Stiffness and Damping Aspects of Fiber Reinforced Elastomeric Bearings as Anti-Seismic Devices
Δυστμησία και Απόψεις Σχετικά με την Απόσβεση Ινοπλισμένων Ελαστομερών Εφεδράνων ως Αντισεισμικών Διατάξεων

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Λέξεις κλειδιά: Elastomeric Bearing, Seismic Protection, Earthquake, Stiffness, Damping, Guidelines

ΠΕΡΙΛΗΨΗ : Η χρήση των ινοπλισμένων ελαστομερών εφεδράνων ως απλών και οικονομικών διατάξεων για υψηλά κτίρια έχει συζητηθεί σε αρκετές δημοσιεύσεις. Στο παρόν άρθρο παρουσιάζεται η επιρροή του ακριβούς καθορισμού της σχέσης μεταξύ οριζόντιας δυστμησίας και απόσβεσης στην αποδοτικότητα οριζοντίων ελαστικών αρμών σε αντισεισμικά τοιχώματα. Προκύπτει ότι ο ακριβής καθορισμός των μηχανικών ιδιοτήτων είναι αναγκαίος για τη βελτιστοποίηση των αποτελεσμάτων. Επίσης καταδεικνύεται η έλλειψη κατάλληλων αναλυτικών λύσεων στους σύγχρονους κανονισμούς.

ABSTRACT: The use of fiber reinforced elastomeric bearings as simple and cheap anti-seismic devices for high-rising structures was discussed in numerous publications. In this paper the influence of the exact tuning of horizontal stiffness and damping on the efficiency of horizontal elastic joints in shear walls is presented. It is shown that an exact determination of the bearing properties is necessary to improve the results. The lack of adequate formulas in the current design codes is pointed out

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INTRODUCTION

High-rising structures, which are common for residential and office buildings, are almost made of prefabricated elements (e.g., prefabricated wall components). This type of construction offers huge cost benefits with respect to traditional methods but still do have cost intensive elements such as a required reinforcement for the connection of seismic loaded shear walls.

In order to reduce the inner forces due to earthquake excitation, anti-seismic devices for the avoidance of resonance effects can be used. This will lead to a possible reduction of the reinforcement particularly at the connection of prefabricated wall elements. A reduced resonance can be obtained by lowering the horizontal stiffness of the shear walls by applying horizontal isolators (elastic joints) between the wall elements. This structure can be represented by a cantilever of low shear stiffness and a reduced natural frequency.

Suitable horizontal isolators with high vertical carrying capacity are fiber reinforced elastomeric bearings (FREB) as a cost efficient and simple solution for the seismic protection of ordinary residential buildings [1]. The advantages of these bearings compared to common steel reinforced elastomeric bearings are the simple fabrication (preparation of the components), the easy fashioning (possible adaption by cutting) and the simple assembly (no anchorage, small weight). The usability of FREB for this type of application is shown in [2].

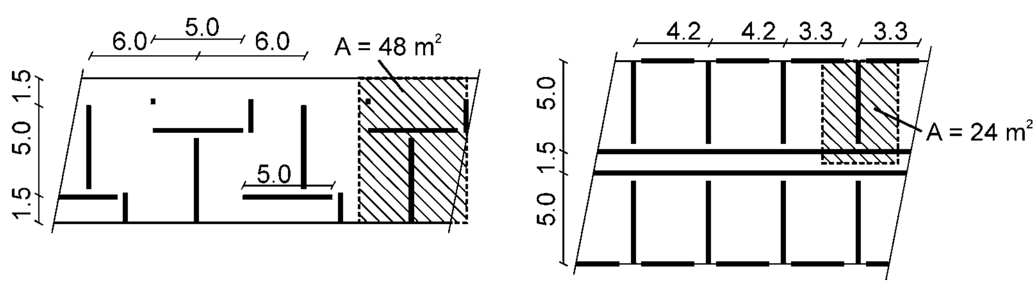

Fig. 1: Floor plan of structures type I (left) and type II (right) of the comparative study with vertical shear joint between the wall elements

The objective of this paper is to present (a) the possible reduction of the inner forces using FREB as anti-seismic devices and (b) to show up the necessity of the exact knowledge of the damping value to achieve optimum results. Comprehensive studies have been performed on a three to ten floor building to present the influence of (1) the mass associated with a standardized floor, (2) the height associated with the number of considered floors (length of the cantilever arm), and of (3) the natural oscillation period. In addition, the relation of the natural frequency of the building to the frequency of the excitation influences the level of resonance and thereby the seismic loading of the building. In particular, a detailed study of the nonlinear material and structural behavior of the anti-seismic devices have been performed in advance for the following investigations.

