9th EWICS

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TÉCNICO LISBOA

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Multidirectional Lateral Loads and Combination Rules in Pushover Analysis

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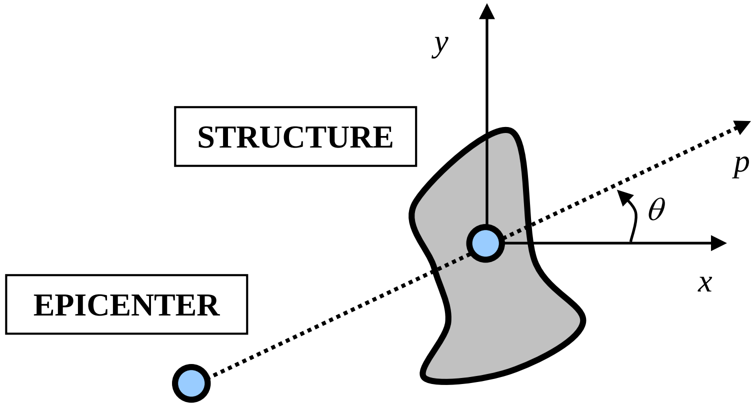
Overview

- **Introduction**: In order to consider multidirectional (orthogonal) excitation effects in the linear field, most current seismic codes require the use of the SRSS rule and alternatively the application of the 30% rule (EC8-Part 1). Different regulatory codes prescribe their application also for Non-Linear Static (pushover) Analyses (NLSAs).
- **Main objective**: Analysis of the validity of the directional combination rules in NLSA
- **Analyses and Results**:
  - The pushover analyses of 3 irregular reinforced concrete structures are performed and the corresponding capacity curves are obtained in their structural direction ±x and ±y.
  - For each considered orthogonal direction the structural demand is calculated using the N2 method (Fajfar, 2000).
  - The obtained results are then combined using the 30% and the SRSS combination rules.
  - Other pushover analyses are performed rotating the pushover seismic force with incident angles θ_i and the corresponding structural demands with the N2 method are calculated.
  - Structural demands obtained from the different NLSAs are compared with those computed by Non-Linear Time History Analyses (NLTHA) performed by using suites of real and generated ground motion records.

Introduction



- The angle of incidence θ is not known and the **direction generating the maximum structural response** (i.e. the critical response) is not known and could vary between 0° and 360° (Anastassiadis et al., 2002).
- In order to take into account for the **multi-directionality of the seismic load**, various researchers proposed to **combine the structural demands obtained by applying the response spectrum analysis simultaneously** in the two principal structural directions.

Origin of the Combination Rules (RSA)

Goodman, L. E., Rosenblueth, E., & Newmark, N. M. (1952) → **SRSS** as **modal combination**
- Linear Elastic behavior
- Uncoupled Vibration Modesi

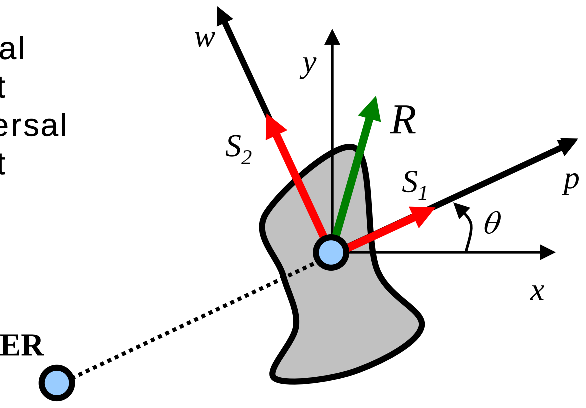
Newmark, N. M., & Rosenblueth, E. (1971) → **SRSS** as **directional combination rule**
- Linear Elastic behavior
- Uncorrelated Seismic Components

Newmark, N. M. (1975)
Rosenblueth, E., & Contreras, H. (1977) → **Percentage Rule** as **directional combination**
- Newmark 100/40
- Rosenblueth and Contreras 100/30
- Both obtained minimizing the differences with the SRSS rule

