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Statistical Analysis of Rubber Compounds Material Tests for Seismic Isolation Bearings and Code Provisions Comparison / Micozzi, F., Dall'Asta, A., Gioiella, L., Ragni, L., Quaglini, V.. - 309:(2023), pp. 326-336. (17th World Conference on Seismic Isolation, WCSI 2022 Torino 12 - 16 September 2022) [10.1007/978-3-031-21187-4_27].

Availability:
This version is available at: 11566/315590 since: 2025-11-21T12:31:16Z

Publisher:
Springer Science and Business Media Deutschland GmbH

Published
DOI:10.1007/978-3-031-21187-4_27

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01 July 2026

Statistical analysis of rubber compounds material tests for seismic isolation bearings and code provisions comparison

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Abstract. Rubber compounds are extensively used for manufacturing rubber bearings for seismic isolation. Current seismic codes prescribe the use of design properties of seismic isolators derived from experimental evaluations to account for the effects of strain rate representative of the design seismic condition, cyclic degradation, frequency and environmental conditions (especially the temperature variation). Moreover, ageing phenomena, which such devices undergo during their service life, should be taken into account. Such tests should be carried out on devices, even though the European Standard on seismic devices (EN 15129) allows for both high and low damping rubber bearings the use of data from material tests performed on the elastomer used in their manufacture, (although extrapolation the results of materials tests to the scale of isolation devices is not always straightforward). In this study a set of experimental data obtained from type tests performed by different manufacturers on both low and high damping compounds with nominal stiffness ranging from 0.4MPa to 1.3MPa is statistically analysed. The effects of shear deformation, cyclic degradation, ageing, frequency and temperature on equivalent shear stiffness and equivalent damping are shown, providing also a view of the intra-supplier variability and inter-supplier variability. As general modification factors, also known as λ-factors, are provided by the codes in case of unavailability of experimental data, a comparison between the codes values and the obtained experimental results is shown.

Keywords: upper-lower bound analysis; rubber bearing; seismic isolation.

1 Introduction

Current seismic codes prescribe the use of design properties of seismic isolators determined from standardized tests performed under specified conditions to account for the change of mechanical parameters during the lifetime of the structure due to different effects. With reference to elastomeric devices, the main effects are the variation of mechanical properties due to the loading history (especially maximum shear deformation and number of cycles), ageing and environmental conditions (mainly temperature variation). Moreover, there are other source of variability (such as the production variability or the frequency content of the earthquake) also influencing the final response of the isolation system. Some sources of variability can be taken into account by using accurate models [1][2] or simplified models in combination with modification parameters, to account for the full range of variation. The latter approach was introduced first by Constantinou et al [3] and then implemented into several seismic codes, such as the AASHTO guide specifications, the European code on bridges (EN 1998 – part 2 [4]) and the European Standard on seismic devices (EN 15129 [5]). This approach is based on property modification factors (also called λ-factors) that represent the ratio between the maximum or minimum value of mechanical parameters with respect to nominal values, defined as the unaged 3^{th} cycle properties, according to [5] at the reference strain amplitude, frequency and temperature. Such properties are the equivalent linear shear stiffness G and equivalent viscous damping coefficient ξ or the post elastic stiffness K_p and the force at zero displacement F_o, for the bilinear models. All the above-mentioned codes suggest default values of λ-factors, but they also specify that it is preferred to derive these values directly from tests carried out on the devices during the qualification process by the manufacturers. However, in the European context, for elastomeric isolators made of High Damping Rubber (HDR) and Low Damping Rubber (LDR) the EN 15129 [5] allows to perform material tests on the elastomer utilized for the bearing manufacturing instead of full-scale or reduced-scale tests on the isolation bearings to define the variation of the parameters related to strain amplitude, frequency, temperature, repeated cycle and ageing. This study statistically analyses a dataset provided by the Politecnico di Milano composed by 18 rubber compounds (7 LDR and 11 HDR) belonging to 5 different manufacturers, with a nominal shear stiffness (G_0) in the range 0.4-1.3 MPa and a nominal damping (ξ_0) in the range 0.034-0.167. The data refer to the results of Type Testing of elastomer for isolators according to the EN 15129 clause 8.2.2 [5], consequently they are already averaged results of a set of 3 samples for each test [6].

