ESTIMATION OF ELASTOMERIC BRIDGE BEARING SHEAR MODULUS USING OPERATIONAL MODAL ANALYSIS

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Abstract

This paper concerns with one of the most important application of composite laminates in the field of design of elastomeric bridge bearings. In this paper, first, the dynamic characteristics of elastometric bearings are extracted from operational modal analysis data. The shear modulus of them is then estimated comparatively with the dynamic properties calculated using conventional finite element analysis of elastomer pads. It was also noted that the calculated shear modulus for the bearings was in the range that has been specified by the AASHTO specification for bridge design. Two specimens are considered and several tests were carried out on each of them. The first specimen is worked as a bearing for more than 35 years in one of the concrete bridges in Isfahan-Tehran highway. The second one is a new bearing that supposed to be replaced with the old one. The results show that the shear moduli are in the range of 1.3-1.8 MPa for new and 0.6-0.8 MPa for old elastomer pads. The results of modal analysis indicate a reduction about 5-10 percent in natural frequencies of worn out elastomer pad in compare with the new one. The damping values for different modes of vibration show a reduction between 10-50 percent.

1 Introduction

Composite laminates have many industrial applications and in recent years, they are widely used in many civil engineering structures. One of the most applications of them that discussed in this article is the design and construction of elastomeric bridge bearings. In location of bridge deck supports, for creation of a simple support with free rotation and restricted longitudinal displacement over piers or abutments, elastomeric bearings may be either “plain” (consisting of elastomer only) or “laminated” (consisting of alternating individual layers of elastomer and internal steel laminates (Reinforced Elastomeric Bearings, REB)). In addition to any internal reinforcement, bearings may have steel load plates bonded to either or both the upper or lower elastomer layers. Steel plates placed within elastomer layers create high vertical stiffness while existence of rubber layers allows rotation and in plane shear deformations. Transverse and rotational displacements, in these types of bearings, are due to shear deformation between different elastomer layers and variation of compressive strain along the laminate respectively.

This type of bearings required proper shear deformability and rotational capacity, to avoid from transmission of large magnitude of horizontal loads and moments to piers or abutments. The vertical stiffness of the bearings should be designed in a way that under applied vertical loads, the change in their thickness be in the acceptable range.
The REB must not be under tension. The maximum allowable rotation is dependent upon the magnitude of vertical loads applied to the support to restrain the elastomer edges from tension. The REB has a key role in energy dissipation of the bridges against earthquake and improves the structural response against seismic loads (Refs [1, 2]). Figure 1 shows typical composite laminates, Steel-REB, and its application as bridge bearings.

Figure 1 Steel-Reinforced Elastomeric Bearings, SREB, and installation in bridge support

Figure 2 shows the three different possible deformation of the REB. The most important properties of elastomeric bearings are the shear ductility and high vertical stiffness in compression.

In general applications, elastomers are categorized by their stiffness parameter, because of its relation with other mechanical constants such as shear and compressive modulus and also the simplicity of its measurement. The degree of hardness for natural and vulcanized elastomer materials, based IRHD standard (International hardness degree for rubber material), is between 20 and 100. For example, this degree is about 30 for soft rubber and 60 for automobile tires. The rubber materials that used in elastomeric bridge bearings have a degree of hardness between 50 to 70 IRDH. These materials can made from natural or artificial rubber (i.e. Neoperene and Polychloroprene). In general, natural rubbers are more suitable for bridge bearings (Ref [3]).

Mechanical properties of these composites are highly dependent upon several factors, i.e. type of rubber, production process etc. Design codes of practice just convey some recommends in this matter and do not have any essential requirements for any especial specification. As mentioned above, accordance of design specifications with constructed ones is important for structural engineers. For this reason, determination of mechanical properties of these composites is a significant topic.

In this paper, first, the shear modulus of SREB is extracted from operational modal analysis data. Two specimens are considered and several tests were carried out on each of them. The first specimen is worked as a bearing for more than 35 years in one of the concrete bridges in Isfahan-Tehran highway. The second one is a new bearing that supposed to be replaced with the old one.