Wilson, E. L., Der Kiureghian, A., & Bayo, E. P. (1981);
Smeby and Der Kiureghian (1985) → **CQC** and **CQC3** as **modal combinations**
- Linear Elastic behavior
- Coupled Vibration Modes
- CQC3 modal responses due to the three seismic components

Introduction

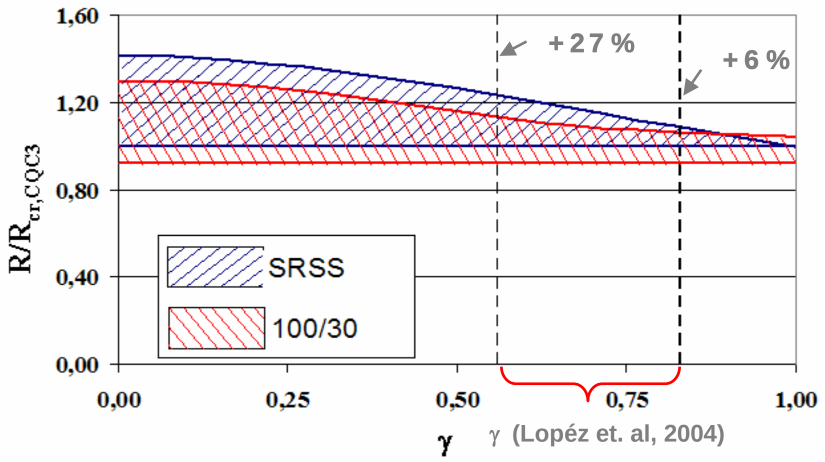
S_1=principal component
S_2=transversal component



Hypothesis: $S_2 = \gamma S_1$ $0 \le \gamma \le 1$

Accordig to Lopez et al., for 97 pairs of spectra: γ = 0.56 - 0.83

Camata et al. (2007)



Origin of the Combination Rules (RSA)

Menun and Der Kiureghian (1998); Anastassiadis et al., 2002, Lopez et al., 2004

CQC3 as directional combination rule

- Generical response quantity in function of the seismic orientation angle θ
- CQC3 is able to identify the **most critical orientation of the ground motion components** for each response quantity
- It can be considered the most general case of the 30%, 40% and SRSS rules

Camata et al. (2007)

Comparison between directional combination rules in RSAs

- **The structural responses obtained by the application of the SRSS rule provides values always greater than the CQC3 critical response**
- The 30% rule can underestimate the response obtained applying the SRSS rule up to 9%.

Application of the combination rules in Non-Linear Static Analyses

Eurocode 8 §4.3.3.5.1 Horizontal components of the seismic action

(6) When using non-linear static (pushover) analysis and applying a spatial model, the combination rules of (2) and (3) in this subclause should be applied (SRSS and 100:30), considering the forces and deformations due to the application of the target displacement in the x direction as E_{Edx} and the forces and deformations due to the application of the target displacement in the y direction as E_{Edy}. **The internal forces resulting from the combination should not exceed the corresponding capacities**.

2b) **The maximum value of each action effect on the structure** due to the two horizontal components of the seismic action may then be estimated by the **square root of the sum of the squared values** of the action effect due to each horizontal component. (…)

(3) As an alternative to b) and c) of **(2)** of this subclause, the action effects due to the combination of the horizontal components of the seismic action may be computed using both of the two following combinations:

a) E_{Edx} "+" $0,30 E_{Edy}$ (4.18)

b) $0,30 E_{Edx}$ "+" E_{Edy} (4.19)

where

"+" implies "to be combined with";

