Ground motion directionality effects on inelastic spectral displacements

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3rd EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING & SEISMOLOGY

BUCHAREST, ROMANIA 2022

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Introduction & Motivation

- Earthquakes produce ground shaking in 3 dimensions
- In practice we usually use the 1 (or 2) as-recorded direction(s)
- There is a need to have a sense on what could be the maximum directional response
- And the expected ground motion (GM) directionality effects, given some underlying seismic hazard conditions

- Main Goals:
  - Understand the general directionality effects of GMs with various characteristics on non-linear (NL) systems
  - Explore the magnitude of difference from the corresponding linear systems
  - Use the maximum directional response as a more comprehensive quantification of GM severity

State of the art - Literature review

- Baker and Cornell (2006) demonstrated the consistent use of spectral acceleration (*Sa*) of an **arbitrary horizontal component**, Sa_{arb}, and the **geometric mean** of Sa of the two as-recorded components, Sa_{gm}, in probabilistic seismic analyses
- Sa_{RotDnn}, **defined as the nn**th **percentile of *Sa* from all rotation angles** (Boore et al. 2006) → State of the art *Sa* intensity measure (IM) to consider the GM in the 2D horizontal plane
- **Shahi and Baker (2014)** motivated this study the most. They developed an **empirical model for** $Sa_{RotD100}$/ Sa_{RotD50} **ratios**, in order to **quantify the polarization of GMs** and enable the **estimation of** $Sa_{RotD100}$ **spectra from** Sa_{RotD50}
- There are **several studies that considered multi-directional excitation** of either **linear or complex non-linear structural systems** (Fontara et al., 2015; Nievas and Sullivan, 2017; Feng et al., 2018; Pinzon et al., 2021)

State of the art - Literature review (Cont.)

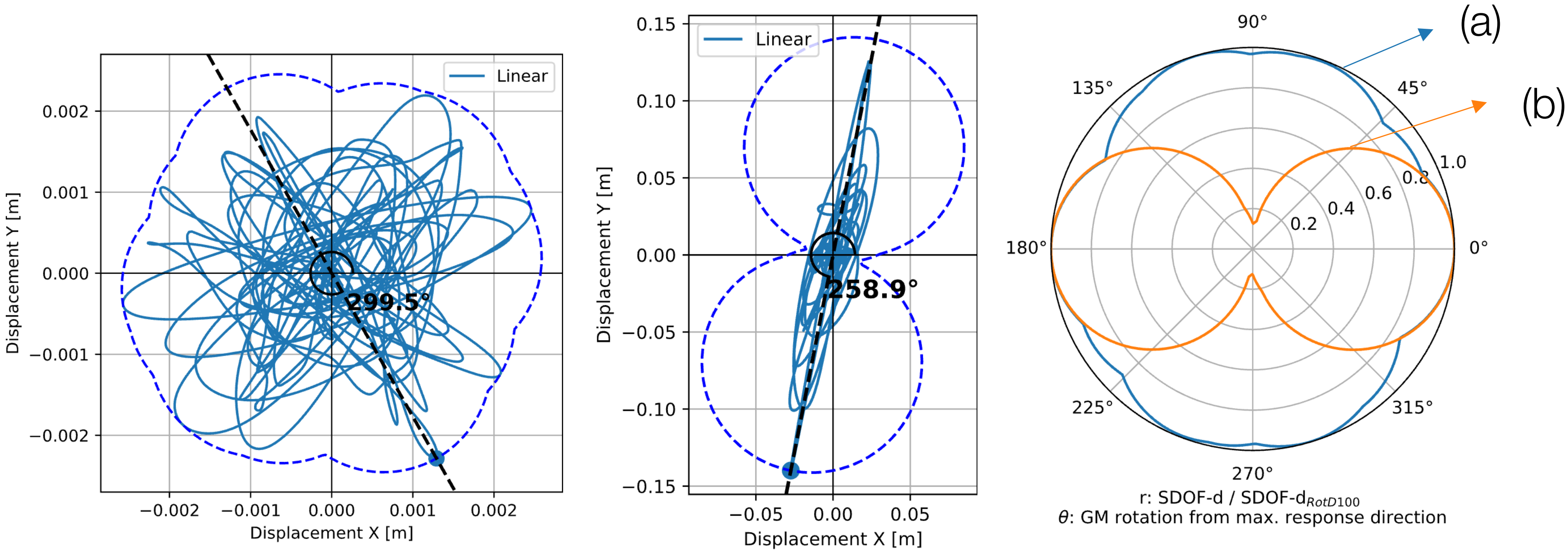
- Many researchers have developed **ground motion models (GMMs) for peak inelastic displacements of SDOF systems, Sd_i,** (Heresi et al., 2018; Huang et al., 2020)
- **Sd_i can be an efficient IM** in relating the ground motion intensity with the inelastic response and, therefore, damage of structural systems (Stafford et al. 2016)

