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A NEW TEST METHOD FOR DETERMINING THE SHEAR MODULUS OF ELASTOMERIC BRIDGE BEARINGS

by

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THESIS

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A NEW TEST METHOD FOR DETERMINING THE SHEAR MODULUS OF ELASTOMERIC BRIDGE BEARINGS

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To a wonderful grandmother

Nevin Durusu

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Only one person deserves great appreciation. He accepted me to the University of Texas and offered me financial assistance. He supported my entire graduate study through the funds from the NCHRP 10-51 project. He is the sole supervisor of this thesis. His guidance and immeasurable patience throughout the course of the study are noteworthy. In short, this thesis could not exist without him.

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ABSTRACT

A NEW TEST METHOD FOR DETERMINING THE SHEAR MODULUS OF ELASTOMERIC BRIDGE BEARINGS

by

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The shear modulus of elastomeric bridge bearings has to be determined reliably for a satisfactory design. Current test methods cited by the design codes are applied to small samples and are not reflective of the full-size bearing performance. Although there are test setups to evaluate the performance of full-size bearings, they cannot be used extensively due to their cost and difficulty of construction. Due to these reasons, there is a need for a new test method that can evaluate the shear modulus of full-size elastomeric bridge bearings easily and cost effectively. This paper concentrates on the evaluation of a new proposed test method. Certain full-size bearings were tested with the new and existing test methods to find out the applicability of this new test method. Test results revealed that the new test method is capable of giving good estimates of shear modulus for laminated bearings but cannot give good estimates for plain pads. In addition, certain test parameters were investigated to standardize this new test method. It was found out that, for a standardized test, the testing time, surface and edge conditions of the bearings have to be specified.

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CHAPTER 1

INTRODUCTION

1.1 Background

Bridge bearings are designed to accommodate the changes in the length of the bridge girder resulting from the temperature variations while simultaneously supporting the dead and live loads. Elastomeric bearings, usually made from natural rubber or neoprene, can sustain high shear deformations while maintaining a high compressive stiffness and are maintenance free. Design of elastomeric bearings for shear requires the determination of the thickness of the pad and the selection of the elastomeric material with desired mechanical properties. Thickness of the pad is determined considering the stresses produced in the elastomer as a result of shearing. In general, rubber can accommodate shear strains larger than 100 percent. However, rubber technologists recommend limiting the shear strains to keep the elastomer stresses low. In Section 14.4.1.3 of the AASHTO Specification (AASHTO, 1996), the shear strain is limited to 50 percent of the pre-loading elastomer thickness by the following relation.

$$h_{rt} \geq 2\,\Delta_s \tag{1.1}$$

where h_{rt}: Total elastomer thickness of the bearing

Δ_s: Shear deformation of the bearing in one direction

The shear deformation of the bearing is related to the change in the length of the bridge girder. Since the change in length can be anticipated during the design, the required thickness of elastomer can be easily found from Eq. 1.1.

On the other hand, the selection of the elastomeric material is related to the desired shear stiffness. Figure 1.1 shows the forces produced during the horizontal deformation of the bridge girder.

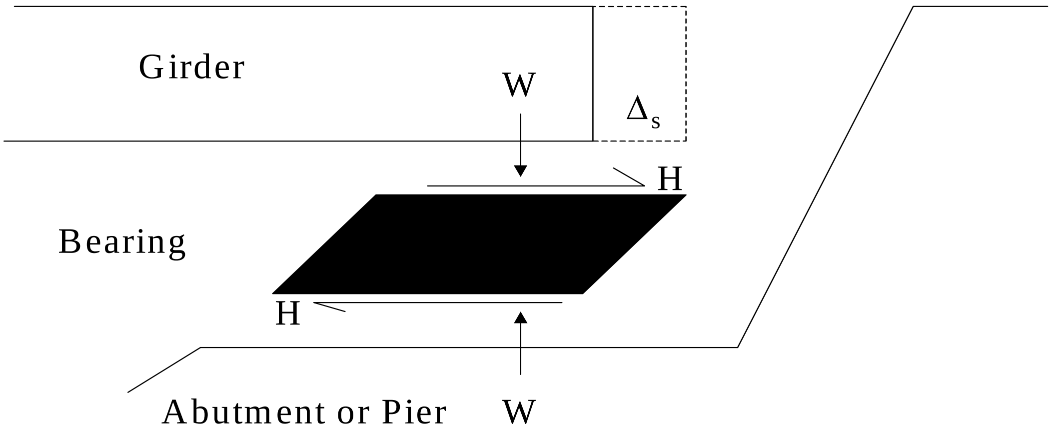

Figure 1.1: Forces on Elastomeric Bearing During Shear

As can be seen from Fig 1.1, shear forces are produced between the girder-bearing and bearing-abutment interfaces. In cases where pads are not directly attached to the girder and abutment with mounting plates, the shear forces are transmitted through friction. If the shear force exceeds the force of friction, the bearing will start to slip. This is undesirable behavior since excessive slip might necessitate the replacement of the pad. Replacement is a very expensive process and requires the bridge to be temporarily taken out of service. In addition to slip, high shear forces may produce undesirable stresses in the girder or foundation. Due to these reasons the shear stiffness of the elastomer has to be selected such that high shear stresses and bearing slip will not occur during the practice. This selection requires a thorough understanding of the behavior of elastomers under shear.

Certain tests can be performed in order to evaluate the response in shear. Some test methods are applied to full-size bearings, while others are applied to the individual elastomeric material that compose the pad. Figure 1.2 shows a typical load-displacement curve obtained from a test on a full-size bearing. Although response is not linear, design equations assume a linear stress-strain relationship in the form:

$$\tau = G\gamma \qquad (1.2)$$

Where τ: Shear stress, G: Shear Modulus and γ: Shear strain

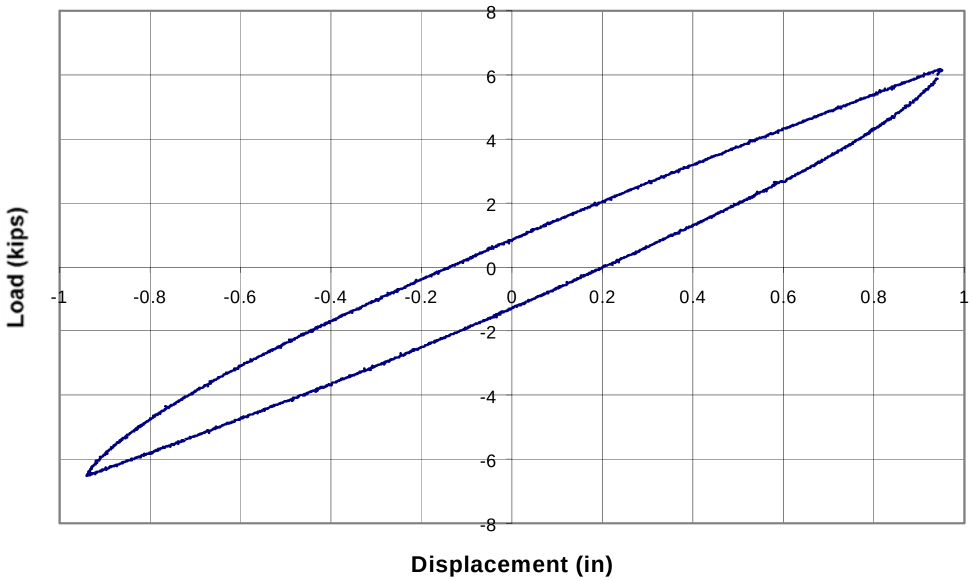

Figure 1.2: Load-Displacement Response of a Full-Size Bearing

By making use of Eq. 1.2, the shear force between the girder-bearing and bearing-abutment interface can be calculated for a given shear strain between 0-50 percent. According to AASHTO, the design shear force on the bearing is calculated as follows:

$$H = \frac{G\,A\,\Delta_h}{h_{rt}} \tag{1.3}$$

where H: Shear force on bearing

Δ_h: Total horizontal movement of superstructure

A: Gross plan area of bearing

The shear modulus of the elastomeric material has to be determined reliably because it directly enters into design equations. Since the response is not linear, the value of the shear modulus depends on how it is defined. It is also dependent on the test method performed to obtain the response characteristics. The following section focuses on the evaluation of different test methods and definitions used for obtaining the shear modulus.

1.2 Test Methods and Definitions Used for Shear Modulus

1.2.1 Hardness Tests

There is a crude relationship between material hardness and shear modulus (Arditzoglou, Yura and Haines, 1997). Hardness is defined as the "reversible, elastic deformation produced by a specially-shaped indentor under a specified load" (Haines, 1996). Various instruments have been used to measure the hardness of the elastomer. The "International Rubber Hardness" (IRH), and "Shore A Hardness" are the two most popular methods. The instrument used to perform hardness measurements is called a durometer. Hardness is the most widely used property of the elastomer since it is very quick and simple to measure. Elastomer manufacturers usually take orders in terms of hardness.