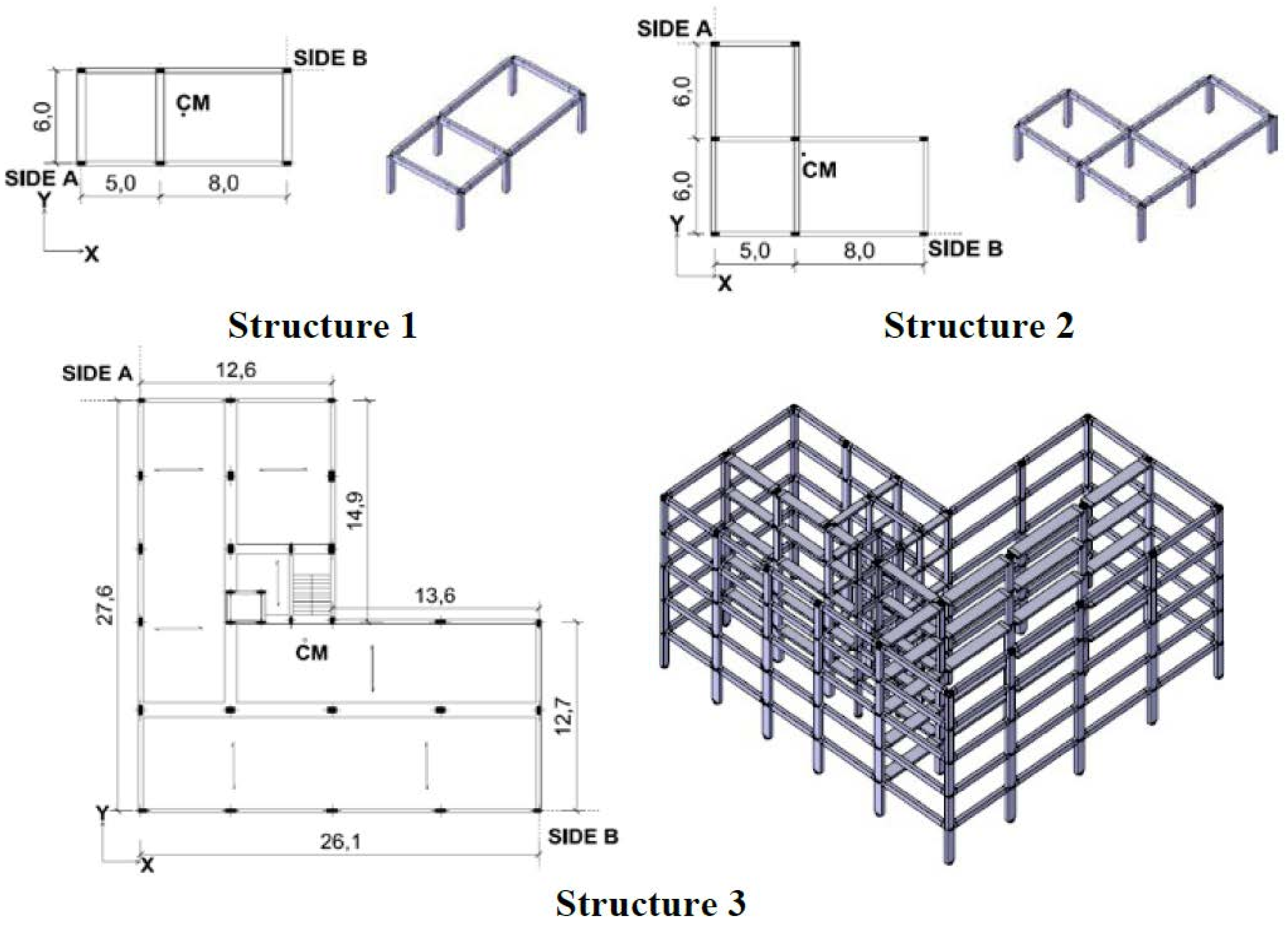
E_{Edx} represents the **action effects** due to the application of the seismic action along the chosen horizontal axis *x* of the structure;

E_{Edy} represents the **action effects** due to the application of the same seismic action along the orthogonal horizontal axis *y* of the structure.

Case Studies

- Software **Opensees** (McKenna et al., 2000) using the pre- and post- processor **STKO** (Petracca et al., 2017).
- **Force-based fiber-section frame model** (Spacone et al. 1996) with 5 Gauss-Lobatto integration points for beams and columns.
- Shear stiffness added to the section
- **Rigid diaphragms** at all levels.
- **Kent-Scott-Park constitutive law** for the concrete, with f_c = 20 MPa and ε_{c0} = 0.002.
- **Giuffré-Menegotto-Pinto** constitutive law for the reinforcing steel, with f_y = 400 MPa, E = 210 GPa and b = 0.02.
- **Gravity loads** applied before non-linear analyses. Floor masses include all dead loads and 30% of live loads.

