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STUDY OF THE BEHAVIOR OF STEEL LAMINATED RUBBER BEARINGS UNDER PRESCRIBED LOADS

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ABSTRACT

The extensive new highway construction in Greece has created an increased interested in rubber bearings as supports of the highway bridges. Summary results are presented of an ongoing experimental investigation focusing on the behavior steel-laminated rubber bearings. Two of the tested isolators were prototypes having small dimensions and were supplied by their manufacturers whereas one was specially constructed as a model isolator. The objective is to obtain their mechanical characteristics when they are subjected to loading sequences prescribed by the Greek regulation for the design of bridges. Apart from obtaining the stiffness and the damping ratio the influence of the axial load as well as the frequency of applying the horizontal displacement is also studied. This experimental investigation is further complemented with a numerical study which tries to simulate the obtained results with relatively simple numerical tools. The obtained numerical predictions are also presented and their agreement with the corresponding experimental results is discussed.

1. INTRODUCTION

Seismic isolation has attracted scientific attention during the last two decades as a promising alternative for earthquake-resistant design of bridges. The main objective of using the isolation technique is to reduce the seismic forces to (or near) the elastic limit capacity of structural elements so as to avoid (or limit) inelastic deformations and related damage phenomena. This is achieved by shifting the fundamental frequency of a structure away from the dominant frequencies of earthquake ground motion and the fundamental frequency of the fixed base superstructure (typically in the range of 0.4-1.5sec). As a result of employing the isolation strategy, the superstructure motion is decoupled from the piers motion during the earthquake (as seen in figure 1), thus producing an effect of the reduction of inertia forces, a fact that is further amplified by energy dissipation concentrated in isolators that are suitably designed for this purpose, in order to reduce the transmitted acceleration into the superstructure.

A variety of isolation devices including elastomeric (Rubber) Bearings (RB), that is, alternating rubber layers and steel plates vulcanised appropriately, Lead Rubber Bearings (LRB), High Damping Rubber Bearings (HDRB) and others, as the Frictional/Sliding Bearings and Roller Bearings, have been developed and used practically for seismic design of buildings and bridges during the last 20 years in countries like USA, Japan, UK, Italy, New Zealand etc. The suitability of a particular arrangement and type of isolation system depends on many factors including the span, the number of continuous spans, the seismicity of the region, as well as of the frequency content of the earthquake while maintenance and replacement issues are also of interest. The detailed review of earlier and recent works on base isolation systems and their applications to buildings and bridges can be found in Kelly (1986), Jangid and Datta (1995), Priestley et al. (1996) and Kunde and Rangid (2003). Several analytical studies in the past have also demonstrated the effectiveness of seismic isolation for earthquake-resistant design of bridges (Constantinou, 1991, Maragakis and Saiidi, 1993, Mahin, 1993, Monti et al., 1995, Calvi and Pavese, 1998, Abe et al., 2004 among others). Extensive experimental research has also been conducted (i.e. Pinto et al., 1998, Dolce and Marnetto, 1998 among others) towards the investigation of the impact of the parameters affecting seismic isolation.

