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Seismic Protection through Elastomeric Base Isolation

Protection sismique grâce aux isolateurs en élastomère

Seismischer Schutz durch Elastomere Isolation

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SUMMARY

Isolation systems are applied for various structures requiring protection against dynamic excitation. By means of a probabilistic design approach, criteria for elastomeric bearings are discussed considering different stochastic quantities. Employing a simple mechanical model, major limit states are analysed. The calculated sensitivity factors of design parameters offer information for the design of seismic protection devices.

RÉSUMÉ

Des systèmes d'isolation sont utilisés pour différentes constructions nécessitant une protection contre des forces dynamiques. Les critères de dimensionnement pour les appareil d'appui en élastomère sont discutés grâce à une approche probabiliste prenant en compte les différentes variables stochastiques. Les états-limites principaux sont analysés en utilisant un modèle mécanique simple. Les facteurs de pondération des paramètres de dimensionnement, ainsi calculés, donnent des informations pour la conception de l'appareil d'appui.

ZUSAMMENFASSUNG

Isolationssysteme werden für verschiedene Bauwerke angewendet, die einen Schutz gegen dynamische Anregung benötigen. Mit Hilfe eines probabilistischen Ansatzes, der verschiedene stochastische Grössen berücksichtigt, werden Entwurfskriterien für Elastomerlager erörtert. Unter Verwendung eines einfachen mechanischen Modells werden wichtige Grenzzustände analysiert. Die errechneten Sensitivitätsfaktoren der Entwurfsparameter bieten Informationen für die Lagergestaltung.

1. INTRODUCTION

The high level of respected reliability of public lifeline systems such bridges and viaducts and required low maintenance costs are stimulating this research. Society is directly affected by a collapse or a reduced utility of a bridge. Such problems become transparent when thinking about High Speed Railways (HSR) build mainly on viaduct systems. Severe earthquakes may partly damage the structure or moderate earthquakes may diminish the operation speed. The second argument in particular affects the maintenance costs, which are being considered more and more by public owners. Looking at the problem from this point of view, the bearings are, beside their semantic meaning, one of the most important links in the chain.

A passive base isolation is the applicable solution for a viaduct HSR structure. Such a structure may be isolated in horizontal and vertical directions. In this paper basic contribution is given on laminated elastomeric bearings for carrying the vertical loads. The characteristic properties will be evaluated by means of a probabilistic approach. The strain due to shear deformations and effects of non-linearity will be neglected. The development of an highly adaptable rubber isolation system (HARIS) will be supported by the Industrial and Materials Technologies program of the Brite-EuRam III action. Principal information is given in [1].

2. PRINCIPLES OF BASE ISOLATION

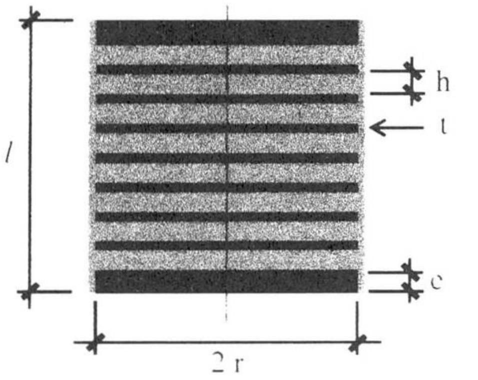
To achieve seismic isolation the superstructure must be decoupled from horizontal accelerations occurring during an earthquake. Anti-seismic devices must have a certain horizontal stiffness able to move the fundamental response frequencies of the structure well below 1 Hz. This is valid for a sufficient rigid soil, where the frequency range is characterized by a low energy content. The structure will behave like a rigid body in the horizontal plane. In the case of too soft soil, base isolation will not be applicable. The decrease of accelerations by means of filtering elements has the disadvantage of increasing the displacements. This can be limited by adding energy dissipating elements with a good self-centering capability to return the structure into its initial position. Another possibility of influencing the damping behaviour is determined through the phenomenon, that the damping remains finite while the lateral stiffness falls to zero. It can be shown, that damping of the bearing may well be significantly greater than that of its constituent elastomer.

The following discussions are based on a simple SDOF model assuming linearity and considering only the longitudinal direction of the bridge. The natural period T_0 of this oscillator is related to its equivalent mass M and stiffness K:

$$T_0 = 2\pi\sqrt{\frac{M}{K}} \tag{1}$$

The elastic response spectrum S_a on a specific site is normalized and depends on the eigenperiod T. The probability of occurrence is given implicitly through the Peak Ground Acceleration (PGA). However, the shape of the spectrum does depend on the site conditions. As mentioned, the discussions are related to a planned HSR. Therefore, a site-specific spectrum is determined from Taiwan. The normalized horizontal acceleration spectrum must be scaled by the PGA value, which is based on a certain return period and is related to the specific site. For a moderate period the spectral acceleration S_a is given by:

$$S_a = Z\frac{c}{T_0} \tag{2}$$



Unit shear stiffness:

$$R = G\pi r^2 \frac{t+h}{h}$$

Unit tilting stiffness:

$$T = \frac{3}{4} G\pi^4 \frac{t+h}{h}\left(1+\frac{r^2}{6h^2}\right)$$

Total height of bearing:

$$l = nh + (n-1)t + 2e$$

Fig. 1 Characteristic values of a circular shaped laminated rubber bearing.