DIMENSIONS OF COMMON RESIDENTIAL BUILDINGS AND STRUCTURAL SYSTEMS

The parametric study which is presented in the following was carried out for two types of common residential and office buildings with three to ten floors. Reasonable dimensions for the buildings as shown below have been discussed in detail in a former study in [2]. The structural system for the parametric study is defined by the seismically active masses and the stiffness of the shear walls. This is based on the dimensions of common residential buildings which are limited by economic considerations leading to span lengths of four to five meters and a typical length of stiffening walls of five meters (see **Fig. 1**). The vertical joints are considered as not capable of transferring shear forces as these joints are a weak point of prefabricated wall elements.

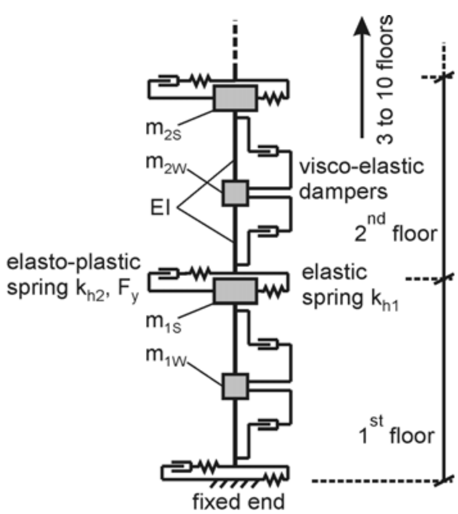

Fig. 2: Structural system of the stiffening structure: mass-spring-system of a building with the masses of the floor slabs m1S = m2S and the masses of the walls m1W = m2W; dampers not shown

Each lateral shear wall gets the seismic influence of a ground-plan area of 24 m^2. The shear walls of type II are of the same length in both directions and all get the seismic influence of an area of 48 m^2. The assumed surface loads are:

a) dead load of the floor slabs = 6.5 kN/m^2 (20 cm floor slab plus floating floor)

b) dead load of the walls = 4.0 kN/m^2 (16 cm concrete walls)

c) live load = 1,0 kN/m^2 (30 % of ultimate live load including nonbearing walls)

This results in the following seismic active masses:

a) mass on floor level: 18.1 t (type I) and 36.2 t (type II)

b) mass on wall level: 15.3 t (for both types and a wall length of 12.5 m)

The height between the floors is presumed to be 3.0 m. The resulting masses for each floor are applied to the mass-spring system as shown in **Fig. 2**.

HORIZONTAL STIFFNESS AND DAMPING ANALYSIS FOR REINFORCED ELASTOMERIC BEARING

The previously mentioned three to ten floor buildings serve as basis for the evaluation of the efficiency of elastomeric isolators as protection against seismic loading of e.g. shear walls. Fiber reinforced elastomeric bearings (FREB) are used as isolators and are implemented as row of quadratic bearings (side length of a = b = 160 mm equal to the thickness of the wall, height of tr = 20 mm) next to each other beneath the wall elements along the whole length of a wall.

In order to evaluate the effect of the horizontal stiffness (stiffness between 100 %, 67 %, 33 %) with respect to the reduction of the inner forces, gaps of g = 0 mm, g = 80 mm and g =160 mm are introduced. This flexible design could be done due to the simple assembly of the FREB, the easy shaping e.g., by cutting, the adjustable damping and a large lateral flexibility of the FREB (see [3]).

The current design codes [4] and [5] only offer a rough approximation to calculate the horizontal stiffness. As described in [6] this formula does not consider the influence of the vertical load (buckling), the rolling off from the planes, material nonlinearities and material degradation. Furthermore there is no formula given to calculate the damping of the bearing, but loading tests are recommended.

