

1 **Title:**

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

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18 **Abstract**

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

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

35 **1. Introduction**

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

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

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

54 These considerations suggest that it is useful to move beyond the question of conservatism alone and focus
55 instead on the definition of a seismic design action and the assumptions, explicit or implicit, embedded in its
56 use. While conservative envelope constructions are an integral part of design codes, the practical effect of a
57 given intensity measure depends on how it is translated into a design action. The objective of this paper is
58 therefore to clarify what different rotation-invariant measures represent as design actions, and why their
59 implications differ when used within conventional component-based deployment and combination rules. The
60 argument is not that RotD100 is inherently conservative or unsuitable for design, but that its meaning and effect
61 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.

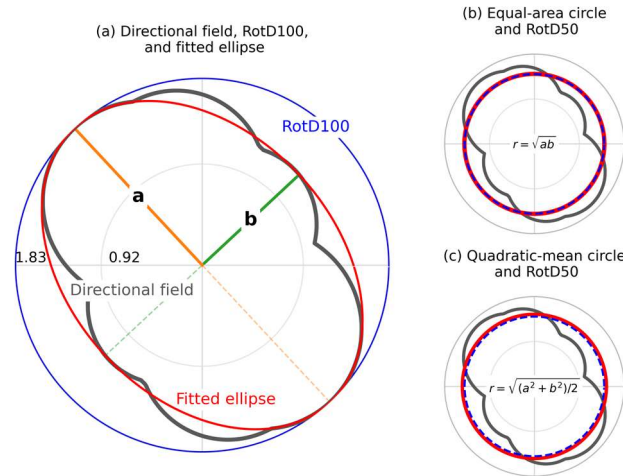
Historically, seismic hazard and design practice often relied on the geometric mean of the two recorded horizontal components as a scalar measure of ground-motion intensity. Strictly speaking, this quantity is not rotation-invariant because it depends on the orientation of the recording sensors. A clearer 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

112 interchangeable descriptions of ground motion, but as different isotropic approximations of the same directional
 113 response. In current design practice, such isotropic representations are used implicitly through scalar intensity
 114 measures such as RotD50 or RotD100. The ellipse can therefore be viewed as the simplest anisotropic
 115 generalization of the isotropic (circular) representation already implicit in design practice. This geometric
 116 framework enables an intuitive comparison of rotation-invariant measures as different scalar reductions of a
 117 common underlying directional field.



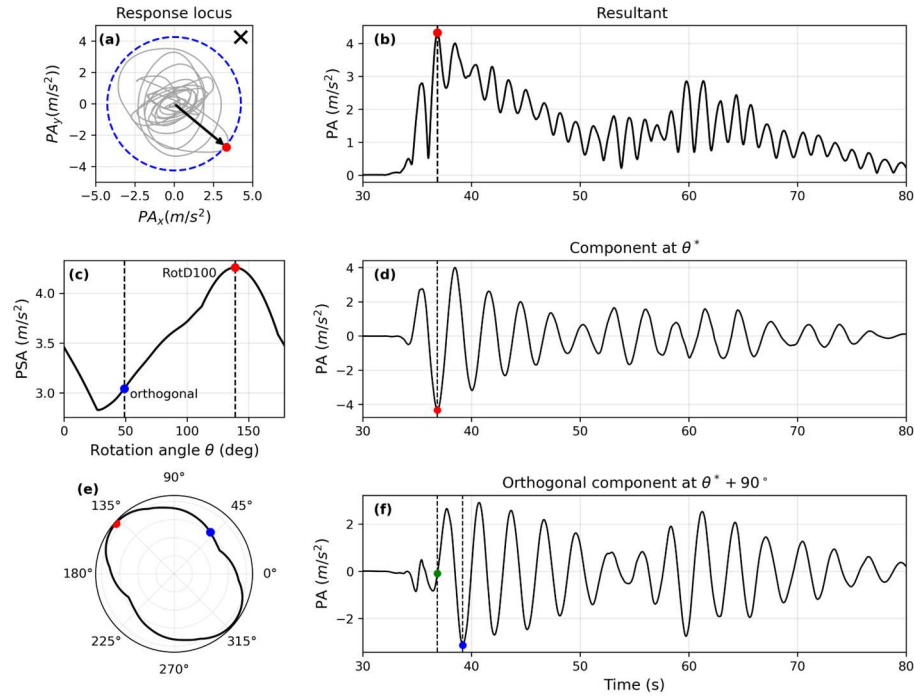
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119 Figure 1. Geometric interpretation of rotation-invariant response measures using the directional pseudo-spectral
 120 (PSA) field of a representative ground motion (event INT-20230206_0000222, station 5811) from the European Strong
 121 Motion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