In particular, in the first part of the paper the statistical results are showed for each test, focusing on the results in terms of variability of the ratio between the equivalent linear shear stiffness G and the equivalent viscous damping coefficient ξ measured in the test and the nominal or reference values by highlighting median, interquartile and maximum-minimum value. Results have been analysed separately for HDR and LDR specimens and for the different manufacturers. Moreover, by grouping all the test data at the nominal conditions, also the production variability has been analysed.

The hypothesis that results of materials tests can be automatically extended to isolation devices is not always appropriate or straightforward because the device dimension and the vulcanization process used to fabricate the isolator can influence significantly the final cyclic behaviour of the bearing as well as the ageing phenomena. In particular, for some effects the variability increases, when moving to a full-scale device, with respect to the results obtained through material test, i.e. the loading history effect or the production variability. On the other hand, the temperature or ageing effects measured by material tests could be overestimated with respect to full-scale bearing. Moreover, other source of variability known in literature (i.e. [7]) are only depictable from bearing tests. However, the trend associated to the rubber compound is usually related to the final full-scale bearing behaviour. For this reason, in the second part of the paper, the obtained results are compared with λ-factors provided by [5], with comments on how such modification factors are currently provided.

2 Test results

Data analysed in this study includes cyclic tests carried out on elastomeric specimens at different strain amplitudes, frequencies, temperatures, ageing conditions and number of cycle. Results are analysed in terms of ratio between experimental values (G and ξ) and nominal values (G_0 and ξ_0). According to the standard, experimental values are measured at the 3rd cycle of each test (unless the code specifies a different cycle), while the nominal value is conventionally defined as the property evaluated in reference conditions: shear deformation $\gamma=1$, temperature T=23°C and frequency f=0.5 Hz.

The statistical outcomes are presented through boxplot, where the box shows the 25th-75th percentiles of the samples whereas the internal line is the sample median. The extended segments instead show the minimum-maximum values range, except for the data considered outliers (values more than 1.5 interquartile range away from the box limits). Where the data are too much to show as boxplots, a simpler median line with all the data in the background have been used to improve the readability of the figures.

2.1 Effect of strain amplitude

The strain amplitude influences the mechanical behaviour of the rubber [8] [9], as shown in Fig. 1, where the variation of stiffness and damping ratios are related to the maximum shear strain. The effect on the stiffness for shear strains lower than the reference one ($\gamma=1$) is higher for HDR than for LDR. Both of them, instead, show median values close to one up to $\gamma=2.5$, suggesting an almost constant behaviour for deformation larger than $\gamma=1$, which is the common range of the design strains. For what concerns damping, the variability is almost linear for HDR with a median value ranging from 1.3 up to 0.75 by increasing shear strain. It is worth to observe that, although LDR has a similar trend, the damping ratio increases towards values higher than 1 for values of γ higher than 2. In [5] there is no limit for the amplitude dependence of the mechanical parameters, but these figures show that the variability between different compound is reduced especially for $\gamma>1$.

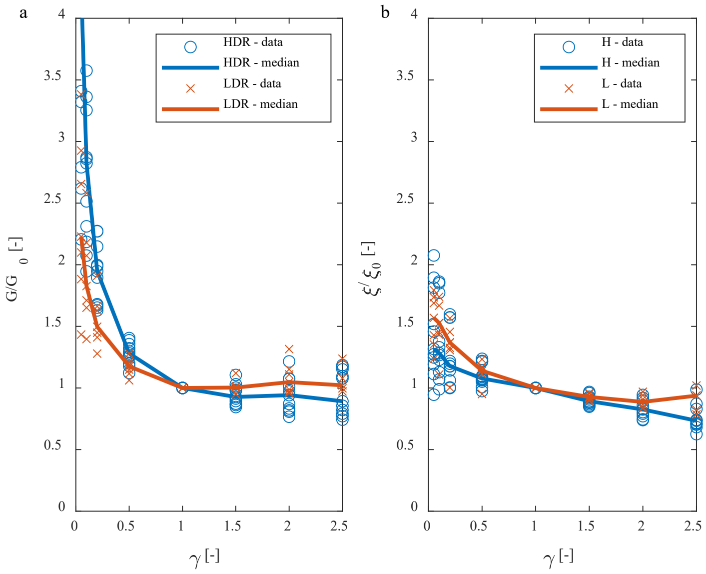

Fig. 1. Effect of deformation amplitude for (a) shear modulus; (b) damping ratio.