In this study:

- The idea was to merge of Sd_i with the orientation independent definitions Sa_{RotDnn}
- The *RotD00*, *RotD50*, *RotD100* period-depended percentiles of Sd_i were calculated for bilinear SDOF systems with varying elastic periods, T_{el}, and force reduction factors, R

Illustration of polarized vs unpolarized GMs

Trace response of an elastic SDOF oscillator with T = 1 s



(a) (b)

(a) Unpolarized GM (HWA031 recording from the 1999 Chi-Chi-04 earthquake)

(b) Strongly polarized GM (Gilroy Array #6 recording from the 1984 Morgan Hill earthquake)

Methodology

From the NGA west2 GM database:

The GMs of interest were selected (**Mw ≥ 5 & Rrup ≤ 300 km**)
Total number of GMs identified: **7167**

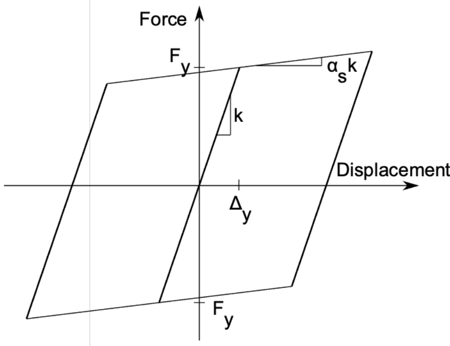
<u>Define the bilinear SDOF systems:</u>

- **R = [1.5, 2, 3, 4, 6]**
- **T_{el} = [0.04, 0.06, 0.1, 0.2, 0.3, 0.5, 1.0, 2.0, 3.0, 4.0]**
- Hysteretic behaviour: non-degrading, non-evolutionary bilinear model with positive strain hardening (post-yield stiffness ratio **α_s = 3%**)
- Damping: **5%** tangent stiffness proportional

The strength reduction factor, R, is calculated using the $Sa_{RotD100}$ given in the flatfile of the database, as follows:

$$F_y = \frac{m \cdot Sa_{RotD100}}{R}$$

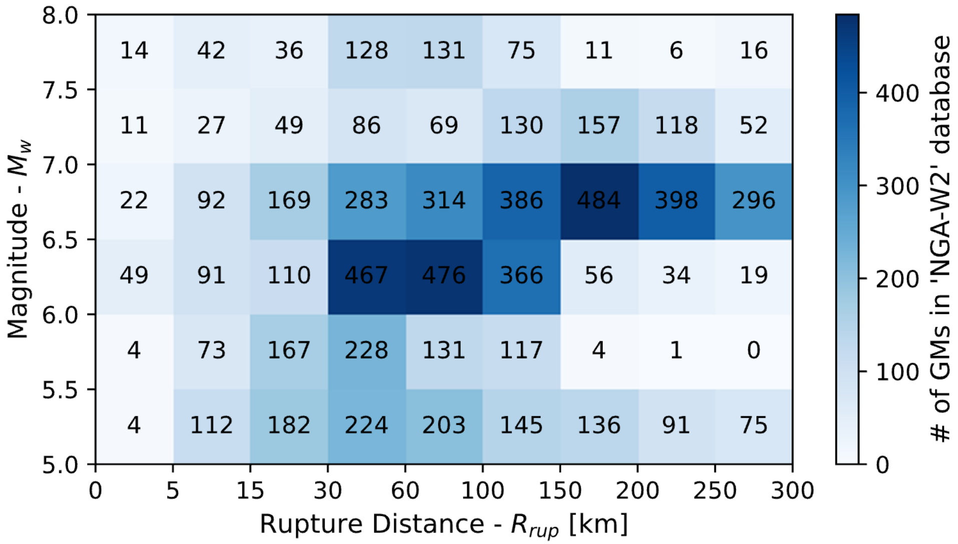
and the same system characteristics are kept throughout the rotation of each GM