where Z is the PGA and c is a factor depending on the soil type, here set to $c = 1$. Eq.2 assumes the damping to be 5% of critical. From this the peak deflection of the elastomeric device may be estimated according to the relation:

$$D = \omega^2 S_a = T_0 Z \frac{c}{(2\pi)^2} \tag{3}$$

The isolation system must be designed to achieve a suitable long fundamental horizontal period. Employing Eq.1, the required stiffness K_s of the device can be calculated. The unit shear and tilting stiffness for a circular shaped device are given in Fig.1.

A bearing must sustain the dead load DL and the train load TL, resulting from one or two trains. A dynamic factor Φ is considered to determine the statical equivalent load effects due to the rolling stock. The vertical load for one bearing is:

$$V = \frac{1}{2}(DL + 2\Phi TL)\frac{L}{2} \tag{4}$$

An elastomeric bearing is characterized by two shape factors. The so-called primary factor S_1 is equal to the ratio between cross section and lateral surface areas of each layer and affects the vertical stiffness, which varies approximately proportional to its square. A low S_1 value indicates a vertical system isolation. The secondary shape factor S_2 equals the ratio between diameter and total rubber thickness and affects mainly the bearing capacity relative to the buckling phenomena.

3. STOCHASTIC MODEL

3.1 Shear stiffness

Uncertainties in the G modulus result from the limited possible accuracy of material production fitting a certain Shore grade value, relative to the expected mechanical property. The method of measuring the shear modulus is very sensitive and is effected by environmental temperature, strain rate and rubber layer thickness, which are neglected herein. Considering the mentioned uncertainty a log-normal distribution is assumed.

The shear stiffness depends mainly upon the vertical loading. In extreme deflection situations a different stiffness behaviour can also be seen relative to the type of end-plate construction, dowel or bolt connection. For a circular shaped laminated elastomeric bearing (LEB) the shear stiffness K_s according to [2] is:

$$K_s = \frac{V^2}{2qT\,tan\,(ql/2) - Vl} \tag{5}$$

In Eq.5 the radius r, the total height l of the bearing and the vertical or compressive loading V are used. The quantity q is defined as $q^2 = V/T(V/R+1)$.

Table 1 Basic variables **X** used in analysis

X	Type	μ	σ	Description
G	LN	1.0	0.1	shear modulus [MPa]
DL_1	N	245	20	self weight [kN/m]
DL_2	LN	172	17	superimposed dead load [kN/m]
TL	T1L	71	10	HSR train load [kN/m]
φ	LN	1.06	0.05	dynamic factor [ ]
T_0	LN	1.87	0.1	natural eigenperiod [s]

3.2 Maximum horizontal deflection

The shear effect is mainly limited by the *roll-out* effect or by cavitation of the rubber. Both phenomenons are caused by large deflections. In extreme deflection situations a different stiffness behaviour can also be seen relative to the type of end plate construction, dowel or bolt connection.

If the end-plates are fixed by bolts the maximum shear deflection is limited by rupture of rubber, initiated through cavitation or extreme shear strains. Cavitation, an effect known from liquids, is also possible for elastomers. It describes an elastic instability when the hydrostatic tension reaches only few MPa, about 3G in the case of rubber. This phenomenon is caused by pure tension, as well as by extreme shear actions and may lead to rupture. Following [4], cavitation is expected to occur in the end rubber layer at a deflection of $d \cong r/2$, when a compressive axial force is assumed. The theoretical value can be calculated from the following expression:

$$D_{cav} = \frac{Vr}{3(V+K_s l)} \frac{2x_m}{3x_m^2 - 1} \tag{6}$$

The location of the minimum pressure can be calculated from:

$$x_m^2 = \frac{(2-3\rho) \mp \sqrt{9\rho^2 - 8\rho}}{2} \tag{7}$$

where $\rho = p_m/(2v)$ with the normalized compressive load $v = V/(\pi r^2 E)$. Cavitation can be evaluated when setting $p_m = -1$.

