Title:

When rotation-invariant spectra enter structural design: interpreting RotD100 and related measures

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When rotation-invariant spectra enter structural design: interpreting RotD100 and related measures

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Abstract

In many design procedures, a scalar response spectrum like RotD50 or RotD100 is interpreted as a component spectrum applied independently along two orthogonal structural directions. When a maximum-direction measure such as RotD100 is used in this way, an implicit assumption is introduced: both structural axes experience the worst possible orientation of ground motion. This has contributed to the view that RotD100 is overly conservative for structural design. This paper clarifies that RotD100 is not inherently conservative, but that it represents a different type of quantity than a typical component response. Unlike RotD50, which represents a typical directional component, RotD100 represents an instantaneous peak response occurring in some direction of the horizontal plane. The properties of different rotation-invariant spectra are examined using a geometric interpretation in which the directional response field of ground motion is approximated by an ellipse. Selecting a scalar design spectrum can then be viewed as replacing this ellipse with a circle. Within this geometric framework, several common misconceptions regarding RotD100 can be clarified and avoided in seismic design. The paper concludes that the suitability of a scalar spectrum for design depends on how it is deployed in structural analysis. Ensuring consistency between the chosen intensity measure and the design-action model is therefore essential for the meaningful use of rotation-invariant spectra in structural design.

Keywords: design action; directional uncertainty; RotD50; RotD100; MaxRotD50; orthogonal combination; vector/pair actions.

1. Introduction

Rotation-invariant horizontal response spectra (Boore, 2010) are now routinely used beyond hazard modelling and record selection, entering everyday design workflows through standard hazard products and code implementations. In particular, U.S. seismic design according to ASCE/SEI 7-22 (American Society of Civil Engineers, 2022), hereafter referred to as ASCE, relies on maximum direction response spectrum, which is commonly known as RotD100.

The opposition to the use of RotD100 is not new. Stewart et al. (2011) discuss the adoption of maximum-direction ground motions in the 2009 NEHRP provisions and frame the issue primarily in terms of risk bias and conservatism for azimuth-dependent structures. I address a related but fundamentally different concern: the interpretation of maximum-direction spectra as design actions within component-based design frameworks.

When RotD100 is treated as a component-based design action, that is, when the same scalar spectrum is applied along two orthogonal structural directions and the resulting effects are recombined using standard design rules, the implied demand state does not correspond to a single realizable excitation. In this interpretation, both structural directions are implicitly associated with the most adverse ground-motion orientation. This issue is not limited to azimuth-dependent structures. Even for isotropic structures, RotD100 should not be interpreted as a two-component action. By contrast, RotD100 can be a legitimate scalar representation when explicitly treated as a unidirectional or resultant action, consistent with its definition. The non-realizability of this implied demand state is not, in itself, a deficiency in simplified design procedures, where conservative envelope assumptions are a recognized feature.

These considerations suggest that it is useful to move beyond the question of conservatism alone and focus instead on the definition of a seismic design action and the assumptions, explicit or implicit, embedded in its use. While conservative envelope constructions are an integral part of design codes, the practical effect of a given intensity measure depends on how it is translated into a design action. The objective of this paper is therefore to clarify what different rotation-invariant measures represent as design actions, and why their implications differ when used within conventional component-based deployment and combination rules. The argument is not that RotD100 is inherently conservative or unsuitable for design, but that its meaning and effect depend on how it is interpreted and deployed within different analysis procedures.

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2. Geometric interpretation of rotation-invariant intensity measures

Horizontal earthquake ground motion is recorded as two orthogonal components. If this component pair is rotated through all possible orientations in the horizontal plane and the pseudo-spectral acceleration (PSA) is evaluated for each orientation, the resulting directional PSA varies smoothly with angle. Figure 1(a) illustrates such a directional response field for a representative ground motion. When plotted in polar coordinates, the directional PSA typically forms a shape that is close to an ellipse. The response variance is exactly elliptical, while the PSA itself exhibits stochastic fluctuations around it due to peak-response variability (Rupakhety and Hernández-Aguirre, 2026a, 2026b). The ellipse representation is not introduced as an exact fit to the directional PSA of individual records, but as an interpretable reduced representation of the bidirectional response field.