127 3. RotD100 as a Resultant Envelope

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

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



141

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

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

157 **4 Distinction between design action and intensity measure**

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

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

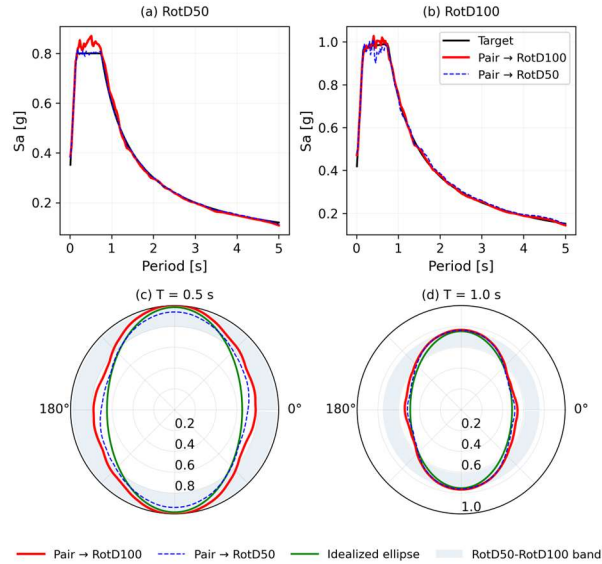
176 Horizontal components of each record were modified using a bidirectional spectral matching procedure
 177 (Montejo, 2021), in which both horizontal components are adjusted simultaneously to match a target
 178 orientation-independent spectrum. In contrast to traditional approaches in which each horizontal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

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

191 The close agreement in Figure 3 is not accidental. It can be easily understood in the geometric interpretation of
 192 directional PSA presented in Section 2. RotD50 and RotD100 define an ellipse of random orientation. The
 193 semi-major axis is $a = \text{RotD100}$, while the semi-minor axis b can be written as $b = \text{RotD50}^2/\text{RotD100}$. This
 194 simple construction is shown in green in Figure 3. Scaling to RotD50 can be understood as starting with an
 195 ellipse (of the seed motion) and stretching it so that its area matches πab . Scaling to RotD100 corresponds to
 196 stretching the seed ellipse so that its semi-major axis matches the target. If the size of the two axes is not
 197 drastically different, the resulting ellipses are similar. To understand this mathematically, let us consider a
 198 simple amplitude scaling. Let a seed pair have $\text{RotD100}^{(s)} = \rho_s \text{RotD50}^{(s)}$ where ρ_s is a constant. If the pair is
 199 scaled to match a RotD50 target $\text{RotD50}^{(t)}$, the scale factor is $\lambda_{50} = \text{RotD50}^{(t)}/\text{RotD50}^{(s)}$, and the resulting
 200 RotD100 becomes $\lambda_{50}\text{RotD100}^{(s)} = \rho_s \text{RotD50}^{(t)}$. If instead the same pair is scaled to a RotD100 target
 201 $\text{RotD100}^{(t)} = \rho_t \text{RotD50}^{(t)}$, the scale factor is

$$202 \quad \lambda_{100} = \frac{\text{RotD100}^{(t)}}{\text{RotD100}^{(s)}} = \frac{\rho_t \text{RotD50}^{(t)}}{\rho_s \text{RotD50}^{(s)}} = \frac{\rho_t}{\rho_s} \lambda_{50}$$

203 The resulting scaled pair is therefore identical when $\rho_s = \rho_t$, and remains very similar when ρ_s is close to ρ_t .
 204 Since the RotD100/RotD50 ratio is typically confined to a relatively narrow range with median values around
 205 1.2–1.3, although varying across records and with period (e.g., Shahi and Baker, 2014), matching to RotD50 or
 206 RotD100 produces nearly the same scaled motions. When such scaled motions are used in structural analysis,
 207 the maximum-direction response represented by RotD100 is generally not realized along the structural axes,
 208 because the principal directions of the response ellipse do not coincide with those axes. As a result, the
 209 component design actions obtained along structural axes are typically smaller than the RotD100 target. In this
 210 context, it is useful to note that scaling each component independently to RotD100 as prescribed for linear time
 211 history analysis in ASCE would result in a larger ellipse than that obtained from joint scaling (see, for example,
 212 Rivera-Figueroa and Montejo, 2022).



213

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

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

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

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

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

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

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

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

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

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

284 **6. Possible directions for practice**

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

286 6.1 Continue with scalar intensity measures within component-based design

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

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

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

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

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

307 6.2 Move toward vector-valued measures of ground-motion intensity

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

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

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

321 7 Conclusions

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

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

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

342 how results across analysis procedures are compared, particularly when methods are used interchangeably or
343 for verification within the same code.

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

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353 the clarity and presentation of the paper. Any remaining errors or interpretations are my own.

354 **Data Availability**

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

357 **Conflict of Interest**

358 There is no conflict of interest.

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