2 Mechanical properties of elastomer material

Mechanical properties of elastomers can be represented by hardness or shear modulus. In the past, only the parameter of hardness have been used for elastomeric bearing pads, but nowadays the shear modulus is a common parameter for the definition of elastomers and it is also recommends that not to use the hardness. In the following sections, both of parameters are briefly explained.
2.1 **Elastomer hardness**

The expression of hardness has several meanings, i.e. strength to elastic deformation or sliding, etc. Different test methods of hardness are based on the measurement of one of these two characteristic. Of course, standard tests that measure the local elastic deformation of material can only be used for deformable materials, such as metals or some plastics. The required tests here are penetration type and may be static or dynamic. In static test, that commonly be used, a specific needle penetrate into the specimen under definite pressure and penetration value is measured. The degree of hardness depends on this value. Although the penetration tests can not measure the wear, but in general, more hardness materials have appropriate slid and abrasion strength.

Before 1985, Durometer Hardness was being used as mechanical property of elastomer bridge bearings. The elastomer must have a nominal hardness between 50 and 70 Durometer (before 1973, it was between 60 and 70) with tolerance of ±5. Just now highly recommended that shear modulus is used instead of hardness for definition of behavioral specifications, since hardness is a limited measurement criterion (Ref [4]). Hardness has been widely used in the past because the test for it is quick and simple. However, the results obtained from it are variable and correlate only loosely with shear modulus.

2.2 **Elastomer shear modulus**

Shear modulus, G, is the most important material property for design, and it is, therefore, the preferred means of specifying the elastomer. Though it is possible that different products of one elastomer have the same hardness and various shear modulus. Shear modulus is a property that is determined from characteristic force-deformation function of one constructed specimen. In some cases, elastomer manufacturers may introduce and categorize their products based hardness. Therefore, designers must be aware and use from the relations between these two parameters to determine the shear modulus. In Ref. [2] the relations between hardness and shear modulus for natural rubber materials, used in elastomeric bearings, are mentioned and summarized in Table 1.

<table>
<thead>
<tr>
<th>Hardness (IRHD(±2))</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
<th>55</th>
<th>60</th>
<th>65</th>
<th>70</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Modulus(G), MPa</td>
<td>0.38</td>
<td>0.45</td>
<td>0.53</td>
<td>0.63</td>
<td>0.75</td>
<td>0.89</td>
<td>1.04</td>
<td>1.22</td>
<td>1.42</td>
</tr>
<tr>
<td>Bulk Modulus(E_b), MPa</td>
<td>2000</td>
<td>2000</td>
<td>2030</td>
<td>2060</td>
<td>2090</td>
<td>2120</td>
<td>2150</td>
<td>2180</td>
<td>2210</td>
</tr>
</tbody>
</table>

The bearing pads shall be constructed in conformance with the American Association of State Highway and Transportation Officials (AASHTO) Specification M 251 (latest edition) and in conformance with details shown in the plans, or the AASHTO Specification for Highway Bridges where referenced. Steel-reinforced elastomeric bearings may be designed using either of two methods commonly referred as Method A and Method B based on section 14.7.5 of AASHTO bridge design specification (Ref [5]). The most important parameters in designing of bearing pads are elastic and shear modulus of elastomer. Section 14.7.5.2 of AASHTO LRFD specification (Ref [5]) explains that the elastomer shall have a shear modulus between 0.6 and 1.3 MPa and a nominal hardness between 50 and 60 on the Shore A scale. It shall conform to the requirements of section 18.2 of the AASHTO LRFD bridge construction specifications (Ref [6]). The shear modulus of the elastomer at 23°C shall be used as a basis for the design. If the elastomer specified explicitly by its shear modulus, that value shall be used in design and the other properties shall be obtained from Table 2. If the material is specified by its hardness, the shear modulus shall be taken as the least
favorable value from the range for that hardness given in Table 2. Intermediate values may be obtained by interpolation (Ref [5]).