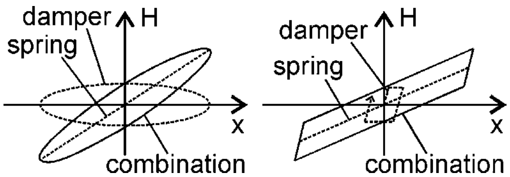

Fig. 3: Spring damper combination: visco-elastic left, friction elastic right (from [2])

In order to get a realistic value for the stiffness and the damping of the real FREB numerous numerical models have been investigated [6]. The calculated load displacement diagrams of bearings with a side length of 160 mm, a height of 20 mm and 10 layers of carbon fabric are shown in **Fig. 4**. For the seismic calculations the bearing behavior has to be modeled with simple spring elements. The considerations leading to the spring models are described in detail in a former publication [2] and can be summarized as follows:

The stiffness of the elastomer was proofed to be rate independent. The damping of the bearings can therefore not be modeled with a viscous damper but with a friction damper as shown in **Fig. 3**. The combination of a friction damper modeled by an elasto-plastic spring and an elastic spring gives a sufficient model of the FREB. Hence the spring parameters for a single bearing with relative damping of 7 % at an amplitude of 100 % = 20 mm (as shown in **Fig. 3**) are:

k_{h1} = 1.34 MN/m the stiffness of the pure elastic spring

k_{h2} = 4.43 MN/m the stiffness of elasto-plastic spring

F_y = 3.47 kN the yield force of the elasto-plastic spring

A variation of the value Fy leads to different values of the relative damping. A multiplication of the values with the factor of 31.3 (wall length divided by bearing length) leads to the values for the whole horizontal joint between the wall elements. For the joints with reduced stiffness (67 % and 33 %, so above) the values are reduced accordingly.

The value of 7 % relative damping and the stiffness of the bearings were measured for bearings with a common elastomer ($G_{elastomer}$ about 1.1 N/mm^2 at 100 % shear). A different damping of the bearings can be obtained by a variation of the consistency of the elastomer material. It has to be mentioned that the correlation of material and bearing damping is not linear as the material of the reinforcement layers and the geometry have an influence on the bearing damping.

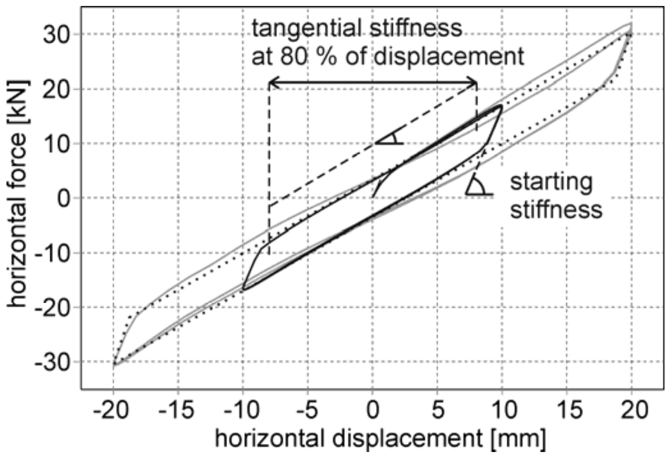

Fig. 4: Load displacement diagram of the bearing models (dimensions: 160 mm x 160 mm x 20 mm; 10 reinforcement layers); dashed line = spring model with 7 % relative damping

To be able to consider the effect of a variation of the bearing damping the damping of the concrete structure is not considered as a global mass proportional damping (as often used). It is modeled by adding a visco-elastic damper between the ends of the beam elements in orthogonal direction as described in [2] leading to a relative damping of 5 % for building type I. The value of the damping coefficient was assumed to be equal for all building models as the stiffening wall elements are equal.

BASIC ASSUMPTIONS FOR SEISMIC CALCULATIONS

These structural systems with a variation of the number of floors and the stiffness and damping of the horizontal joint are used for the seismic calculations. In order to make the results of the present study comparable the target response spectrum was defined with the same parameters as used in former studies [3] and [2] according to Austrian standard [7]:

- area of Vienna (zone 3; a_h = 0.80 m/s^2)
- ground type group II (highly consolidated sediment, sand and gravel)
- maximum ordinate $S_{e,m}$ = 1.34 m/s^2
- T_B = 0.15 s, T_C = 0.60 s and T_D = 2.00 s

Small differences in the shape of the response spectrum to the values given in the European standard [8] have no influence on the qualitative statements of this study and on the effectiveness of elastomeric bearings as simple anti-seismic devices in general.

