when there was no bearing slip.

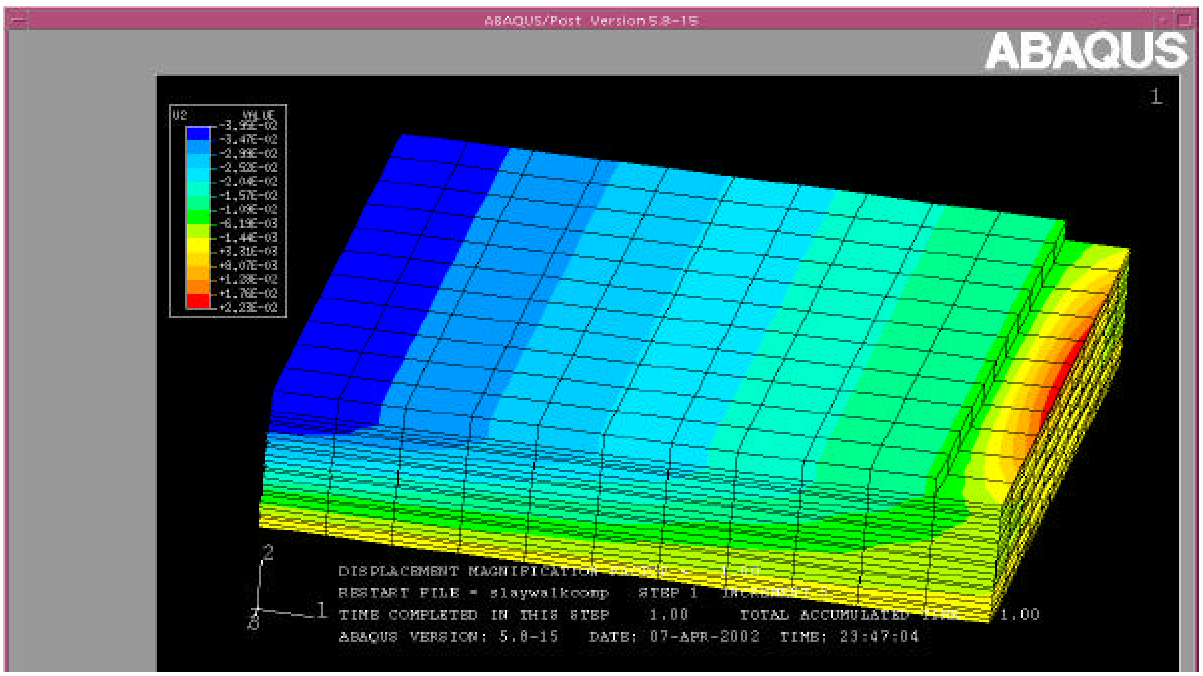


Figure 59. Deflection of the circular bearing under compression.

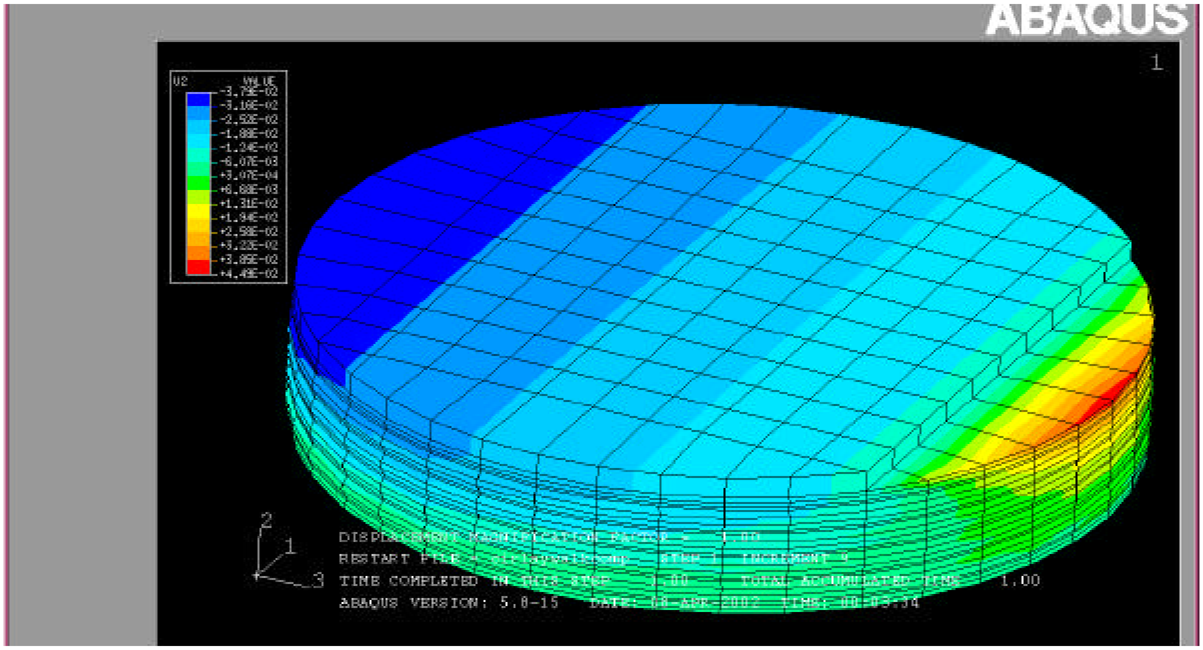


Figure 60. Deflection of the circular bearing under compression.