In this geometric interpretation, the directional response can be approximated by an ellipse characterized by two principal radii: a major radius a and a minor radius b. An elliptical representation with radii defined in this manner is compared with the actual directional field in Figure 1(a). The major radius a is taken as the maximum directional PSA, while the minor radius b is taken as the PSA in the direction orthogonal to the orientation of maximum response. Due to peak-response variability, this orthogonal value does not necessarily coincide with the global minimum PSA. Because PSA is defined as the maximum response over time, the responses associated with these principal directions do not occur simultaneously; they represent directional extrema of the response field and do not correspond to a single simultaneous excitation state. If horizontal ground motion were to be represented explicitly in this form, it would require two response spectra, one for each principal direction. This representation provides a compact way to describe the directional structure of response using two principal axes, while retaining a clear geometric interpretation.

Seismic design codes, however, typically specify a single horizontal response spectrum that can be applied along any structural axis. Geometrically, this corresponds to replacing the directional ellipse with a circle. The circle represents an isotropic approximation of the directional response field. From this perspective, different rotation-invariant scalar intensity measures correspond to different ways of selecting a circle that represents the underlying ellipse.

Historically, seismic hazard and design practice often relied on the geometric mean of the two recorded horizontal components as a scalar measure of ground-motion intensity. Strictly speaking, this quantity is not rotation-invariant because it depends on the orientation of the recording sensors. A clearer geometric interpretation emerges if the response is considered in the principal directions of the ellipse. In that coordinate system, the directional field is described by the axes a and b, and a natural scalar representation is the equal-area circle, whose radius is $r = \sqrt{ab}$. This construction corresponds to the geometric mean of the principal-axis responses.

The rotation-invariant measure RotD50 was later introduced to estimate a typical directional response. RotD50 is defined as the median of the PSA values obtained over all orientations. In the geometric interpretation it corresponds approximately to a circle whose radius equals the quadratic mean of the principal axes (Rupakhety and Sigbjörnsson, 2013), $r = \sqrt{(a^2 + b^2)/2}$. As illustrated in Figure 1(c), the quadratic-mean circle is often nearly identical to the RotD50 circle for typical ground motions. A comparison of Figure 1(b) and 1(c) shows that the equal-area and quadratic circles are also very similar. This occurs when the ellipse is not strongly elongated, which is the case for most ground motions, and helps explain why the geometric-mean measure is close to RotD50.

A different scalar representation is obtained by selecting the circle whose radius equals the largest radius of the ellipse, a. This corresponds to RotD100. One motivation for introducing RotD100 in design provisions was the observation that measures such as the geometric mean or RotD50 represent only typical directional response levels and may be exceeded along some structural orientations. Using RotD100 was expected to account for directional variability by considering the most unfavourable direction.

However, replacing one scalar measure with another does not fundamentally change the geometry of the representation. Both RotD50 (or the geometric mean) and RotD100 describe the directional response using a single circle rather than the underlying ellipse. The change therefore enlarges the circle but does not introduce an explicit representation of directional structure, which would require two spectra corresponding to the principal response directions. In this sense, different rotation-invariant measures should be viewed not as interchangeable descriptions of ground motion, but as different isotropic approximations of the same directional response. In current design practice, such isotropic representations are used implicitly through scalar intensity measures such as RotD50 or RotD100. The ellipse can therefore be viewed as the simplest anisotropic generalization of the isotropic (circular) representation already implicit in design practice. This geometric framework enables an intuitive comparison of rotation-invariant measures as different scalar reductions of a common underlying directional field.