This spectrum can be used for a modal response spectrum analysis (MRSA) as presented in [3] to get a first approximation of the inner forces and of the effectiveness of the system. Nonlinear effects and the specific damping behavior of the elastomeric bearings can not be considered with this method. Therefore the study presented here is based on time-history analysis using a synthetic earthquake. This time-acceleration data was generated to match the described response spectrum.

PARAMETRIC STUDY ON EFFICIENCY OF ANTI-SEISMIC DEVICE

The effect of earthquake impact on buildings can be compared regarding the restraint moment at the lower end of the stiffening walls [2]. In order to resist the moment vertical reinforcement has to be located at the end of the wall elements. In particular for prefabricated wall elements the tensile connection of the reinforcement causes considerable costs. The occurring moments at buildings with elastic joints are set in relation to those at conventional buildings with rigid joints leading to a reduction factor η. This factor can be considered as a measure for the effectiveness of elastomeric bearings as seismic protection devices.

Part of the vertical forces due to restraint moments is neutralized by vertical forces from dead and live loads (gray area in **Fig. 5** and **Fig. 6**). The reduction factor η is therefore not an appropriate measure for the necessary amount of vertical reinforcement. But it can be used to compare the efficiency of the application of the anti-seismic device.

The parametric study associated with the previously discussed FREB has been performed for buildings with three to ten floors and with three different horizontal FREB stiffnesses and a variation of the relative damping of the elastic joints, see chapter 0. In addition two variants of application are analyzed: bearings only in the basement or located in each floor level. **Fig. 5** and **Fig. 6** portray the effect of the anti-seismic devices with a relative damping value of 7 %. At this η = 1.0 represents the value of buildings with rigid joints (no anti-seismic devices).

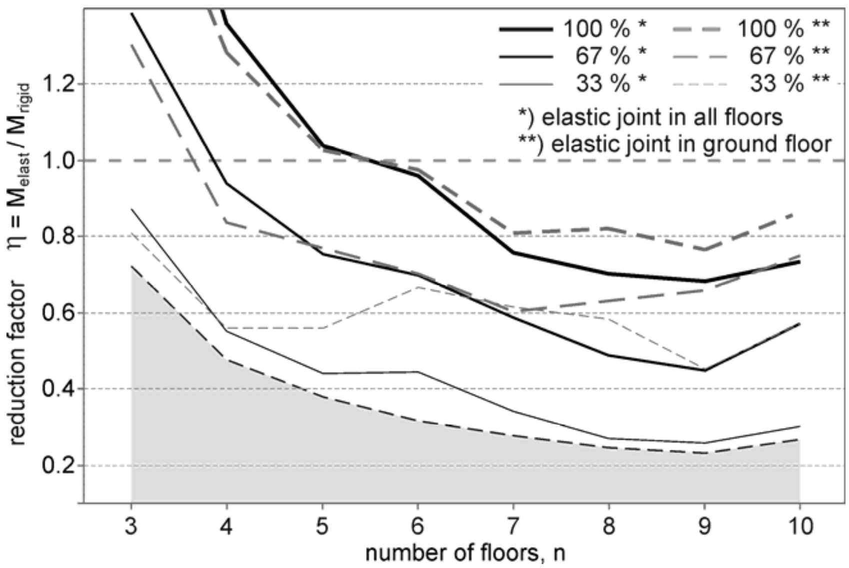

Fig. 5: Structure type I with 7 % relative damping of the elastic joint; reduction of the restraint moments at the base point of the stiffening wall due to installation of elastic joints; the ratio of the restraint moments that is neutralized by the vertical loads is highlighted grey (from [2])

As described in chapter 0 the value of 7 % relative damping of the bearings were measured for bearings with a common elastomer. Bearings with a relative damping of more than 6 % are called high damping bearings according to [5]. Bearings with less than 2 % of damping may not be possible with the known techniques for elastomeric bearings. Bearings with a much higher damping value would need a lead core and are therefore not considered in this study. The variation of the damping of the elastic joints (isolators) is therefore carried out for damping values from 3 % to 9 %.

The results are shown in **Fig. 7**, **Fig. 8** and. The values of the relative damping that lead to minimum reduction factors were estimated and marked with a circle.