2.2 Effect of repeated cycles

The results of G and ξ measured at each cycle, with respect to the values recorded at the 2nd cycle, are reported in Fig. 2 (a, b). All the compounds are in compliance with the limit of 0.7 prescribed in [5] for the ratios recorded between the 2nd and the 10th cycle. Moreover, it is worth to note that all the values are higher than 0.85, with a median even higher than 0.9, suggesting that the cyclic degradation of rubber characteristics have been reduced during time by the manufacturers and it is currently a marginal source of variability of the material. Also, the limit of 0.6 for the ratio between the 1st and the 10th cycle for G (Fig. 2c) is largely satisfied (the lower value is 0.71, while the median value is 0.83). There are no limits prescribed by the code for the variation of the damping ratio between the 1st and the 10th cycle, nevertheless the related results are reported in Fig. 2d.

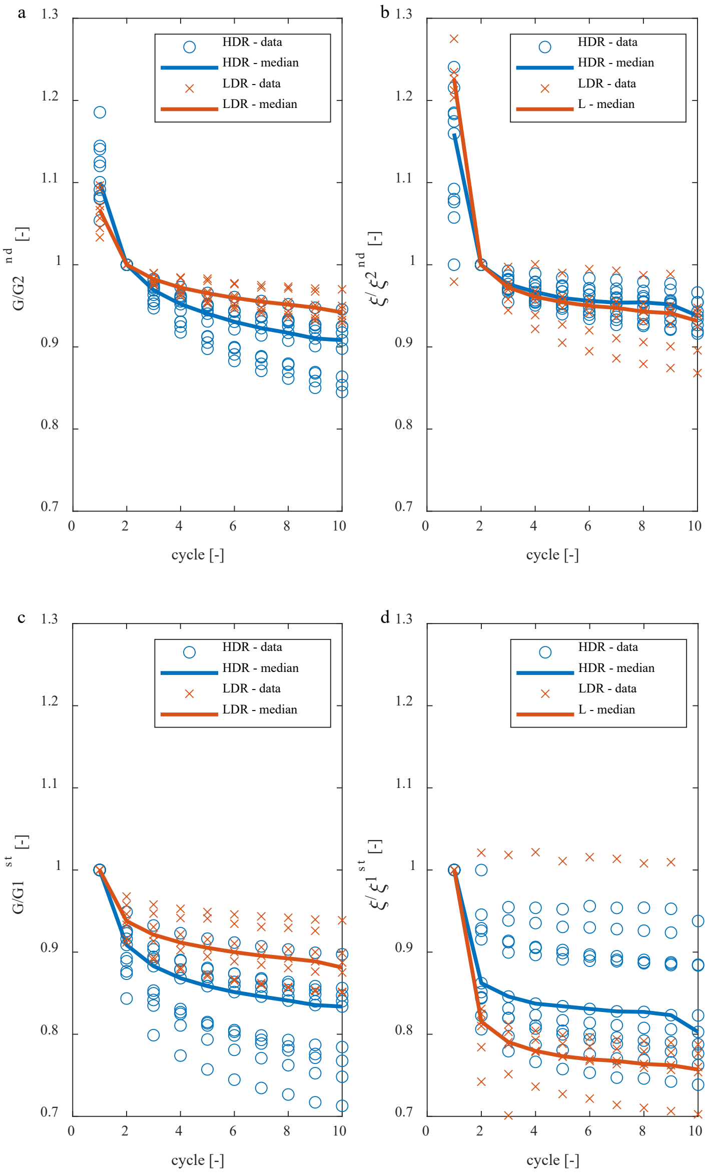

Fig. 2. Cyclic effect for (a, c) shear modulus; (b, d) damping ratio with respect to the (a, b) second and (c, d) first cycle.