Table 2. Shear modulus, G, based AASHTO specifications (Ref [3])

<table>
<thead>
<tr>
<th>Hardness (Shore A)</th>
<th>50</th>
<th>60</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Modulus (MPa) @ 23°C</td>
<td>0.66-0.90</td>
<td>0.90-1.38</td>
<td>1.38-2.07</td>
</tr>
</tbody>
</table>

Ref. [4] addresses the results of the widest experiments have been applied on several different elastomeric bridge bearings. In addition, the effect of some parameters including thermal effect, dynamic loading, creep, loading cycles etc. have been also investigated. The results of this research are used for improvement of the AASHTO specification for elastomeric bearings.

Service life of elastomeric bearings is depends upon environmental condition of structure and loading situation. Design manuals predict the effective life between 30 and 50 years. Over this life if the periodic or in-depth inspections show that their workability have reduced, replacement of the bearings is recommended. It is evident that replacement of these elements is difficult workmanship and it is costly. Also, traffic over bridge shall be closed during operation.

Disregarding the shape and the size of these elements that are determined based on external loads and properties of each elastomer layers, in different loading and environmental conditions, several types of damages, as following, may be detected over service life.

1. Delamination or split of steel and elastomer layers which causes extreme reduction in shear strength.
2. Tearing of elastomer layers, due to inadequate shear strength or incorrect design.
3. Crushing of elastomer layers, due to excessive overloads or rotation.
4. Aging of elastomer and thus loss of mechanical properties respect to design specifications.

Some of detected damages on laminated composites and the effect of them on general properties of these elements have been investigated on several papers (Refs [7, 8]).

With notice to several damages that may be occurred in service life of these elements, evaluation of behavior and determination of mechanical properties of these composites and compare them with design or code recommended values is important. Also, a criterion that can predict the replacement time of elastomeric bridges bearings will help to bridge maintenance and repair agencies. In addition, mechanical properties of the bearings are essential for modeling, behavior assessment, seismic evaluation and retrofitting of existing bridges. Therefore, a simple method that can have an initial estimation for shear and elastic modulus of elastomeric bearings will be an important issue. In this paper, the shear modulus of two steel-reinforced elastomeric bridge bearings is extracted with appropriate accuracy, using operational modal analysis.

3 Standard test methods for determination of mechanical constants of elastomeric pads

In AASHTO specification M251-97, three test methods have been described for extraction of elastomeric bridge bearing shear modulus, including as:

3.1 four-handed shear test (based ASTM D4014-89)

This test is performed on small sliced specimens made from one bearing, as shown in Figure 3. Theses sliced segments are loaded under tension until 50% of shear strain is reached. The shear
modulus is calculated based on stresses and strains associated with 25% of shear strain. In this method, elastomer pads are loaded only in one direction.

3.2 Nondestructive compressive-shear test of confined full scale elastomeric bearing

In this method, as shown in Figure 4, a compressive vertical load is applied on two sets of elastomeric bearings and steel cover plates and are kept constant during the test, then, the middle plate is loaded horizontally, as actual modeling of bridge deck displacement. The applied shear force may be in one or two direction.

The results of this full scale test method are more realistic with respect to four-handed test. However, it is more costly. Maalek et al. (Ref [3]) used this test method to determine mechanical constants of three different actual size electrometric bridge bearing.

3.3 Slant shear test

This method is simple and accurate in determination of shear modulus of elastomeric bearings. This method is recommended in Ref [4] for using in future developments of AASHTO specifications. The results of this method have a better correlation with the technique described in 3.2. The test setup is shown in Figure 5. The surfaces of steel plates became rough to keep bearing away from slid.