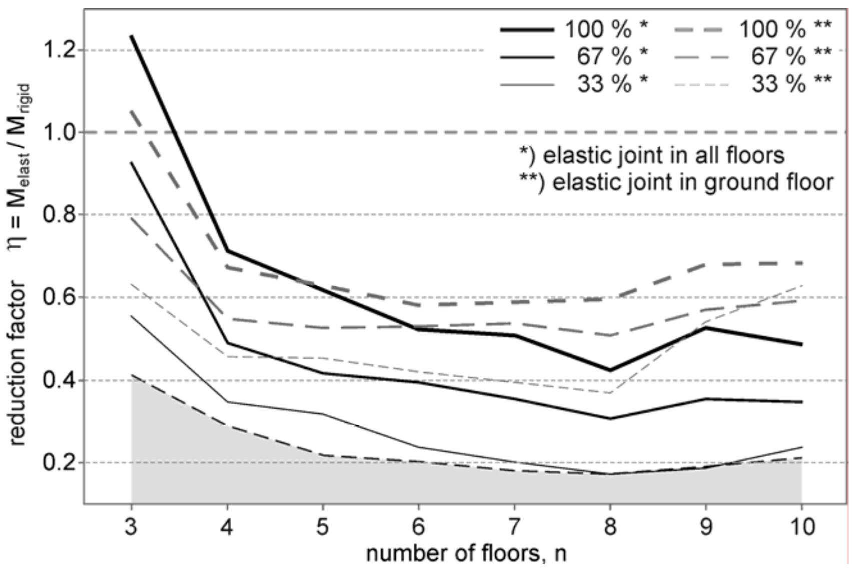

Fig. 6: Structure type II with 7 % relative damping of the elastic joint; reduction of the restraint moments at the base point of the stiffening wall due to installation of elastic joints; the ratio of the restraint moments that is neutralized by the vertical loads is highlighted grey (from [2])

RESULTS OF THE PARAMETRIC STUDY

The diagrams in **Fig. 5** and **Fig. 6** show that for both types of buildings the restraint moments at the base points of the stiffening walls are reduced for five floors or more (values lower than $\eta = 1.0$). As described in [2] a reduction of the restraint moments of up to 80 % is possible when using a relative damping of 7 %. For small buildings with a natural frequency lower than the main frequency of the earthquake excitation the application of elastic joints results in a rise of the natural frequency of the building and therefore the resonance effect is enhanced.

The figures also show that the application of elastic joints in all floors only brings an improvement of the results in few cases. Regarding the costs for the application of the bearings it is therefore recommendable to apply elastic joints only in the ground floor.

The diagrams in **Fig. 7** and **Fig. 8** show that the lower the horizontal stiffness is (stiffness: straight line = 100 %, dashed line = 67 %; dotted line = 33 %) the higher the optimum value of the relative damping gets. The diagrams make obvious that an exact tuning of the stiffness in combination with the damping extremely important. For example: for buildings of 8 to 10 floors with elastic joints only in the ground floor the variation of the relative damping between 3 % and 9 % results in a reduction of the moment of about 0 % to 70 % (reduction factor 1.0 to 0.3).

Fig. 7 illustrates firstly that for higher buildings, which means for buildings with lower horizontal stiffness, the optimum damping ratio rises. Secondly it shows that a lower horizontal stiffness of the elastic joint in the ground floor demands a higher damping ratio. The low values of the optimum damping in **Fig. 8** (elastic joints in all floors) show that in most of the cases a relative damping of less than 3 % should lead to optimum results. As it might not be possible to build bearings with a damping ratio lower than about 2 % the possible limits of the application are reached for the assumptions discussed above.

As mentioned above an exact tuning of the damping allows an optimum reduction of the restraint moment. **Fig. 9** and **Fig. 10** show the maximum possible reduction for relative damping ratios in the range of 3 % to 9 %. Especially for building type I a significant improvement is possible. For the structures with elastic joints only in the ground floor a reduction factor of 0.45 to 0.92 is possible for 4 to 10 floors with a significant improvement for the smaller buildings. Compared to the reduction factors with a constant damping of the elastic joint of 7 % this means an improvement of up to 45 % with an average of 13 % (4 to 10 floors, elastic joint only in ground floor).