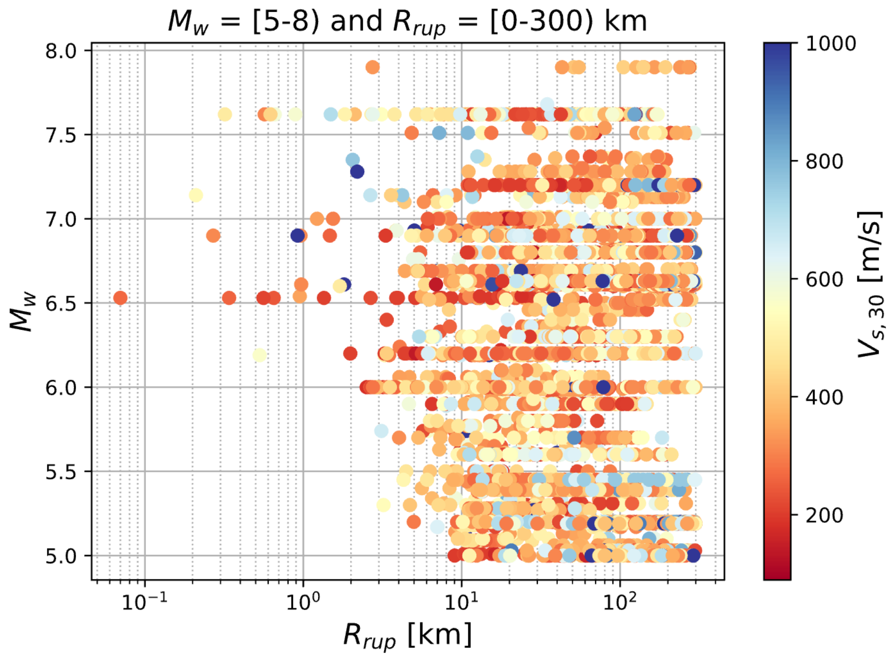


Each ground motion was rotated from the first horizontal direction (as given in the NGA database) with an **increment of 6°** in the **range of 0° to 180°** and applied to the SDOF system
The **maximum displacement** of the oscillator was recorded **per GM per rotation angle**

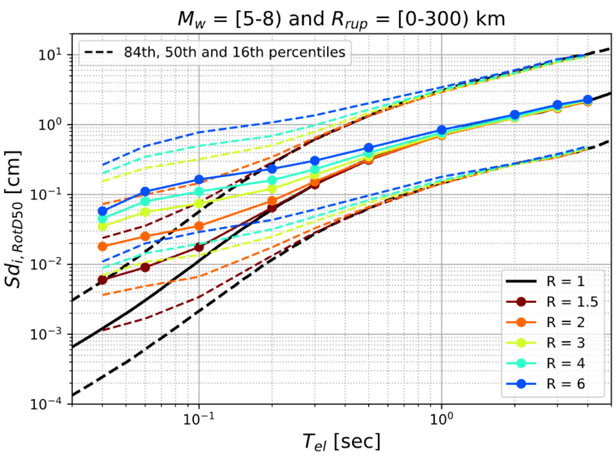
The 00th, 50th and 100th percentile of these responses was then calculated and plotted

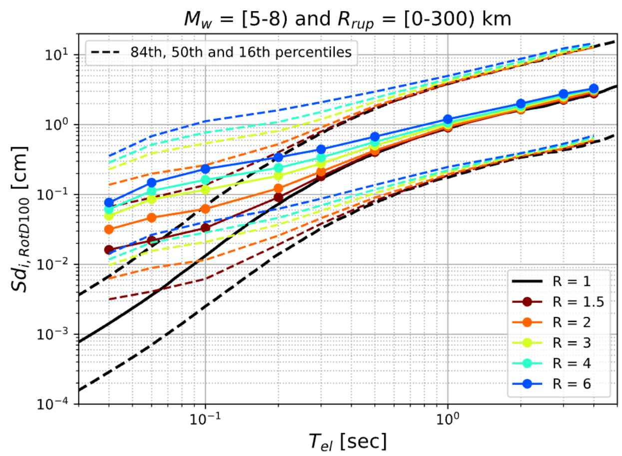
- NGA-West2 database (Ancheta et al. 2013): Shallow crustal earthquakes in active tectonic regions