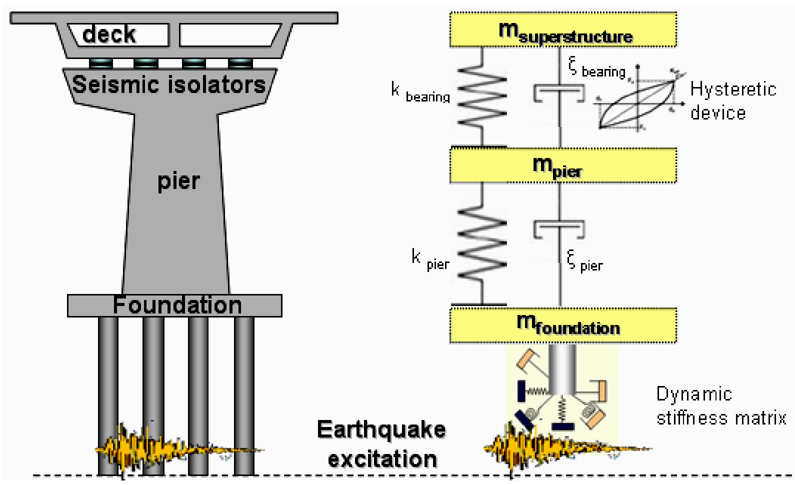

Figure 1 Representation of the dynamic response of an isolated bridge structure

2. EGNATIA HIGHWAY - GREECE: A LARGE PHYSICAL LABORATORY FOR BRIDGE ENGINEERING

During the last decade, a large road network has been constructed in Greece along the ancient Roman path of Egnatia crossing in 670km northern Greece from the Adriatic Sea to the Greek-Turkish borders. The owner of the new highway is Egnatia Odos SA (EOAE, www.egnatia.gr), which is a socie´te´ anonyme company, whose sole shareholder is the Ministry of Environment, Physical Planning and Public Works of Greece. It is noticeable that the topographic conditions in certain locations are so unfavorable, that more than 646 bridges of total 40km length had to be built at a budget of 700M$ (590M€) to bridge the mountainous (and of high seismic activity) areas along Egnatia highway, thus making the overall effort essentially a large physical laboratory. From the aforementioned stock of 647 bridges, more than 100 are overbridges (overcrossing bridges), 235 are underbridges, 205 are normal bridges while the rest are small structures (i.e. culverts) as is depicted in Figure 2. The vast majority of the Egnatia bridges can be considered of small span length (i.e. <25m, 69%), small overall length (i.e <100m, 82%), and are mainly constructed by Reinforced Concrete, while seismic isolation has been applied in many cases (Panetsos and Konstantinidis, 2003).

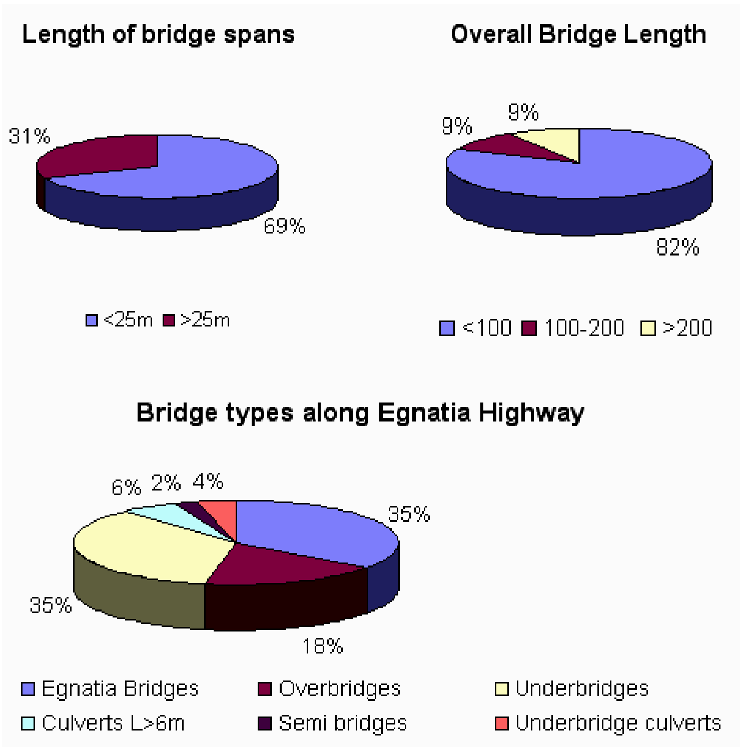

Figure 2 Profile of bridges constructed along the 670km Egnatia Highway in Greece (www.egnatia.gr)