3.4 Modal analysis

Another method to determine mechanical properties of composite laminates, as described in literature, is using vibration data, including natural frequencies, damping and mode shapes extracted from modal analysis. In this paper, a new and appropriate modal test method, Operational Modal Analysis (OMA), is used for extraction of modal data from several elastomeric bridge bearings (Ref [9]). In the next section, the performed test and its results are illustrated.

4 OMA tests of elastomeric bridge bearings and test results

In this study, 35 years old steel-reinforced elastomeric bridge bearings of a two span simply supported reinforced concrete bridge in the middle of Isfahan-Tehran highway have been used. According to in-depth inspections of this bridge, several damages had been distinguished and replacement of elastomeric bearings with new pads was proposed. Longitudinal view and bridge deck section are shown in Figures 6 and 7, respectively.

The bridge deck must be lifted up for exiting of worn out elastomer pads. One steel frame and four vertical heavy hydraulic jacks with 500 Ton capacity that worked simultaneously was used for this work. The operation shown in Figure 8 is for bridge pier and one abutment.
Several local damages were distinguished in worn out elastomer pads. Initial visual inspection has shown that some of them are weathering and completely unusable. Cross section of elastomer pads and location of reinforcement steel plates, also apparent view of new and worn out elastomer pads is shown in Figure 9.

OMA technique is used for identification of dynamical and mechanical properties of elastomeric pads after exiting of them. With notice that top and bottom layers of this elastomer pads have been covered by elastomer material (see Figure 9), classical modal analysis, using hammer impulse method as excitation force, was inapplicable and creation of actual excitation conditions nearly impossible. Two alternative methods for removing this problem was exist: 1) Harmonic excitation with a shaker and, 2) OMA test.

OMA method was selected, because of simplicity, existing equipments and time saving. For creation of excitation conditions for elastomeric bearing and using OMA technique, a small unbalanced vibration motor installed on a steel plate near to elastomeric pad. OMA post-processing computer program also is employed. Figure 10 shows a picture of test setup and measurement process.

Each elastomer pad itself is supported over a steel plate which is regarded as stiff compared to the pad itself. Measurement degree of freedom and accelerometer locations for each pad is shown in Figure 11. Accelerometer was located at different points. Sixteen time-recordings were taken, with the mobile accelerometers perpendicular to the surface (in these tests only Z-direction, vertical excitation, is investigated). The reference accelerometers were kept at one corner (in Figure 11, point number 17) on the plate and all other measurements were performed on the 16 DOFs. One-axial accelerometer model 4381 and B&K Pulse modal test consultant is used for all tests (Ref [10]). The measurements for the operational modal analysis, as well as the mobility-based modal
analysis, were performed using the B&K Pulse-Multi-analyzer System, model 3560C, as shown in Figure 10. The raw time data was captured by a “Time Capture Analyzer” for each measurement set. The capture analyzer was setup for a frequency span of 600 Hz, and a track length of 20 seconds, to allow for a run-up, and then rundown of the electric motor.

The first step of the analysis is to perform a Discrete Fourier Transform (DFT) on the raw time data, to obtain the Power Spectral Density (PSD) matrices that will contain all the frequency information. PSD matrices are then estimated from to a Singular Value Decomposition (SVD). The final form of the PSD matrix is then decomposed into a set of singular values, and singular vectors, using the SVD technique. This decomposition is performed to identify single degree of freedom models to the problem. Modal extraction is then performed using Frequency Domain Decomposition (FDD) techniques.

Figure 12 show the result of the SVD of the spectral density matrix of all measurements of the new and worn out elastomer pad. We obtain 2 singular values, and 2 singular vectors for each of the spectral density matrices. The singular values and their corresponding singular vectors are ranked in singular value descending order for each of the spectral density matrices. Each of the SDOF systems obtained by the SVD, allows us to identify the natural frequency, and mode shape (unscaled), at a particular peak. Peak-Picking is used on the average of the normalized singular values of the PSD matrix for all data sets. Several structural modes were extracted on the elastomer pads to perform the FE Model updating.

