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EFFECT OF ISOLATION BEARING MODELING ON THE SEISMIC FRAGILITY OF BRIDGES

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ABSTRACT: In the present paper, the epistemic uncertainty related to the finite element modeling of low damping rubber bearings (LDRB) is investigated for the case of an existing 11-span bridge. Several time-history analyses are performed for increasing levels of earthquake intensity and the effect of bearing-related modeling uncertainty is quantitatively assessed.

KEY WORDS: base isolation, bearing modeling, bridges, fragility analysis

1 INTRODUCTION

The common practice in the design of isolated bridges involves the execution of response spectrum analyses and the assumption of linear elastic behaviour for the base isolation devices. This approach often involves a number of iterations until a reliable estimate of the earthquake intensity-dependent bearing stiffness is achieved. However, when non linear time-history analyses have to be carried out, primarily for assessment purposes, the equivalent linear approach is not valid anymore since there the bearing damping and stiffness varies at each earthquake loading cycle. Due to the inherent complexity of the bearing cyclic response though, the above problem has to be tackled on the basis of various simplifying assumptions and alternative implicit modeling approaches. As the seismic response of an isolated bridge greatly depends on the mechanical properties of the bearings though, the issue of the reliable modeling of the bearings cyclic response becomes of paramount importance. Despite this fact, the effect of the bearing-related modeling decisions has not yet been quantified. Along these lines, the objective of this paper is to investigate alternative analytical models that are commonly used in the framework of the seismic assessment of isolated bridges and to quantify the corresponding modeling uncertainty introduced, in terms of the predicted vulnerability. For this purpose an existing R/C bridge is parametrically assessed and the uncertainty associated with bearing finite element modeling is estimated. The theoretical and numerical backgrounds as well as the analysis results are presented in the following.

2 BACKGROUND

2.1 Cyclic behaviour of low damping rubber bearings

There are numerous experimental studies related to the mechanical properties of different types of bearings but only a few of them [1], [2] have investigated the behavior of low damping rubber bearings. However, the principles of LDRB cyclic response have been identified and it is quite common to be accounted for in numerical modeling. As regard to the horizontal stiffness of the bearings, it has been observed that their stress-strain relationship is typically of mild non-linearity, presenting a softening up to 100% stain and then a hardening for larger strain levels. This hardening can be primarily attributed to material nonlinearity in the natural rubber due to crystallization effects at high strains. The hysteresis loops observed in all the experiments were thin and stable providing an equivalent viscous damping ratio that ranged from 3% to 6% depending on the applied strain rate (Figure 1). It should be also noted that loading frequency has only a minor influence on the equivalent stiffness and damping ratio values that are used in design. As regard to the vertical stiffness of the bearings it has been observed to increase with increasing load and to decrease with increasing horizontal deflection.

2.2 Common approaches for modeling the LDRB

Due to the highly non linear behavior that have that have been described in the previous section, finite element modeling of low damping rubber bearings is inevitably made on the basis of simplifying assumptions. Most seismic codes propose that LDRBs are modeled by linear elastic elements with an equivalent viscous damping ratio (commonly taken approximately 6%) and an effective linear stiffness K_{eff} that is calculated based on elastic theory as:

$$K_{eff}= \frac{GA}{t_r} \tag{1}$$

where G is the shear modulus of the elastomer (rubber), A is the overall cross-sectional area, and t_r is the total thickness of the rubber. Similar equations have also been proposed for the estimation of vertical and bending stiffness [3].

However, the thin hysteresis loops that low damping bearings form under cyclic loading, can be also approximated by a bilinear model which is most commonly used for the modeling of other types of bearings (such as, lead-rubber bearings and friction pendulum system). The parameters needed in this case for the bilinear modeling of the LDRB isolation device are the elastic stiffness K_1, the post-elastic stiffness K_2, and the characteristic strength Q (Figure 2).

In a more sophisticated modeling approach, a multi-linear law that takes into account the hardening effect could be used.

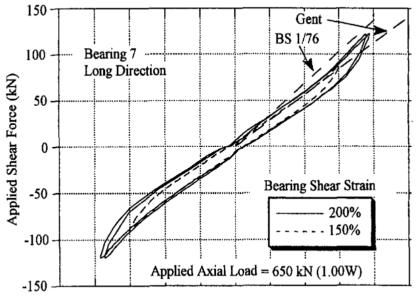


Figure 1. Typical hysteretic behaviour of low damping rubber bearings [1]

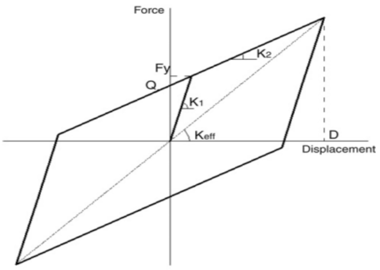


Figure 2. Bi-linear model of the cyclic response of LDR bearings [3]