	Structure 1				Structure 2				Structure 3			
Mode No	T_i (sec)	m_x (%)	m_y (%)	m_z (%)	T_i (sec)	m_x (%)	m_y (%)	m_z (%)	T_i (sec)	m_x (%)	m_y (%)	m_z (%)
1	0.32	0	**98.3**	1.7	0.35	0	**99.9**	0	1.12	**30.6**	**30.7**	16.7
2	0.25	0	1.7	**98.3**	0.26	5.50	0.1	**94.4**	1.06	**44.1**	**32.2**	1.8
3	0.21	**100**	0	0	0.24	**94.5**	0	5.5	0.88	3.2	15.6	60.2



Analysis and Discussion of Results

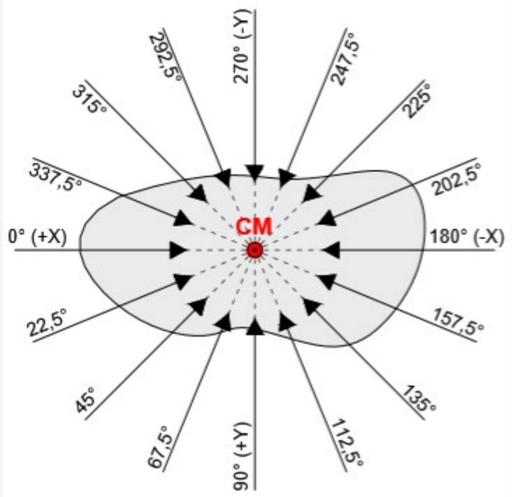
Pushover Analysis

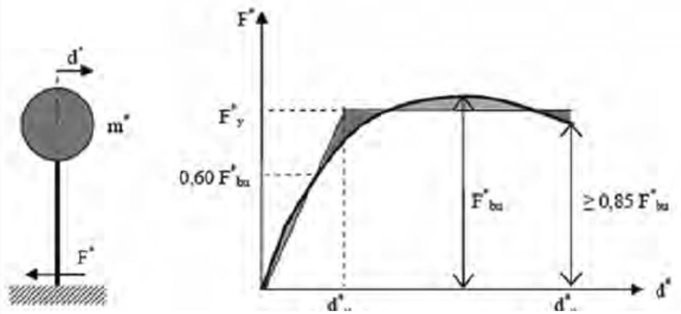
2 invariant lateral load patterns:

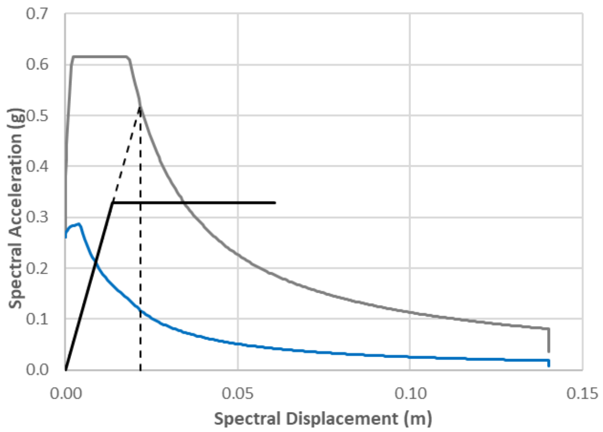
a) mass proportional distribution

b) load pattern proportional to **the story forces calculated in a linear dynamic analysis**, including a number of modes with a total mass participation of not less than 85%.

Each force distribution is applied along the directions θ_i from 0° to 360°, with steps of 22.5°.