Figure 3 Typical bridge overcrossings in Greece

2.1. Typical Overpass bridges studied

Based on the profile of the new bridges constructed during the last decade in northern Greece, it was deemed of major practical interest to assess the importance of seismic isolation not for all possible structural systems (where apparently the effect of isolation could be strongly case dependent), but rather for bridges of relatively small dimensions (i.e. L<100m), especially R/C/ overcrossings, which as shown in figure 2 represent the major part of the bridges constructed along the Egnatia. This decision was further supported by the fact that there is a large number of older, already constructed bridges within the existing road network, which have been designed for lower level of seismic forces (i.e. as prescribed by earlier provisions of the Greek seismic code) as for which the implementation of the appropriate elastomeric bearings as a means of intervention and upgrade towards the increased seismic demand is an internationally acceptable solution that is widely applied in practice

Along these lines, an inventory of existing bridges located in the overall Thessaloniki Metropolitan Area has been created extending the data gathered by the Laboratory of Soil Mechanics and Foundation Engineering (including general geometrical data, design and construction methods as well as design details and drawings). The electronic database that has been developed herein specifically for the bridge overcrossings of Thessaloniki is also used for classification purposes in order to permit a more systematic study of the main overpasses constructed. The particular bridges are therefore studied according to their a) period of construction and the corresponding seismic code used, b) their pier type and cross-section, c) their deck type and d) their pier-deck connection (as can be seen in Table 1) based on a similar classification performed by the Laboratory of Reinforced Concrete of Aristotle University of Thessaloniki for all the different bridge types along the Egnatia highway.

Table 1 Classification of typical bridge overcrossings in Greece

Code	Pier type	Deck type	Pier-deck connection	Construction Year
0	No middle piers	Hollow or solid plate	Monolithic	>1995
1	Circular piers	Box girder (single hollow)	Bearing type (with or without seismic isolation)	1985<X≤1995
2	Rectangular hollow piers	Continuous pre-fabricated cast-in-situ plate	Monolithic and bearing type	1970<X≤1985
3	Frame	Box girder (multiple hollow)	Simple support	≤1970
4	Wall			
5	Y-shaped			