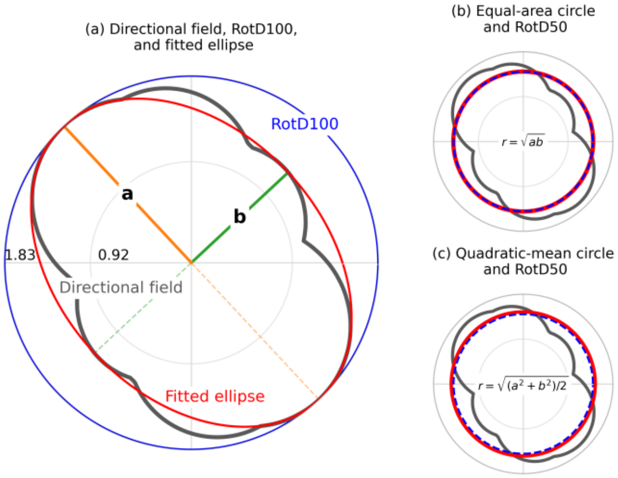

Figure 1. Geometric interpretation of rotation-invariant response measures using the directional pseudo-spectral acceleration (PSA) field of a representative ground motion (event INT-20230206_0000222, station 5811) from the European Strong Motion (ESM) database(Luzi et al., 2016; Lanzano et al., 2021)). The response corresponds to $T = 0.3$ s and 5% damping. **(a)** Directional PSA (gray), its idealized elliptical approximation (red), and the RotD100 circle (blue). The principal radii a and b define the major and minor axes of the ellipse. **(b)** Equal-area circle with radius $r = \sqrt{ab}$ (red) compared with the RotD50 circle (blue dashed). **(c)** Quadratic-mean circle with radius $r = \sqrt{(a^2 + b^2)/2}$ (red) compared with RotD50 (blue dashed). The gray curve in all panels shows the directional PSA field. Different rotation-invariant spectral measures correspond to different isotropic (circular) approximations of the underlying directional response.

3. RotD100 as a Resultant Envelope

RotD100 was originally defined as the 100th percentile of PSA obtained by rotating two horizontal components of ground motions through all non-redundant angles (Boore, 2010). This definition may suggest an interpretation of RotD100 as a component action associated with a single critical direction of motion. However, RotD100 is not a component of motion in any fixed direction. Rather, it is a resultant envelope statistic, representing the maximum value of a directional response field (Rupakhety and Sigbjörnsson, 2013).

Figure 2(a) shows the locus of the instantaneous bidirectional oscillator response, expressed in pseudo-acceleration form $a_p(t) = \omega^2 u(t)$, of a ground motion record in the PA_x–PA_y (as-recorded) plane. Pseudo-acceleration response here is defined as the relative displacement response multiplied by the squared angular frequency of the SDOF oscillator. Pseudo-spectral acceleration corresponds to the maximum absolute value of this pseudo-acceleration time series. The blue dashed circle represents the RotD100 envelope, whose radius equals the maximum over time of the instantaneous resultant magnitude $\sqrt{PA_x^2(t) + PA_y^2(t)}$. The red point marks the realizable response state at which this maximum resultant is attained. The black cross marks a response state corresponding to (RotD100, RotD100) and lies outside the response envelope.

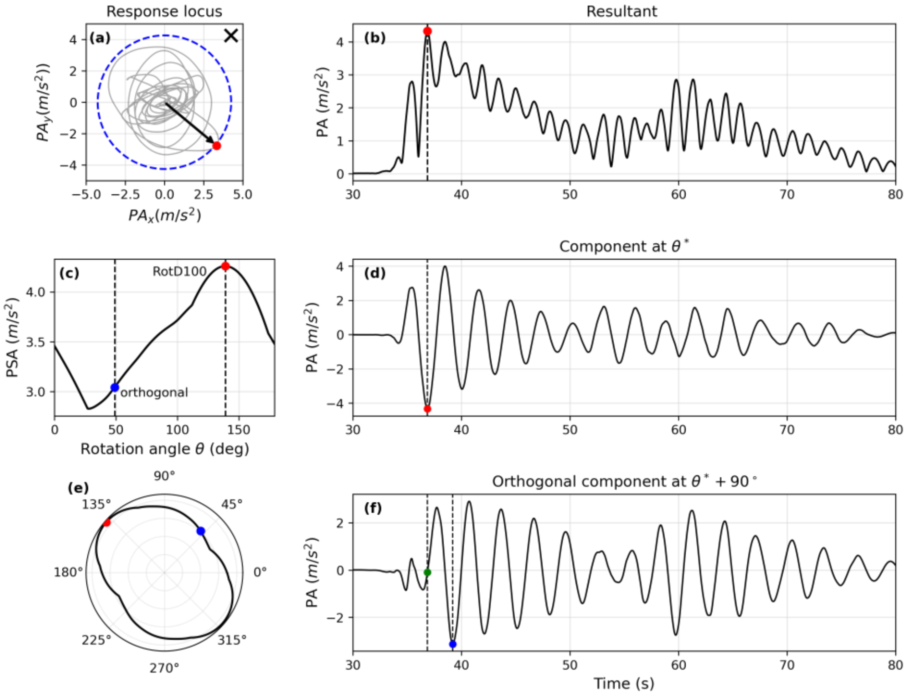

Figure 2. Contrast between instantaneous bidirectional pseudo-acceleration response and time-collapsed maxima for a strong-motion record from the 6 February 2023 Türkiye earthquake (M_w 7.7), ESM event ID INT-20230206_0000008, Station 4615 (epicentral distance 19.5 km).