Apart from its wide usage, there are some disadvantages of the hardness measurements. It has been explained by many researchers (e.g. Arditzoglou, Yura and Haines, 1997) that hardness is not a good indication of the material property because it is a surface measurement and depends strongly on the operator who takes the measurement. In addition, it does not allow precise bearing design. This is due to the fact that there is not a one-to-one correspondence between the hardness and shear modulus values. Table 1.1 constructed by Arditzoglou,(1994) shows the scatter of published shear modulus values with respect to the durometer hardness of an elastomer.

Table 1.1: Scatter of Published Shear Modulus Values with Respect to Hardness

	J.E. Long 1974	Stanton J.F. 1983	Roberts A.D. London 1988	Payne A.R. London 1960	AASHTO 1989	AASHTO 1992	Lee D.J. London 1971	Lindley P.B. 1982	DuPont 1959
Hardness	Shear Modulus (psi)								
50	87	93	93	90-115	85-110	95-130	71	91	110
60	145	154	154	135-165	120-155	130-200	114	129	160
70	203	254	251	200-260	160-260	200-300	157	177	215

The scatter between the two properties proves that hardness cannot be used in precise bearing design calculations. That is why the 1992 AASHTO Design Specification for Bridges recommends the use of shear modulus rather than durometer in specifying the material for use in bridge bearings.

1.2.2 Current Test Methods

The only test method cited by AASHTO for determining the shear modulus is the ASTM D-4014 Quadruple Shear Test. Annex A of the ASTM D-4014 Specification explains the test procedure and the calculation of the shear modulus. In this test, original elastomeric bearing material is cut into small rubber samples that have lengths and widths that are at least four times the thickness. The four rubber blocks are bonded to rigid steel plates as shown in Fig1.3.

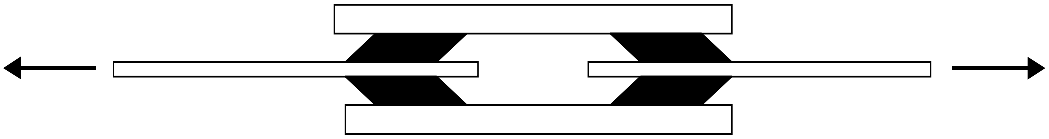

Figure 1.3: ASTM D-4014 Quadruple Shear Test

The test piece is strained in a tension machine at least six times up to an extension equal to the average rubber thickness of one block (an average 50% strain in each rubber block). Shear modulus values are calculated from the sixth loading cycle based on the stress at a change in strain of 25%. In this test the elastomer is strained in only one direction. Based on the same quadruple shear test, different interpretations of the shear modulus are also possible. For example, Arditzoglou, Yura and Haines, 1997 defined the shear modulus based on a change in stress between a strain of 20%-40%.

In the cold temperature tests performed at the University of Washington (Stanton, Roeder, 1989), specimens were subjected to a cyclic strain of +/- 25%, a two way test. The shear stiffness measurements were taken after the first three quarters of the first cycle.

1.2.3 Full-Scale Shear Test

The typical full-scale shear test setup uses two full-size bearings sandwiched between three concrete slabs or steel platens (Fig1.4) (Muscarella, 1995). A compressive force is applied to the assemblage and is held constant during the test. A horizontal shear deformation is applied to the middle platen to simulate the bridge movement due to temperature changes. The shear deformation can be applied in one or two directions. The loading and unloading are repeated until the stress-strain curve stabilizes. The linear portion of the final stress-strain curve is usually used to calculate the shear modulus of the bearing. Figure 1.2 shows a typical load-displacement response obtained by a full-scale shear test.

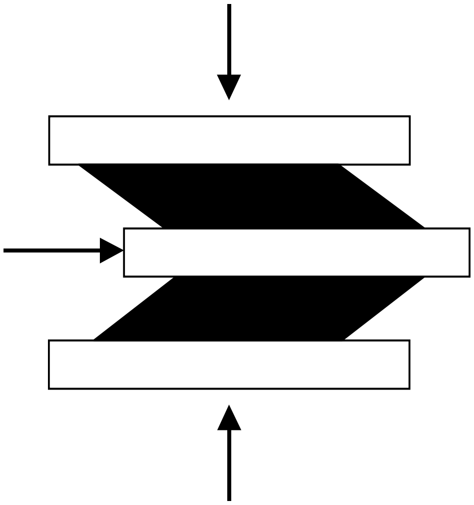

Figure 1.4: Full-Scale Shear Test

1.3 Comparison of Different Definitions of Shear Modulus

Since the load-displacement response in shear is not linear, the value of the shear modulus changes with its definition. Figure 1.5 shows a load-displacement response curve of a natural rubber bearing having dimensions of 14x9x2 inches. The bearing was tested with the full-scale shear test setup and the applied compressive pressure was 1200 psi. The total thickness of the elastomer layers (1.75 in) is used to define the percent shear strain. Table 1.2 shows the values of shear modulus for different tangent modulus or secant modulus definitions. The values range from 162 psi to 228 psi.

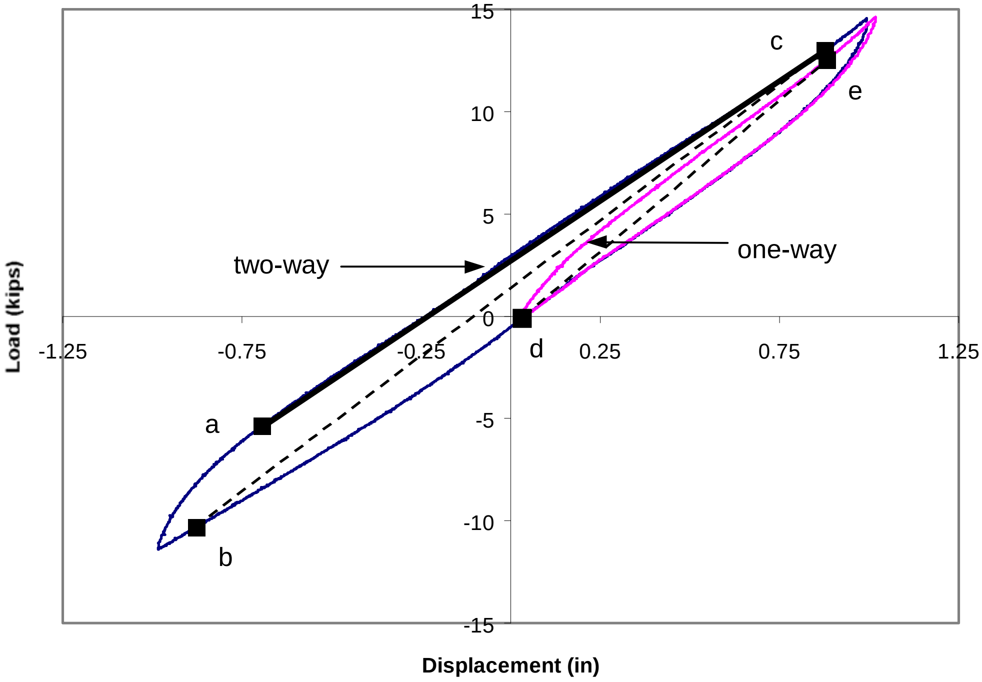

Figure 1.5: Load-Displacement Response of an Elastomer Under Shear

Table 1.2: Comparison of Shear Modulus Values with Different Definitions

Definition of Shear Modulus	Test Direction	Shear Modulus (psi)
0-25 percent secant	One-way	227.9
0-50 percent secant (d-e)	One-way	204.2
20-40 percent tangent	One-way	181.9
+/- 50 percent secant (b-c)	Two-way	189.4
+/- 25 percent tangent	Two-way (Top line)	162.7
+/- 25 percent tangent	Two-way (Bottom line)	170.3
U. of Washington (a-c)	Two-way (Top line)	162.3

As presented in Table 1.2, when the shear modulus is based on lower strains, its value is higher. For design the specified shear modulus should be associated with the maximum anticipated strain. There is not too much difference between the measured shear modulus based on maximum strain for either one-way or two-way behavior(204 psi vs.189 psi respectively). The use of the maximum strain and stress to define the shear modulus will result in the correct evaluation of the maximum shear force and the factor of safety against slip. Defining the shear modulus based on the flat portions of the stress-strain curve for either loading or unloading gives a lower shear modulus and unconservative estimates of the maximum anticipated shear force.

Due to these reasons, for a one way test, the shear modulus reported herein will be based on the slope of a straight line drawn between the origin and the measured shear stress at the maximum specified shear strain, otherwise known as the secant shear modulus. On the other hand, for a two way test a secant line drawn between the positive and negative maximum specified strain will be used in calculations.