2.3 Effect of frequency

The effect of frequency on the response(again in terms of *G* and *ξ*, normalized to unity with respect to the results achieved at 0.5 Hz) is limited by the code [5] within a range of 0.8-1.2 for frequencies spanning from 0.1 to 2 Hz. Fig. 3 (a,b) shows that all the values are in compliance with the code limits. Regarding the shear modulus ratio for HDR, the values are close to 1 for a frequency of 0.1 Hz, i.e. negligible effect, while the values are slightly higher for a frequency of 2 Hz (with a median value around 1.13). The effect of frequency for LDR is instead always negligible, as expected.

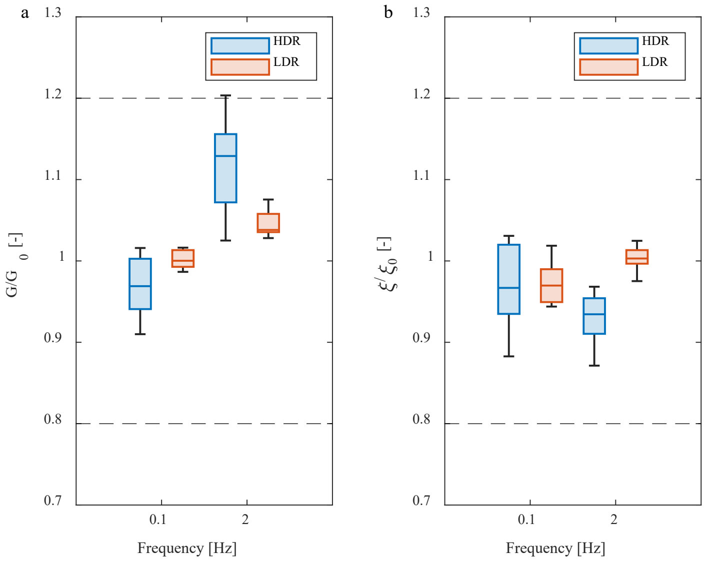

Fig. 3. Frequency effects for (a) shear modulus; (b) damping ratio.

2.4 Effect of ageing

The ageing effect on the rubber compound, according to [5], shall be estimated to be less than 20% over the expected service life of the isolator. The tests results are reported in Fig. 4 (a,b). The code allows to consider this condition satisfied for the bearings if the elastomer material satisfies the requirements under the standard ageing conditions. In the Authors' opinion, even if the accelerated aging test performed on rubber material is substantially different respect to the real ageing process of bearings, it is expected that the real ageing effect should be lower than the one tested on material. For example external surface of the elastomeric bearings are normally fabricated with a layer of cover rubber that includes anti-oxidants to protect the core from significant infiltration by oxygen and ozone [10] [11]. Moreover, this external surface reduces its porosity with ageing, leading to a less and less oxidation from the surface to a critical depth [12]. Thus, material tests provide an upper (and conservative) limit for the real ageing effect [13].

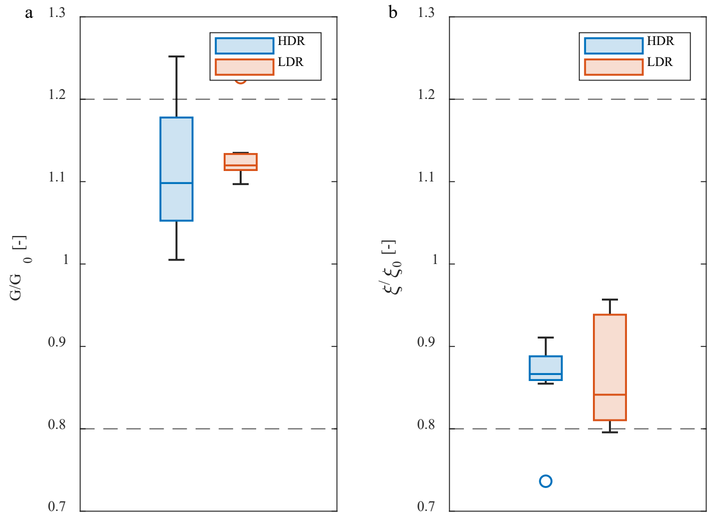

Fig. 4. Ageing effects for (a) shear modulus; (b) damping ratio.