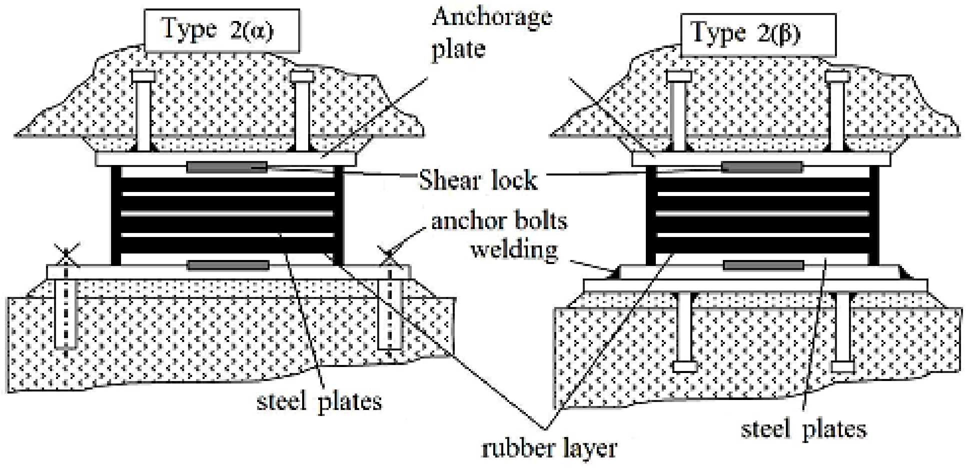

Figure 4: Types of steel laminated rubber bearings tested at the laboratory

3. FRAMEWORK FOR PERFORMING LABORATORY TESTING

The Greek Seismic Code (EAK 2000) quotes “for projects that allow for partial or full base isolation it is required that this code must be supplemented with additional provisions”. The performance check for rubber bearings is described in the Guidelines for the seismic design of bridges that was initially issued by the Ministry of Public Works in 1999. Of particular interest are the latest Guidelines (2006) that address the Design of Bridges with Seismic Isolation. These guidelines specify the basic requirements, the compliance criteria and the proposed methods of analysis for seismically isolated bridges. Moreover, these guidelines in supplement A, adopt the corresponding Eurocode 8 (part 2, supplement J) provisions, whereby the required tests are described for determining the variability of the most important properties of the bearings that are required for them to be included in the overall design. These tests, although are not aiming at the quality control certification of the bearings, are of particular interest as they provide the possibility to check through them the sufficiency of bearings intended to be employed in base isolation systems in Greece. The described in these guidelines tests together with the increased interest that base isolation applications are attracting in Greece have formed the necessary ingredients that resulted in the experimental investigation to be presented in the following. An experimental investigation was therefore performed at the Laboratory of Strength of Materials and Structures of Aristotle University that attempted to study the variability of the most significant response parameters of steel laminated rubber bearings when basic characteristics of their loading conditions are varied. The types of steel laminated bearings that became part of the current investigation are depicted in figure 4.

3.1. The sequence of tests described in the guidelines

In what follows, the sequence of tests described in the above guidelines and the way in which it was materialized during the tests performed in the laboratory is presented. The application of vertical compressive load is required in all tests simultaneously with a certain level of dynamic horizontal displacement possessing particular dynamic characteristics. For each required test the frequency of the dynamic displacement its amplitude and the required number of cycles are specifically described. Because the objective of these tests are steel laminated bearings to be employed to actual structures (bridges) it was deemed necessary to specify levels of vertical compressive loads that such bearings would be subjected to together with the corresponding horizontal displacement levels (shear strain levels). The compressive load levels were determined by examining representative bridge systems whereby such steel laminated bearings were used. For such bearings a normal stress in the range of $\boldsymbol{\sigma}_{G+Q}$=5~7Mpa was estimated. This range was also confirmed by other researchers (Heliades 2001, Abe et al., 2004).

The horizontal displacement levels (shear strain levels) were determined from the literature whereby it was found that the such bearings are subjected experimentally to maximum shear strains of the order of $\boldsymbol{\gamma}$=100~150%. (Abe et al., 2004, Kelly and Takhirov, 2001). Because it was not possible by the utilized experimental facilities to reach shear strain levels higher than 100% as well as because the guidelines do not require the determination of the failure strain all tests of the current investigation have as maximum shear strain limit the value of $\boldsymbol{\gamma}_{max}$=100%. Table 2 lists the selected level of shear strain for during each test belonging to the sequence required by the mentioned before guidelines. These levels were determined on the basis of this limit value of the shear strain ($\boldsymbol{\gamma}_{max}$=100%) and the parametric variability followed during the current investigation. For each one of these tests a sequential code name is adopted (e.g. T1, T2 etc). For tests T3,T4 and T6 the frequency of applying a prescribed level of shear strain is also required, because it is specified by the guidelines that these tests must be performed with a frequency equal to the inverse period of the base isolated structural system. A frequency equal to ν_{eff}=1Hz was selected as a result of investigating a number base isolated bridges, which were thought to be of representative at this stage of the current study.

Table 2 Requirements of the guidelines and corresponding shear strain levels employed during the experimental campaign

Test	Requirement by the Guidelines	Max. Level of the experimentally applied shear strain γs %	Description of applied loading Frequency or velocity Hz mm/s	Number of fully reversed Cycles
T1	Thermal Displacement	25%	Static 0.10mm/s	3
T2	Maximum non-seismic design reaction	50%	Dynamic 0.5Hz	20
T3	Total design seismic displacement	75%	Dynamic 1.0Hz	3
T4	Design displacement	100%	Dynamic 1.0Hz	20
T5	Repetition of Test T2	50%	Dynamic 0.5Hz	3
T6	Total design seismic displ. (with vertical load considering overturning)	100%	Dynamic	1