Panels (c) and (e) show the directional PSA response. The red marker identifies the maximum over θ, thereby defining the orientation θ^*. The blue marker indicates the PSA at $\theta^* + 90°$. Panels (d) and (f) resolve the response histories along the orientations $\theta^*$and $\theta^* + 90°$, respectively. At the instant RotD100 occurs at θ^*, the response in the orthogonal direction is 0, as indicated by the green marker in panel (f). Angular or polar representations of directional PSA (c and e) can suggest that RotD100 corresponds to a component action along a least-favourable orientation θ^*, accompanied by a non-zero orthogonal component. This interpretation is, however, misleading. The non-zero orthogonal PSA arises from independent maximization over time at each orientation, rather than from a simultaneous bidirectional response. The large peak in the orthogonal component marked by the blue circle in panel (f) occurs at a different time and is responsible for the non-zero orthogonal pseudo-spectral acceleration observed in panels (c) and (e). This distinction becomes important when RotD100 is interpreted as a design action, particularly in component-based procedures where it may be treated as if it were a directional component.

4 Distinction between design action and intensity measure

In component-based design, actions are aligned with structural axes, and design checks are performed along principal axes of structural elements. In this framework, a response spectrum becomes a design action only after its deployment rules specify how the scalar intensity measure is translated into component actions and how orthogonal responses are combined. In the ASCE provisions for the equivalent lateral force procedure and for modal response spectrum analysis, the target spectrum is interpreted as a component spectrum along each structural axis, and structural responses from the two orthogonal directions are combined using rules such as the familiar 100/30 orthogonal combination. In linear response-history analysis, two horizontal components of ground motion are separately scaled to the target spectrum. In nonlinear response-history analysis, however, two horizontal components are scaled so that their combined spectrum matches the target spectrum. In each case the same spectral target is translated into a design action through different deployment rules. As a result, the same spectral target may correspond to different effective design actions depending on the analysis procedure.

To illustrate the practical implications of deployment rules, let us consider ground motion scaling according to the ASCE deployment for non-linear time history analysis. A code-type design spectrum was constructed and interpreted as a RotD50 target. The corresponding RotD100 spectrum was obtained using the empirical RotD100/RotD50 ratio proposed by Shahi and Baker (2014). From a set of 4610 ground motions from the European Strong Motion (ESM) database (Lanzano et al., 2021) corresponding to $\mathrm{M_w} > 5$ and $\mathrm{R_{JB}} < 200$ km, ten records were randomly selected as seed motions.

Horizontal components of each record were modified using a bidirectional spectral matching procedure (Montejo, 2021), in which both horizontal components are adjusted simultaneously to match a target orientation-independent spectrum. In contrast to traditional approaches in which each horizontal component is matched independently, bidirectional procedures preserve key features of the ground motion, including its polarization and period-dependent orientation of principal response directions. The discussion that follows is not intended to compare specific matching algorithms, but to illustrate, through a simplified geometric interpretation, how scaling to RotD50 or RotD100 affects the directional response field.

Figure 3 shows the mean results obtained from the matched record sets. Panels (a) and (b) compare the resulting RotD50 and RotD100 spectra, respectively. Both matching strategies reproduce their respective targets, but the resulting RotD100 spectra of the matched records are nearly identical regardless of whether the target was RotD100 or RotD50. Panels (c) and (d) show the directional pseudo-spectral acceleration at two representative periods. The directional response forms an approximately elliptical pattern bounded by RotD50 and RotD100, and the directional fields obtained from the two matching strategies are nearly indistinguishable. This observation highlights that the conservatism often associated with RotD100 is not necessarily realized in this deployment.

