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SUMMARY

The text deals with the seismic isolation of bridges using low damping elastomeric bearings. In order to reduce the seismic response to horizontal seismic action, bridges are sometimes provided with seismic isolation devices, mainly located between superstructure and piers` / abutments` tops. The reduction can be achieved by increasing the fundamental oscilating period T, so reducing forces, but increasing deformations also; by increasing the damping, so decreasing displacements, and sometimes forces, or by combination of both ways stated above. The example bridge is used to compare the results to other ways of seismic action counteract, as well as some conclusions are reported.

Key words: seismic isolation, elastomeric bearings, energy dissipation, bridges

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SEISMIC ISOLATION OF BRIDGES USING SIMPLE – LOW DAMPING ELASTOMERIC BEARINGS. STRUCTURAL ANALYSIS, EXAMPLES AND CONCLUSIONS

1. Seismic action to EN1998-2

The design philosophy of the Standard is to fulfill the non-collapse criterium in the seismic design situation (ultimate limit states), as well as to minimize the construction damages due to the probable seismic effects (in serviceability limit states). The aim is also to limit the damages to areas of energy dissipation. The elastic spectrum of the design seismic action is used, unless the equivalent linear method is used (behaviour factor „q“), when the design spectrum is applied.

The bridges shall be designed to the intended seismic behaviour – ductile, limited ductile / essentially elastic, or elastic. The factors for the choice (which should be checked in the analysis) are the seismic region, type of structure, piers` stiffnesses, type of superstructure / substructure connection, etc. The bridge behaviour chosen (and achieved) is characterised by force / displacement relationship of the construction :

Ductile – usually preferable in regions of moderate to high seismicity, in order to dissipate a large amount of seismic energy. The aim is fulfilled providing plastic hinges, preferably at piers' connections to superstructure.

Limited ductile – a region of significant reduction in stiffness need not to be appeared under the design seismic action, but some amount of dissipated energy is enabled.

The yielding in plastic hinges regions should be provided in piers. If no seismic isolation is performed, that yielding is necessary in high seismic regions, i.e. ductile behaviour is to be provided (see statements above). The next diagram explains all stated above :

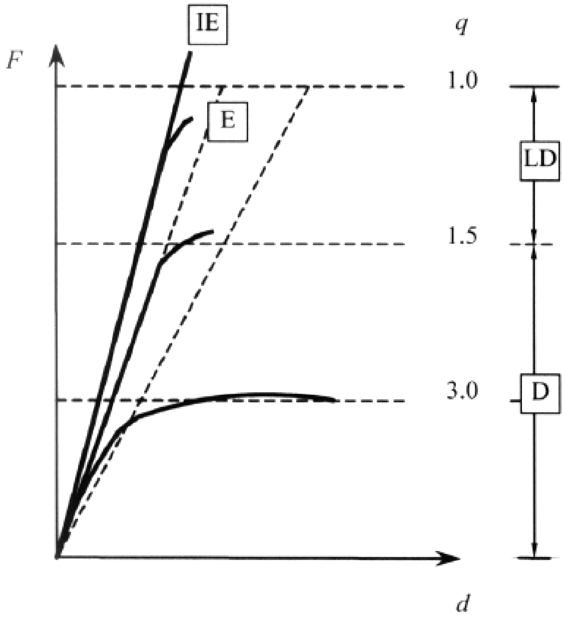
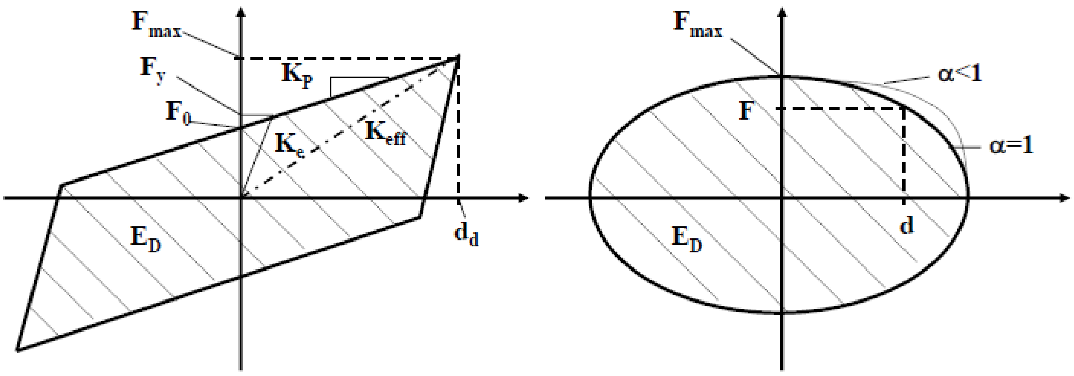


Fig. 1 – seismic behaviour

2. Seismic isolation of bridges

In order to reduce the seismic response to horizontal seismic action, bridges are sometimes provided with seismic isolation devices, mainly located between superstructure and piers` / abutments` tops. The reduction can be achieved by increasing the fundamental oscilating period T, so reducing forces, but increasing deformations also; by increasing the damping, so decreasing displacements, and sometimes forces, or by combination of both ways stated above.