For building type II the exact tuning of the damping of the elastic joint only in the ground floor of buildings with 4 to 10 floors leads to a reduction factor of 0.45 to 0.92. This means a improvement of the reduction factor of up to 23 % with an average of 7 % compared to the reduction factors with a constant damping of the elastic joint of 7 %.

This shows clearly that an exact tuning of the horizontal stiffness and the relative damping is necessary to achieve a maximum efficiency of the application. For the application with elastic joints in all floors the exact tuning has an even larger effect but it has to be proved that the extra expense of elastic joints in all floors is justifiable by the larger efficiency.

All these considerations are focused on the inner forces at the bottom. Obviously the reduction of the inner forces affects the whole building. The ratio of floors where no uplifting vertical forces at all between the wall elements are necessary (no vertical reinforcement due to earthquake impact) also rises.

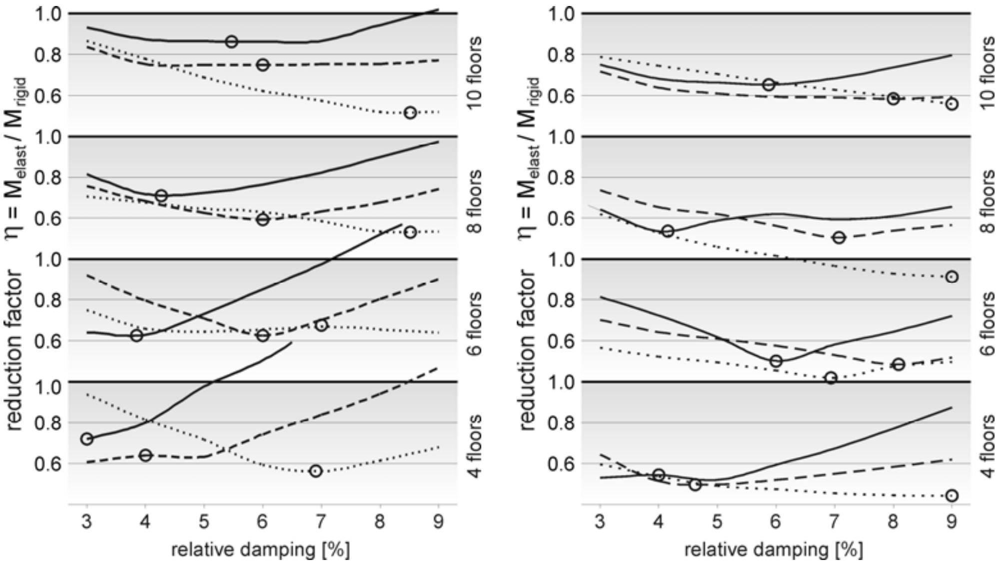

Fig. 7: Structure type I (left) and type II (right) with elastic joint in ground floor; reduction of the restraint moments at the base point (stiffness: straight line = 100 %, dashed line = 67 %; dotted line = 33 %)

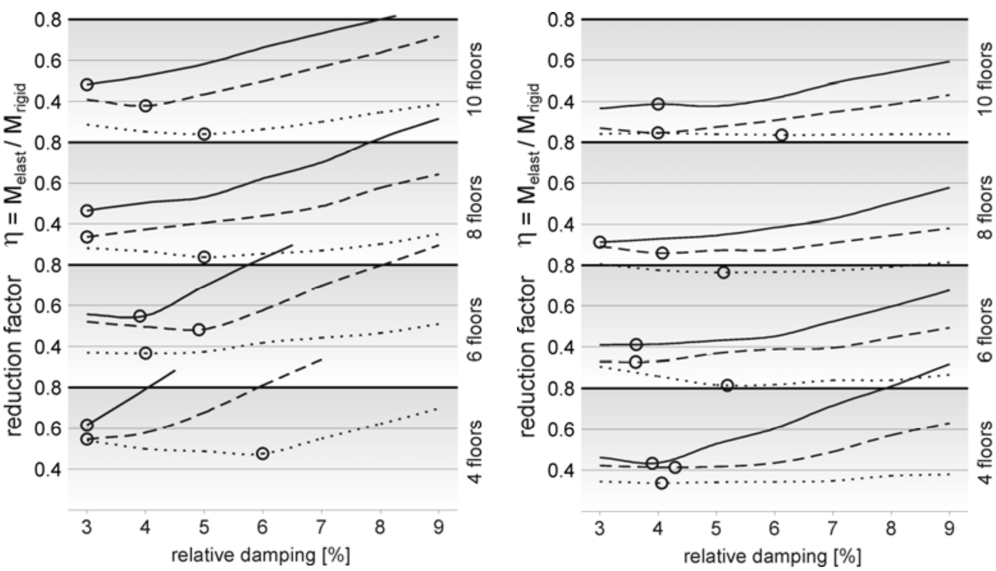

Fig. 8: Structure type I (left) and type II (right) with elastic joint in all floors; reduction of the restraint moments at the base point (stiffness: straight line = 100 %, dashed line = 67 %; dotted line = 33 %)