3.2. Experimental Testing Arrangement

Following the previously described sequence of tests (Table 2) the behavior of steel laminated bearing specimens was examined utilizing the testing arrangement depicted in figure 5. The vertical compressive load was applied through testing devices with a range of 400kN to 6000kN. The shear strains were applied utilizing an electronically controlled dynamic actuator with a capability of responding to a frequency range from 0 to 50 Hz. As can be seen in figure 5, the bearing specimens were subjected to a compressive load corresponding to a normal stress equal to either 2.5MPa or 5.0MPa. Initially, the bearing specimens wee subjected to the specified for each test compressive load and then the specified shear strain reversed number of cycles were performed with the specified frequency. The tested bearings were provided by the manufacturer with specific shear locks at the upper and lower anchoring steel plate. Special arrangement was constructed to keep the upper anchoring steel plate horizontal. Moreover, below the lower plate a sliding device made of cylindrical rollers was placed. The variation of the following parameters was monitored throughout each test (see figure 5).

(a) Vertical load by a specific load cell placed on the upper part of the bearing. Any variation of the vertical compressive force was recorded from this sensor.

(b) Applied static or dynamic horizontal load, through a specific load cell located between the actuator and the tested bearing.

(c) Imposed horizontal displacement measured at the two edges of the upper steel anchoring plate of the tested bearing.

(d) Imposed vertical displacement, which developed between the upper and the lower steel anchoring plate of the tested bearing.

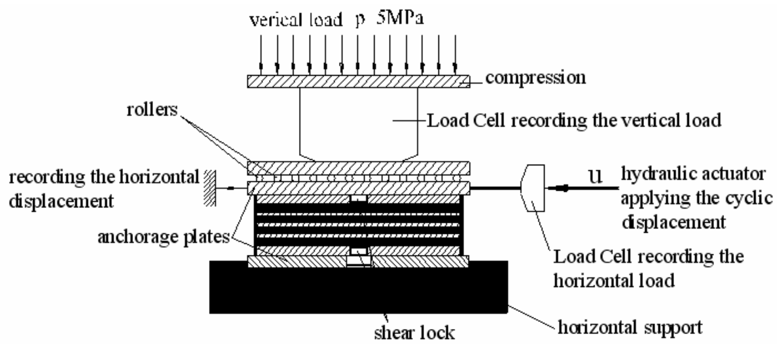

Figure 5 Testing Arrangement

4. SELECTED RESULTS

Two following different types of steel laminated bearings were tested:

(a) Cylindrical bearing with a diameter ***d***=200mm, total height ***h***=71mm and total rubber thickness Σt_i=32mm, of conventional form. For this bearing the symbol ***Ø200x71(32)*** is employed (figure 6a).

(b) Rectangular prism with a cross section $b_x \cdot b_y$=200x250mm, total height ***h***=134mm and total rubber thickness Σt_i=56mm of conventional form. For this bearing the symbol ***200x250x134(56)*** is employed (figure 6b).

(c) Rectangular prism with a cross section $b_x \cdot b_y$=150x150mm, total height ***h***=150mm and total rubber thickness Σt_i=120mm, of non-conventional form. For this bearing the symbol ***150x150x150(120)*** is employed.

Figure 6a Cylindrical bearing ***Ø200x71(32)***

Figure 6 Rectangular bearing specimen ***200x250x134(56)***.

The hysteretic loops, that were obtained from the testing sequence, are presented in terms of applied horizontal shear force (***F***) versus horizontal displacement (***u***) Alternatively, the same measurements can be presented in terms of the corresponding applied shear stress (τ) versus shear strain (γ) through the relationships 1 and 2.

$$\tau = \frac{F}{A} \quad (1)$$

$$\gamma = \frac{u}{\Sigma t_i} \quad (2)$$

4.1 Shear stiffness of the tested bearings

The effective bearing shear stiffness K_{eff}, was determined from the measured response through the following relationship:

$$K_{eff} = (F_p - F_n)/(d_p - d_n) \tag{3}$$

where d_p and d_n are the maximum positive and negative displacement during a test and F_p and F_n are the corresponding forces. The guidelines specify that the effective shear thickness K_{eff} must be determined from each one of the specified tests (T1 to T6).