3 OVERVIEW OF THE CASE STUDY

3.1 Description and modeling of the Lissor river bridge

The bridge studied is crossing the Lissos River along the Komotini-Mesti part of the 680km long Egnatia Motorway in Northern Greece. It is a 60/30 class bridge consisted of two similar branches, for serving the traffic in each traffic direction. The superstructure consists of a continuous, one-cell box, pre-stressed concrete girder. It is straight in plan with a total length of 433.31m and rests on 10 piers (hereafter denoted as M1÷M10) and 2 abutments (A1 and A11) through twenty, 1000x1000x175mm, low damping rubber bearings. The height of the deck is 2.75m except from the last span where the height is reduced to 1.35m and the section becomes rigid. In order to prevent excessive movements in the transverse direction, transverse side stoppers of 1.2m height have been placed on the top of each pier permitting a clearance of ±10cm. All piers of the bridge are wall type having a section of 2.5x6.5m and rounded edges, while pile foundations comprising of 100mm diameter piles have been used to support the bridge. The design of the bridge has been made in accordance to 1995 Greek Seismic Code considering PGA value equal to 0,16g and soil class C.

For the numerical analysis of the system, the computer program SAP2000 v.14 was used. The piers, the deck and the side stoppers were modeled by beam elements, while various types of the link elements have been used to model the cyclic behavior of the bearings in compliance to the different modeling approaches each time adopted. In order to filter-out any possible systematic bias attributed to the dynamic interaction between the superstructure, the foundation and the soil, fully fixed support conditions were assumed for all analyses conducted. Based on the actual boundary conditions of the system the deck-abutment connection was assumed free at the longitudinal direction and fixed at the transverse one.

3.2 Description and numerical modelling of the bearings

Four different analytical approaches where used herein to model the cyclic behavior of the bearings (Table 1) in the framework of the nonlinear dynamic analysis required for the assessment of the bridge vulnerability, in particular:

- *a linear model :* the common linear model which is proposed in most seismic codes [4] was used with 5% equivalent viscous damping ratio and an equivalent horizontal stiffness that was calculated by eq.1 as equal to K_{eff} =4457KN/m.
- *two alternative bilinear models*: in the first bilinear model (b1), the post-elastic stiffness K_2 was determined according to equation (1), while the initial stiffness K_1 was taken as a function of K_2 ($K_1=5K_2$). The required strength Q was obtained by assuming a yielding displacement ($u_y=0.1t_r$) [5]. The second model (b2) was also bilinear; however, it was made the assumption that the equivalent viscous damping ratio 5% occurs at a strain of 200% according to [6]. It should be noted that the estimation of the above parameters is rather arbitral. That is because, as opposed to other types of bearings, low damping rubber bearings do not have a specific yielding point and the bi-linearization of their actual force-displacement relationship essentially depends on the assumptions made as regard to their actual yielding point and the sharpness of the stress-strain curve close to yield.
- *a tri-linear model:* the tri-linear model was derived by introducing a third branch to the (b2) stress-strain curve with stiffness identical to the initial one (i.e., $K_3=K_1$) in order to take into account the hardening that occurs when the strain exceeds 100%. As the multi-linear link element provided by the computer program used was found to produce unstable hysteresis loops, the foreseen tri-linear stress-strain relationship was achieved by combining a Wen and a gap element in a series system (Figure 3).