1.4 Evaluation of the Test Methods Used for Determining the Shear Modulus

As explained in the previous sections, the value of the shear modulus changes with the test procedure applied. The test method which best reflects the field performance of the bearings would be the most desirable. Currently, there are three test methods to find shear modulus, namely, hardness test, ASTM D-4014 Quadruple Shear Test, and the full-scale shear test. Each test has certain advantages and disadvantages. Hardness test is easy and simple but precise shear modulus values are not obtained. ASTM D-4014 Quadruple Shear Test only considers the elastomeric material and is not directly applicable to full-size bearings. In a study by Arditzoglou, Yura, and Haines, 1997 it was found out that there are considerable differences between the quadruple shear test and the full-scale shear test. These differences are due to the fact that the quad-shear method uses small specimens and those specimens are not cut from the original bearing. In addition, the applied level of strain and the surface conditions are found to have influence on the differences between two test methods. Among all three, the full-scale shear test is the one which is capable of evaluating the field performance of full-size bearings. However, full-scale shear test setups are not easy to construct, are expensive and are difficult to operate.

1.5 A Proposed Test – The Inclined Compression Test

Due to the above mentioned reasons, there is a need for a test method which is capable of evaluating the performance of full-size bearings easily and cost effectively. It is the focus of this research to develop a new test procedure. To accomplish this task, an inclined compression test was conceived. In this test, two bearings are sandwiched between three inclined platens under the sole application of a compressive force. The detailed explanation of this new test method and its performance on full-size bearings will be presented herein.

An experimental program was designed to evaluate the performance of the inclined compression test on full-size bearings. In order to make a sound evaluation, certain bearings were tested by the full-scale shear test and the inclined compression test. Successive chapters will include the explanation of these test setups and the correlation between the shear modulus values obtained from these two test methods. In addition, the effects of certain test parameters were investigated in order to establish a valid test procedure with the new test method. These parameters are compressive stress, shape factor, surface conditions, speed of testing, and edge cover.

CHAPTER 2

TEST SETUPS AND SPECIMENS

2.1 Inclined Compression Test Setup

In the inclined compression test setup, two bearings are sandwiched between three inclined aluminum platens (Figures 2.1 and 2.2). Aluminum was chosen for the platen material because of its lightweight and the low cost of milling the slope. Platens were 20x20 inches in plan dimension. These dimensions were adequate to accommodate most typical sizes of bridge bearings, both circular and rectangular. Top and bottom plates were mounted to a 600-kip compression machine. Two sets of inclined platens were used in the research program. One set had a slope of 1:10 and the other set had a 1:20 slope. Platen surfaces were roughened to simulate a concrete surface in order to prevent slipping of the bearings. Several surface conditions were tried; sand blasted, sand paper and mechanically roughened. Finally, the platen surfaces were roughened by an impacting machine used to roughen concrete surfaces. Figures 2.3 and 2.4 show a roughened surface and the roughening tool. Details related to different surface conditions will be given in the next chapter. According to the slope of platens, a certain percentage of compressive force is transmitted to the bearing as a shear force (5% for 1:20 slopes, 10% for 1:10 slopes). Therefore, under the application of compressive force from the test machine, the bearings are subjected to simultaneous compressive and shear stresses. Compressive load and displacement of the middle platen were recorded during testing using a data acquisition system. Data was recorded every one second so that the complete load-displacement response could be documented. Linear potentiometers accurate to 0.001 in were used to monitor the displacement. The same data acquisition system was used in all test setups.

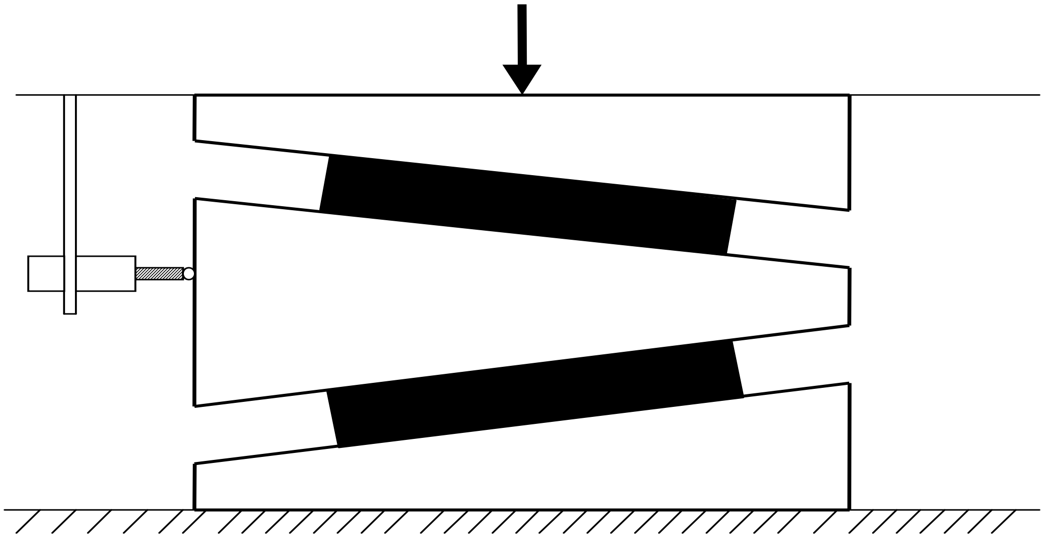

Figure 2.1: Schematic of the Inclined Compression Test

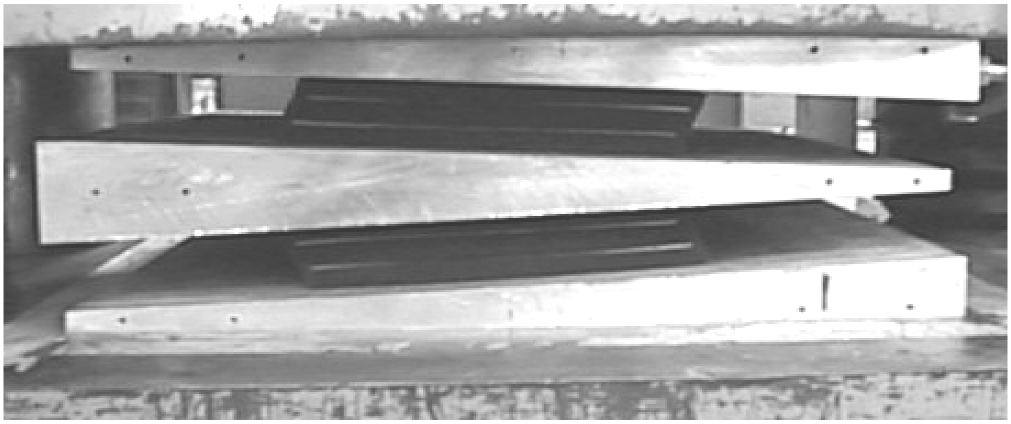

Figure 2.2: Side View of the Inclined Compression Test Setup

2.2 Full-Scale Shear Test Setup

A setup constructed for another research project was used to perform the full-scale shear tests. This setup consists of a three dimensional frame in which two bearings are sandwiched between three platens (Fig 2.5). It was designed to duplicate the dead weight and the daily thermal deformation response of the bridge girder. In order to

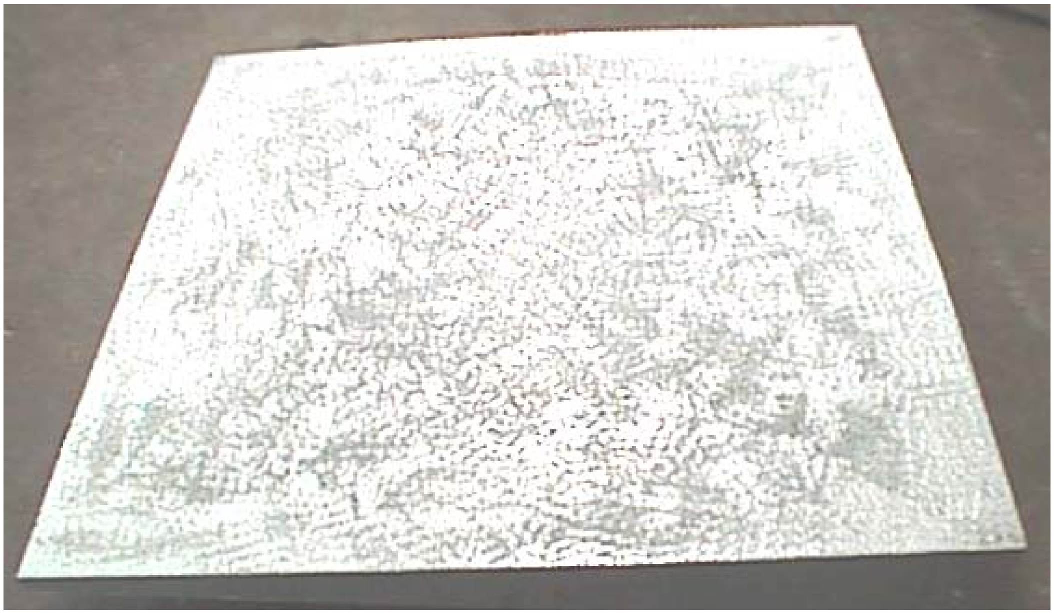

Figure 2.3: Roughened Aluminum Platen

Figure 2.4: Head of the Roughening Tool

simulate the same surface conditions, flat aluminum platens with the same roughness as the inclined compression setup were used. Compressive stress was applied by a 600-ton hydraulic ram. A dead weight system was used to maintain a constant compressive stress during a test. The horizontal movement of the bridge girder was simulated by displacing the middle platen using two 35-ton screw jacks. Horizontal load was measured by the 50-kip load cells that were connected to the screw jacks. Linear potentiometers were mounted to record the middle platen displacement. Details of this test setup are given in Muscarella, 1995.