Figure 9 Details and apparent view of new (right hand) and one nearly well selected worn out (left hand) elastomeric bearing

Figure 10 OMA test setup and measurement process
A number of analyses were performed using the SSI method. A maximum state-space dimension of 200, corresponding to a maximum of 100 modes, is applied in a frequency range of 0 to 600 Hz. With the Canonical Variate Analysis (CVA) algorithm, models with a state-space dimension of around 140 were produced. The produced models are in agreement with the measured data for frequencies of approximately 400 Hz. This is verified by looking at the stabilization diagrams (Figure 13) and synthesizing the response auto- and cross-spectra from the model and then comparing them with the measured spectra. Higher model order does not produce better and more accurate results. Finally, the damping is estimated by the logarithmic decrement technique from the logarithmic envelope of the correlation function. The estimation is performed by using a linear regression technique.

Table 3 summarized the results of modal analysis for first six modes, using FDD and SSI methods in frequency span of 600Hz, on new and worn out elastomer pads.

![Figure 11 Geometry and measurement points](image)

![Figure 12 FDD in terms of the average of normalized singular values of spectral density matrix of all data sets (Right for new and left for worn out specimens).](image)

![Figure 13 Stabilization diagram for the CVA algorithm. + indicate stable and × indicate unstable and noise modes (Right for new and left for worn out specimens).](image)
Table 3. Comparison of the modal data estimated from FDD and SSI methods

<table>
<thead>
<tr>
<th>Mode number</th>
<th>New specimen</th>
<th></th>
<th>Worn out specimen</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Natural frequency (Hz)</td>
<td>Damping</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FDD</td>
<td>SSI</td>
<td>FDD</td>
<td>SSI</td>
</tr>
<tr>
<td>Mode 1</td>
<td>72</td>
<td>70.28</td>
<td>0.16</td>
<td>62</td>
</tr>
<tr>
<td>Mode 2</td>
<td>142</td>
<td>142.6</td>
<td>0.415</td>
<td>124</td>
</tr>
<tr>
<td>Mode 3</td>
<td>213</td>
<td>217.4</td>
<td>0.358</td>
<td>186</td>
</tr>
<tr>
<td>Mode 4</td>
<td>290</td>
<td>289.9</td>
<td>0.625</td>
<td>241</td>
</tr>
<tr>
<td>Mode 5</td>
<td>360</td>
<td>361.3</td>
<td>1.252</td>
<td>300</td>
</tr>
<tr>
<td>Mode 6</td>
<td>431</td>
<td>435.2</td>
<td>1.857</td>
<td>421</td>
</tr>
</tbody>
</table>

The natural frequencies and dampings for each mode of vibration of two new and old specimens are depicted in Figures 14 and 15 respectively. Also, the first six modes of vibration are shown in Figure 16.

Figure 15 Variations of damping versus mode number of two specimens

Figure 14 Variations of natural frequencies versus mode number of two specimens

Figure 16 Comparison of first six mode shapes of elastomer pads
5 Initial FE model of composite elastomer pad

An FE model, as shown in Figure 17, was established to simulate the laminated composite. ANSYS was used throughout the study. Eight-node linear solid element (SOLID46) was adopted for the modeling. This element type provides a layered version allowing up to 250 different material layers (Ref [7]). Several mechanical properties (shear and elastic modulus) of composite between the upper and lower limits of the AASHTO specifications, listed in Table 2, were entered into ANSYS. Normal modal analysis was performed to obtain the natural frequencies and the associated mode shapes of the composites, up to 600 Hz. The results are summarized in Table 4. The analytical and test mode shapes have good agreements. Therefore, one can conclude that the FE model can predict the behavior of the composite plate in the frequency range of interest.

Comparison of the FE and test results for five values of shear modulus is shown in Figures 18 and 19. Based on FE results, Figure 19, the relation of natural frequency versus shear modulus for each mode is constant (slope of lines are nearly the same) and this relation is: 
$G \text{ (MPa)} = 0.085 f \text{ (Hz)}$.