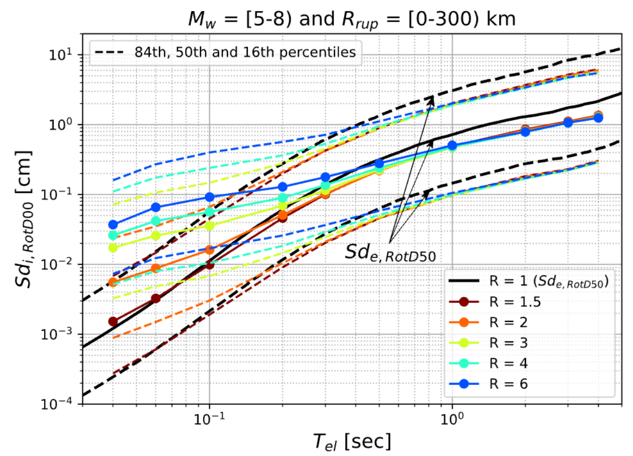




$Sd_{i,\mathrm{RotDnn}}$ spectra



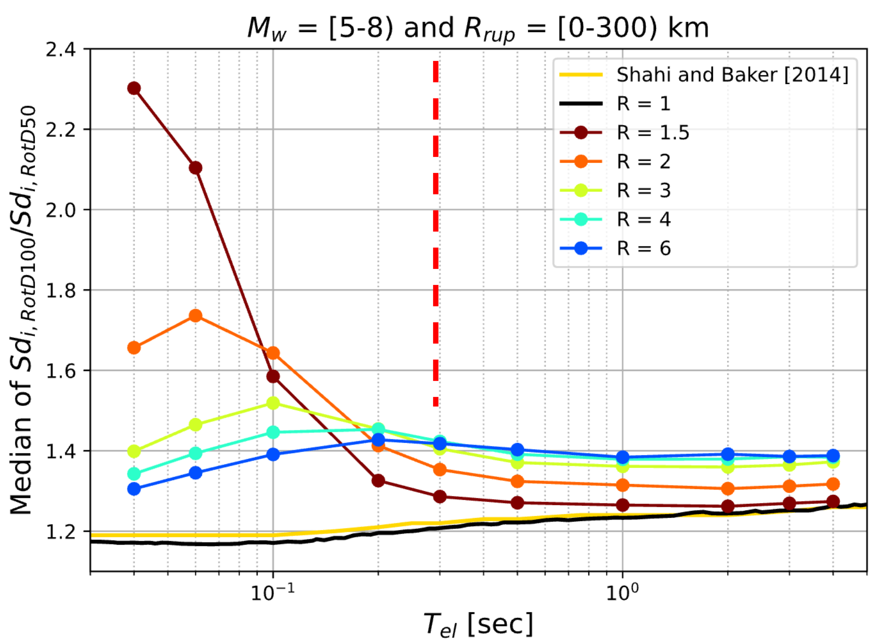


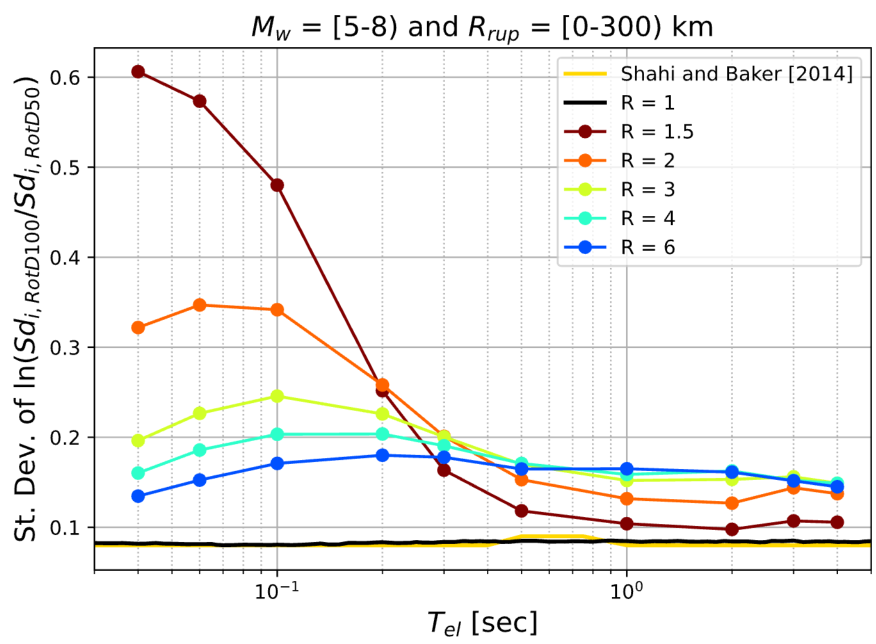


- Median Sd_i increases with an increase in R
- For long periods, the inelastic response approaches the elastic → Equal-displacement rule (Chopra, 2014)