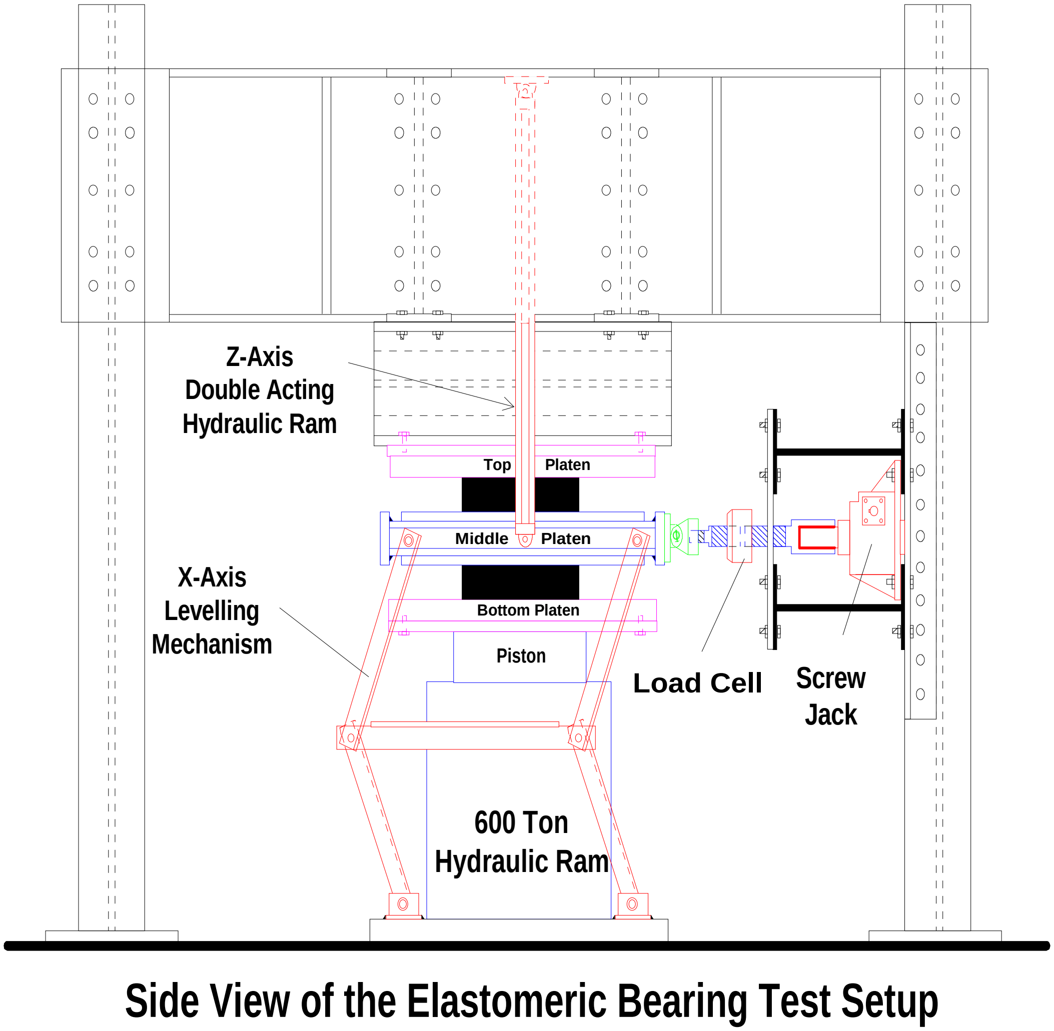

Figure 2.5: Schematic of the Full-Scale Shear Test Setup

2.3 Test Specimens

All bearings were ordered from the same manufacturer with the shear modulus specified, not hardness. In order to investigate the possible differences between compounds, two types of elastomeric material were ordered, namely Natural Rubber and Neoprene. All bearings were flat. Bearings were ordered with three different shear modulus values (100 psi, 150 psi and 200 psi). These modulus values encompass the typical values used in practice. Most bearings ordered were rectangular in shape. There were two types of rectangular bearings, namely, laminated and plain. Laminated bearings had specified dimensions of 28x9x1.75 inches and plain bearings had specified dimensions of 28x9x1 inches. These bearings were cut in half (14x9) so that the two pads in each of the two setups were cut from the same bearing. When cut in half, these bearings have dimensions commonly used in practice.

In order to investigate the effects of shape factor, laminated circular bearings were ordered. Since the effect of the elastomeric material was going to be investigated on rectangular pads, circular pads were ordered with three different shear modulus for only one compound, namely, Natural Rubber. For circular pads, two complete bearings from the same batch were used in each of the two setups.

All laminated pads have two shims having a thickness of 0.125 inches and have an edge cover of 0.25 inches. There are three elastomer layers having a thickness of 0.5 inches. Table 2.1, Table 2.2, and Table 2.3 present the specified physical properties of the laminated rectangular, laminated circular, and plain rectangular pads, respectively. In general, the supplied bearings had dimensions close to the specified ones. Some minor variations were present but they do not significantly influence the test results so the specified dimensions will be used in calculations. In addition, when bearings were cut, it was observed that there was no significant shim misalignment. The tolerance values for shim misalignment in the AASHTO code was satisfied. The surfaces of the bearings were steam cleaned prior to testing to remove surface wax.

Table 2.1: Specified Properties of Laminated Rectangular Bearing Test Specimens

Specimen Number	Compound	Requested Modulus (psi)	W (in)	L (in)	Thickness (in)	Total Elastomer Thickness (in)
01	NR	100	14	9	1.75	1.50
02	NEO	100	14	9	1.75	1.50
03	NR	150	14	9	1.75	1.50
04	NEO	150	14	9	1.75	1.50
05	NR	200	14	9	1.75	1.50
06	NEO	200	14	9	1.75	1.50

Table 2.2: Specified Properties of Laminated Circular Bearing Test Specimens

Specimen Number	Compound	Requested Modulus (psi)	Diameter (in)	Thickness (in)	Total Elastomer Thickness (in)
07	NR	100	15	1.75	1.50
08	NR	150	15	1.75	1.50
09	NR	200	15	1.75	1.50

Table 2.3: Specified Properties of Plain Rectangular Bearing Test Specimens

Specimen Number	Compound	Requested Modulus (psi)	W (in)	L (in)	Thickness (in)
10	NR	100	14	9	1.00
11	NEO	100	14	9	1.00
12	NR	150	14	9	1.00
13	NEO	150	14	9	1.00
14	NR	200	14	9	1.00
15	NEO	200	14	9	1.00

NR: Natural Rubber, NEO: Neoprene, W: Width, L: Length

CHAPTER 3

TEST RESULTS AND DISCUSSION

This chapter focuses on the presentation of test results in two parts. In first part, tests performed for shear modulus correlation will be presented while the second part will be devoted to the investigation of testing parameters.

3.1 Tests for Shear Modulus Correlation

For correlation purpose all bearings were tested in the full-scale shear test setup and the inclined compression test setup. Roughened aluminum surfaces were used on both test setups. For the full-scale shear tests, a compressive stress of 450 psi was applied to laminated and plain rectangular bearings while a stress of 650 psi was applied to laminated circular pads. A horizontal force was applied and the pads were sheared to slightly higher than 50 percent in one direction. The direction of the force was then reversed and the pads were sheared to slightly higher than 50 percent strain in the opposite direction. The rate of displacement of the bearings was 1 in/18 min. The loading and unloading cycles were repeated until the load-displacement curve stabilized. Fig 3.1 shows a typical load-displacement curve obtained from a full-scale shear test. In addition to the two-way test, a one-way test was also performed on specimens.