Whatever system is used, anti seismic devices serve as seismic energy dissipators. Energy dissipation can be either **hysteretic** (displacement activated dampers), or **viscous** (velocity activated) :



General Hysteretic behaviour (left), and Viscous behaviour (right).

Fig. 2 – hysteretic & viscous behaviour

The spectrum used is the elastic response spectrum (q = 1), as the superstructure, in the seismic design situation, have to remain in elastic range. Types of seismic isolators : METALIC AND FRICTION DAMPERS, VISCOUS & VISCOELASTIC DAMPERS, SELF – CENTERING, ELECTEORHEOLOGICAL & MAGNETORHEOLOGICAL DAMPERS, ELASTOMERIC ISOLATORS, SLIDING DEVICES

3. Simple (low damping) elastomeric bearings in seismic design situation

In dealing with the seismic actions, free standing (not guided) simple – low damping elastomeric bearings are the elements whose resistance, together with a low price, is unreasonably neglected. The reasons are few – manufacturers` intention to sell more expensive and complicated dampers, triple bearing pendulum systems, flat or spherical friction bearings, elastomer bearings with lead core, high damping elastomeric bearings ... , as well as designers` and engineers` fear, or nescience, to apply simple elastomeric bearings as seismic isolators. Of course – where possible.

It is true that the effects of simple elastomeric bearings in dealing with seismic effects are less, compared to the systems quoted above, but in many cases they are sufficient. Colloquially said – if one has to kill the fly on a wall, he should do it by flypaper, and not by gun ! The bridges predestined for the above mentioned way of counteracting to seismic forces are bridges with stiff (low height) piers, which remains essentially elastic (behaviour factor q = 1) in the seismic design situation, bridges in the areas where the peak ground acceleration is 0.2g or less ($a_{gR} \leq 0.2$), say, zones where max expected earthquake intensity is ≈ VIII degree to MCS scale.

The benefits achieved using simple elastomeric bearings to resist seismic forces consists in decrease of spectral acceleration and seismic forces exerted to construction, as elastomeric bearings behave as energy disipators, increasing the oscilating period of construction, so the lower cost estimate for the superstructure is obtained. The increase in displacements is the result, also, but it can be handled, as well. The elastomeric bearings with low horizontal stiffness shift fundamental time period of the structure to avoid resonance with the exications. The bridge analysis in seismic design situation can be performed in a few ways: Fundamental Mode Method – as in the excel sheet attached, for pretty „regular“ bridges, Linear dynamic analysis – response spectrum method, or Non – linear dynamic time history analysis.

It`ll be more explained the first method ( FMM – SDOF ), as the other methods need modelling of a bridge`s elements analysed, including elastomeric bearings. The method is useful in preliminary design stages. Two ways of taking into account the elastomeric bearings contribution to the seismic force decrease and / or oscilating period increase, is possible : either approach A) - to model the elastomeric bearings as linear elastic elements with the equivalent elastic stiffness ($K_{eq,el}$ =

$A_r\ G\ /\ T_r$), or approach B) - to model them with secant stiffness (K_{eff}) of the element at the expected design displacement.

In the second approach mentioned above (B), the effect of energy dissipation of the isolation system is accounted for representing the isolators as equivalent linear viscous elements on the basis of the energy dissipated per cycle at the expected displacement. The response is then calculated using a response spectrum that is modified for the effect of damping larger than 5% of critical. Given that the expected displacement is unknown until the analysis is performed, these method require some iteration until the assumed and calculated values of isolator displacement are equal.

So, for the iterative computation, stated in **approach B)**, with the usage of benefitial effects of energy dissipated in hysteretic loops of bearings, the test results should be obtained. For the relevant results, usable in seismic calculations, it`ll be useful to perform hysteretic tests for low damping elastomeric bearings : Tests should be made for the displacement amplitude up to ± D, where D is max

elastomeric bearing displacement on allowable shear strain in seismic design situation, of 2, say, for $D = \pm\ 2T_{e,}$ where T_e is the sum of elastomer layers in the bearing. *Extreme forces* F^+ *and* F^- *corresponds to extreme displacements* D^+ *and* D^-.