The close agreement in Figure 3 is not accidental. It can be easily understood in the geometric interpretation of directional PSA presented in Section 2. RotD50 and RotD100 define an ellipse of random orientation. The semi-major axis is $a = \mathrm{RotD100}$, while the semi-minor axis b can be written as $b = \mathrm{RotD50}^2/\mathrm{RotD100}$. This simple construction is shown in green in Figure 3. Scaling to RotD50 can be understood as starting with an ellipse (of the seed motion) and stretching it so that its area matches πab. Scaling to RotD100 corresponds to stretching the seed ellipse so that its semi-major axis matches the target. If the size of the two axes is not drastically different, the resulting ellipses are similar. To understand this mathematically, let us consider a simple amplitude scaling. Let a seed pair have $\mathrm{RotD100}^{(s)} = \rho_s\,\mathrm{RotD50}^{(s)}$ where ρ_s is a constant. If the pair is scaled to match a RotD50 target $\mathrm{RotD50}^{(t)}$, the scale factor is $\lambda_{50} = \mathrm{RotD50}^{(t)}/\mathrm{RotD50}^{(s)}$, and the resulting RotD100 becomes $\lambda_{50}\mathrm{RotD100}^{(s)} = \rho_s\,\mathrm{RotD50}^{(t)}$.If instead the same pair is scaled to a RotD100 target $\mathrm{RotD100}^{(t)} = \rho_t\,\mathrm{RotD50}^{(t)}$, the scale factor is

$$\lambda_{100} = \frac{\mathrm{RotD100}^{(t)}}{\mathrm{RotD100}^{(s)}} = \frac{\rho_t}{\rho_s}\frac{\mathrm{RotD50}^{(t)}}{\mathrm{RotD50}^{(s)}} = \frac{\rho_t}{\rho_s}\lambda_{50} \tag{204}$$

The resulting scaled pair is therefore identical when $\rho_s = \rho_t$, and remains very similar when ρ_s is close to ρ_t. Since the RotD100/RotD50 ratio is typically confined to a relatively narrow range with median values around 1.2–1.3, although varying across records and with period (e.g., Shahi and Baker, 2014), matching to RotD50 or RotD100 produces nearly the same scaled motions. When such scaled motions are used in structural analysis, the maximum-direction response represented by RotD100 is generally not realized along the structural axes, because the principal directions of the response ellipse do not coincide with those axes. As a result, the component design actions obtained along structural axes are typically smaller than the RotD100 target. In this context, it is useful to note that scaling each component independently to RotD100 as prescribed for linear time history analysis in ASCE would result in a larger ellipse than that obtained from joint scaling (see, for example, Rivera-Figueroa and Montejo, 2022).

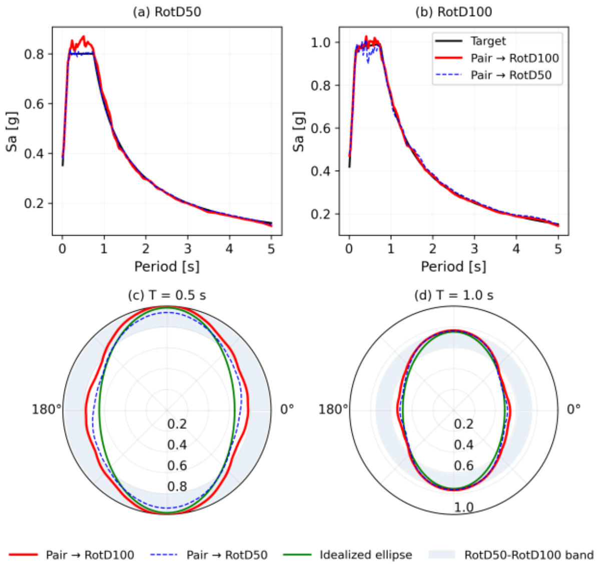

Figure 3. Comparison of ground motion response spectra (5% damped PSA) obtained by pair spectral matching to RotD100 and RotD50 targets. Top: resulting RotD50 and RotD100 spectra. Bottom: directional pseudo-spectral acceleration at selected periods. Both matching strategies produce nearly identical directional response fields bounded by RotD50 and RotD100. The results show average obtained from 10 randomly selected seed pairs. The idealized ellipse, shown in green, does not have a preferred direction, but is rotated here to facilitate visual comparison with the scaled ground motions.

5. What RotD100 represents—and what it does not represent in structural design

Because a design action consists not only of a spectral target but also of how that spectrum is deployed in structural analysis, the meaning of a rotation-invariant intensity measure depends on how it is translated into a design action. The following example illustrates this dependence.