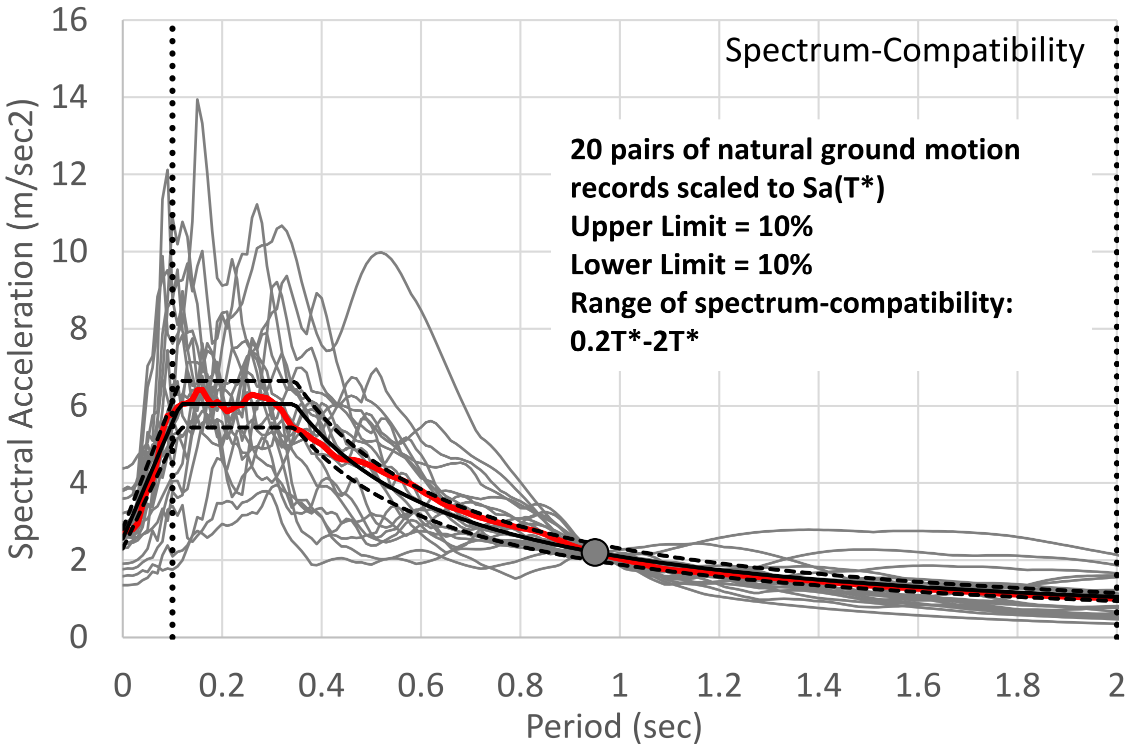






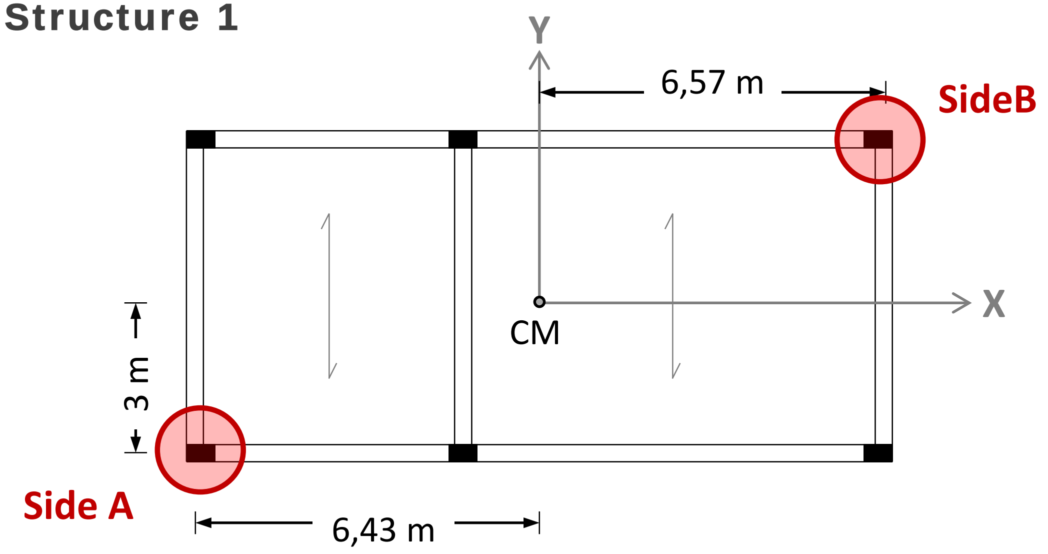
Non-Linear Time History Analysis

NLTHAs of Structure 1 and Structure 2 are performed using **20 pairs of natural records**. The reference is located on rock soil in L'Aquila (AQ-Italy). In order to reduce the influence of the record variability, NLTHA of Structure 3 are performed with **7pairs generated records**. Structure 2 is analyzed with both natural and generated records.