The 5% - damped elastic response spectra is usually used to describe the seismic hazard for bridge design. Spectra for higher levels of damping have to be constructed for the application of simplified methods of analysis. Elastic spectra constructed for higher levels of viscous damping are useful for the analysis of linear elastic structures with linear viscous damping systems. Moreover, they are used in the simplified analysis of yielding structures or structures exibiting hysteretic behaviour, since simplified methods of analysis are based on the premise that these structures can be analyzed by using equivalent linear and viscous representations.

First of all, the bridge superstructure weight should be calculated (selfweight, additional dead load and a part of traffic load expected on the bridge in seismic).

Approach A) - after checking that the bridge`s geometry corresponds to the limitations stated for the FMM method, the stiffnesses of all seismic carrying elements are to be calculated (foundations, piers, elastomeric bearings) – chapter 7.5.4. in EN 1998 – 2.

The earthquake elements should be choosen – type of spectra, ground soil type, peak ground acceleration, important class... After the oscilation period is calculated, the spectral acceleration and design displacement is found. It should be emphasized that the calculations are performed to elastic response spectra (q = 1) when total seismic force is to be resisted by free elastomeric bearings only, see 6.6.2.3. (1)c in EN 1998 – 2.

T_{eff}	S_e	d_{cd}
$T_C \le T_{eff} < T_D$	$2{,}5\ T_C\ \eta_{eff}\ a_g\ S\ /\ T_{eff}$	$T_{eff}\ d_C\ /\ T_C$
$T_D \le T_{eff} \le 4$ sec	$2{,}5\ T_C\ T_D\ \eta_{eff}\ a_g\ S\ /\ T^2_{eff}$	$T_D\ d_C\ /\ T_C$

where $a_g = \gamma_I\ a_{g,R}$ and $d_C = 0{,}625\ a_g\ S\ \eta_{eff}\ T^2_C\ /\ \pi^2$

The next item is to calculate seismic shear forces on top of each pier and abutments (using design displacement of the deck) → $V_d = S_e\ M_d = \mathbf{K_{eq,el}}\ d_{cd}$, and then to calculate the displacements of piers` tops due to the shear forces calculated. The movements of elastomeric bearings are calculated as the difference between deck seismic design displacements $d_{cd}$ and displacements of piers` (abutments`) tops. It's clear that the bearings on abutments will experience bigger movements because the abutments are very stiff, while on the piers the bearings' deformations are decreased by piers' movements. The total movements of elastomeric bearings in seismic design situation is the sum of seismic design movements [multiplied by factor 1.5 – see 7.6.2. (1)P in EN 1998 – 2] and displacements due to permanent actions and part of temperature: $d`_{Ed} = 1.5\ d_{cd} + d_g + \Psi_2\ d_T$

.... where $\Psi_2 = 0.5$ for temperature. Note that the multiplicator 1.5 is used for elastomeric bearings check only, and not for the substructure elements check, as shear forces on piers' tops are obtained by multiplying total stiffness and design deck displacement ($K_{eq,el}\ d_{cd}$) !

For the expansion joint determination : $d'_{Ed} = 0,4 \times 1,5\ d_{cd} + d_g + 0,5\ d_T$

For the structural distance determination : $d'_{Ed} = 1,5\ d_{cd} + d_g + 0,5\ d_T$

All elements of the super and substructure should be verified to have an essentially elastic behaviour. All elastomeric bearings should be able to function at the total maximum displacements. According to equation (1) in chapter 5.3.3. from EN 1337 – 03, maximum design strain of elastomeric bearing due to seismic design situation is: $\varepsilon_{t,d} = K_L\ (\ \varepsilon_{c,d} + \varepsilon_{q,d} + \varepsilon_{\alpha,d}\ )$.

... while for the seismic design situation $K_L = 1,0$ and next conditions should be verified:

$\varepsilon_{c,d} \leq 2,5$ (compression strain), $\varepsilon_{q,d} \leq 2,0$ (shear strain), $\varepsilon_{t,d} \leq 7,0 / 1,15 = 6,09$ (total strain)

Approach B) – all the same as stated above, but the iterative computations should be done calculating dissipated energy in elastomeric bearings and correcting oscilating periods and damping factors different of 5% (hysteretic tests, for the elastomeric bearings used, should be provided):