Let us consider an idealized circular column with equal stiffness and strength in all horizontal directions. Let M denote the peak moment demand under a ground motion whose response spectrum matches the RotD100 target at the fundamental period. Because the system is axisymmetric, RotD100 can be interpreted as a scalar envelope of directional response corresponding to a maximum-direction demand of magnitude M. The associated biaxial demand may be expressed as $(M\cos\,\theta, M\sin\,\theta)$ for some orientation θ, with resultant equal to M. Although idealized, this example isolates the role of ground-motion representation from structural directionality.

When this scalar target is deployed within different analysis procedures, it leads to distinct biaxial design actions. In the equivalent lateral force (ELF) and response spectrum analysis (RSA) procedures, RotD100 is applied as a component spectrum along each structural axis and combined using the 100%+30% rule. This results in a biaxial demand state $(M, 0.3M)$, corresponding to a resultant demand of approximately $1.04M$, reflecting a bounded and controlled level of conservatism consistent with simplified design procedures.

In linear response-history analysis, ASCE requires that the horizontal components of ground motion be matched independently to RotD100. This alters the directional characteristics of the ground-motion pair, effectively inflating the weaker component. As a result, both components can attain large values simultaneously, leading to a resultant response that exceeds the RotD100-consistent level M. Independent component matching therefore constructs a bidirectional demand closer to (M, M). In the limiting case, the resultant approaches $\sqrt{2}M$, although typical amplification is smaller. Rivera-Figueroa and Montejo (2022) showed that independently matched records produce realized RotD100 spectra exceeding the target, with mean amplification on the order of 20–25% and individual exceedances up to about 57%. This represents an inflation of an already conservative maximum-direction target and arises from deploying a resultant-based intensity measure as if it were a component action.

In nonlinear response-history analysis, both horizontal components are spectrally modified jointly to attain a RotD100 target. This preserves their correlation and directional structure, and the resulting structural response reflects a physically consistent biaxial excitation. The bidirectional demand state $\left(M_x(t), M_y(t)\right)$evolves over time and remains governed by the directional characteristics of the ground motion. However, RotD100 does not enforce alignment of the maximum-direction demand with the structural axes. The response therefore remains dependent on the angle of incidence, and the "worst direction" interpretation implicitly achieved in ELF and RSA is not retained, as the analysis in Section 4 illustrates. As a result, while the excitation is physically consistent, the intended role of RotD100 as a surrogate for directional uncertainty is not fully realized. These observations show that the conservatism associated with RotD100 is not intrinsic to the measure itself but depends on how it is deployed. Consequently, if the design objective is to identify the maximum possible response along the building axes, the ground motion must still be rotated to determine the critical angle of attack. This behaviour has been demonstrated in previous studies (Rivera-Figueroa and Montejo, 2023)

RotD100 was introduced in design with the expectation that it accounts for directional variability of ground motion. ASCE provisions in nonlinear time history analysis deployment require that the average component spectra applied along the two orthogonal structural axes remain approximately balanced, which tends to isotropize the applied spectral field. As a result, the effective design action becomes similar to that obtained using RotD50, as discussed in Section 4. RotD100, as deployed in nonlinear time history analysis in ASCE, neither ensures a maximum response along the structural axes nor adequately accounts for directional variability of ground motion.

The example above highlights that the effect of adopting RotD100 is not uniform but depends on how the intensity measure is translated into a design action. RotD100 is a resultant envelope over orientations, not a marginal component of motion in fixed axes. When it is interpreted as a component spectrum applied independently along structural directions, its meaning changes. This does not invalidate its use in simplified procedures, where envelope assumptions are an accepted feature, but it does affect how the resulting design action should be understood. The issue is therefore not the use of non-realizable envelope assumptions per se, but how a maximum-direction measure is interpreted when translated into component-based design actions.

The statement that a structure "never sees RotD100" is sometimes used in discussions questioning the conservatism of RotD100 (Montejo, 2021). It reflects the observation that the probability of the worst direction of ground motion aligning exactly with a structural axis is small. To make the unlikeliness of this scenario more obvious, one can think of designing for RotD100 as assuming that the structure being designed will be, at least at one instant in time, excited by a ground motion that is linearly polarized, with all energy concentrated along one of the building axes. However, this interpretation arises from a component-based view of structural response. In reality, a structure always experiences the full directional field which contains RotD100. The key point is not that this response is unlikely to occur, but that it generally occurs along an orientation different from the structural axes used for design checks. When viewed as a 100th-percentile spectrum over orientations, RotD100 may appear unlikely to be experienced by a structure. When interpreted as the peak resultant response of an individual oscillator, it represents a realizable response quantity. However, for a multi-degree-of-freedom (MDOF) system, RotD100 as a spectrum does not correspond to a simultaneously realizable structural state, since the orientations at which modal responses peak are generally not the same.