Since the difference in shear modulus between a one-way and a two-way test was minimal, shear modulus was determined from the secant line between +/- 50% strain utilizing equation 3.1. For this case Δ_s was taken between +/- 50 % strain contrary to its previous definition.

$$G = \frac{H\, h_{rt}}{A\, \Delta_s} \qquad (3.1)$$

Specimens were tested in the inclined compression test setup for both the 1:20 and 1:10 sloped platens. A compressive force was applied such that the shear strain on the bearings was slightly higher than 50 percent. Then, the compressive force was reduced until it reached 1 kip. A similar loading procedure was used for the successive cycles. Testing was continued until the load-displacement curve stabilized. Stabilization was generally achieved after the fourth cycle. In general, the first cycle was significantly different from the others. The rate of displacement of the bearings was similar to that used in the full-scale shear test. Figure 3.2 shows a typical load-displacement curve obtained from an inclined compression test. The shear modulus was determined from the secant line between 0-50 % strain utilizing Eq. 3.1. For this typical test, the shear modulus changed from 140 psi to 144 psi from first to fifth cycle.

Table 3.1 shows the test results for the full-scale shear tests. ASTM Quadruple Shear Tests were performed on the rubber specimens during manufacturing process. The test results from the quadruple shear test were supplied by the manufacturer. These values are also presented in Table 3.1 under the heading of mill report. Quad-shear results are within +/- 15% tolerance required by AASHTO. In addition, Figure 3.3 shows a bar chart of the experimental shear modulus from the quad shear and full-scale tests normalized with respect to specified modulus.

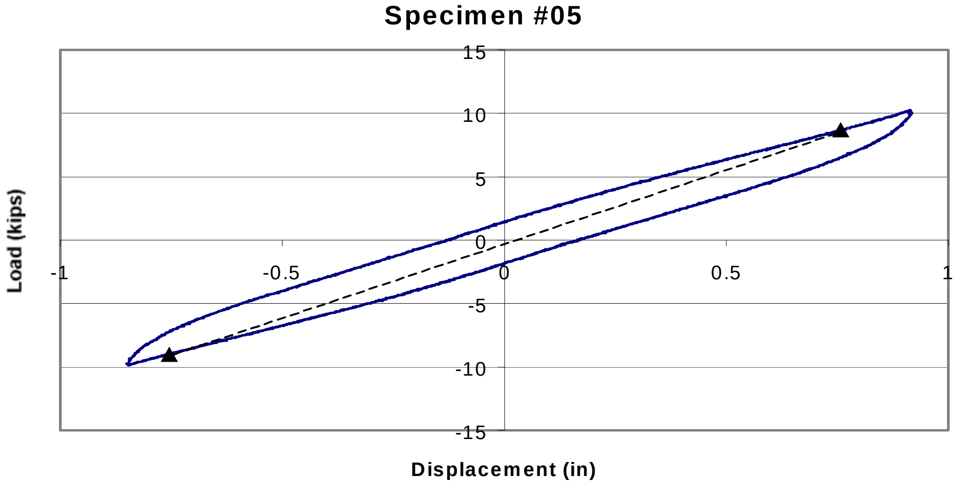

Figure 3.1: Typical Load-Displacement Curve from a Full-Scale Shear Test

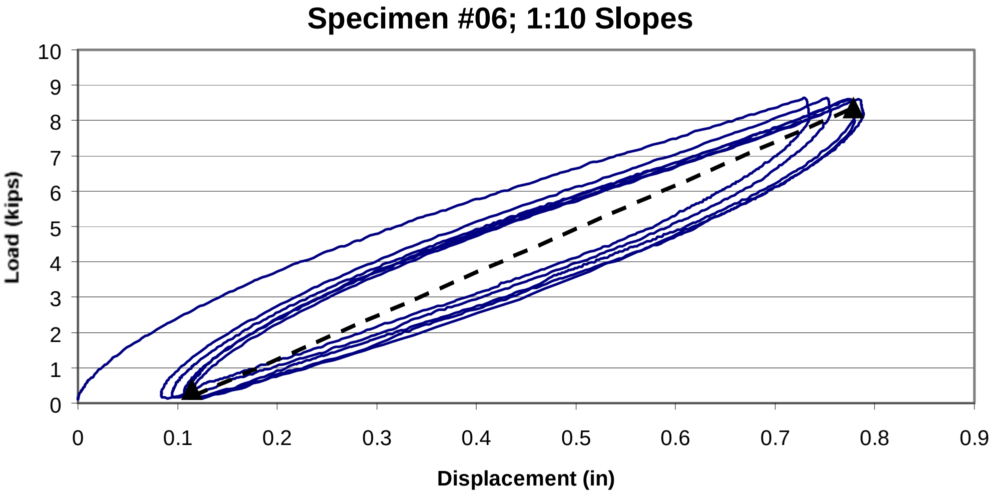

Figure 3.2: Typical Load-Displacement Curve from an Inclined Compression Test

Table 3.1: Quad-shear and Full-Scale Test Results

Compound	Specified Modulus (psi)	Mill Report (psi)	Percent Difference	Specimen Number	Type	Full-Scale Test (psi)	Percent Difference
NR	100	113.6	+13.6	01	R	84.9	-15.1
				07	C	72.8	-27.2
				10	P	85.4	-14.6
NR	150	141.1	-5.93	03	R	93.6	-37.6
				08	C	110.2	-26.5
				12	P	156.5	+4.33
NR	200	194.4	-2.80	05	R	139.2	-30.4
				09	C	151.5	-24.3
				14	P	153.5	-23.3
NEO	100	91.6	-8.40	02	R	70.4	-29.6
				11	P	96.7	-3.30
NEO	150	153.5	+2.33	04	R	125.6	-16.3
				13	P	118.0	-21.3
NEO	200	181.7	-9.15	06	R	140.4	-29.8
				15	P	162.2	-18.9

R: Laminated Rectangular ; C: Laminated Circular; P: Plain Rectangular

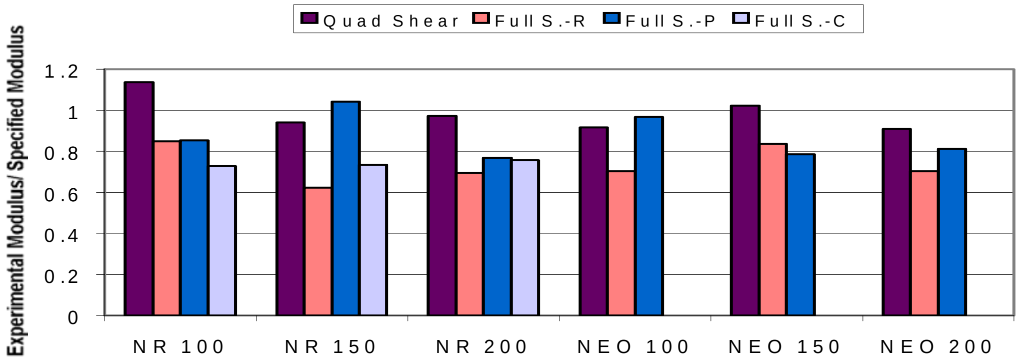

Figure 3.3: Comparison of Quad Shear and Full-Scale Shear Test Results

The full-scale test, in general, gives lower shear modulus values compared to the quadruple-shear test. The same conclusion was drawn by Arditzoglou, Yura and Haines,1997. Specimen size and amount of strain have great influences on the differences between these two test methods. In the quad-shear test modulus was determined at 25 percent strain while in the full-scale test, modulus was calculated between +/- 50 percent strain. Due to the nonlinear response characteristics of rubber, shear modulus decreases as the percent strain increases in the range of shear strain found in bridge bearings (+/- 50%). A better comparison can be made if the same amount of strain is used in the definition of shear modulus for both test methods. Since the modulus at 50 percent for the quad shear test was not reported by the manufacturer, it is not possible to make comparisons at 50 percent strain. On the other hand, in order to make comparisons at 25 percent, full-scale specimens have to be strained close to this value. Straining to a much higher value like 50 percent and calculating the modulus at +/- 25 percent gives erroneous results. Figure 3.4 shows a load-displacement curve for a specimen strained to various different levels by using the full-scale shear test setup. For this kind of setup, the response curve is like a boundary which enlarges with the increased strain. Figure 3.4 is for a neoprene specimen of dimensions 8.25x13.5x1.75 in (edge cover removed) with a specified modulus of 150 psi. The specimen was strained to 30, 50 ,and 60 percent strain. If the shear modulus is calculated at 30 percent strain, its value appears to be 154psi, 165 psi, and 178 psi for 30 percent, 50 percent, and 60 percent strain curves, respectively. Therefore, if the specimens are strained to a much higher value than the value at which modulus is calculated, inaccurate modulus values can be encountered. Since it is not the scope of this thesis to investigate the differences between quad-shear and full-scale shear test, no additional tests were performed for lower strains.

