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Research Article

Variability of Dynamic Properties of Rubber Compounds for Elastomeric Bearings

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The λ-factors for stiffness and damping of rubber bearings should be experimentally assessed during the qualification process or deduced from tests performed on material specimens. Moreover, the λ-factors suggested in the informative annexes of EN 15129 and of EC8-part 2 can be also used as reference values. However, they are derived from outdated experimental campaigns and do not refer to all the sources of variability. In this paper, a statistical analysis on a significant set of rubber compounds, certified according to EN 15129 from different suppliers, is carried out to assess the current variability of the dynamic properties of such compounds. Different sources of variability may be identified by distinguishing between behavioural and environmental effects. For elastomeric bearings, especially high-damping rubber (HDR) ones, the main behavioural effects are strain amplitude, strain rate dependence, and cyclic degradation, whereas the environmental effects are due to temperature variation and ageing. All these sources of variability have been analysed in this paper. The results of the statistical analysis have been used to propose a new set of λ-factors for all the source of variability studied. Such new values have been compared with the ones suggested by the codes when available. The main inconsistencies found have been highlighted and commented in this paper. Finally, some considerations about the influence of such variability on the structural response of base-isolated structures have been drawn by focusing on both the isolation system and the superstructure.

1. Introduction

Base isolation is a very efficient and widespread technique for the structural control of buildings and bridges under seismic excitations, especially for their conceptual simplicity. The analysis of base-isolated structures is also characterized by a low level of complexity during the design process because the behaviour of the superstructure should be linear elastic, while the nonlinear effects are limited to the isolation system. Nevertheless, either in the case of linear or nonlinear behaviour of the isolation system, the analysis and design of base-isolated structures should account for the variability of dynamic properties of the isolation bearings that may notably affect the response of such structures. As also underlined by most advanced seismic codes [1–6], the sources of variability to be considered should be distinguished between behavioural effects and environmental ones. For low-damping rubber (LDR) bearings and more significantly for high-damping rubber (HDR) ones, the main behavioural effects are the strain amplitude, the dependence of the rubber shear response to the strain rate, and the load history dependence due to the so called Mullins effect [7–11]. The strain amplitude effect, which is commonly known in the literature [8] as the Payne effect when referred to rubber, mainly consists of a stiffness increment of the rubber for small shear strain amplitudes. The stiffness of rubber compounds increases also by increasing the strain rate, i.e., the frequency of cyclic tests. This effect, which is usually moderate in the frequency range of interest for seismic applications, is instead remarkable when moving from quasistatic to dynamic tests [10, 11]. For what concerns the Mullins effect, also called in seismic codes and technical literature [9] as "scragging," it consists in a progressive reduction of the rubber stiffness during cyclic loads up to a stable or "fully scragged" behaviour [9, 11]. This effect is more complex and can be explained in general as the dependence on the load history of the shear rubber response due to a progressive breakdown of the filler-filler structure and the rubber-filler interaction during the deformation path [10, 11]. The shear response of elastomeric bearings is influenced not only by the rubber shear properties but also by the vertical load acting on them [12–14].

Furthermore, also the environmental conditions, such as temperature variation and ageing, can notably influence the rubber behaviour and thus the response of both LDR and HDR bearings. As well established in the literature, all rubber compounds are sensitive to temperature variations, especially to low ones that cause a significant increase of the rubber stiffness [15]. Moreover, stiffening at low temperatures can be also increased by the rubber crystallization [16, 17] that is associated to the gradual orientation of molecular chains when the rubber is exposed to constant low temperatures for a long time. Also, ageing increases the stiffness [18] during time. However, for large rubber bearings, the effects of both temperature and ageing may be reduced due to a larger internal protected rubber core, as explained later in the paper.

Nowadays, most of the behavioural effects, as well as the environmental ones, can be included into advanced numerical models [9–14, 19–22]. Nonetheless, current seismic codes also allow adopting simplified models to be used in combination with property modification factors called λ-factors in the European context. More in detail, by applying such factors to nominal design properties (NDPs) of the isolation bearings, two sets of properties are obtained, namely, the upper-bound design properties (UBDPs) and the lower-bound design properties (LBDPs). Consequently, two set of structural analyses, namely, UB and LB analyses, should be carried out. The former usually leads to the maximum base shear force and to the maxima accelerations for the superstructure, while the latter provides the maximum displacement for the isolation system.

Current seismic standards suggest to derive λ-factors from experimental data obtained from qualification tests on bearings or, in some cases, from tests performed on material specimens, as allowed by the European product standard on antiseismic devices EN 15129 [3]. For this reason, in the first part of the paper, a statistical analysis is carried out on a large set of material tests performed according to EN 15129 [3] on low- and high-damping rubber compounds from different European suppliers currently used for elastomeric bearings, with shear modulus ranging from 0.4 MPa to 1.3 MPa.

For each source of variability, the response has been analysed in terms of equivalent linear properties. More in detail, the effect of different behavioural and environmental phenomena (i.e., shear strain amplitude and strain rate, cyclic degradation, ageing, and temperature) on the dynamic shear modulus (G) and the damping ratio (ξ) is described. Results are reported in terms of the statistical distribution of the relative variation with respect to the reference condition (i.e., properties measured at the 3rd experimental cycle on unaged specimens at the reference strain amplitude, frequency, and temperature). The production variability is also analysed by considering data coming from each supplier and the whole experimental set of data.

The second part of the paper examines the feasibility of deriving full-scale device properties from material tests by using available experimental data on full-scale bearings and by conducting a literature review. Successively, updated λ-factors for G and ξ are proposed to directly perform UB and LB dynamic linear analyses, as allowed by most seismic codes for elastomeric bearings [1–6]. The proposed values are also compared to λ-factors suggested in the two informative annexes of Eurocodes (annex J of EN 15129 [3] and annex JJ of Eurocode 8-part 2 [4]) which can be used when no experimental data are available. However, it is worth to note that these λ-factors refer to a two-parameters bilinear response model, i.e., to the postyield stiffness and strength at zero displacement, thus they cannot be directly used in linear analysis of base-isolated structures encompassing elastomeric bearings. Moreover, they are taken from outdated documents [23–25] based on limited data not referring to the current European production of elastomeric bearings [26]. For this reason, the main differences between the proposed values and the values coming from these annexes are highlighted and commented.

Finally, the impact on the seismic response of base-isolated structures of both the sets of λ-factors (i.e., the proposed ones and those derived by the informative annexes of the Eurocodes) has been evaluated by assuming a simplified S-DOF linear model to simulate the behaviour of the base-isolated structure. The aim of this insight is to evaluate either the impact of the two sets of λ-factors in the design procedure and to evaluate if the proposed ones can become a widely accepted set of λ-factors, agreed by both suppliers and structural engineers. This agreement would be adherent to the new process suggested by the ISO 22762 [27], ensuring that structural engineers have access to reliable values of UBDPs and LBDPs, regardless of the specific supplier.

2. Analysis of Elastomeric Compounds Data

The dataset used in this study collects results of qualification tests carried out by the Materials Testing Laboratory of Politecnico di Milano, which is a notified body for testing, inspection, and certification of antiseismic devices according to EN 15129 since 2011 [28]. The dataset is composed by 18 rubber compounds (7 LDRs and 11 HDRs) belonging to 5 different European suppliers, with a shear modulus (G) in the range 0.4–1.3 MPa (Table 1). Data refer to the results of dynamic tests carried out to evaluate the influence on the dynamic properties (dynamic shear modulus, G, and damping, ξ) of different effects, i.e., strain amplitude, frequency, temperature, ageing, and repeated cycles. These tests are all part of type tests carried out according to the EN 15129-§8.2.2 [3] to verify that the compounds meet code

Table 1: List of rubber compounds.

Compound identifiers	Rubber types	Supplier	G_0 (MPa)	ξ_0 (—)
1 A (0.7)	LDR	Supplier 1	0.74	0.058
1 B (0.7)	LDR	Supplier 1	0.75	0.042
1 C (0.6)	LDR	Supplier 1	0.58	0.034
1 D (0.9)	LDR	Supplier 1	0.91	0.062
1 E (1.2)	LDR	Supplier 1	1.17	0.049
2 F (0.6)	LDR	Supplier 2	0.61	0.050
3 G (0.4)	LDR	Supplier 3	0.45	0.059
3 H (0.4)	HDR	Supplier 3	0.45	0.117
3 I (0.8)	HDR	Supplier 3	0.81	0.155
3 L (1.2)	HDR	Supplier 3	1.18	0.151
3 M (0.7)	HDR	Supplier 3	0.72	0.083
4 O (0.7)	HDR	Supplier 4	0.74	0.092
5 P (0.4)	HDR	Supplier 5	0.39	0.132
5 Q (0.5)	HDR	Supplier 5	0.51	0.086
5 R (0.7)	HDR	Supplier 5	0.66	0.113
5 S (0.9)	HDR	Supplier 5	0.86	0.126
2 T (1.1)	HDR	Supplier 2	1.09	0.077
2 U (1.3)	HDR	Supplier 2	1.30	0.167

requirements for their use in isolation bearings. The other tests required by the qualification procedure (shear bond test, resistance to low temperature crystallisation, and resistance to slow crack growth) are not object of this study. Table 1 reports the list of rubber compounds with the indication of the dynamic properties (including the damping for LDR even though not the object of qualification) related to specimens used for the strain amplitude effect evaluation. It can be observed that values of G are all close to nominal values reported in the compound identifier and that values of ξ are all lower than 6% for LDR and lower than 17% for HDR. According to the EN 15129, tests to assess the property variation are made on a set of 3 samples for each effect and the reported values are the averaged results. In detail, dynamic parameters considered in this paper are defined according to §G.5 of EN 15129 and computed by the following expressions:

$$G = \frac{\tau^+ - \tau^-}{\gamma^+ - \gamma^-}, \xi = \frac{2\mathrm{H}}{\pi G\left(\gamma^+ - \gamma^-\right)}, \tag{1}$$