6. Possible directions for practice

For component-based design procedures, two possible directions for practice are outlined below.

6.1 Continue with scalar intensity measures within component-based design

One option is to retain the current component-based design framework and use a scalar spectral measure that is compatible with it. In this context, a measure such as RotD50 is a natural choice, as it represents a typical component response under directional uncertainty without constraining the accompanying orthogonal component. When used as a target spectrum, RotD50 is consistent with the way seismic actions are currently deployed in most design procedures.

Within this approach, the issue of the maximum response direction not coinciding with the structural axes remains. If the objective is to design for the maximum response direction, two alternatives may be considered:

(i) apply RotD100 as a unidirectional action, or (ii) rotate the applied ground motions relative to the structural axes to identify the critical response. It is noted that for ground-motion pairs matched to a RotD100 target, any consistent rotation of the pair preserves the RotD100 spectrum. This reflects the rotational invariance of the measure but does not resolve the question of which orientation produces the critical structural response.

Other measures, such as RotD100 or the more recently proposed MaxRotD50 (Poulos and Miranda, 2022), are not suitable if interpreted as interchangeable component actions. In the geometric interpretation presented earlier, MaxRotD50 can be understood as the median of the larger of two orthogonal radii sampled from the directional response ellipse. Because this selection is biased toward the major axis, MaxRotD50 lies between RotD50 and RotD100.

In cases where the response quantity of interest is a resultant rather than a component response, a RotD100-type measure is more appropriate. For structures with equal stiffness and strength in all directions, RotD100 can be used effectively, provided it is applied as a unidirectional action. This approach preserves the existing design framework while maintaining consistency between the intensity measure and the applied seismic action.

6.2 Move toward vector-valued measures of ground-motion intensity

A second, more forward-looking direction is to move beyond scalar intensity measures and explicitly represent the directional structure of ground motion. Such an approach recognizes that horizontal ground motion is fundamentally a two-dimensional phenomenon, and that directional effects are an intrinsic part of the excitation.

Conservative design procedures often arise from difficulties in representing complex aspects of ground motion, among which directional variability is a key example. However, observations of ground-motion records show that the directional field of pseudo-spectral acceleration is typically smooth and can be well described by an elliptical pattern, with structured stochastic perturbations (Rupakhety and Hernández-Aguirre, 2026a, 2026b).

Within this framework, the directional response field can be represented by an ellipse characterized by two parameters: an overall scale and a measure of anisotropy. The scale may be associated with RotD50, while the anisotropy parameter quantifies the degree of directional variation(Rupakhety and Hernández-Aguirre, 2026c). A probabilistic description of this anisotropy could then be incorporated into hazard analysis and ground-motion selection procedures. Such an approach would allow directional uncertainty to be represented explicitly.

7 Conclusions

Consistency between how an intensity measure is defined and how it is used in design codes has practical consequences. When that consistency is blurred, the deployment of intensity measures and the interpretation of their intended versus actual effects become unclear. This paper uses the ASCE replacement of median-based intensity measures by RotD100 to examine the practical consequences for design action prescription across the analysis methods in the code. Replacing a typical-direction measure such as RotD50 by RotD100 introduces conservatism, which has long been debated. That debate is set aside here in favor of examining the interpretability and practical consequences of this replacement.

In simplified procedures such as ELF and RSA, the use of RotD100 leads to an increase in demand relative to a RotD100-consistent unidirectional response. This arises because orthogonal combination rules, such as 100/30, originally calibrated for component-based actions, are applied to a resultant-based measure. The magnitude of this increase depends on structural characteristics, particularly torsional response. For structural systems that are not prone to significant torsional effects and are well suited to such simplified procedures, the resulting increase in design action is typically modest, consistent with the conservative envelope assumptions of these methods.