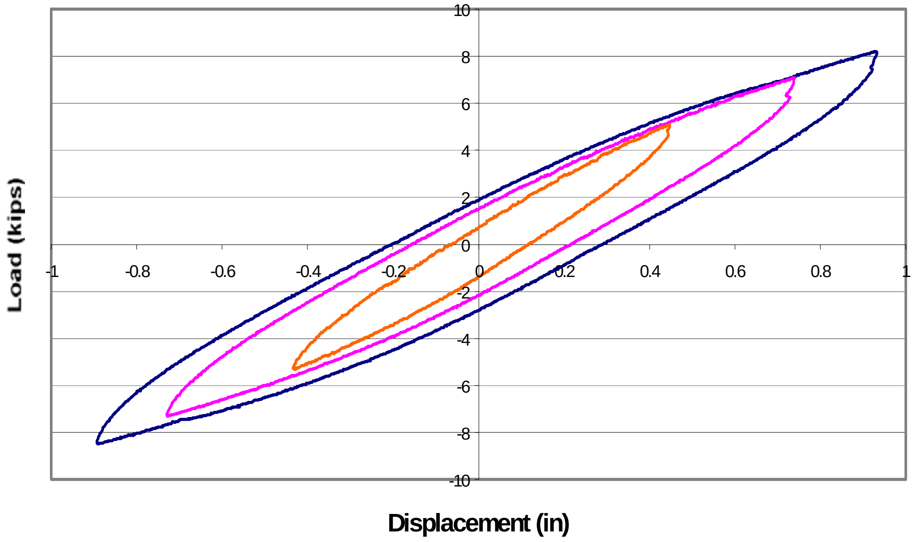

Figure 3.4: Full-Scale Shear Test at Different Strain Levels

It is evident from Table 3.1, that there is a large difference between the two test methods and the quad-shear test is not capable of adequately evaluating the performance of full-size bearings. In addition, for the same elastomeric compound there are differences in shear modulus values for different types of full-size specimens. All these findings confirmed the need for a new test method for full-size bearings.

Tables 3.2, 3.3, and 3.4 shows the test results from the inclined compression test for two different slopes and also includes the percent differences with respect to the full-scale shear test results. In addition, Fig 3.5 shows the bar chart of the inclined test results normalized with respect to full-scale test results.

Table 3.2: Inclined Compression Test Results for Laminated Rectangular Bearings

Specimen Number	Comp.	Specified Modulus (psi)	Full-Scale Test (psi)	Inclined Test 1:20 (psi)	Percent Difference	Inclined Test 1:10 (psi)	Percent Difference
01	NR	100	84.9	85.2	+0.35	93.7	+10.4
02	NEO	100	70.4	66.7	-5.26	75.7	+7.53
03	NR	150	93.6	94.5	+0.96	106.3	+13.6
04	NEO	150	125.6	131.6	+4.78	142.8	+13.7
05	NR	200	139.2	122.4	-12.1	159.7	+14.7
06	NEO	200	140.4	134.2	-4.42	144.2	+2.71

Table 3.2: Inclined Compression Test Results for Laminated Circular Bearings

Specimen Number	Comp.	Specified Modulus (psi)	Full-Scale Test (psi)	Inclined Test 1:20 (psi)	Percent Difference	Inclined Test 1:10 (psi)	Percent Difference
07	NR	100	72.8	67.3	-7.55	75.8	+4.12
08	NR	150	110.2	98.0	-11.1	112.6	+2.17
09	NR	200	151.5	149.0	-1.65	166.5	+9.90

Table 3.3: Inclined Compression Test Results for Plain Rectangular Bearings

Specimen Number	Comp.	Specified Modulus (psi)	Full-Scale Test (psi)	Inclined Test 1:20 (psi)	Percent Difference	Inclined Test 1:10 (psi)	Percent Difference
10	NR	100	85.4	59.6	-30.2	65.9	-22.8
11	NEO	100	96.7	56.0	-42.1	70.4	-27.2
12	NR	150	156.5	119.8	-23.5	129.8	-17.1
13	NEO	150	118.0	63.6	-46.1	71.8	-39.2
14	NR	200	153.5	145.4	-5.28	154.5	+0.65
15	NEO	200	162.2	121.1	-25.3	134.1	-17.3

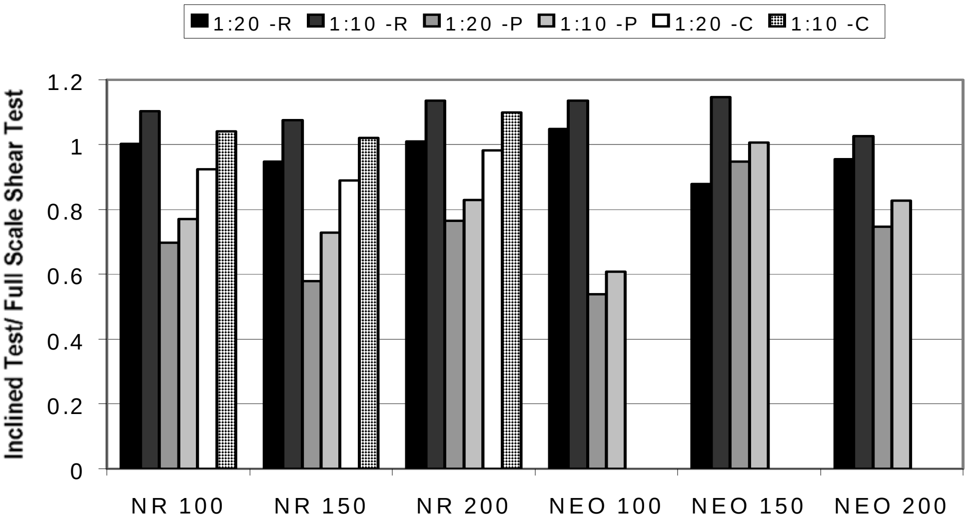

Figure 3.5: Comparison of Inclined and Full-Scale Test Results

According to the test results, the inclined compression test is capable of giving good estimations of shear modulus at 50 percent strain for laminated pads. For these pads the difference in shear modulus is within +5 to -12 percent range. Tests with 1:10 slopes give higher shear modulus values compared to the ones with 1:20 slopes. This fact might be related to the level of compressive stress. A bearing tested with 1:20 slopes is subjected to twice the compressive stress of the case with 1:10 slopes. This will be discussed in more detail later.

On the other hand, for the plain rectangular pads, there are large differences between two test methods. For some bearings the difference exceeds 40 percent. In general, the inclined test exhibits a flexible behavior compared to the full-scale shear test for the plain pads. This might be due to the fact that under the action of compressive stress, plain pads bulge and excessive slipping occurs at the edges. Since it is not possible to perfectly align the bearings in the setup, the edges of the bearing slip unequally. This unequal slip phenomenon results in the global slipping of the bearings.

This fact could best be investigated by examining the load-displacement response of a plain pad . Figure 3.6 shows a typical response curve for the first two cycles.

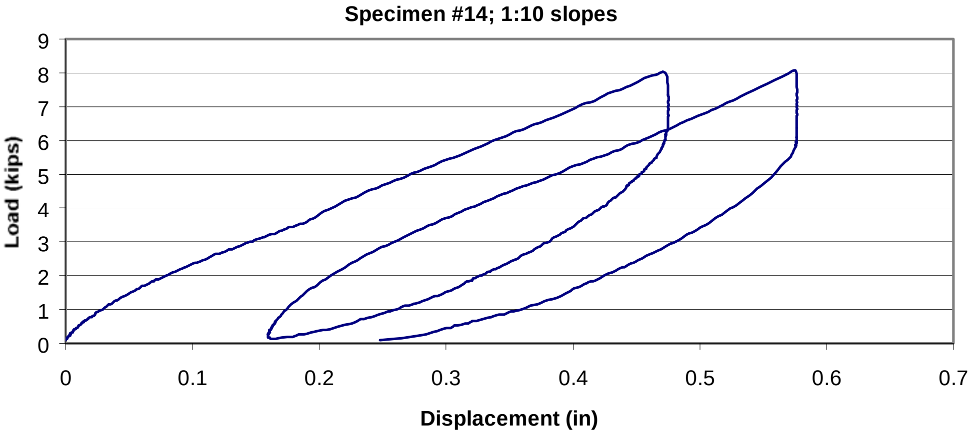

Figure 3.6: Load-Displacement Curve for a Plain Pad Tested under Inclined Compression

Contrary to laminated pads, in plain pads the middle platen does not return to its original position. This proves that bearings are slipping. In this kind of pad, the load-displacement curve never stabilizes. Therefore, in the tests only two cycles were carried out for plain pads.