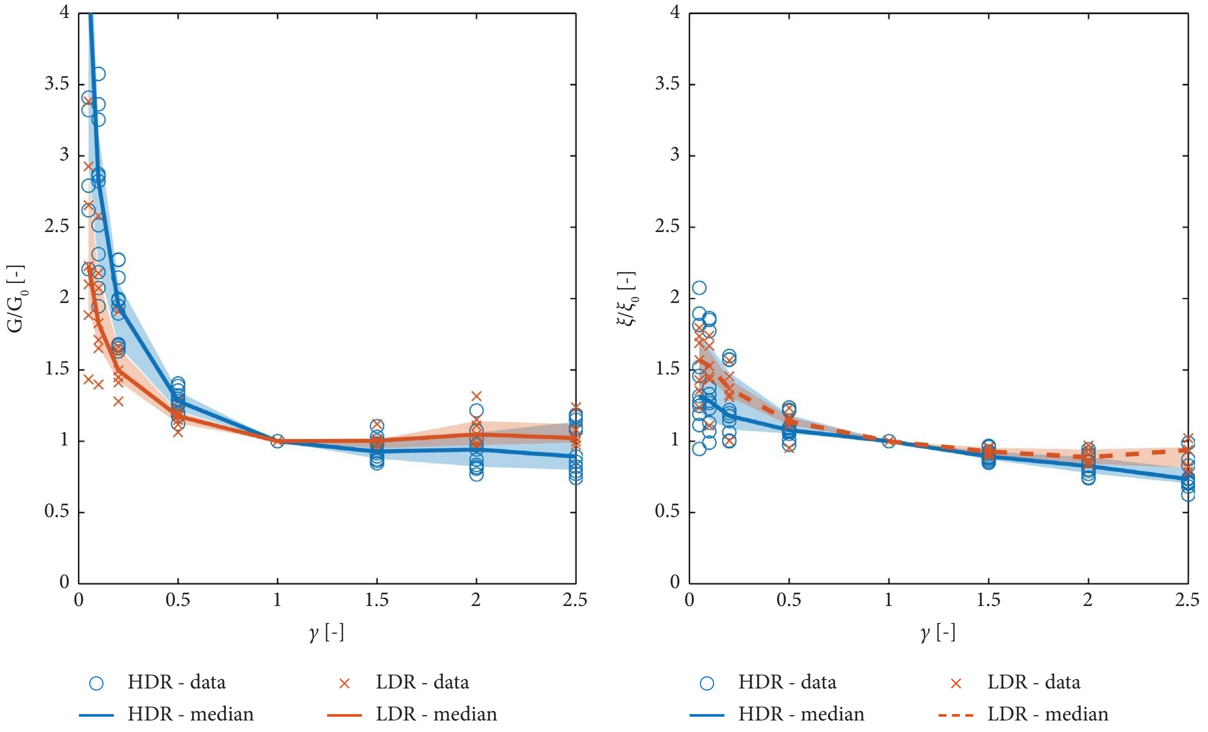
where γ^+ and γ^- are the maximum and minimum values of the shear strain of the cycle, τ^+ and τ^- are the shear stress at those strains, and H is the area of the hysteresis loop. For each test sequence, reference values of the dynamic parameters (G_0 and ξ_0) measured at the reference condition (the 3rd cycle at shear strain $\gamma = 1$, temperature $T = 23°\mathrm{C}$, and frequency $f = 0.5\,\mathrm{Hz}$) are identified. In the following sections, the results are shown in terms of ratio between the values measured at a specific condition (G and ξ) and the values measured in the same test at the reference condition (G_0 and ξ_0) for each behavioural and environmental factor (i.e., shear strain, cyclic degradation, strain rate, ageing, and temperature). This way, the production variability is removed and discussed later. Moreover, results are separately presented for LDRs and HDRs. The effects on ξ for LDRs (dashed line) is reported only for comparison purpose since it is usually neglected in the design practice and not object of the qualification procedure.

2.1. Strain Amplitude.

2.1. Strain Amplitude. Figures 1(a) and 1(b), as other figures of the paper, show for each set of data (HDR in blue and LDR in orange) a solid line representing median values of the experimental dataset and an area in the background representing the range between the 25th and 75th percentile [29]. More in detail, for $\gamma < 1$, the ratio G/G_0 (Figure 1(a)) is higher for HDRs than for LDRs, whereas for $\gamma > 1$, this ratio shows a constant value close to 1 up to $\gamma = 2.5$. Thus, for these rubbers, the hardening behaviour typically at large strains does not occur up to $\gamma = 2.5$ and stiffness is consequently almost constant in the common range of design shear strains. This means that during strong seismic motions, the expected isolation period is approximately constant regardless the earthquake intensity, while for lower seismic motions or other service actions, the bearing stiffness is higher, ensuring low displacements. For the damping ratio, the trend follows an almost linearly decreasing pattern with γ for HDRs with median values ranging from 1.3 to 0.75 by increasing the shear strain. The effect on ξ for LDRs is reported for comparison purpose only (dashed line), as the damping for this kind of rubber is not considered in common design practice. Finally, no significant relation between other compound features (e.g., manufacturer or nominal stiffness) and the effect of strain amplitude is recognised, except for the difference between LDR and HDR compounds. This leads to a small variability between different compounds, as shown by the small narrow area of the 25th and 75th percentiles in the background (Figure 1).

2.2. Repeated Cycles. According to [3], the dependence of the rubber properties on repeated cycles may be evaluated by performing material tests at the reference strain of $\gamma = 1$ and by verifying that the ratios between the values of G and ξ measured at the 10th cycle and at the 2nd cycle are not lower than 0.7. Moreover, the ratio between G values measured at the 10th and at the 1st cycle must be not lower than 0.6, whereas no limits are prescribed for the ξ ratio between these cycles. Figures 2(a) and 2(b) show the ratios between G and ξ values measured at each cycle with respect to the values recorded at the 2nd cycle (G_2 and ξ_2). It can be observed that all compounds comply with the prescribed limit of 0.7 with a significant margin. More in details, for HDRs, G/G_2 at the 10th cycle is always higher than 0.85, with a median value higher than 0.9. The limit of 0.6, required for the ratio between the 10th and the 1st cycle, is also satisfied as the lower single value is 0.71, while the median value is 0.83.

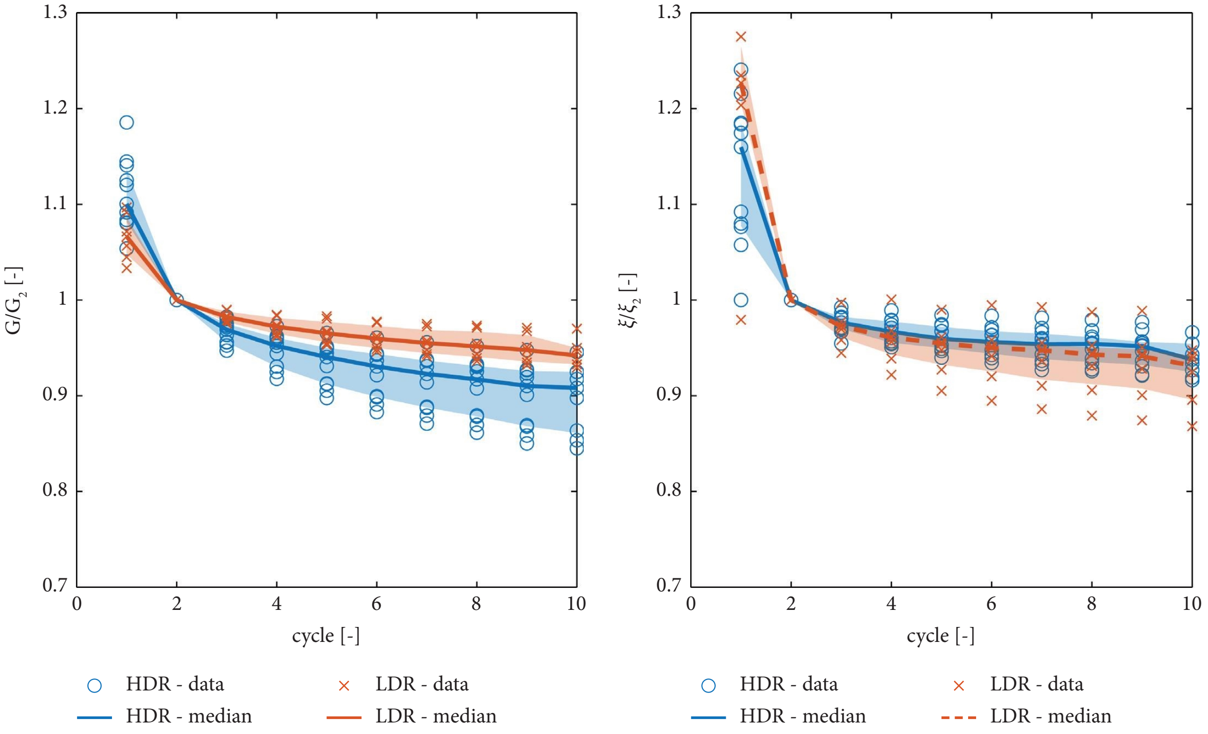
Figures 2(c) and 2(d) refer to the same data but in terms of G/G_0 and ξ/ξ_0 ratios since the 3rd cycle is the reference condition to evaluate nominal properties according to EN 15129. By considering the first cycle, the G/G_0 ratio is always lower than 1.26 with median values of 1.13 and 1.08 for HDRs and LDRs, respectively, and 1.18 in terms of ξ/ξ_0 for HDRs. On the other side, the ratio between the 10th and the