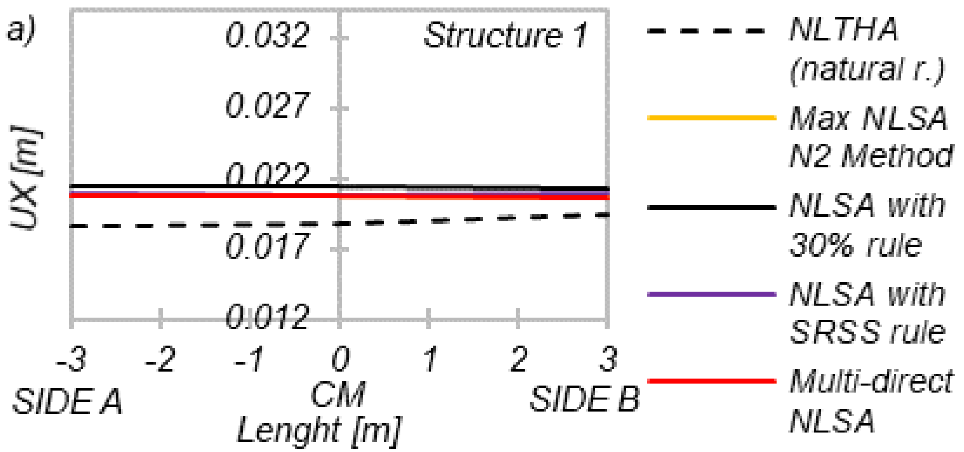
Analysis and Discussion of Results

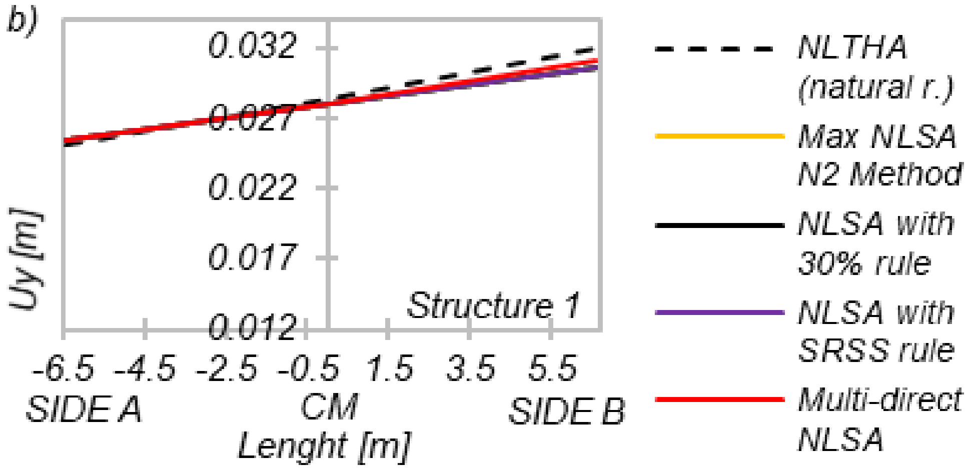
Structure 1



Displacement demands

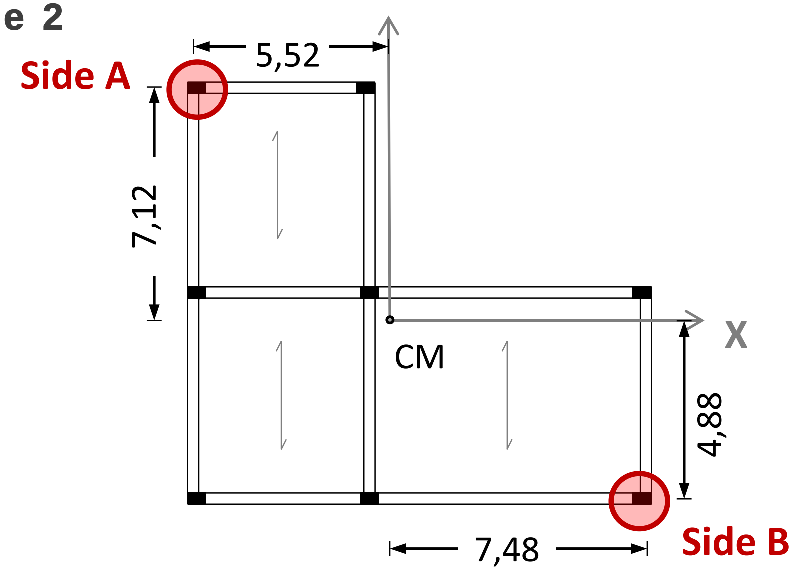
- Maximum PO displacement in ±*x* direction are conservative with respect to the results of NLTHAs (Fig.a).