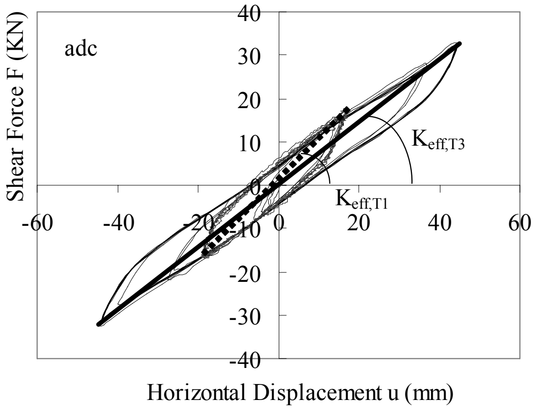

Figure 7 Tests T1 and T3 for rectangular bearing specimen ***200x250x134(56)***.

The hysteretic loops ***F- u*** in figure 7 were obtained from tests T1 and T3 for the rectangular bearing specimen with the symbol ***200x250x134(56)***. For the relatively low shear strain level of test T1 the obtained value of effective shear stiffness is equal to K_{eff}=951KN/m, whereas for the relatively large shear strain levels of test T3 the corresponding value us equal to K_{eff}=735KN/m. This observation is in agreement with similar observations from tests with bearings conducted by other researchers (Kelly 1997, Abe et al., 2004). Similar observations can be deduced from the measurements of the cyclic response of cylindrical bearing specimen ***Ø200x71(32)*** (figure 8).

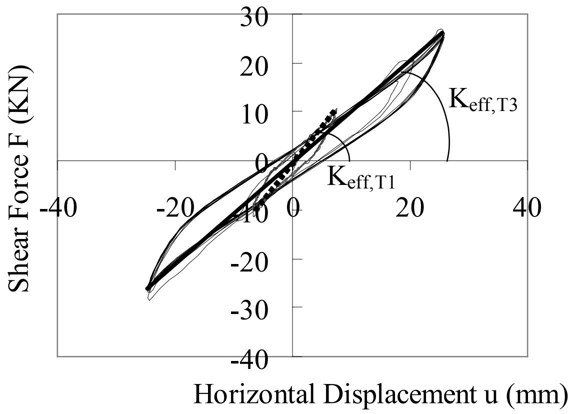

Figure 8 Tests T1 and T3 for cylindrical bearing specimen ***Ø200x71(32)***.

4.2 Determination of the hysteretic energy

The hysteretic energy $\boldsymbol{E_D}$ for each cycle during testing and its approximation with an elliptical shape is depicted in figure 9. The equivalent effective damping ratio can be estimated employing the following relationship (Chopra 1995):

$$\xi_{eff} = \frac{1}{2\pi}\left[\frac{E_D}{K_{eff} \cdot d_b^{\,2}}\right] \tag{6}$$

where $\boldsymbol{K_{eff}}$ the effective bearing shear stiffness, and $\boldsymbol{d_b}$ the aimed for maximum displacement as was measured during each test. For low damping bearings ξ_{eff}<6% and for high damping bearings 10%<ξ_{eff}<20% (Naeim and Kelly, 1999).