2.5 Effect of temperature

As for the ageing effect, also the tests for the temperature effect on rubber bearings, according to [5], may be substituted by material tests. The values at the lowest temperature shall not differ by more than +80% or –20% from the corresponding values at 23°C, and the values at the highest temperature shall not differ by more than ±20% from those at 23°C. Fig. 5 shows data and median curves for the tests available in a range of -40 +50°C, even if the temperature suggested by the code are between -20 +40°C. With reference to Fig. 5, the results shown are not always in compliance with the code prescriptions, especially for the *G* ratio at the lower temperature; the median curve for HDR, indeed, is inside the code limit only down to -15°C. Looking at each value, most of the data are inside the code limit in the temperature range -10 +40°C, that is actually enough for most of the applications (except for bearings used in bridges in very cold regions, which can experience very low temperatures).

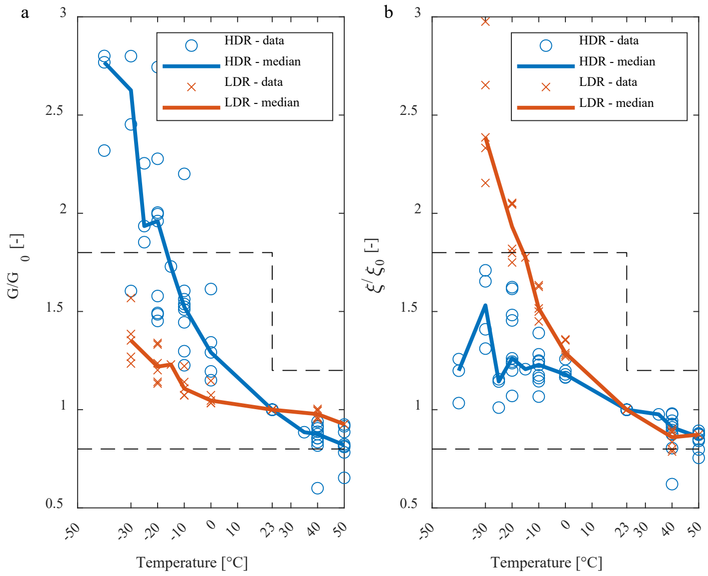

Fig. 5. Temperature effect for (a) shear modulus; (b) damping ratio.

2.6 Production variability

As shown in the previous chapter, all the results are shown in terms of ratio to the nominal value in reference conditions (γ=1, temperature T=23°C and frequency f=0.5 Hz). Consequently, for each test a set of values refers to the nominal condition. Grouping this data, a larger set can be collected to properly analyse the production variability on each rubber compound. Fig. 6 shows the variability of the ratio between the measured values of *G* and *ξ* with respect to the nominal ones declared by the manufacturers, for both the HDR and LDR compounds. All data of the shear stiffness (Fig. 6a) are in the range prescribed by the code (0.8-1.2). Moreover, most of the data (25th-75th percentiles) are close to 1, especially for the damping ratio, suggesting that usually the suppliers have a good control of the production process and real values match the nominal ones. The large number of outliers for the LDR damping is justified as the damping for this compound is not controlled (usually it is around 0.05). This is in compliance with the results on test performed also on bearings [14] where a statistical analysis has been performed to define the overall production variability and also the one within and between batch variability.

To have an insight on these data, showing them for each manufacturer, it is possible to make the same evaluation but enabling the analysis of intra-manufacturer variability and inter-manufacturer variability. The variation range is often smaller respect the whole data, as shown in Fig. 6 (c,d), confirming that the individual manufacturer has a specific compound, that is able to control