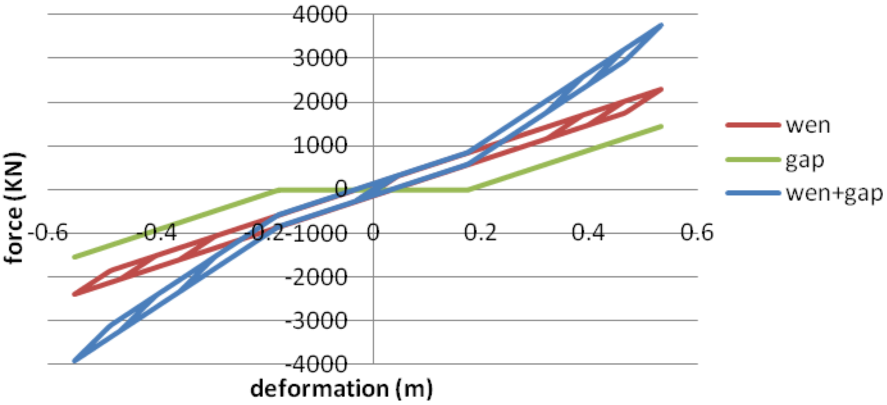


Figure 3. The tri-linear force-displacement model

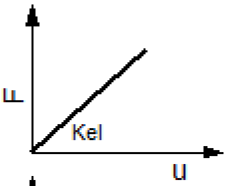
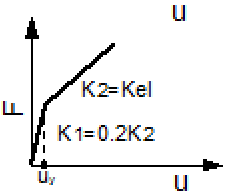
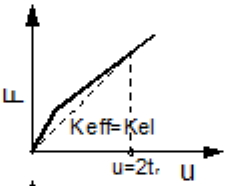
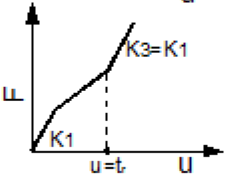
mode	material law	modeling approach	assumptions made
a		linear elastic theory	• nominal G
b1		wen model	• nominal G • factor a = 0.2 • yielding diplacment uy = 0.10 tr • $K_2=K_{el}$
b2		wen model	• nominal G • factor a = 0.5 • $K_{eff}=K_{el}$ for $u = 2t_r$ • β_{eff} = 5% for $u = 2t_r$
c		multi-linear model	• for u < tr same as b2 law • for u >= tr $K_3=K_1=K_{el}$

Table 1. Alternative bearing models used in the framework of the fragility analysis

3.3 Nonlinear time history analysis

Twenty ground motion records were selected from the PEER-NGA strong motion database. Each ground motion was scaled to 20 levels of spectral acceleration at the fundamental period of the bridge (T_1=2,44 sec) which was considered as the most appropriate intensity measure (IM) [7]. The response of the bridge was computed by inducing the selected acceleration time-histories as support excitation along the longitudinal direction. For the case of the linear elastic bearings, a constant modal damping of 5% was assumed for the entire structure, while for the remaining models the bearing damping was taken into account explicitly through their individual hysteresis loops, in addition to a 5% modal damping prescribed for the concrete parts.

3.4 Fragility analysis

The impact of the aforementioned modeling assumptions has been studied on the basis of the predicted bridge vulnerability for various earthquake intensity levels and damage states. . Four damage states, namely, slight, moderate, major, and collapse were defined to express the condition of damage, corresponding at 0.5, 1.5, 2.0 and 5.0 bearing shear strain. A log-normal distribution of the intensity measure over each DS was assumed, hence, the fragility functions (i.e. the probability of reaching a certain damage state) can be written as:

$$P_{fi}(Sa) = \Phi[\frac{1}{\beta}\ln(\frac{Sa}{S_a m})] \tag{2}$$

where Φ is the standard normal cumulative distribution function, $S_a m$ and β are the median value and the standard deviation of the natural logarithm of S_a values at which the bearing reaches the threshold of damage state i. These S_a values for each DS are specified by linearly interpolating the values of two consecutive S_a levels (Figure 4). Figure 5 compares the fragility curves derived for the four alternative bearing models and for each individual damage state. It can be noted that at the DS1 and DS2, the linear model leads to higher conditional probabilities of failure for the entire range of earthquake intensity, as expressed by S_a. This implies that the linear model is a rather conservative approach for design purposes that commonly correspond to such levels of bearing deformation (i.e., $\gamma<1.5$). However, when it comes to examine the probability of collapse (DS4), the bilinear2 model tends to predict the highest vulnerability, therefore it can be claimed that the assumption of linear behavior for the bridge bearings underestimates the probability of collapse. Another interesting issue is related to the high slope observed for the fragility curve that corresponds to the linear model. This can be attributed to the fact that for the particular structural system, the mass that is activated in the first mode is high, hence the variability in the response of a linear elastic system under earthquake records that have been scaled to the spectral acceleration at the fundamental period, is naturally, very low.

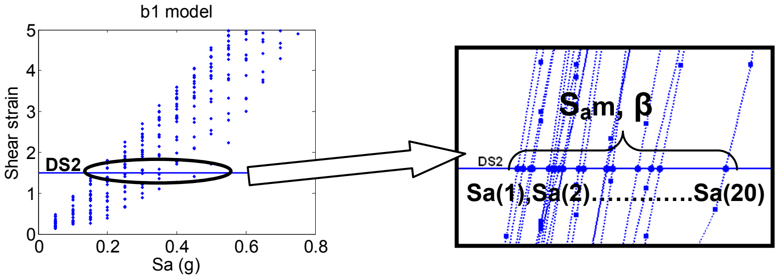


Figure 4. Derivation of the median value and the standard deviation of the natural logarithm of Sa values at which the bearing reaches the threshold of damage state 2.