CONCLUSION AND RECOMMENDATIONS

The following conclusions can be drawn based on the data collected from the bearing survey:

1- There is no reason that would prevent consideration of circular elastomeric bearings as an alternative to square or rectangular elastomeric bearings.

2- Eight states already use circular bearings in their bridges. Texas and New Hampshire provide standard drawings for circular elastomeric bearings and recommendations on their use.

3- Twelve states are willing to consider circular bearings and see no reason why they cannot be used. Some states thought circular may be more expensive than square bearings.

4- Circular bearings are used on skewed and curved bridges with span lengths less than 100 ft. In some cases circular bearings been specified for spans up to 150 ft.

5- The majority of circular bearings used have diameters varying from 12 in to 24 in. Few states used diameters between 24 in and 36 in.

6- The majority of circular bearing used is between 2 in -3 in thick. Few states used 3 in – 4 in thick bearings.

7- Most of the states using circular bearings did not have enough data to compare maintenance of circular bearings to square and rectangular bearings. Few states reported insignificant differences in maintenance.

8- Most of the states using circular bearings did not have enough data to compare cost of circular bearings to square bearings. Texas reported a slight increase (about 10 percent in the cost of circular bearings). Results from the bearing suppliers and manufacturers showed only minor differences in the cost between circular and square bearings.

The following conclusions can be drawn based on the data collected from the finite element analysis:

1- Smaller vertical deformations were observed in circular bearings compared to square bearings with the same thickness and shear area. Vertical deformations of circular bearings were about 10 percent to 15 percent lower than for square bearings. This can be attributed mainly to the larger shape factor (higher stiffness) of circular bearings.

2- Under combined normal stress and shear, tensile stresses were observed at the interface between upper elastomer layer and steel plate for both circular and square bearings. The level of tension was approximately 75 psi for circular bearings compared to 100 psi for square bearings.

3- When portion of the bearing is not in direct contact with the girder due to bearing walking out or uplift, the tensile stresses observed in conclusion 2 became higher. For a 15 percent of the area of the bearing with no contact, the tensile stresses at the interface increased form 100 psi to 150 psi for square bearings and from 75 psi to 100 psi for circular bearings.

4- Finite element analysis showed concentric stress contours for circular bearings compared to square contours for the square bearings especially away from the center. Discontinuities in the stress contours were observed in the square bearing and rectangular bearings. These discontinuities were amplified when applied shear stresses are added to the applied compressive stresses.

5- The behavior of circular bearing and square bearing under applied load and rotation showed that square bearings have approximately linear load-rotation relationship. For circular bearings, the load-relationship was non-linear. For the same applied load, there were less rotation observed in circular bearings compared to square bearings, indicating a higher rotational stiffness of circular bearings.

6- The vertical deflections of elastomeric bearings with glass-fiber composite laminates were higher than those with steel shims by about 10 percent to 15 percent. This is because of the lower stiffness of the composite compared to steel. To maintain compressive strain limits comparable to bearings with steel laminates, the maximum stress limits on bearings with glass-fiber composite laminates need to be reduced by 10 percent to 15 percent.

7- The magnitude of the normal stresses in the bearing between the center and the edge of the bearing is not constant. The normal stress is maximum at the center and drops to much smaller value at the edge while the average stress remains equal to the applied stress. This was observed for all three bearing geometries.

8- The variation of the normal stress between the center and the edge of the bearing is non-linear with a sharp drop close to the edge. For the square and the rectangular bearings, the drop along the diagonal was less than those along the longitudinal and the transverse directions. Comparing the three bearing geometries, the circular bearing showed milder drop in normal stresses between the center and the edge.

Based on the results of this study, the following recommendations can be made:

1- Circular bearings should be considered as an acceptable bearing geometry along with square and rectangular bearings for bridges. For straight and very wide bridges, circular bearings should be considered because transverse thermal movements in these bridges could be significant.

2- Circular bearings should be considered for highly skewed bridges, curved bridges, and very wide bridges because of their geometry and easy alignment.

3- Circular bearings subjected to large rotations should be carefully evaluated. Accurate prediction of bearing rotational capacity will be required when designing bearings in those situations. Alternatively, details that eliminate or minimize rotations at the bearings can be used.

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