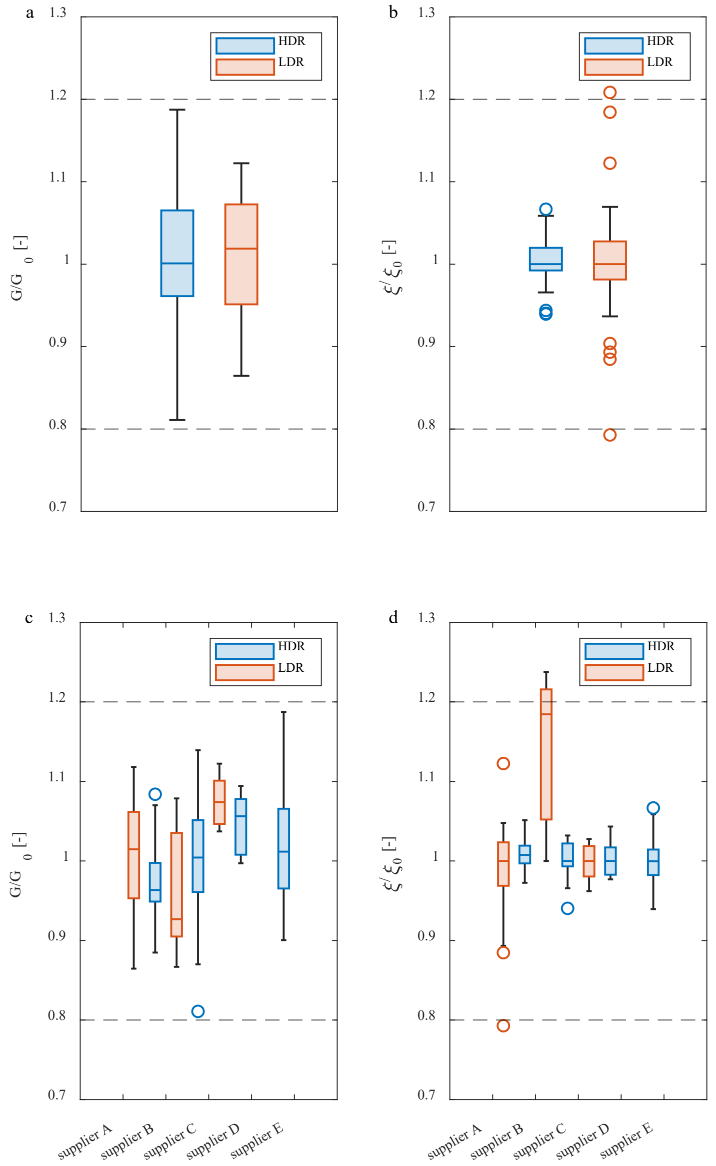

Fig. 6. Production variability for (a, c) shear modulus; (b, d) damping ratio for (a, b) overall data and (c,d) each supplier.

3 Code comparison of λ-factors

Starting from the λ-factors provided by the EN 15129 (annex J) [5] and the EN 1998 – part 2 (annex J) [4] in terms of K_p and F_0 it is possible to define the equivalent values in terms of G_0 and ξ_0 through simple formulas reported in ISO 22762 [15]. In this way it is possible to compare directly the λ-factors provided by the code and the mean value obtained by the data previously shown. Moreover, to deal with the variability of the data and the low number of samples, the 90% confidence interval is also reported (using the Student's t-distribution). The comparison is reported in Fig. 7, for G (a,c) and ξ (b,d) related to LDR (a,b) and HDR (c,d). In each tile the values for ageing and two on three temperature (0 and -10°C) considered by the code (for HDR with $\xi_0 \leq 15\%$) are reported. The -30°C temperature is not considered in this comparison as most of the data for that temperature are not in compliance with the limit prescribed by EN 15129 (see §2.5) and therefore the associated λ-factor is not available for the design. It is worth to note that in [5] HDRs compounds are divided in two categories based on the nominal ξ_0. In the comparison only the λ-factors related to $\xi_0 \leq 15\%$ are reported as only one compound (with a damping of 16.7%) out of 11 exceeds this limit. Regarding LDR (Fig. 7 a,b), the values suggested by the code are in agreement with the data obtained by the tests regarding the shear stiffness, while the λ-factors obtained for the damping are different. However, the damping of LDR is negligible and usually not considered in the design process. Moreover, the underestimation of the damping for low temperatures should be considered on the safety side and so as an extra source of reliability of the system.