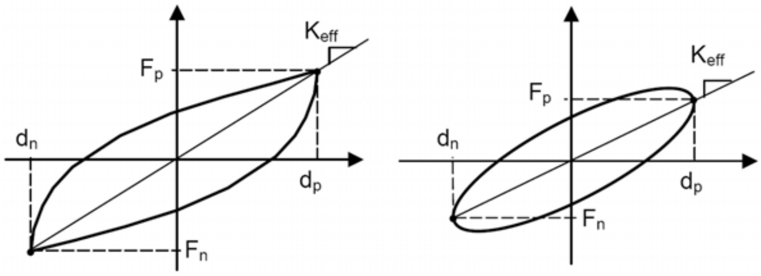

Figure 9 Determination of the equivalent effective damping ratio

Figure 10 depicts the τ - γ response for bearing specimens ***200x250x134(56)*** and ***Ø200x71(32)*** when they were both subjected to test T3 for γ=75% and the compression load resulted to a normal stress equal to σ_e=5MPa, which corresponds to a vertical load of the bearings during normal operation. Both bearings have quite similar hysteretic response, which corresponds to an equivalent effective damping ratio equal toξ_{eff}=7.5%. Thus, both tested bearing specimens can be classified as rather low than high damping bearings. Eurocode 8 part 2, (§7.5.2.2.2(5)) specifies that they can deviate up to 20% relative to the value specified by the design.

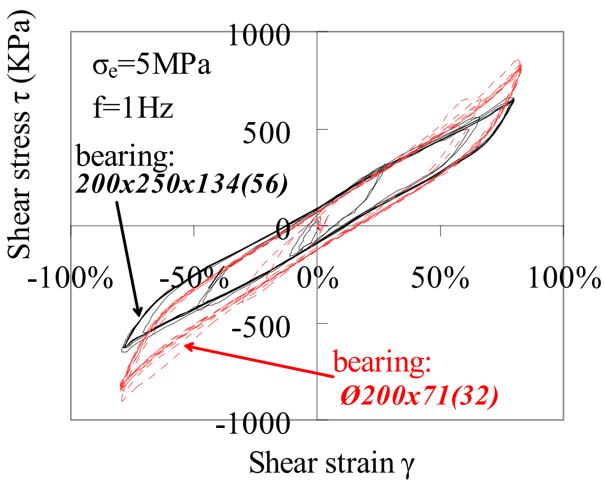

Figure 10. The τ - γ response for bearing specimens ***200x250x134(56)*** and ***Ø200x71(32)***

4.3 Investigation of the influence of the level of compression

The influence of the level of compressive stress σ_e on the effective shear stiffness and the equivalent effective damping ratio was investigated employing the rectangular bearing specimen ***200x250x134(56)*** and utilizing test T2. Figure 11 depicts the obtained response for two levels of applied compressive stress; $\sigma_{e,1}$=5Mpa (compressive force = 250kN) and $\sigma_{e,2}$=10Mpa (compressive force = 500kN). The applied maximum shear strain level was equal to γ=55%. Table 3 includes the obtained results. Figures 12a and 12b depict the variation of the effective shear stiffness and the equivalent effective damping ratio with the variation of the compressive stress. These results were obtained from tests with the non-conventional rectangular bearing specimen ***50x150x150(120).*** The decrease in the effective shear stiffness and increase in the equivalent effective damping ratio (figures 12a and 12b) with the increase in the compressive stress level was also observed during tests with bearings conducted by other researchers (Kelly 1997, Abe et al., 2004, Ryan, et al., 2004).

Table 3 Influence of the level of compression. Rectangular bearing specimen ***200x250x134(56)***

Bearing specimen 200x250x134(56)	Compressive stress σ_e=5MPa	Compressive stress σ_e=10MPa
K_{eff}	827KN/m	852KN/m.
ξ_{eff}	12%	17%