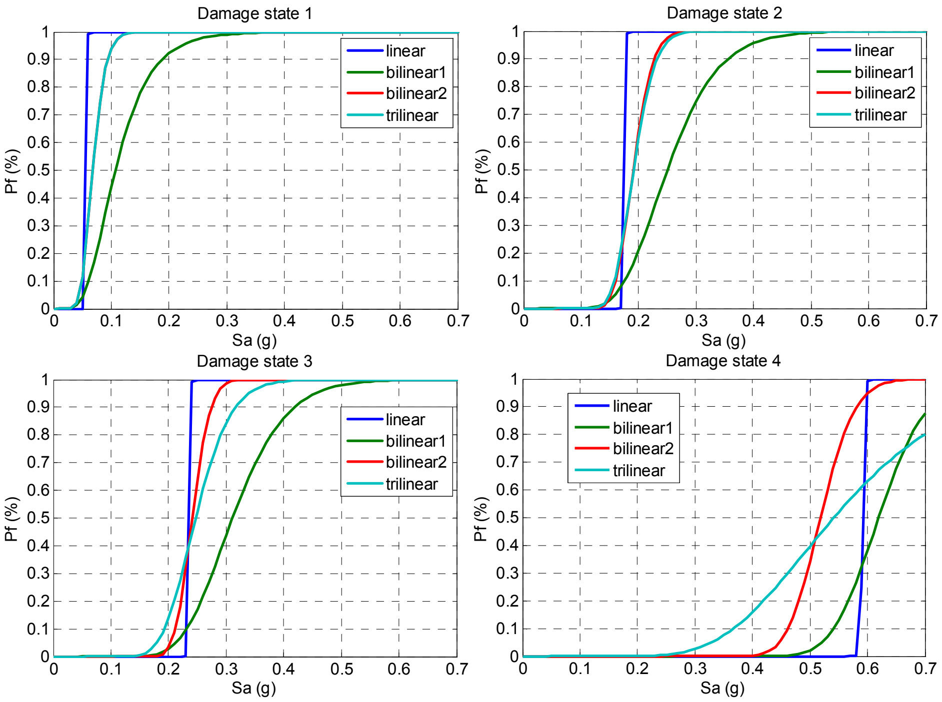


Figure 5. Fragility curves for the four different modeling approaches adopted for the bearings and the four damage states examined.

		linear	blinear1	bilinear2	trilinear
DS1	**S_am (g)**	0.059	0.107	0.067	0.067
	β	0.005	0.440	0.253	0.253
DS2	**S_am (g)**	0.178	0.249	0.191	0.191
	β	0.005	0.274	0.136	0.150
DS3	**S_am (g)**	0.237	0.310	0.241	0.246
	β	0.005	0.231	0.101	0.193
DS4	**S_am (g)**	0.592	0.619	0.518	0.539
	β	0.005	0.105	0.090	0.304

Table 2. Dispersion parameters for the four alternative bearing modeling approaches

Table 2 summarizes the dispersion parameters $S_a m$, β for the four alternative bearing modeling approaches. A comparison of the four models can be made on the basis of their median value ($S_a m$) that corresponds to the value of S_a that has 50% probability of exceedance. It can be seen that $S_a m$ varies from 0.059g to 0.107g for DS1, 0.178g to 0.249g for DS2, 0.237g to 0.31g for DS3 and 0.518g to 0.619g for DS4.This difference of 81,4%, 39,9%, 30,8% and 19,5% (for DS1-DS4) between the highest and the lowest $S_a m$ value clearly reflects the fact that as the seismic demand increases the response dispersion among the four bearing models decreases, hence, for more critical damage states, the decisions related to bearing modeling are less significant, although still non-negligible. It is notable that the linear and bilinear2 model have similar median values at DS3, a fact which was anticipated since both models have the same equivalent viscous damping ratios and stiffness at 200% shear strain. Finally, it is seen that the linear model is associated to the lowest standard deviation (β) which is approximately equal to 0.005 while bilinear1 (DS1, DS2, DS3) and tri-linear (DS4) lead to significantly higher values of β.

4 CONCLUSIONS

This paper attempts to quantify the uncertainty introduced in the fragility analysis of an existing R/C bridge due to different assumptions made regarding the finite element modeling of specific bearings used in design. As all other vulnerability analyses remained deliberately identical, the particular study revealed dispersions in the predicted probability of failure that can be solely attributed to the interplay between the force-displacement relationships adopted for the bearings, the dynamic characteristics of the bridge and the frequency content of the earthquake motions used. Through the fragility analysis that has been carried out, it was shown that different assumptions related to the modeling of bridge bearings may significantly alter the median values of the intensity measure associated to a particular damage state. It was also shown that the assumption of linear elastic bearings leads to a conservative estimate of the probability of exceedance of the lower (i.e., less critical damage states), a situation that is reversed for the case of major damage and collapse. Finally, it was shown that the more critical the damage stage, the less significant the decisions on the bearing modeling become; however, the associated dispersion is certainly non-negligible and hence, further research towards the quantification of the epistemic uncertainty are certainly needed.

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