- The last figure investigates whether the elastic RotD50 response can be higher than the minimum inelastic response

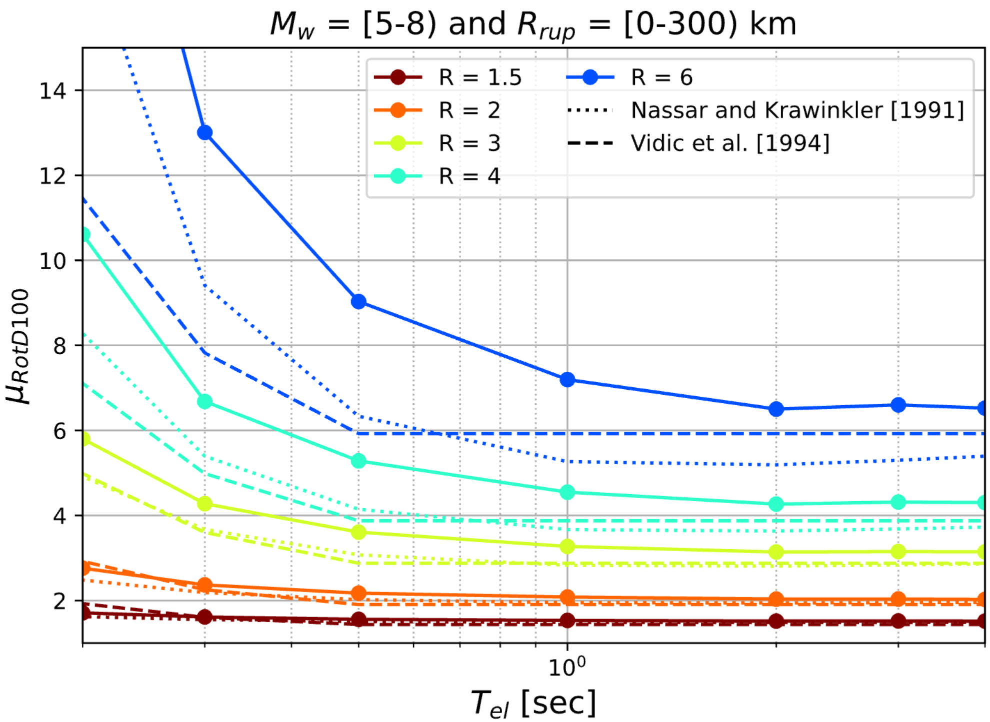
Directionality measure

- This simple scalar measure describes well the GM directionality
- Range of values for elastic systems: $Sa_{\mathrm{RotD100}}/Sa_{\mathrm{RotD50}}$ = 1 to 1.41