(a)

(b)

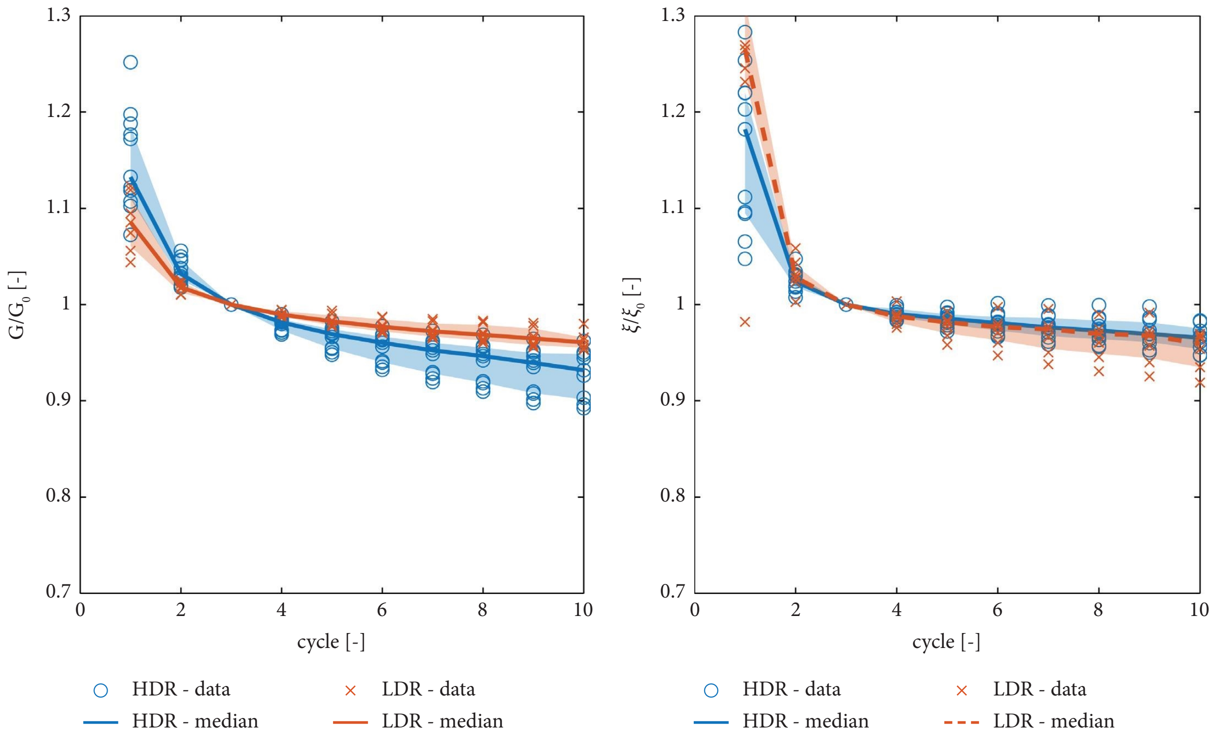
Figure 1: Strain amplitude effect on the shear modulus (a) and the damping ratio (b).



(a)

(b)

Figure 2: Continued.



(c)

(d)

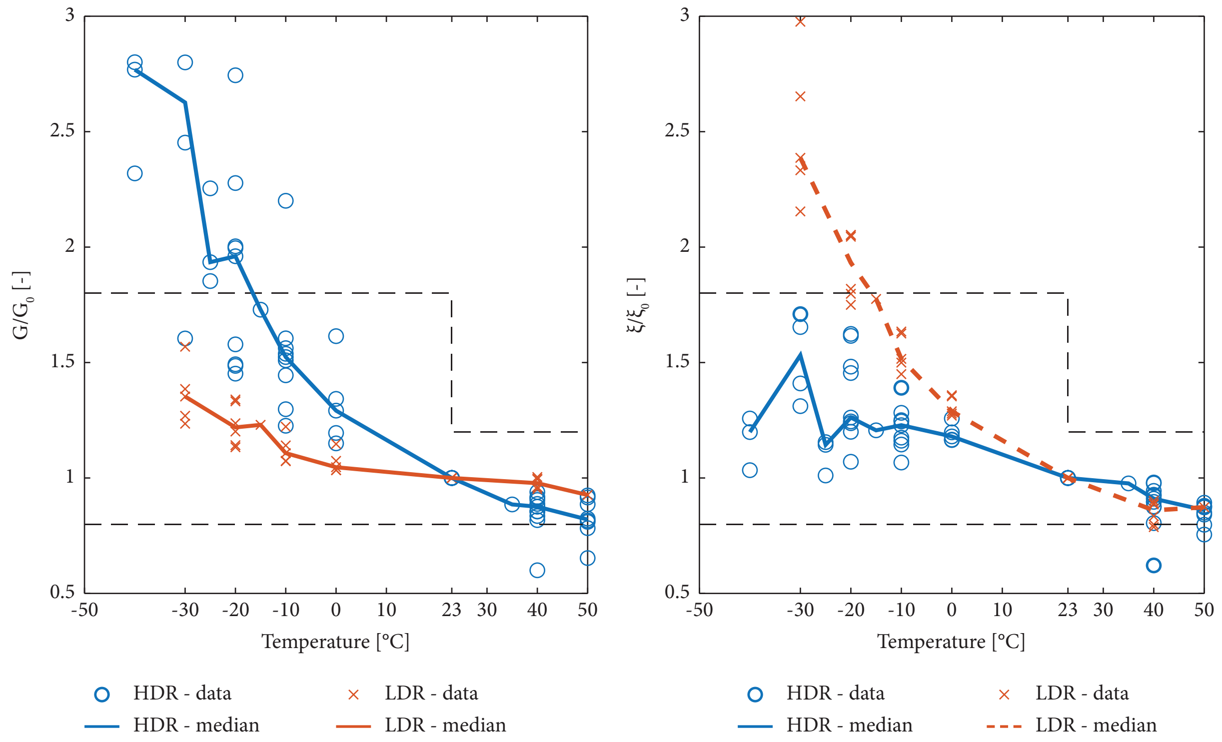
Figure 2: Cyclic effect on the shear modulus and the damping ratio with respect to the second cycle (a-b) and the third cycle (c-d).

3rd cycle is always higher than 0.89 for G with median values of 0.93 and 0.96 for HDRs and LDRs, respectively, and 0.97 in terms of ξ for HDRs. This means that current rubber compounds are less sensitive to the effect of repeated cycles than in the past, regardless of the shear modulus or of the equivalent damping. Actually, HDRs exhibit a behaviour similar to that of LDRs, which are generally considered unaffected by this effect. This is an important point since in the past, HDR bearings with low shear modulus and/or high damping ratios were considered affected by a large "scragging" [9, 25] and this have significantly limited their use, especially for strategic structures in the U.S. [30]. Actually, this behaviour was limited to HDR bearings where the low shear modulus or the high damping capacity were obtained by incomplete curing [25], which is no more representative of the current production of HDR bearings.

2.3. Environmental Temperature. For what concerns environmental temperature, samples have been tested according to [3], thus conditioned for the minimum time required to reach the specified temperature (according to ISO 23529 [31]), avoiding the crystallization as much as possible. Actually, crystallization is assessed by a specific test procedure (see §8.2.2.1.5 of [3]) and it is not considered as a variability factor by the code. Moreover, the internal heating effect is negligible due to the small size of tested specimens.

According to [3], the evaluation of the temperature effect may be done by performing material tests at different temperatures ranging from −20°C to 40°C but higher or lower temperature can be tested if required. Figures 3(a) and 3(b) show single data and median curves for the temperature effect analysed in the range of $-40^{\circ}\mathrm{C} + 50^{\circ}\mathrm{C}$. As the numerosity of data at each temperature is quite different for the dataset analysed in this paper, the 25th–75th percentiles range is not represented. The code prescribes different limits for the variation of dynamic properties with respect to the reference temperature of 23°C as follows: for higher temperatures, the admitted variability is in the ±20% range, while for lower temperatures, the admitted range is from −20% to 80%. These different limits are represented in Figure 3 as black dashed lines. All LDR compounds comply with the code prescriptions while for HDR compounds, many data are out of the boundaries, especially for the G/G_0 ratio at low temperatures. Since the rubber suppliers usually test the compounds for the whole range of temperature, they obtain the qualification only for the temperature range where data fulfil code limits and most of the compounds analysed fulfil code requirements for temperatures between −10°C and +40°C. As expected, HDRs have higher variability with temperature with respect to LDRs. For this reason, for rubber isolation bearings exposed in very cold regions, it could be more reliable to use LDR in combination with other sources of damping.

2.4. Ageing. EN 15129 [3] prescribes a variation of the dynamic properties of elastomeric bearings less than 20% due to the ageing effect. This condition is verified under accelerated anaerobic ageing of rubber compound samples.