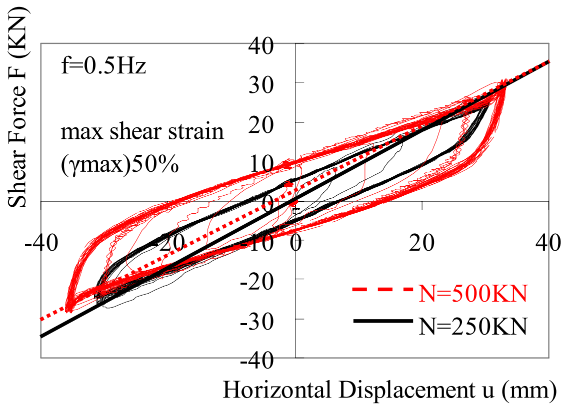

Figure 11 Test T2, Rectangular bearing specimen ***200x250x134(56)***

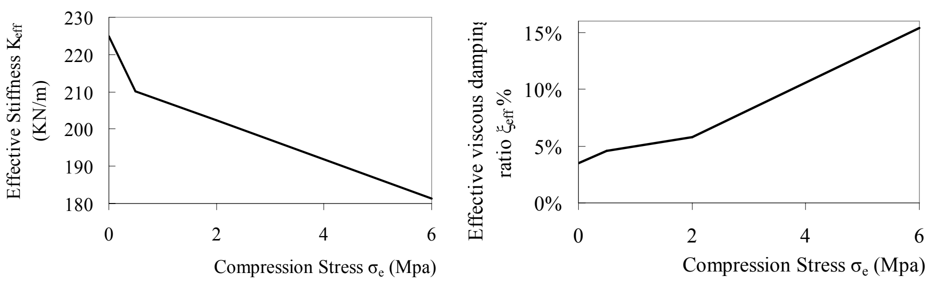

Figure 12a (left) Influence of the level of compression on the effective shear stiffness
Figure 12b (right) Influence of the level of compression on the equivalent effective damping ratio.

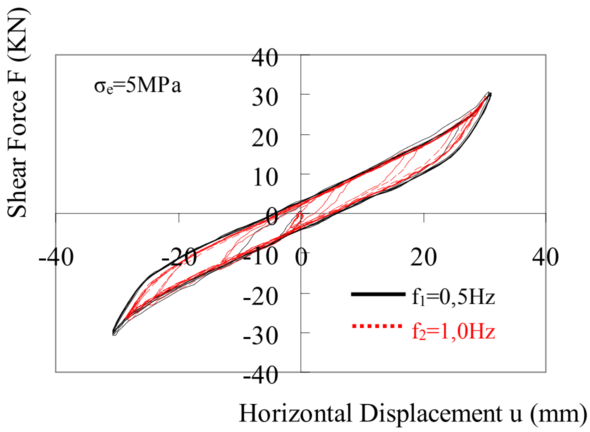

Figure 13 Cylindrical bearing specimen ***Ø200x71(32)***

4.4 Investigation of the influence of the frequency of the applied shear strain

Figure 13 depicts the hysteretic ***F- u*** response, which was obtained subjecting the cylindrical bearing specimen ***Ø200x71(32)*** to test T4. The normal compressive stress level was equal to σ_e= 6,0MPa. One test was conducted with the frequency of the applied shear strain equal to f_1=0,5Hz whereas during the second the frequency value was doubled (f_2=1,0Hz). In both cases the maximum applied shear strain value was γ=100%. From the measured response it can be observed that this variation of frequency of the applied shear strain did not have a noticeable effect on the obtained effective shear stiffness or on the equivalent effective damping ratio. This observation is valid for the specific frequency range that was applied. The same observation was made for the rectangular bearing specimen ***200x250x134(56)***.

3. CONCLUSIONS

The results presented here are from an on going investigation conducted at the Laboratory of Strength of Material and Structures of Aristotle University as a response of an increasing interest of applying seismic isolation devices as bearings of bridges on newly constructed road works in Greece. On the basis of the results obtained so far the following conclusions can be drawn. As already stated these conclusions are in agreement with similar observations that were obtained during tests with bearings conducted by other researchers.

- A decrease in the effective shear stiffness value was observed with the increase in the compressive stress level
- An increase in the equivalent effective damping ratio value was observed with the increase in the compressive stress level.
- From the measured response of limited number of tests it can be observed that this variation of frequency of the applied shear strain did not have a noticeable effect on the obtained effective shear stiffness or on the equivalent effective damping ratio.

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