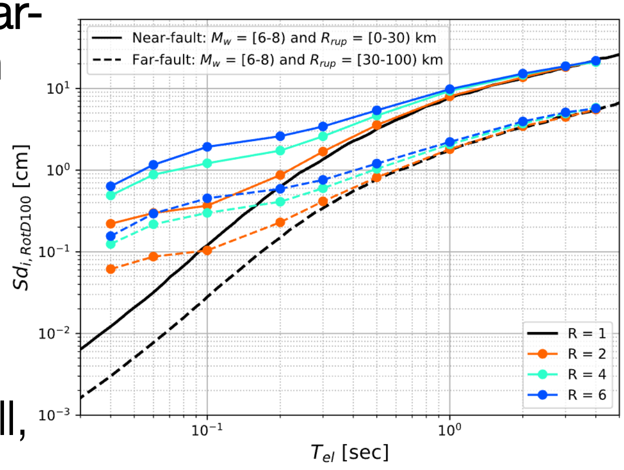
Maximum displacement ductility

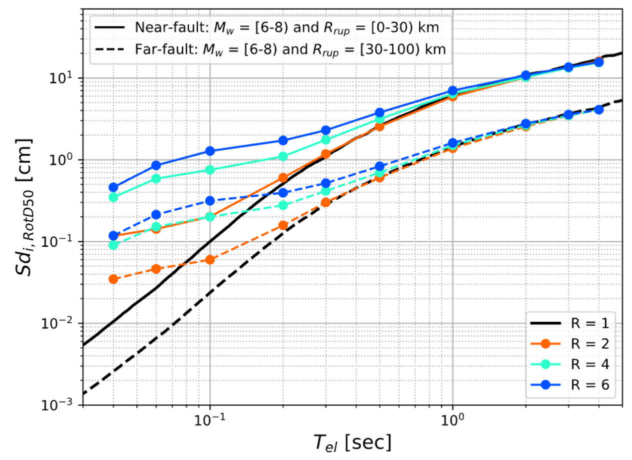


- Calculated as $Sd_{i,RotD100}/\Delta_y$.
- The values of this study are higher because:
  - Δ_y calculated for GM rotated to the 100th percentile of linear-elastic response. While $Sd_{i,RotD100}$ is the 100th percentile of inelastic response
  - The other studies were performed for the two as-recorded components of GMs
  - Differences in the post-yield stiffness and assumption of viscous damping
  - Very different GM database

Examining directionality in near- and far-fault ground motions (using heuristic method)

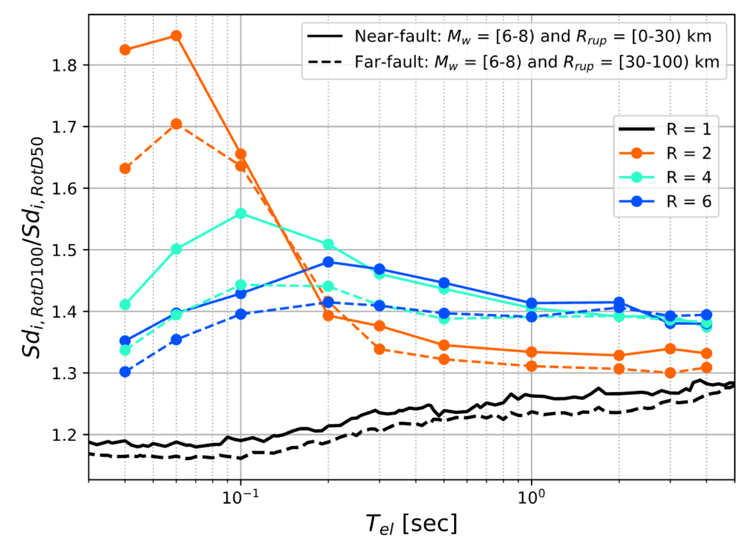
- Different **bins of near- and far-fault GMs** were examined in term of **inelastic directional response** and **directionality measure**





- Near-fault GMs result in higher displacements overall, as expected

- Near-fault GMs exhibit higher directionality effects (Bray and Rodriguez-Marek 2004; Huang et al. 2009; Tarbali 2017) → higher directionality measure



Summary and conclusions

- The directionality of GMs in the NGA-West2 database on a range of inelastic SDOF systems was examined
- Bilinear hysteretic behaviour with varying T_{el} and *R*
- Inelastic displacement spectra for *RotD00*, *RotD50* and *RotD100* were computed and plotted
- The effect of directionality, quantified via the *RotD100/RotD50* ratio, increases with *R* for $T_{el} > 0.3$s, whereas the opposite trend was observed for $T_{el} < 0.3$s
- Differences and impacts of considering directionality compared to traditional R-μ-T models were also shown
- A subset of near-fault ground motions showed higher elastic and inelastic displacements and higher directionality for the entire range of T_{el}

Limitations and future developments

- Different hysteretic models with different post-yield behaviours
- The analyses will be extended to full 3D buildings or bridge structures
- Similar analyses can be conducted for GMs caused by subduction earthquakes

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The work presented herein has been developed within the framework of the project "Dipartimenti di Eccellenza", funded by the Italian Ministry of Education, University and Research at IUSS Pavia.

Thank you for your attention!