(a)

(b)

Figure 3: Temperature effect on the shear modulus (a) and the damping ratio (b).

Different to the previous factors, for the ageing effect, only one ratio can be computed (aged divided unaged values), thus results are reported as boxplots [32]. Figures 4(a) and 4(b) show G/G_0 and ξ/ξ_0, respectively, where G_0 and ξ_0 are unaged values. Each coloured box represents the interquartile range (25th and 75th percentiles of the samples), while the line inside the box is the sample median. As in the previous figures, two different colours are used for HDR and LDR. All the statistical characteristics are computed as previously described. The extended segments show the minimum-maximum values range. Moreover, values are considered outliers if they are out the range of the box limits, i.e., plus-minus 1.5 times the interquartile range. The variability related to ξ/ξ_0 for LDR is shaded because it is not used in the design process. The results show, as expected, an increase of stiffness, which is similar for HDR and LDR (with a median value around 1.11) but with a higher dispersion for HDR. The damping, instead, decreases with a median value of 0.86 for HDR and a quite small dispersion.

2.5. Strain Rate (Frequency). Rubber bearings may show a remarkable dependence of the response due to viscous effects by passing from quasistatic load histories to dynamic input, as also observed during in situ tests [33]. However, in the range of frequencies of interest for seismic applications (between 0.5 Hz and 0.2 Hz), this dependence is not very high, though not negligible, and should be assessed. According to [3], the effect of the strain rate on G and ξ can be evaluated by performing cyclic tests on material specimens at frequencies in the range between 0.1 Hz and 2 Hz. The code prescription establishes that the dynamic modulus and damping at the lowest and highest frequencies shall not differ by more than 20% from the value recorded at 0.5 Hz (reference condition). As previously described for the ageing effect, Figure 5 shows the 25th–75th percentile range, median values, and the minimum-maximum range of ratios G/G_0 and ξ/ξ_0 (where G_0 and ξ_0 are values computed at 0.5 Hz) for the two boundary frequencies 0.1 Hz and 2 Hz. The limits of ±20% are also reported as dashed lines. All the compounds analysed comply with code limits. More in detail, G/G_0 for HDR are close to 1 for a frequency of 0.1 Hz, whereas values are slightly higher for the frequency of 2 Hz (with a median value of 1.13); ξ/ξ_0 is close to 1 for both 0.1 Hz and 2 Hz. On the other hand, the effect of frequency for LDR is negligible, as already known in the literature [25].

2.6. Production Variability. All data of the previous sections have been analysed in terms of G/G_0 and ξ/ξ_0 ratios, where G_0 and ξ_0 are values at the reference condition determined for each test. Thus, for each effect, a set of G_0 and ξ_0 has been measured on a different rubber specimen. By grouping all these values, a large set of data at the reference condition can be collected to analyse the production variability of each rubber compound. Figures 6(a) and 6(b) show the variability of the ratio between the measured values of G_0 and ξ_0 with respect to those of the strain amplitude test (see Table 1) and are called G_{nom} and ξ_{nom} here to avoid misunderstandings.

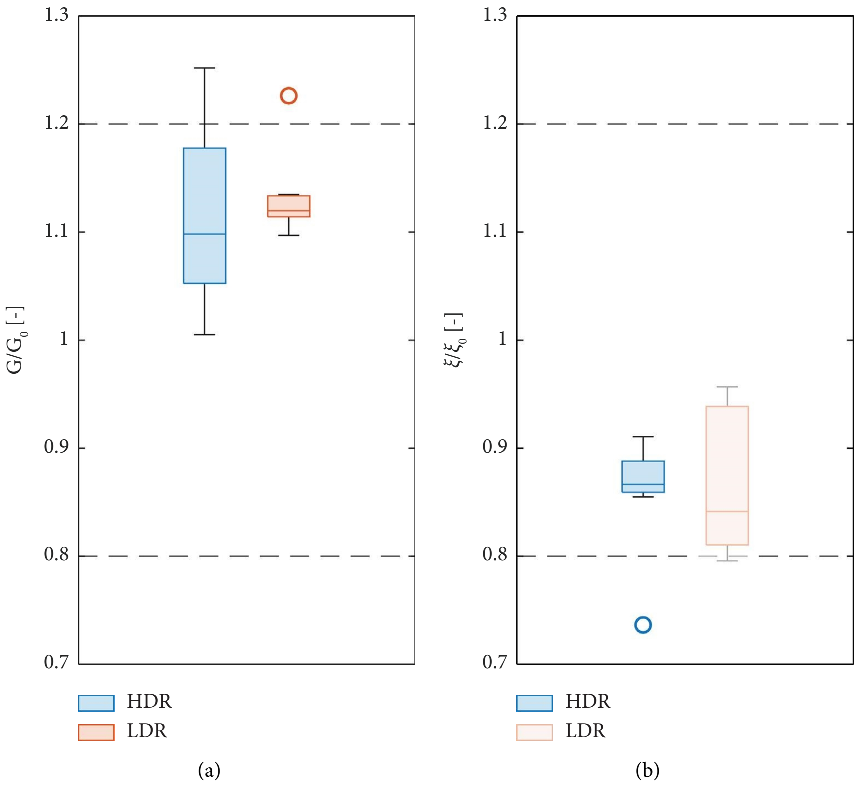


FIGURE 4: Ageing effect on the shear modulus (a) and the damping ratio (b).

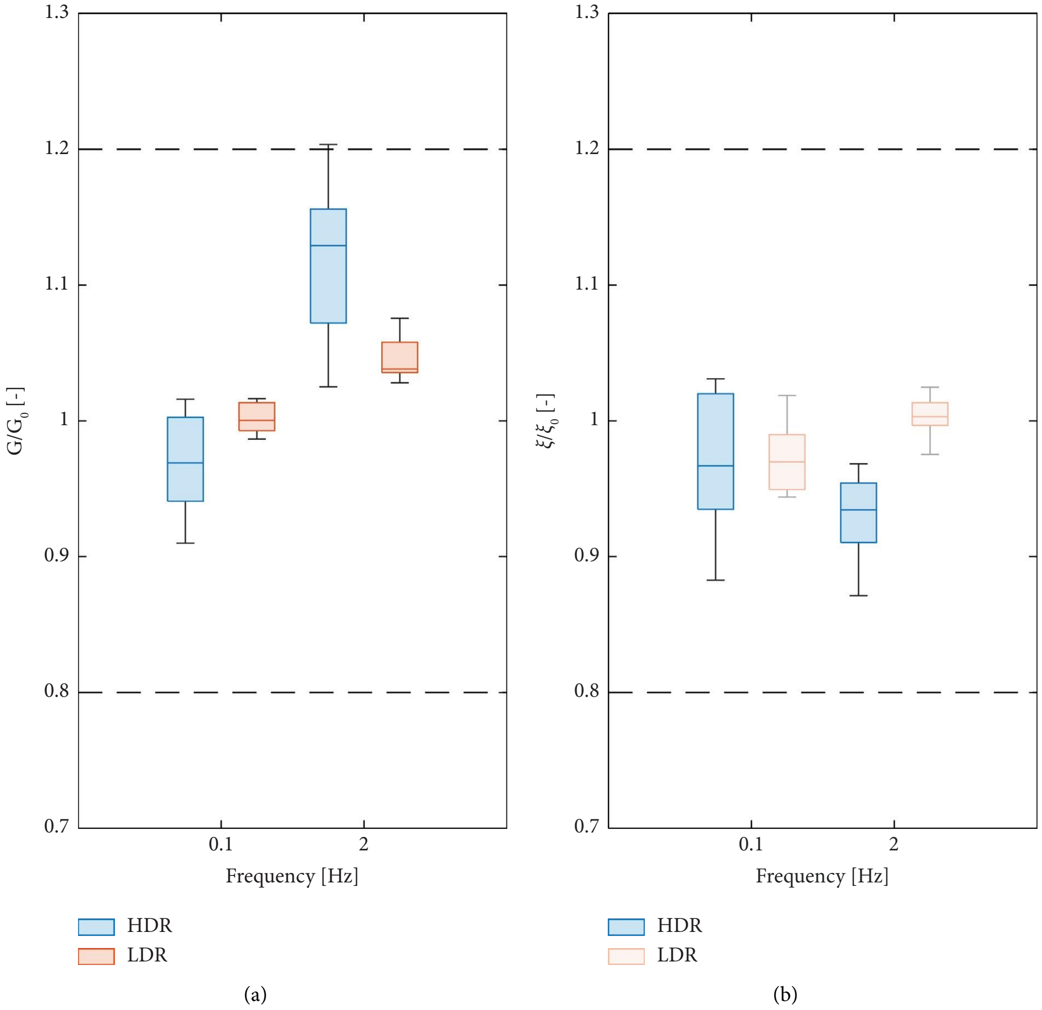
The resulting statistical distribution of G_0/G_{nom} (Figure 6(a)) has a median value very close to 1, with 25th–75th percentiles close to the median value and all the values within the range prescribed by the code (±20%). In other words, current suppliers can control quite well the production process and dynamic properties of the compounds match the nominal ones. To have a further insight into these data, it is possible to analyse each supplier's variability. As expected, the variation ranges are even smaller with respect to the whole data variability, as shown in Figures 6(c) and 6(d), confirming the high control level of some individual suppliers. These results are in compliance with [33] where a large set of tests performed at the bearing scale is analysed, showing that the overall variability (all the manufacturers) is much higher than the single batch variability (single manufacturer).