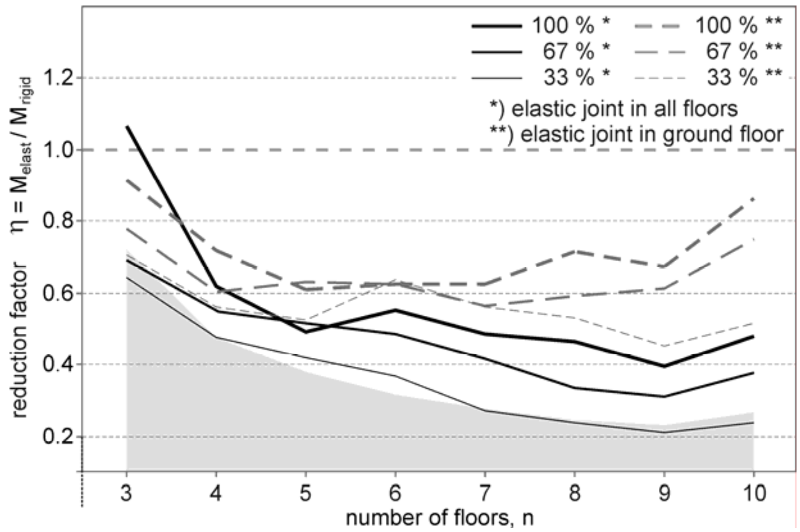

Fig. 9: Structure type I with optimum relative damping of the elastic joint (analogous **Fig. 5** but with optimized damping of the elastic joint)

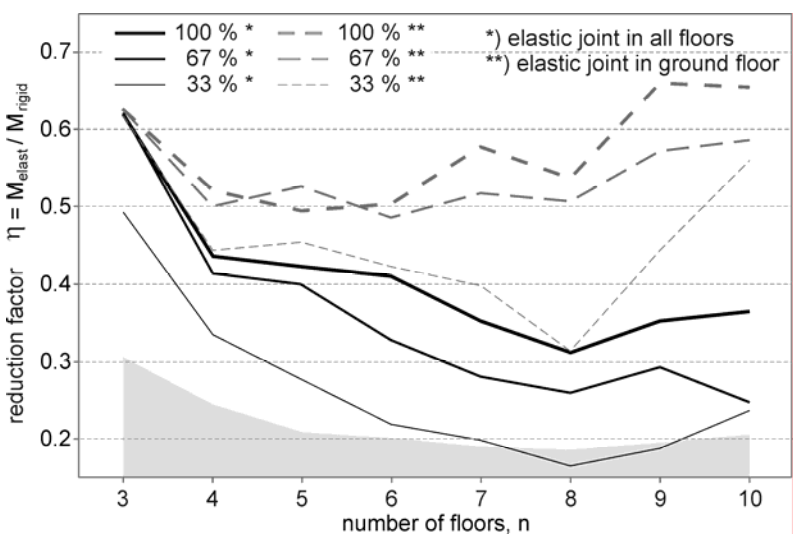

Fig. 10: Structure type I with optimum relative damping of the elastic joint (analogous **Fig. 6** but with optimized damping of the elastic joint)

CONCLUSIONS

The results of the study show clearly that the exact tuning of the horizontal stiffness and the relative damping of elastomeric bearings used as anti-seismic devices in high-rising is extremely important for the efficiency of the application. The determination of the horizontal stiffness based on the material parameters using the design guidelines of the current European design codes is only a rough approximation and not optimal for this range of application. For the calculation of the damping of elastomeric bearings no formula is provided in the guidelines.

To avoid expensive loading tests advanced guidelines should be developed to allow a calculation of the bearing properties with sufficient accuracy as mentioned in [6].

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