In the case of dowelled connections of the end-plates to the super- and substructure the *roll-out* effect will limit the possible shear deflections. The end-plates would be free of bend and at large deflections there could not be a hydrostatic tension in the end rubber layer. The *roll-out* threshold is defined by:

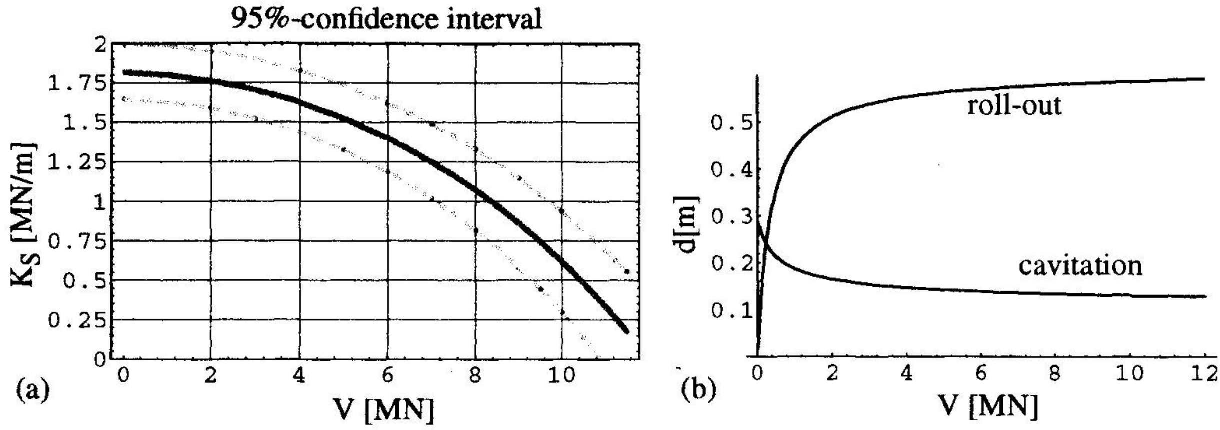


Fig. 2 The scatter of the shear stiffness (a) and critical deflections causing roll-out or cavitation (b).

$$D_{roll} = \frac{2Vr}{K_s l + V} \tag{8}$$

Cylindrical bearings may be deflected to 80% of their diameter without failure. Devices with bolted end-plates may have deflections 30% higher than the diameter given a suitable compressive load. Failure will occur at smaller deflections, when the bearing is subjected to a tensile load. The mechanism of failure is characterized by a crack propagation, initiated in the region of maximum tension.

3.3 Maximum compressive load

The instability load of a laminated elastomeric bearing is given, when the shear stiffness given in Eq.5 reaches zero. In [6] a formula for circular shaped bearings is given by:

$$P_{cr} = \frac{R}{2}\left[\sqrt{1 + \frac{4\pi^2 T}{R l^2}} - 1\right] \tag{9}$$

The dead load is divided into the self weight of the box girder DL_1 with normal distribution and the superimposed dead load DL_2 consisting of ballast, sidewalks and tracks, which is defined by a lognormal distribution. The railway load takes the transverse load distribution for a ballasted track into account, and is given by an equivalent uniformly distributed load TL. A Gumbel distribution is employed considering the time variability. The dynamic factor Φ is taken as lognormal quantity reflecting the uncertainties of the dynamic behaviour. The distribution types are selected according to [3] and summarized in Tab.1 with their characteristic values.

4. RELIABILITY ANALYSIS

The influence of different compressive loads on the scatter of the shear stiffness in Eq.5 is evaluated by a 95% confidence interval plotted in Fig.2. A suitable Johnson curve is fitted to the first four statistical moments. With this information an approximate confidence interval can easily be calculated. Bearings can sustain a certain compressive load V given in Eq.4 depending on the shear deformations. The elastic instability is given by the limit state formulation in Eq.10. The sensitivity of the reliability factor β with respect to the basic variables given in Tab.1 and design parameters $\{r,n,h,t\}^T$ are calculated by a FORM analysis using the VaP program [5].

$$M_1 = P_{cr}(r, h, t, n) - V \tag{10}$$

Setting the parameters to {0.3, 8,0.015, 0.005} a calculation gives the sensitivity values reported in Tab.2, which are relative to the reliability index β. Further, in the event of a server earthquake a LRB must resist to extreme horizontal displacements.

$$M_2 = D_{cav} - D \tag{11}$$

A simple approach for evaluating the extreme horizontal displacement is used by employing Eq.3 with a PGA of $Z = 0.3 m/s^2$ and assuming a connection of the end-plates by bolts. Therefore the cavitation effects becomes the critical event. In the same manner as Eq.10 the influence of certain parameters will be evaluated in Eq.11.

Table 2: Sensitivities of basic variables and design parameters.

X	DL_1	DL_2	G	Φ	TL	r	n	h	t
M_1	0.286	0.337	-0.626	0.045	0.641	211	-2.07	-2140	68.3
M_2	0.367	0.2502	-0.514	0.037	0.589	6.77	-0.050	-43.9	1.17

5. CONCLUSIONS

The property of the elastomeric material is characterized mainly by the shear modulus G and influences therefore in consequence the stiffness of the device. It can easily be seen that the scatter of the shear stiffness is proportional to that of the shear modulus. The sensitivity factors due to a FORM analysis are showing the same importance of shear modulus and load contribution. This defines the starting point for further investigation.

The influence of various design parameters in terms of reliability measures have been quantified. These can be used to discuss different device layouts with respect to failure of probability or appropriate cost models. For the research work is now in progress only principal statements are given in this paper. But one central postulate can be drawn, that a precise manufactured elastomeric material will be most important to guarantee a reliable device.

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