On the contrary, for HDR (Fig. 7 c,d) the tests show an underestimation of the temperature effects on the shear stiffness. As mentioned before, [5] allows to extend the material tests at the bearing scale but, given the data obtained, specific full-scale tests for low temperature are strongly recommended in the case of seismic isolation in cold region with a design temperature lower than 0°C. The ageing λ-factor for HDR damping provided by the code is 1, while the data show a reduction of the damping capacity around 0.85. This effect, even if somehow intuitive is not recognized by the code and should be better investigated. On the contrary, as a higher damping could be considered a positive effect on the seismic response, the λ-factor for temperature effects on ξ may be acceptable as quite close to the ones provided by the code and on the safety side.

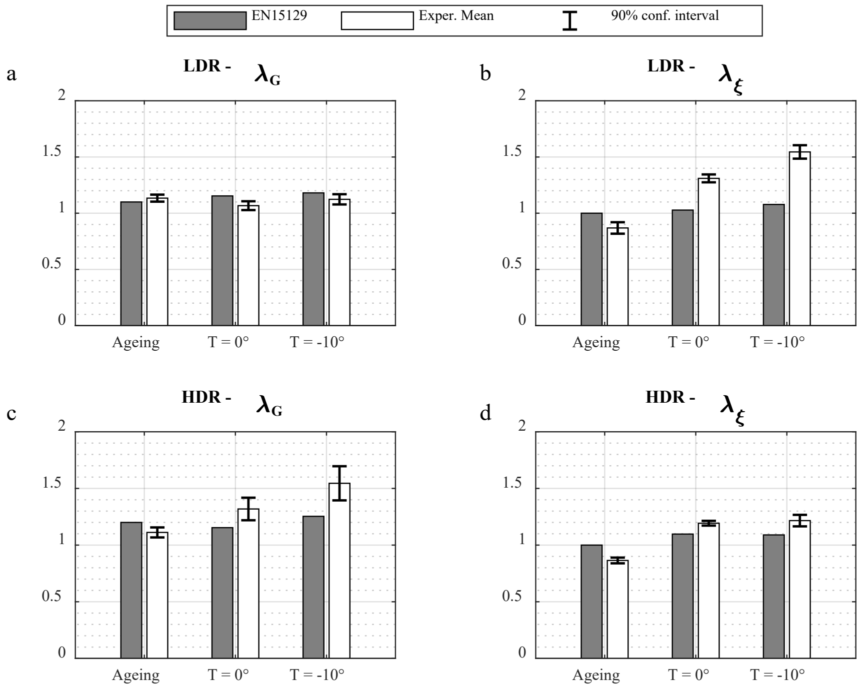

Fig. 7. λ-factors comparison between code values and data.

The implementation of a direct λ-factor format in terms of G and ξ is highly recommended because the equivalent linear parameters are commonly used by the designer to define the isolation system and it is possible to obtain a good linear approximation of the seismic response even for HDR [16]. On the contrary, bilinear models are no more commonly used because new models, also implemented in commercial software, [17] can be easily modified using the equivalent linear λ-factors.

In general, it is important for the structural engineering which design the base-isolation system, that λ-factors should be provided by the manufactures and tuned based on their current production. This is import for all the effects but essential for some effects, such as the low temperature or the repeated cycling effects. To this purpose, the manufacturers should provide material (when significant) or bearing tests properly carried out during the qualification procedure. Also the codes (in particular the EN15129 [5] in the European contest) should be improved by requiring bearing tests (in addition to material tests) to properly define λ-factors

4 Conclusion

This paper describes a statistical analysis of the material tests carried out according to EN 15129 [5] on a set of different rubber compounds from five different manufacturers. Based on the outcomes of the present study, the following conclusions can be drawn::

- Among the different sources of variability, temperature and ageing are quite important, while frequency and cyclic degradation seems to be of lower importance or even negligible;
- Production variability is overall inside the code limit of 0.8-1.2 and even lower for each individual manufacturer, however material tests do not allow to assess the effect of the production process of the elastomeric bearing, which could introduce important sources of variability. Therefore a comparison with tests performed on isolation devices is required to extend this result to the bearing scale and use it by the designers;
- Also for the others effects comparison between material and device tests should be performed in order to validate the results shown in this paper;
- Current λ-factors provided by the code EN 15129 [5] are related to the bilinear model while values in terms of equivalent linear parameter (stiffness and damping) should be also provided directly by the manufacturers,

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