However, in response-history analysis, the same intensity measure, as prescribed in ASCE, does not lead to a consistent level of conservatism. In linear response-history analysis, independent component matching can significantly amplify bidirectional demand beyond that associated with the RotD100 target, while in nonlinear analysis, joint scaling preserves physical consistency but does not ensure that structural axes experience maximum-direction response. As a result, the use of RotD100 does not correspond to a uniform or predictable design action across analysis methods. This lack of uniformity affects how design targets are interpreted and how results across analysis procedures are compared, particularly when methods are used interchangeably or for verification within the same code.

The key conclusion of this paper is not that one rotation-invariant spectral measure is universally preferable to another, but that consistency between the spectral measure and the design action is essential. Rotation-invariant measures summarize directional ground-motion intensity, whereas design procedures operate within a component-based framework. Maintaining compatibility between these two perspectives is crucial for the meaningful use of rotation-invariant spectra in structural design.

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Data Availability

The ground motion data used in this research are publicly available at the European Strong Motion database, https://esm-db.eu/#/home

Conflict of Interest

There is no conflict of interest.

References

American Society of Civil Engineers, 2021. Minimum Design Loads and Associated Criteria for Buildings and Other Structures. American Society of Civil Engineers, Reston, VA. https://doi.org/10.1061/9780784415788

Boore, D.M., 2010. Orientation-independent, nongeometric-mean measures of seismic intensity from two horizontal components of motion. Bull. Seismol. Soc. Am. 100, 1830–1835.

Lanzano, G., Luzi, L., Cauzzi, C., Bienkowski, J., Bindi, D., Clinton, J., Cocco, M., D'Amico, M., Douglas, J., Faenza, L., Felicetta, C., Gallovic, F., Giardini, D., Ktenidou, O., Lauciani, V., Manakou, M., Marmureanu, A., Maufroy, E., Michelini, A., Özener, H., Puglia, R., Rupakhety, R., Russo, E., Shahvar, M., Sleeman, R., Theodoulidis, N., 2021. Accessing European Strong-Motion Data: An Update on ORFEUS Coordinated Services. Seismol. Res. Lett. 92, 1642–1658. https://doi.org/10.1785/0220200398

Montejo, L.A., 2021. Response spectral matching of horizontal ground motion components to an orientation-independent spectrum (RotDnn). Earthq. Spectra 37, 1127–1144.

Poulos, A., Miranda, E., 2022. Proposal of orientation-independent measure of intensity for earthquake-resistant design. Earthq. Spectra 38, 235–253. https://doi.org/10.1177/87552930211038240

Rivera-Figueroa, A., Montejo, L.A., 2023. Ground motion rotation effects on bidirectional inelastic response using seismic input compatible to a target RotD100 spectrum. Structures 50, 97–107. https://doi.org/10.1016/j.istruc.2023.02.032

Rivera-Figueroa, A., Montejo, L.A., 2022. Spectral matching RotD100 target spectra: Effect on records characteristics and seismic response. Earthq. Spectra 38, 1570–1586. https://doi.org/10.1177/87552930211049259

Rupakhety, R., Hernández-Aguirre, V.M., 2026a. Directional Peak Factors of Strong-Motion Response Spectra: A Stochastic Field Representation on the Circle. https://doi.org/10.31223/X5VX74

Rupakhety, R., Hernández-Aguirre, V.M., 2026b. Rotation-Invariant Ground-Motion as Directional Selection Operators: A Closed-Form Framework for RotD Response Spectra. https://doi.org/10.31223/X50R1C

Rupakhety, R., Hernández-Aguirre, V.M., 2026c. On the Origin of Directional Variability in Earthquake Response Spectra: A Stochastic Covariance Framework.

Rupakhety, R., Sigbjörnsson, R., 2013. Rotation-invariant measures of earthquake response spectra. Bull. Earthq. Eng. 11, 1885–1893. https://doi.org/10.1007/s10518-013-9472-1

Shahi, S.K., Baker, J.W., 2014. NGA-West2 Models for Ground Motion Directionality. Earthq. Spectra 30, 1285–1300. https://doi.org/10.1193/040913EQS097M

Stewart, J.P., Abrahamson, N.A., Atkinson, G.M., Baker, J.W., Boore, D.M., Bozorgnia, Y., Campbell, K.W., Comartin, C.D., Idriss, I.M., Lew, M., 2011. Representation of bidirectional ground motions for design spectra in building codes. Earthq. Spectra 27, 927–937.