3. Comparison between Experimental Results at the Material and Bearing Scales

As already mentioned, the EN 15129 code [3] allows to use material tests results to define the variability of dynamic properties. However, the hypothesis that tests performed on rubber compound at material scale can be extended to full-scale bearings is not always considered appropriate or straightforward; the device dimension and the vulcanization process used to fabricate the isolators may significantly affect the final cyclic behaviour of the bearing.

In the literature, there is contradictory information. In [9], the different curing process used for material specimens, or moderate-scale elastomeric bearings, with respect to full-scale bearings is identified as the source of difference in their final behaviour. On the contrary, in [34], scale effects are considered negligible, except for the rising temperature for long-duration earthquakes (more than 10 full cycles at 200% shear strain) and very big bearings (diameter larger than 1000 mm). Similarly, in [15], a direct comparison between material tests and a full bearing test (diameter 800 mm, total rubber thickness 270 mm) for a pseudostatic full cycle (100% shear strain and 0.01 Hz) shows that the stress-strain behaviour is almost the same at both the material and the bearing scales. A source of variability, already known in the literature [35], may arise from the vertical load imposed to bearings during the horizontal shear tests, which can increase the damping ratio with respect to values obtained from material tests performed in simple shear. However, this is not actually a scale effect (related to the dimension of the sample), but rather a different test condition (vertical pressure increases viscosity and friction-induced energy dissipation between rubber molecules).

To provide a further contribution to this topic, in this paper, a comparison is made between material tests of a compound belonging to the analysed dataset, i.e., 5 P (0.4), and the type tests (TTs) and the factory production control tests (FPCTs) carried out on full-scale bearings made of that compound. Tests have been performed during the design and construction process of the CHIP building (chemistry interdisciplinary project) [36, 37]. All the tests were carried out according to EN 15129 [3] for a total of 8 bearings. Thus, it is possible to compare the behaviours at the material and bearing scales. Bearings have a diameter of 800 mm and



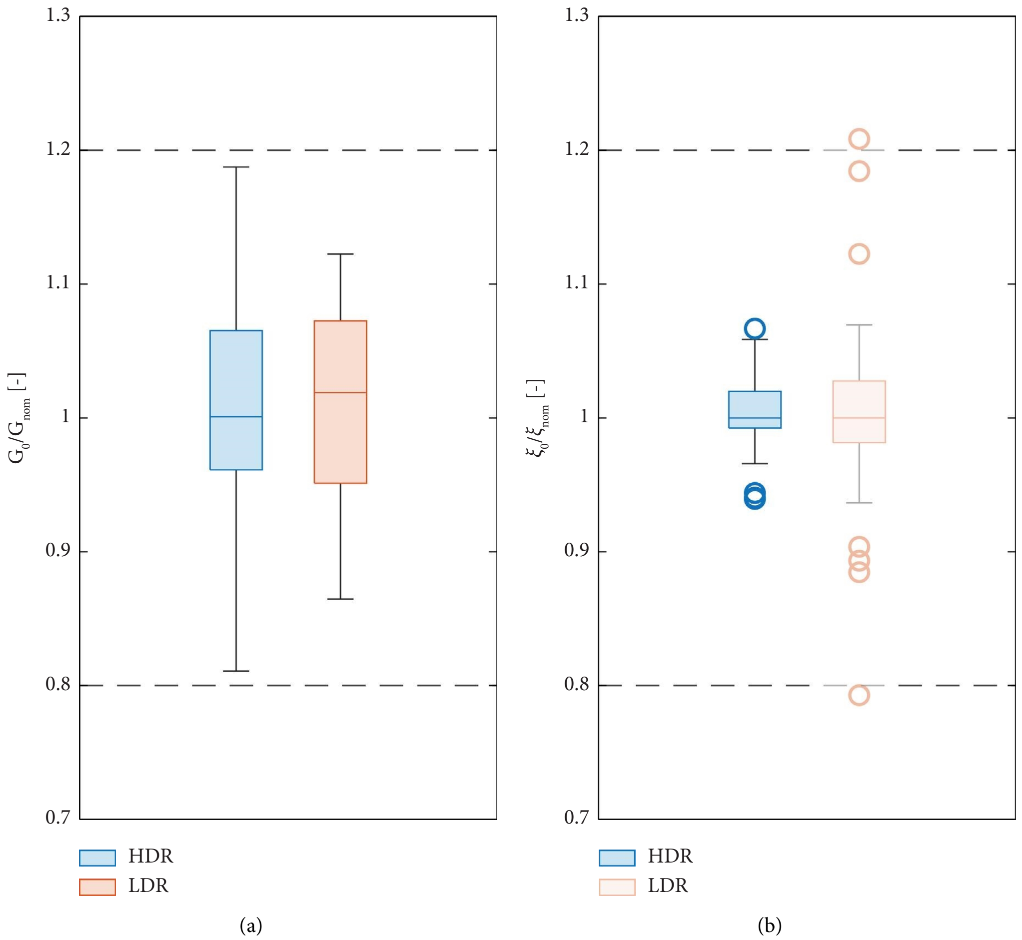
(a)

(b)

Figure 5: Frequency effect on the shear modulus (a) and the damping ratio (b).

a total rubber thickness of 184 mm. They are tested up to $\gamma = 2$ for the dynamic cyclic test (8.2.1.2.2 of [3]) and up to $\gamma = 2.18$ for lateral displacement capacity (§8.2.1.2.7 of [3]). Figures 7(a) and 7(b) show a direct comparison between G and ξ for the material specimen and the bearing results. There is a quite good agreement between mean values of G for the compound and the bearings, but with a significative dispersion related to the manufacturing process of bearings. On the contrary, mean values of ξ are always higher for the bearings with respect to the compound. These results are in line with other experimental tests [35, 38] showing that in the range of vertical pressure from 0 MPa to 6 MPa, which are the conditions of the material tests and bearing tests, respectively, the shear modulus is not affected, while the damping ratio can increase up to 1.4 times [35]. Figures 8(a) and 8(b) display the same data as Figure 7, even though values of G and ξ are divided by those recorded under nominal conditions (shear strain $\gamma = 1$, 3rd cycle, cf. Figure 1). First, it is evident that the variability is reduced, confirming that the higher dispersion of the bearings is primarily due to the manufacturing process. In addition, values of G/G_0 and ξ/ξ_0 closely align with the mean curve of the compound at small shear strains, while some differences become apparent at larger strains. This implies that the trend of the shear amplitude effect is influenced by the scale effect only at large shear strains. The same results are obtained for the effect of repeated cycles, as shown in Figure 9. Even in this case, data are plotted by dividing the values of G and ξ by those recorded at the nominal conditions (shear strain $\gamma = 1$, 3rd cycle). It can be observed that the shear modulus reduction is almost the same either for the compound or the bearings. A good agreement, even though not as close as the one recorded for the ratio G/G_0, is also obtained for the ratio ξ/ξ_0. As previously mentioned, the reason for such larger difference can be ascribed to the vertical pressure, which can affect not only the absolute value of damping but also its variation with cycles.

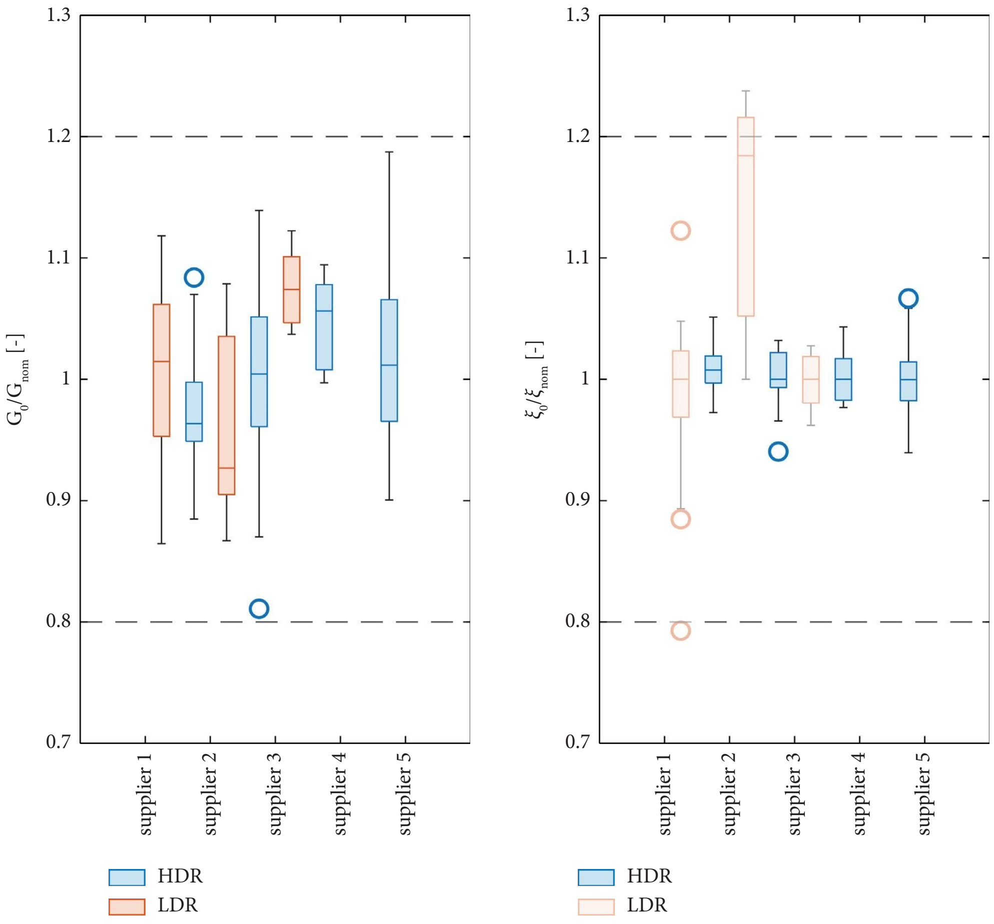
As a final remark, it is worth observing that evaluating the environmental effects through tests carried out on material specimens is a more complex task than the evaluation of behavioural effects. Several papers have shown that the influence of air temperature and ageing is expected to be, in general, less significant at the scale of bearings rather than for material tests. For the temperature effect, the works of



(a)

(b)

Figure 6: Continued.