$K_{eff} = [\ F^+ + F^-\ ] / [\ D^+ + D^-\ ] = F_{max} / d_{cd}$	effective stiffness (in the second iteration, $D_{II} = d_{cd,I}$)
$G_{eff} = K_{eff}\ T_r / A_r$	effective shear modulus
$ECD = 2\pi\ \beta_{eff}\ K_{eff}\ D^2$	dissipated energy
$\beta_{eff} = 2\ [\ EDC / K_{eff} / (\ D^+ + D^-\ )^2\ ] / \pi$	effective damping
$T_{eff} = 2\pi\ (\ M_d / K_{eff}\ )^{0.5}$	effective period

... then, according to the equations bellow, calculate design displacements $\boldsymbol{d_{cd}}$ (due to the tabelle above, as in approach A), ... compare them with the displacements obtained in the first iteration (D^+ and D^-), and continue or stop with the iterations.

4. Example – BGM viaduct on NAR2, New Belgrade

The comparing example is the BGM (Belgrade Metro) viaduct on NAR2 – North Approach Roads to Sava bridge, in New Belgrade. The viaduct were analysed in four (4) variants :

1a/ Elastomeric bearings on all piers and abutments, linear calculation,

1b/ Elastomeric bearings on all piers and abutments, non - linear (hysteretic) calculation,

2/ POT bearings – guided on abutments and first piers next to abutments, fixed ones on other,

3/ Monolitic connection on middle three piers, guided POT bearings on abutments and first piers,

The elements compared were displcements, oscilating periods, total bridge stiffnesses, total shear forces, amount of reinforcement, and finally, the prices of the bridge substructures variants analysed :

	Variant 1a	**Variant 1b**	**Variant 2**	**Variant 3**
Behaviour factor	**q = 1**	**q = 1**	**q = 3,5**	**q = 3,5**
Effects due to SEISMIC ONLY	**El. bearings only, LINEAR**	**El. bear. only, NONLINEAR**	**POT bearings**	**MONOLITIC connection**
Number of piers / abutments resisting seismic force	5 / 2	**5 / 2**	3 / 0	3 / 0
Total shear force, $V = M_d\ S_{e(d)} =$ $= K_{eff}\ d_E$	7.655 (≈ 1.093 kN per pier)	**4.504 (≈ 643 kN per pier)**	2.222 (≈ 741 kN per pier)	3.089 (≈ 1.030 kN per pier)
Oscilating period, T (sec)	2,06	**2,53**	2,05	1,51

Movement of the abutment bearing	183 x 1,5 = 274	**162 x 1,5 = 242**	183	138
Movement for the expan. joint choice	274 x 0,4 = 110	**242 x 0,4 = 97**	183 x 0,4 = 73	138 x 0,4 = 55
Pier's elast. bearing maximal movement	126 x 1,5 = 189	**127 x 1,5 = 190**	/	/
Spectral acceleration, [$S_{e(d)}$ / g]	0,17 (elastic spectra)	**0,10 (elastic spectra)**	0,05 (design spectra)	0,07 (design spectra)
Total stiffness, **$K_{eff,tot}$** (kN/m)	41.882	**27.884**	42.556	78.595
Total piers' reinforcement price, (ratio)	1,07	**1,00**	**1,45** (large confinement reinforcement amount)	**1,76** (large confinement reinforcement amount)
Bearings & expan. joint devices price	1,05	**1,00**	2,01	1,04
Total piers & devices price (ratio)	**1,03**	**1,00**	**1,34**	**1,20**
... including :	**no damage in piers**		**piers damaged (plastic hinges appeared) !**	

5. Conclusions

Taking the careful insight in the tabelles above, it can be concluded that the variant with elastomeric bearings is the most cost - effective variant in dealing with seismic action. Of course, the conditions for the use of this type of seismic isolation must be fulfilled.

Besides the obvious cost - effectiveness, the important advantage of the solution is that piers remain elastic, so no superstructure damage is expected in seismic design situation. The only potential damages are limited to expansion joint devices, as well as parapet backwalls, if not designed for the „structural clearance“ demands !

Important to observe – after the seismic event, there's no extra costs for piers repair if elastomeric bearings are performed, as the piers are calculated to remain elastic in the seismic design situation, while the piers in cases 2 & 3 must be repaired after the earthquake, as the plastic hinges will appear in piers.

6. References

1. EN 1998 – 1, Design of structures for earthquake resistance, general rules, buildings
2. EN 1998 – 2, Design of structures for earthquake resistance, bridges
3. EN 1337 – 3, Structural bearings, elastomeric bearings
4. Executive / detailed design of viaducts BGM OTC1/2, north approach roads to the Ada bridge in Belgrade, NAR lot 2, Zoran Kovrlija, 2012./2013.