In summary, the inclined compression test is capable of estimating the behavior of full-size laminated pads. However, this test method gives inaccurate values of shear modulus for the plain pads. Further studies would have to be carried out to investigate the applicability of this test method to plain pads.

3.2 Investigation of Testing Parameters

3.2.1 Effect of Compressive Stress

As presented in the previous section, there is a difference in shear modulus between tests with two platen slopes used in the inclined compression test. The compressive force applied in the inclined compression test is related to the slope of the platens. As the slope gets steeper, less compressive force is required to attain a certain percentage of shear strain. In order to understand whether the difference in test results is related with compressive stress or not, the effect of compressive stress was investigated. For this purpose, additional tests were performed with the full-scale shear test setup. Tests were conducted on laminated rectangular bearings and the compressive stress was increased from 450 psi to 900 psi. The same test procedure explained in Section 3.1 was applied. Table 3.4 shows the test results for the two different compressive stress values together with the maximum applied compressive stress in the inclined compression test.

Table 3.4: Test Results for the Effect of Compressive Stress

Specimen Number	Comp.	Specified Modulus (psi)	Maximum Applied Compressive Stress (psi)		Shear Modulus Full-Scale Test (psi)		% change
			1:20 Slopes	1:10 Slopes	450 psi	900 psi	
01	NR	100	852	469	84.9	84.5	-0.47
02	NEO	100	667	379	70.4	68.5	-2.70
03	NR	150	945	532	93.6	103.4	+10.5
04	NEO	150	1316	714	125.6	136.7	+8.84
05	NR	200	1224	799	139.2	149.8	+7.61
06	NEO	200	1342	721	140.4	142.9	+1.78

According to full-scale shear test results, there is a slight change in shear modulus with the increase in compressive stress. In general, the shear modulus value appears to increase with an increase in compressive stress. On the other hand, for the inclined compression test, specimens with low compressive stress(1:10 slopes) appear to give higher shear modulus values compared to the ones subjected to high compressive stress(1:20 slopes). In terms of the effect of compressive stress, the two test methods are contradictory. The reason for this contradiction is inconclusive. The difference in experimental shear modulus from test setups with two different platen slopes cannot be explained by the level of compressive stress. However, the application of compressive stress might have an effect on the results. In the full-scale test setup, compressive stress is kept constant throughout the test period. On the other hand, in the inclined compression test, compressive stress is increased from zero to the maximum value at each cycle. The difference in inclined compression test results cannot be fully explained by making use of the full-scale shear test results because of the difference in the application of compressive stress.

3.2.2 Effect of the Speed of Testing

In order to establish a test method, the effect of the speed of testing has to be investigated. To accomplish this task certain bearings were tested in the inclined compression test setup for different duration. Platens with 1:20 slopes were used to perform the tests. Neoprene laminated rectangular bearings with specified shear moduli of 100 and 200 psi were chosen as the test specimens. In previously presented tests, specimens were strained to 50 percent in 14 minutes. In service, bearings are strained in a much longer time period like 12 hours. On the other hand, for commercial evaluation of material properties, tests with short loading duration are preferred. Due to these reasons, bearings were strained to 50 percent over time periods that ranged from two minutes to seven hours.

First, bearings were cycled three times not considering the duration. Then data were collected during the fourth cycle every 1 second for short duration tests and in every 100 seconds for the long duration tests. Table 3.5 shows the test results for the time of testing. The duration shown are for the loading from zero to 50 percent strain. In addition, Fig. 3.7 shows the load-displacement response of the neoprene bearing with a specified modulus of 200 psi for different test periods.

Test results revealed that testing time has an influence on the shear modulus. Under fast loading bearings tend to exhibit stiffer behavior. The difference between the results can be related to the creep of the elastomer. A slowly loaded specimen creeps more so it shows more flexible behavior. These findings revealed that the testing time should be specified for a standardized test method. Short duration tests give conservative estimates of the shear modulus.

Table 3.5: Test Results for the Speed of Testing

Specimen Number	Compound	Specified Modulus (psi)	Testing Time	Experimental Modulus (psi)	% difference
02	NEO	100	2 Minutes	68.6	+2.85
			14 Minutes	66.7	0
			3 Hours	57.0	-14.5
06	NEO	200	2 Minutes	140.9	+4.99
			14 Minutes	134.2	0
			7 Hours	129.2	-3.73

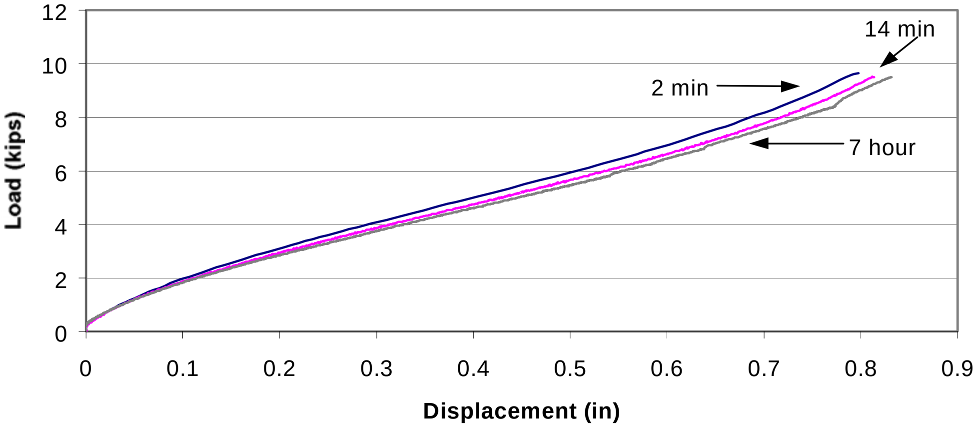

Figure 3.7: Load-Displacement Response for Different Test Duration

3.2.3 Effect of Testing Surfaces

A significant research effort was dedicated to the investigation of testing surfaces. The purpose was to choose a robust test surface for the inclined compression test that simulates a concrete surface which prevents slipping of bearings, is reproducible and is not costly. First the surfaces were sand blasted. There was little slipping with the sand blasted surfaces but the roughness appeared to deteriorate from use. Then, 40 grit cloth sandpaper was glued to the metal platens. The tests with the glued sandpaper showed no slip. Unfortunately, the sandpaper deteriorated and tore rather quickly so such a surface is not practical for a standardized test. Finally, the aluminum surfaces were roughened with a tool used to prepare concrete surfaces. These surfaces solved the slip problem and were used in all of the tests performed in both test setups.

The problem of wax built-up on aluminum surfaces was also investigated. First, a laminated rectangular natural rubber bearing with a specified modulus of 200 psi was tested with the full-scale shear test setup. Then several bearings were tested with the same setup. The surfaces of the aluminum platens were not cleaned after each test. As a last step the same natural rubber bearing was retested. It was observed that the same bearing shows a different load-displacement behavior due to slipping. There was significant amount of wax built-up on the aluminum surfaces that caused the bearing slip before attaining 50 percent strain. Figure 3.8 shows the load-displacement behavior of the bearing for slipping and non-slipping surfaces. In order to solve the wax built-up problem, surfaces were cleaned with acetone. Then the same bearing was tested with the cleaned surfaces. The load-displacement response was exactly the same with the first test. This shows that after each test the surfaces of the platens should be cleaned to eliminate slip.

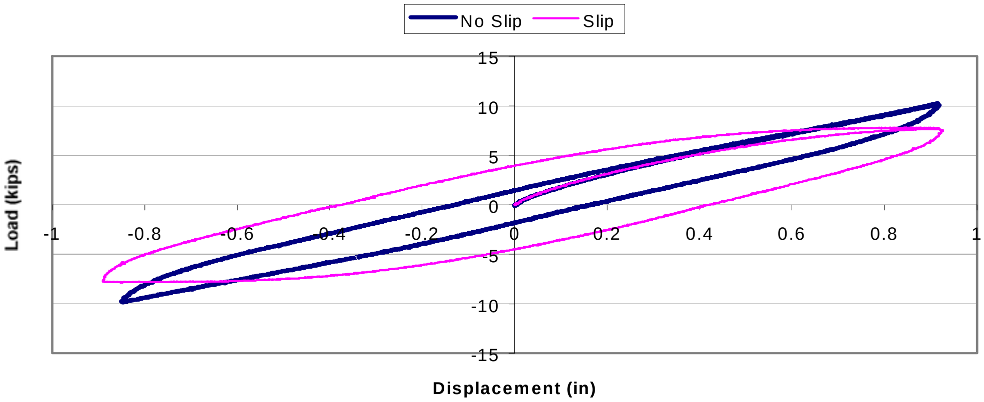

Figure 3.8: Effect of Wax Built-up

Another issue related with the testing surfaces is the use of sole plates. The effect of bonding the surfaces was investigated. Four types of laminated rectangular bearings were bonded to steel plates and tested in the full-scale shear test setup and inclined compression test setup (with 1:20 and 1:10 slopes). A compressive stress of 450 psi was applied in the full-scale shear tests. Table 3.8, 3.9, and 3.10 presents the test results for bonded surfaces.