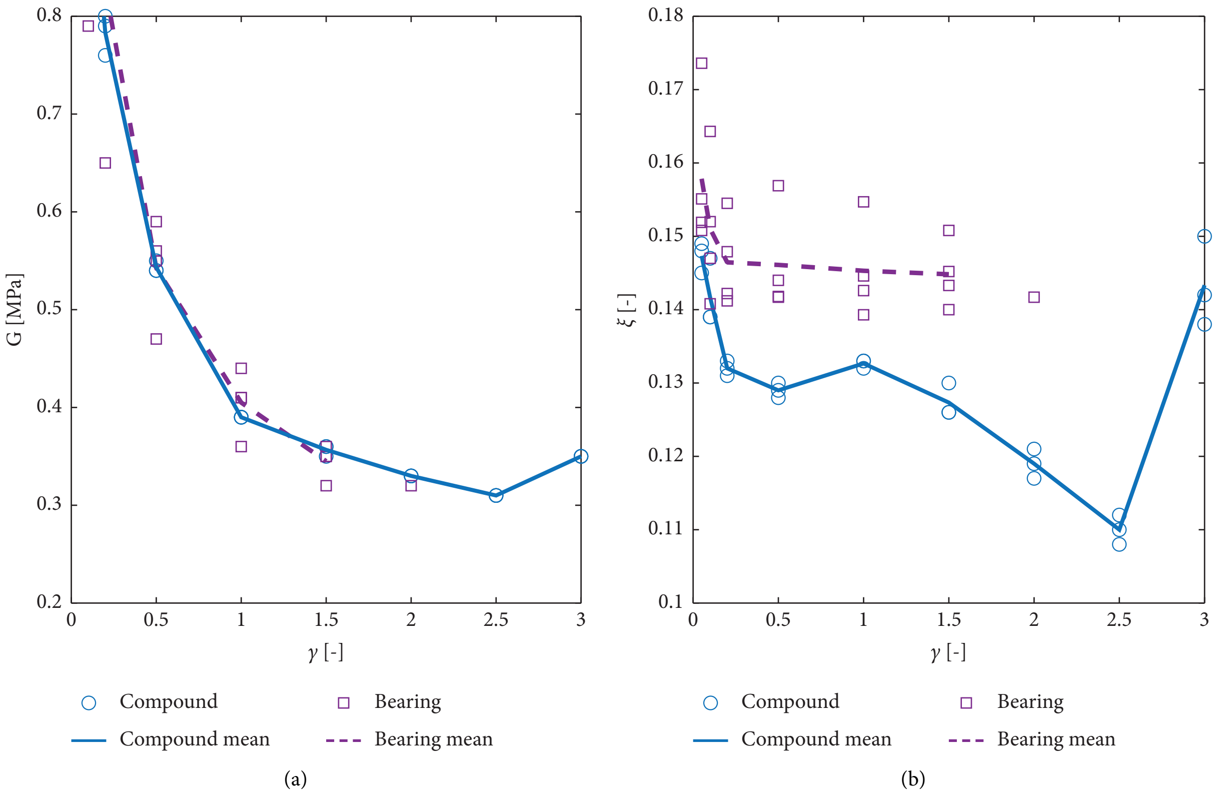


(c)

(d)

Figure 6: Production variability on the shear modulus and the damping ratio for the overall data (a-b) and each supplier (c-d).

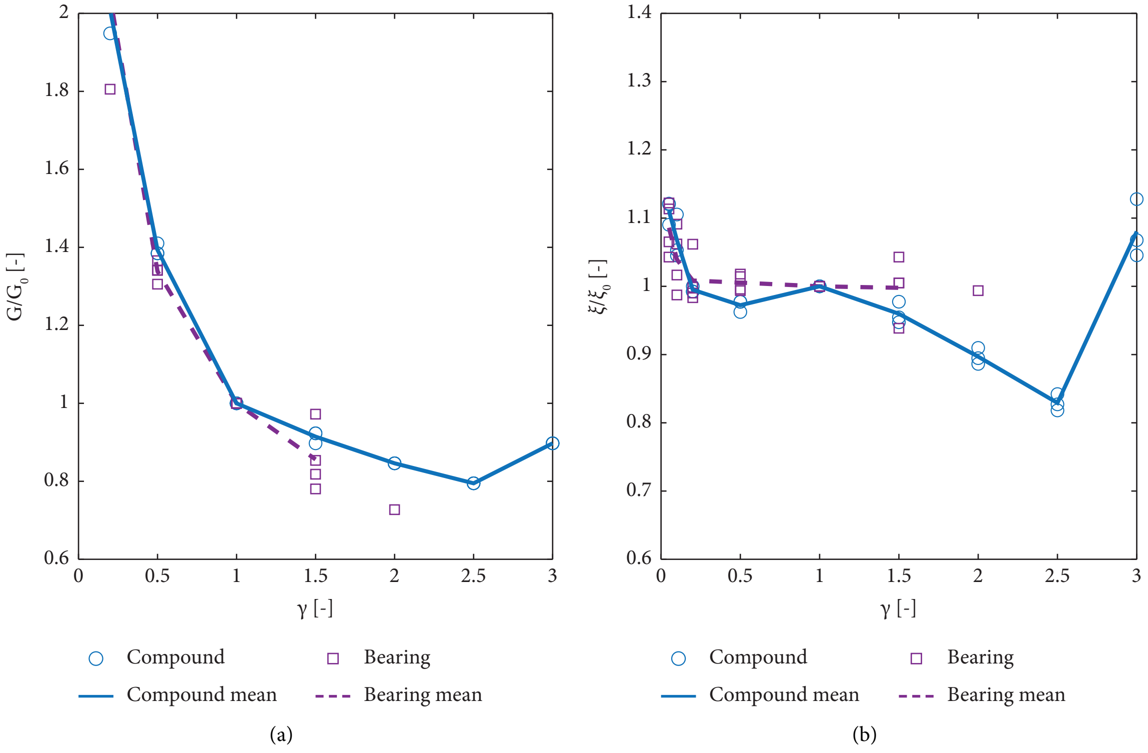
[15, 16] need to be mentioned for the tests at the material scale. Moreover, several experimental tests on full-scale elastomeric bearings with different air temperature have been conducted and reported in [38–40]. The main result of the first two papers is that the temperature effect strongly depends on the elastomeric compound used in the bearing manufacturing and that such effect at the bearing scale is similar or lower than that at the material scale. For example, in [38], the experimental tests carried out on HDR bearings conditioned for 3 days at −20°C showed a stiffness increment of about +40% for $G = 0.8$ MPa and +72% for $G = 0.4$ MPa with respect to values at the reference temperature of 23°C that are lower than the tests made by the same author at the material scale. Moreover, the heating effect, i.e., the increment of the temperature during dynamic tests carried out on large bearings may notably reduce the effect of low air temperature during an earthquake, as shown in [34]. With reference to the ageing effect, in [18], numerous ageing tests were conducted on various compounds utilized in bridge bearings (natural rubber, chloroprene rubber, ethylene propylene rubber, and high-damping rubber). These tests revealed that the effect on the dynamic properties is significant and should not be disregarded. Nevertheless, in a study conducted by the same authors [41], ageing tests were carried out at both material and bearing scales for HDR; the findings indicated that the results from material and bearing tests are comparable and do not exhibit substantial differences. Some tests conducted on old rubber bearings extracted from real isolated structures [42], as well as direct push and release tests on old isolated buildings [43], have also demonstrated that ageing effects are quite low. In authors' opinion, this phenomenon can be attributed to several aspects. First, the external surface of the elastomeric bearings is currently manufactured with a cover rubber layer containing antioxidants, which protects the core from the exposure to oxygen and ozone [25, 44]; furthermore, this external surface undergoes a reduction in porosity over time, leading to progressively lesser oxidation up to a critical depth, as discussed in [45]. Only in few works, such as [25], the ageing effect on rubber bearings has been observed to be significant for HDR, with a 1.3 shear stiffness multiplier. However, as for the repeated cycles effect, it is specified that this is primarily associated to HDR bearings featuring incomplete curing of the elastomer. In such case, the ageing is amplified by the continuation of the chemical processes in the rubber. Furthermore, this phenomenon is no more representative of the current production of HDR bearings (with large damping and/or low shear modulus) where



(a)

(b)

Figure 7: Compound-bearing comparison of G (a) and ξ (b) for the strain amplitude effect.



(a)

(b)

Figure 8: Compound-bearing comparison of G/G_0 (a) and ξ/ξ_0 (b) ratios for the strain amplitude effect.