The results of modal test for the first six modes of vibration for the new and worn out bearings are summarized in Table 5. The results extracted from FE model were also included in this table. Clearly, a good degree of correlation between the test and the FE results can be identified.
Table 4 Variation of the natural frequencies for several shear and elastic modulus of elastomer material for first six vertical modes

<table>
<thead>
<tr>
<th>E (MPa)</th>
<th>G (MPa)</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.5</td>
<td>3</td>
<td>3.7</td>
<td>4</td>
<td>4.5</td>
</tr>
<tr>
<td>2</td>
<td>0.67</td>
<td>60.9</td>
<td>124</td>
<td>182</td>
<td>281</td>
<td>336</td>
<td>404</td>
</tr>
<tr>
<td>2.5</td>
<td>0.84</td>
<td>63.1</td>
<td>127</td>
<td>186</td>
<td>283</td>
<td>340</td>
<td>407</td>
</tr>
<tr>
<td>3</td>
<td>1.12</td>
<td>65.3</td>
<td>129</td>
<td>188</td>
<td>285</td>
<td>342</td>
<td>410</td>
</tr>
<tr>
<td>3.7</td>
<td>1.24</td>
<td>68.2</td>
<td>133</td>
<td>191</td>
<td>288</td>
<td>345</td>
<td>413</td>
</tr>
<tr>
<td>4</td>
<td>1.34</td>
<td>69.4</td>
<td>134</td>
<td>192</td>
<td>289</td>
<td>346</td>
<td>415</td>
</tr>
<tr>
<td>4.5</td>
<td>1.51</td>
<td>71.3</td>
<td>136</td>
<td>193</td>
<td>291</td>
<td>348</td>
<td>417</td>
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<tr>
<td>5</td>
<td>1.68</td>
<td>73.2</td>
<td>139</td>
<td>195</td>
<td>293</td>
<td>349</td>
<td>419</td>
</tr>
<tr>
<td>5.5</td>
<td>1.85</td>
<td>75</td>
<td>141</td>
<td>197</td>
<td>295</td>
<td>351</td>
<td>421</td>
</tr>
<tr>
<td>6</td>
<td>2.01</td>
<td>76.8</td>
<td>143</td>
<td>198</td>
<td>297</td>
<td>352</td>
<td>423</td>
</tr>
</tbody>
</table>

Table 5 Comparison between modal test results for two values of shear modulus and FE results

<table>
<thead>
<tr>
<th>Mode number</th>
<th>New specimen</th>
<th>Worn out specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OMA results</td>
<td>FE results with G=1.51 MPa</td>
</tr>
<tr>
<td>1</td>
<td>70.28</td>
<td>71.3</td>
</tr>
<tr>
<td>2</td>
<td>142.6</td>
<td>136</td>
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<tr>
<td>3</td>
<td>217.4</td>
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<td>4</td>
<td>289.9</td>
<td>291</td>
</tr>
<tr>
<td>5</td>
<td>361.3</td>
<td>348</td>
</tr>
<tr>
<td>6</td>
<td>435.2</td>
<td>417</td>
</tr>
</tbody>
</table>

6 Conclusions

In this paper, behavior of elastomeric bridge bearings is explained and one of the most important mechanical constants, shear modulus of steel-reinforced elastomer bearings, is estimated from modal analysis of two new and 35 years old specimens comparatively with FE analysis results. The results showed that operational modal testing is a simple, fast and appropriate technique for initial prediction of shear modulus of plate shape elastomeric bearings. The results also showed that for these two composite steel-reinforced elastomer bearings, natural frequencies with shear modulus between 1.3 and 1.8 MPa have a good correlation with shear modulus of the new specimen and shear modulus between 0.6 and 0.8 MPa for the worn out one. Also, the worn out specimen have a reduction between 5 and 10 percent in natural frequency and 10 to 50 percent in damping in contrast with the new one.

7 References