Table 3.8: Test Results for Bonded Surfaces: Full-Scale Shear Test

Specimen Number	Compound	Specified Modulus (psi)	Experimental Modulus (psi)		% Change
			w/o sole plates	Sole Plates	
01	NR	100	84.9	94.4	+11.2
02	NEO	100	70.4	77.8	+10.5
05	NR	200	139.2	154.9	+11.3
06	NEO	200	140.4	145.7	+3.77

Table 3.9: Test Results for Bonded Surfaces: Inclined Compression (1:20 slopes)

Specimen Number	Compound	Specified Modulus (psi)	Experimental Modulus (psi)		% Change
			w/o sole plates	Sole Plates	
01	NR	100	85.2	89.8	+5.40
02	NEO	100	66.7	72.8	+9.15
05	NR	200	122.4	172.6	+41.0
06	NEO	200	134.2	150.0	+11.8

Table 3.10: Test Results for Bonded Surfaces: Inclined Compression (1:10 slopes)

Specimen Number	Compound	Specified Modulus (psi)	Experimental Modulus (psi)		% Change
			w/o sole plates	Sole Plates	
01	NR	100	93.7	93.3	-0.43
02	NEO	100	75.7	79.9	+5.55
05	NR	200	159.7	154.8	-3.07
06	NEO	200	144.2	145.7	+1.04

In general, the shear modulus values tend to increase when specimens are bonded. In bonded bearings edges cannot lift so there is an increased area of contact compared to unbonded specimens. As the contact area increases it is more difficult to deform the material so the bearing shows a stiffer response. In general, the change in shear modulus is between –3 to +10 percent. For the natural rubber specimen with a specified modulus of 200 psi, there is a significant change in shear modulus for inclined test with 1:20 slopes. This specimen showed a very flexible behavior in the test with aluminum surfaces. This might be an experimental error. Table 3.11 shows the differences between three test setups for the bonded bearings.

Table 3.11: Comparison of Test Setups for Bonded Bearings

Specimen Number	Comp.	Specified Modulus (psi)	Full-Scale Test (psi)	Inclined Test 1:20 (psi)	Percent Difference	Inclined Test 1:10 (psi)	Percent Difference
01	NR	100	94.4	89.8	-4.87	93.3	-1.17
02	NEO	100	77.8	72.8	-6.43	79.9	+2.70
05	NR	200	154.9	172.6	+11.4	154.8	-0.06
06	NEO	200	145.7	150.0	+2.95	145.7	0.00

It is evident from the test data that both 1:20 and 1:10 slopes are capable of estimating the shear modulus of bonded bearings. For this kind of bearings 1:10 slopes give closer values to the full-scale shear test results.

3.2.4 Effects of Edge Cover

Tests were performed to investigate the effects of edge cover on shear modulus. Laminated rectangular pads had an edge cover on three sides. The edges of two types of bearings were trimmed off so that the new dimensions became 13.5x8.25x1.75 inches. These bearings were retested in three different test types. Table 3.12 shows the test results for the trimmed bearings.

Table 3.12: Test Results of Bearings with Trimmed Edges

Specimen Number	Compound	Specified Modulus (psi)	Test Setup	Exper. Modulus (psi)		% change
				Not Trimmed	Trimmed	
03	NR	150	Full-Scale	93.6	106.7	+14.0
			Inclined 1:20	94.5	91.8	-2.86
			Inclined 1:10	106.3	106.4	+0.09
04	NEO	150	Full-Scale	125.6	134.5	+7.09
			Inclined 1:20	131.6	119.8	-8.97
			Inclined 1:10	142.8	133.8	-6.30

Test results showed that edge trimming makes little difference on shear modulus. Shear modulus tends to increase with edge trimming when specimens are tested in the full-scale shear test setup. On the other hand, modulus decreases when specimens are tested in inclined compression test setup. These changes are contradictory. However, it is worth to note that after edge trimming, full-scale test setup and inclined compression test with 1:10 slopes gives very close shear modulus values. This shows that inclined test with 1:10 slopes gives better estimates of shear modulus than the one with 1:20 slopes. All these findings revealed that in a standardized test method the edge type of specimens has to be specified.

3.2.5 Effects of Shape Factor

Performing full-size bearing experiments requires high capacity testing machines. For example, in the case of a 15 inch diameter circular bearing with a modulus of 150 psi tested under an inclined compression setup with 1:20 slopes, 265 kips of compressive force is required to strain the pad up to 50 percent. Because of limited test machine capacity full-size bearings may have to be cut into smaller sizes for testing. A change in dimensions indicates a change in the shape factor of the bearing. This section focuses on the effects of shape factor on shear modulus. Three types of circular bearings which had a shape factor of 7.5 were cut into squares. The squares had an edge length of

10 inches and had a shape factor of 5.0. These bearings were then tested in the inclined compression test setup (both 1:20 and 1:10 slopes) to find out the change in shear modulus due to a change in shape factor. Table 3.14 shows the test results for these bearings.

Table 3.14: Test Results for Investigating the Effects of Shape Factor

Specimen Number	Compound	Specified Modulus (psi)	Test Setup	Exper. Modulus (psi)		% change
				Circular	Square	
07	NR	100	Inclined 1:20	67.3	67.0	-0.45
			Inclined 1:10	75.8	74.6	-1.58
08	NR	150	Inclined 1:20	98.0	96.1	-1.94
			Inclined 1:10	112.6	114.8	+1.95
09	NR	200	Inclined 1:20	149.0	137.6	-7.65
			Inclined 1:10	166.5	149.1	-10.5

Test results showed that shape factor does not adversely affect the shear modulus of the product. Especially for the material having shear modulus between 65 to 115 psi, there is very little change in modulus. On the other hand, changes up to 10 percent were encountered for stiffer material. In general, there was a decrease in shear modulus due to a decrease in shape factor.

CHAPTER 4

SUMMARY AND CONCLUSIONS

This research aimed to evaluate the applicability of a new test method, the inclined compression test, for finding the shear modulus of full-size elastomeric bridge bearings. For evaluation purposes, laminated and plain bearings were tested with the full-scale shear test setup and the inclined compression test setup (using two different slopes). For the inclined compression test, the shear modulus was determined from the slope of the secant line drawn from zero to 50 percent shear strain. Comparisons with the full-scale test results revealed that the inclined compression test gives good estimates of shear modulus for laminated pads. However, for plain pads there are large differences in shear modulus between two test setups. This is due to the fact that plain pads tend to slip in the inclined compression test. Due to slip they exhibit a flexible behavior which is not similar to their behavior in the full-scale shear test.

Between the two slopes (1:10 and 1:20) used in inclined compression test there were differences in shear modulus. Attempts to explain the differences were not successful.

In order to standardize the inclined compression test, the effects of certain test parameters were investigated. Tests for the loading time showed that short duration tests (2 min. and 14 min.) give higher shear modulus compared to the long duration tests (3 hours and 7 hours) due to the creep of the elastomer. In addition, the effects of bonded surfaces were investigated. Certain specimens were bonded to steel plates and retested with both test setups. In general, shear modulus increased with the bonding of surfaces. The inclined compression test showed a similar increase in shear modulus due to bonding. Another test parameter was the presence of edge cover. Edge trimming resulted in an increase in shear modulus for the full-scale test while it resulted in a decrease in modulus for the inclined compression test. However, the test results for full-scale shear test and the inclined compression test with 1:10 slopes are very close for these kind of bearings (within 1 percent).

Finally, the effects of shape factor on shear modulus were investigated. Circular bearings with a shape factor 7.5 were cut into squares with a shape factor 5.0 and retested. Test results revealed that there was a change up to 10 percent in shear modulus due to a change in shape factor.

As a result, for a standardized test, the testing time, surface and edge conditions of the bearings have to be specified. A limited number of tests were conducted to determine the effect of specimen size. There was a small effect (up to 10 percent max.) for reducing a specimen from 15 in. diameter to a 10x10 in. square. Further tests on even smaller specimen need to be conducted to establish a lower limit specimen size.

Inclined compression test is suitable for determining the shear modulus of laminated elastomeric bridge bearings. Future research should concentrate on the applicability of inclined compression test method on plain pads. Additional research should be done on bearings with different dimensions and shim orientation. Also different compounds from other manufacturers have to be tested to increase the validity of this new test method.

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