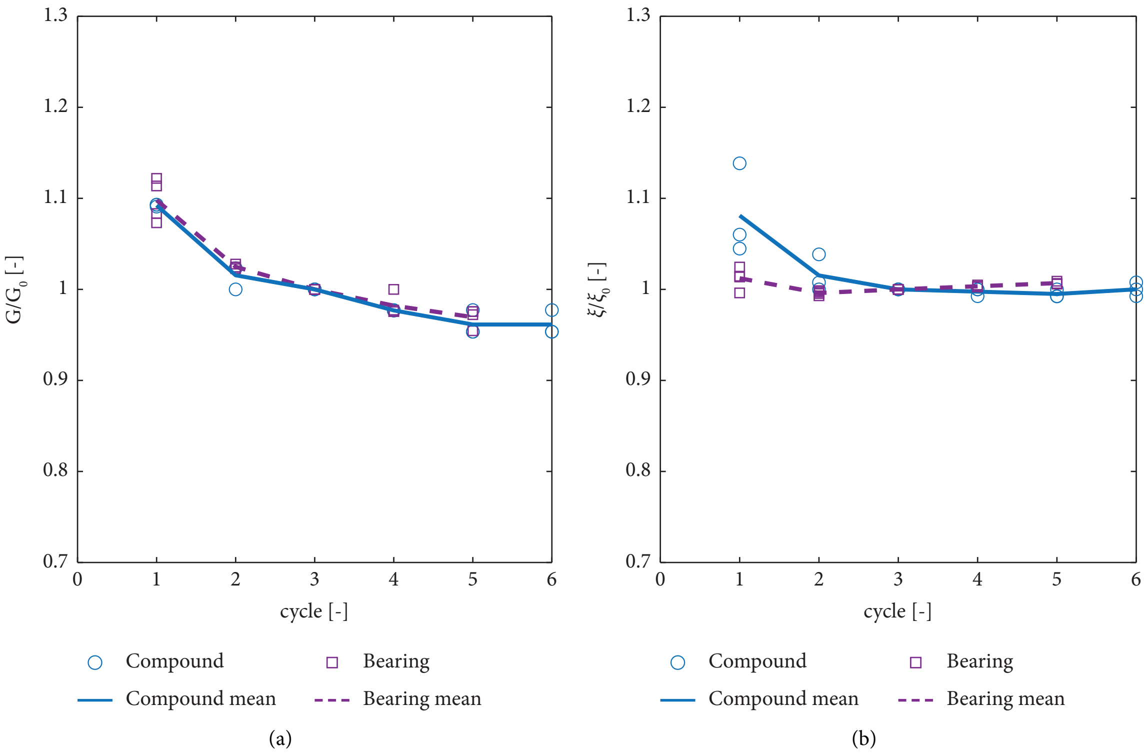


FIGURE 9: Compound-bearing comparison of G/G_0 (a) and ξ/ξ_0 (b) ratios for the cyclic effect.

incomplete curing is no more accepted as the manufacturing process to increase the rubber damping. In conclusion, the ageing effect for current HDR bearings is generally low, while the low temperature effect remains the most critical one. In addition, the tests on the material provide an upper and conservative limit for the variability of the properties expected during the service life of the devices.

4. Proposal for Updated λ-Factors and Potential Impact on Structural Seismic Response

A set of new λ-factors is proposed in Table 2 for LDRs and in Table 3 for HDRs in terms of G and ξ for each environmental and behavioural effect, namely, the strain rate, repeated cycles, ageing, temperature, and production variability. Strain amplitude is not considered since it is supposed that the design shear strain is larger than 1 (according to Figure 1). Two values are provided for both UB and LB as follows: one is related to the experimental data while the other (bracketed) is the limit implicitly imposed by the code during the material type test (see §8.2.2.1 of [3]). Consequently, the latter can be considered a hard limit for the variability of dynamic properties of bearings, as discussed in the previous section. The λ-factors for G derived from the experimental data refer to the 75th percentile for UB values and the 25th for LB values, respectively. This way, the dispersion of the results is also considered. For ξ, instead, the 25th percentile has been chosen for both UB and LB values as lower damping is always a conservative value for the analysis. An exception is made for the temperature, for which the median values have been chosen since the sample size at each temperature is not large enough to derive a reliable 25th–75th percentile range. As shown in the previous sections, most of the experimental data fall within the code limits. This is because most of the compound suppliers in the European context have de facto updated their products to comply with code prescriptions.

For comparison purpose, values derived from the informative annex J of EN 15129 [3] and informative annex JJ of EN 1998–part 2 [4] are also included in Table 2 and in Table 3 for ageing and temperature. Such values are given in terms of K_p (postelastic stiffness) and F_0 (strength at zero displacement) of the bilinear model; therefore, equivalent values in terms of G and ξ are computed by using formulas reported in ISO 22762 [27]. Some remarks should be done at this regard as follows: (i) in [3], HDR compounds are divided in two categories based on the nominal value of ξ; however, in Table 3, only factors related to $\xi_0 \leq 15\%$ are reported, as almost all the compounds analysed fall within this limit; (ii) values for K_p and F_0 relevant to the temperature effect provided by [3, 4] are inverted compared to the original table in AASHTO [23] as already highlighted in [46], thus the correct values of [23] have been used for this elaboration; and (iii) values suggested by these annexes are based on outdated experimental campaigns conducted on rubber compounds produced by non-European suppliers [26]; therefore, they are not coherent with the qualification process required by [3].

Regarding the temperature effect, for LDRs, the limit of 1.8 proposed by the code for G is significantly higher than the values of annex J of EN 15129, even for the lower temperature of −30°. Values derived from experimental tests

Table 2: λ-factors for LDRs from experimental data, material test limits (bracketed), and annex J of [3].

		Experimental data and (EN 15129 §8.2.2.1)		EN 15129 annex J
		G		G
		LB	UB	
Temperature	50°C	0.93 (0.80)	—	—
	40°C	0.98 (0.80)	—	—
	0°C	—	1.05	1.15
	−10°C	—	1.11	1.18
	−20°C	—	1.22	—
	−30°C	—	1.35 (1.80)	1.35
Ageing		1.00	1.14 (1.20)	1.20
Frequency		1.00 (0.80)	1.06 (1.20)	—
Repeated cycles		0.95 (0.80*)	1.11 (1.35*)	—
Production variability		0.95 (0.80)	1.07 (1.20)	—

*Values calibrated from data and in compliance with EN 15129 prescriptions.

Table 3: λ-factors for HDRs from experimental data, material test limits (bracketed), and annex J of [3].

		Experimental data and (EN 15129 §8.2.2.1)				EN 15129 annex J	
		G		ξ		G	ξ
		LB	UB	LB	UB		
Temperature	50°C	0.82 (0.80)	—	0.87 (0.80)	—	—	—
	40°C	0.88 (0.80)	—	0.91 (0.80)	—	—	—
	0°C	—	1.30	—	1.18	1.15	1.10
	−10°C	—	1.52 (1.80)	—	1.23 (1.8)	1.25	1.09
	−20°C	—	−(1.80)	—	1.26 (1.8)	—	—
	−30°C	—	−(1.80)	—	1.53 (1.80)	1.56	1.20
Ageing		1.00 (1.00)	1.18 (1.20)	1.00 (1.00)	0.86 (0.80)	1.20	1.00
Frequency		0.94 (0.80)	1.16 (1.20)	0.93 (0.80)	0.91 (0.80)	—	—
Repeated cycles		0.90 (0.80*)	1.18 (1.35*)	0.95 (0.80*)	1.09 (1.00*)	—	—
Production variability		0.95 (0.80)	1.07 (1.20)	1.00 (0.80)	1.00 (0.80)	—	—

*Values calibrated from data and in compliance with EN 15129 prescriptions.

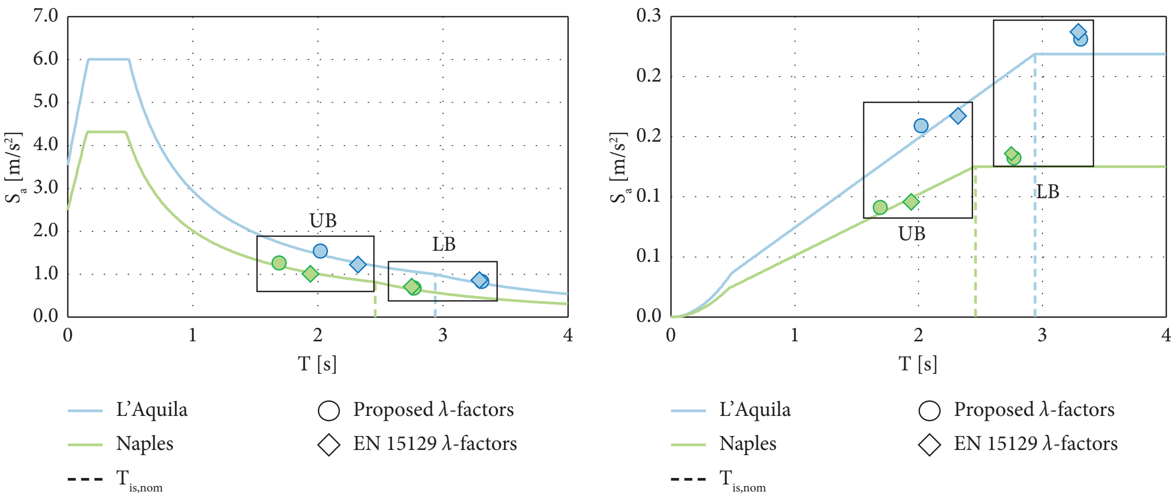
are significantly lower than 1.8, thus they are more in agreement with the indications of annex J. On the other hand, for HDRs, most of data relevant to G fall outside the material test limit of 1.8 at −30°C or even at −20°C. Consequently, for HDRs and temperature lower than −10°C, the code value of 1.8 is the only suggested value. In this case, values coming from the annex J strongly underestimate the variability associated to low temperatures for both the parameters G and ξ. Moreover, for high temperatures, both the rubbers exhibit a decrease in the mechanical parameters, which is disregarded by the code annexes. For what concerns ageing, the code limit proposed for G is consistent with the indication of the annex J of EN 15129 for both LDRs and HDRs. The value derived from the experimental data is a little lower for LDRs and very similar for HDRs. However, for HDRs, the annex does not account for the experimentally observed decrease of ξ, which the code allows in the qualification process.

For frequency and repeated cycles effects, there are no suggested values in annex J of EN 15129, so the proposal is entirely new. Specifically, for the effect of repeated cycles, the proposal has been formulated for the 1st and the 10th cycles with respect to the reference condition (3rd cycle). This way, the proposal follows both the limits for material tests in EN 15129 §8.2.2.1 and the experimental data. The result is an UB value of 1.35 and a LB value of 0.8 for G, which are consistent with the limit of 0.6 for the variation between the 10th and the 1st cycles ($0.8/1.35 = 0.6$) and reasonably in agreement with the 0.7 limit for the variation between the 10th and the 2nd cycles. Moreover, for ξ, values of 0.8 for LB and 1.0 for UB are recommended. Concerning production variability, the experimental dataset exhibits a lower variation than the code limits of 1.2 and 0.8. However, it is worth noting that production variability at the material scale may be lower than that at the full-scale bearing level due to more complex manufacturing process of the latter. Thus, code limits may be assumed as correct reference values.

To better understand the impact of the proposed λ-factors on seismic isolation response and the difference between the old values (descending from the informative annexes) and new ones (proposed), a simplified application is presented hereafter. In detail, a single degree of the freedom model is analysed using response spectra to calculate the pseudoacceleration and displacement of a base-

Table 4: Proposed experimental λ-factors, λ-factors from EN 15129 annex J, and related coefficient of combinations ψ for the UB/LB analyses.

	Proposed				EN 15129				ψ
	G		ξ		G		ξ		
	LB	UB	LB	UB	LB	UB	LB	UB	LB/UB
Temperature (40°/−10°)	0.88	1.52	0.91	1.23	1.00	1.25	1.00	1.09	0.70
Ageing	1.00	1.18	1.00	0.86	1.00	1.20	1.00	1.20	1.00
Frequency	0.94	1.16	0.93	0.91	—	—	—	—	0.70
Repeated cycles	0.90	1.18	0.95	1.09	—	—	—	—	0.70
Production	0.95	1.07	1.00	1.00	0.80	1.20	0.80	1.20	0.70
Combined	0.79	2.11	0.86	0.86	0.80	1.61	0.80	1.09	



(a)

(b)

Figure 10: Pseudoacceleration (a) and displacement (b) response spectra at the design and U/L bound condition for high- (cyan) and medium-hazard (green) seismic areas.

isolated structure encompassing HDR bearings. A temperature range of −10°C–+40°C is considered. First, it is worth to note that while proposed λ-factors include all the effects (temperature range, the ageing, the frequency, and the repeated cycles), λ-factors of annex J are provided only for the temperature and ageing. While in both cases, the production variability is assumed equal to the code range 0.8–1.2. Table 4 summarizes both the proposed λ-factors and those taken from annex J, for G and ξ, along with the corresponding combination coefficients ψ. Moreover, the bottom row of Table 4 shows the combined λ-factors obtained for the UB and LB analyses that are computed according to the combination rule proposed by annex J of EC8-part2 [4]. The common combination factor ψ of 0.7 is employed to account for the low probability of the simultaneous occurrence of the maximum adverse effects except for the ageing for which it is equal to 1 [3]. It can be observed that results computed according to the two set of values are similar for the LB conditions, whereas for the UB ones, the new proposal leads to a higher λ-factor for G (1.52 rather than 1.25) mainly due to the temperature and the first cycle effect and to a lower λ-factor for ξ (0.86 rather than 1.2) primarily due to the ageing effect. However, it is worth to recall that according to code prescriptions, the temperature effects shall be disregarded in the design process if rubber bearings are protected from environmental exposure.

Figure 10 shows response spectra in terms of pseudoacceleration S_a and displacement S_d for two sites in Italy, L'Aquila and Naples, corresponding to high-hazard and medium-hazard seismic areas, respectively. Response spectra have been evaluated according to NTC 2018 [47] with a return period of 950 years, corresponding to a 5% probability of exceedance in 50 years. The nominal isolation periods chosen for the two sites are $T_{\mathrm{is,nom}} = 2.45\,s$ for Naples and $T_{\mathrm{is,nom}} = 2.95\,s$ for L'Aquila, both equal to the beginning of the constant displacement branch of the spectrum. The nominal isolation damping is $\xi_{\mathrm{is}} = 15\%$ for both the sites. The effect of the variability of G can be easily converted in terms of the modified isolation period, as T_{is} is proportional to the inverse of the square root of G (disregarding the effect of damping variability on the isolation period).

By analysing the spectra of Figure 10, the following observations can be drawn:

(1) Periods of vibration and damping ratios computed according to the proposed λ-factors and those computed according to informative annexes are similar for the LB condition, whereas they are significantly different for the UB condition.

(2) For spectral acceleration (Figure 10(a)), the UB analysis using the proposed λ-factors results in pseudoaccelerations approximately 54% higher than the value relevant to the nominal design properties (NDPs) for both the considered sites, whereas by using λ-factors provided by informative annexes, the increment is about 23%.

(3) For spectral displacement (Figure 10(b)), LB analyses using proposed λ-factors and those from informative annexes give similar displacements. For both the sites, the increment with respect to the displacement obtained by using the NDPs is lower than 8%.

Previous results confirm that adopting a design period in the range of constant displacement spectra leads to a robust solution for what concerns the displacement increment in the LB condition. Conversely, the base shear increment in the UB condition is significant if all the effects are correctly considered.

5. Conclusion

In this paper, a set of data relevant to recent material tests carried out according to EN 15129 on 18 different rubber compounds from 5 different suppliers are collected and analysed. The analysis focused on the variability of the shear modulus G and the damping coefficient ξ due to strain amplitude, strain rate, repeated cycles, ageing, temperature, and production variability. Based on the statistical evaluations of the experimental data collected, the following conclusions can be drawn:

(i) The low temperature effect is the most significant source of variability for rubber compounds, especially in the case of high-damping rubber (HDR), while the effects of ageing and cyclic degradation are lower.

(ii) Production variability of the overall dataset is within code limits of 0.8–1.2 and even lower for each individual supplier.

(iii) Comparison between the experimental behaviour at the material scale and the bearing scale shows a good agreement of the effects of strain amplitude and cyclic degradation. For ageing and temperature, acceptance limits of material tests may be considered as conservative limits for the real variation at the bearing scale.

In the last part of the paper, the proposed λ-factors are compared with λ-factors provided by the informative annexes of European codes that are currently the only reference for designers. The effect of such factors on the seismic response of base-isolated structures has been assessed in terms of displacement and pseudoacceleration response spectra by assuming an S-DOF linear model. Based on the obtained results, the following conclusions can be drawn.

(iv) The λ-factors proposed in this paper are provided in terms of equivalent linear properties of the elastomeric bearings (equivalent stiffness and damping) so that they can be used directly in linear seismic analyses. Conversely, those provided by informative annexes of European codes are in terms of the bilinear model; consequently, they are suitable only for nonlinear analyses.

(v) The proposed λ-factor values are consistent with code limits concerning qualification tests, thus with the current production of European suppliers. Conversely, the factors provided by the informative annexes of European codes are not representative of the current European production.

(vi) The proposed values account for all the effects, including the cyclic degradation one. The latter seems to affect current rubber compounds less than forecasted from past indications, especially for HDRs.

(vii) UB analysis performed using the proposed λ-factors results in pseudoaccelerations approximately 25% higher than those achieved using λ-factors provided by the informative annexes, whereas in the LB conditions, displacements obtained by these two sets of λ-factors are very similar. It is worth noting that the proposed λ-factors take into account all the sources of variability, and consequently, the results provided by UB and LB analyses are more robust.

(viii) By using the proposed set of values, the UBDPs lead to a more demanding condition in terms of base shear and floor absolute accelerations for the superstructure with respect to the NDPs, while the LBDPs provide a small increment of displacement for the isolation devices, if the isolation period is properly selected.

These preliminary results suggest that the proposed λ-factors could be acceptable for both the manufacturers and the engineers, as they lead to tolerable differences on the response of the base-isolated systems. At the same time, the paper demonstrates that most of the rubber suppliers currently comply with these variabilities. Thus, the proposed values could be a new generally accepted set of λ-factors agreed between suppliers and structural engineers, in compliance with the new process suggested by the ISO 22762.

Data Availability

The data used to support the findings of this study are available on request by sending an e-mail to the corresponding author (laura.gioiella@unicam.it) or to Prof. Virginio Quaglini (virginio.quaglini@polimi.it).

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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