- The combination rules further increase this result up to a maximum of 11% with the 30% rule. In weak direction (y-direction), all non-linear analyses generate similar displacements.





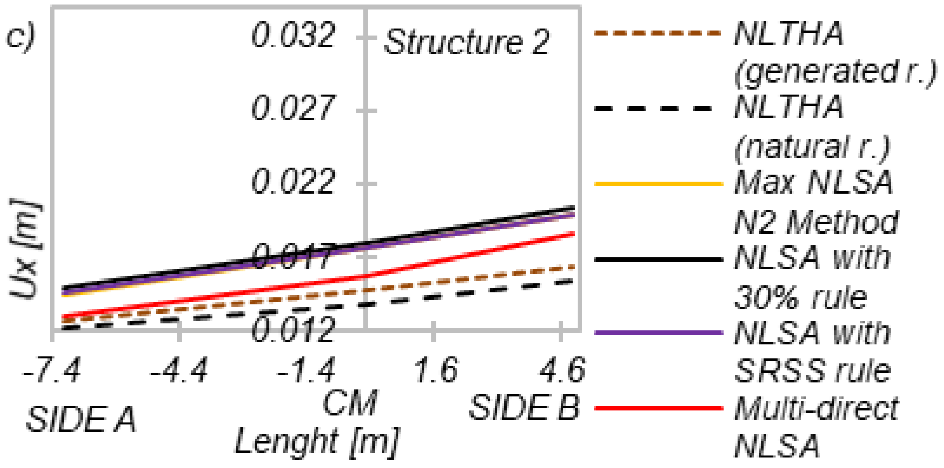
Analysis and Discussion of Results

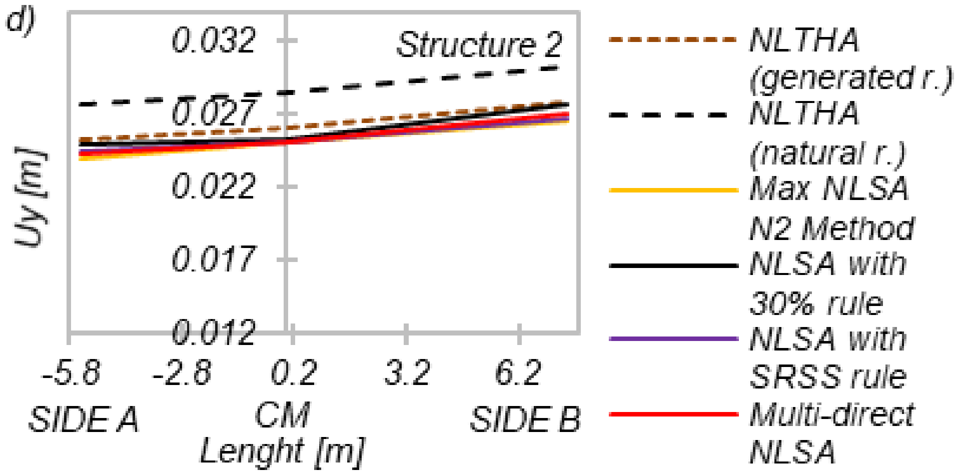
Structure 2



Displacement demands

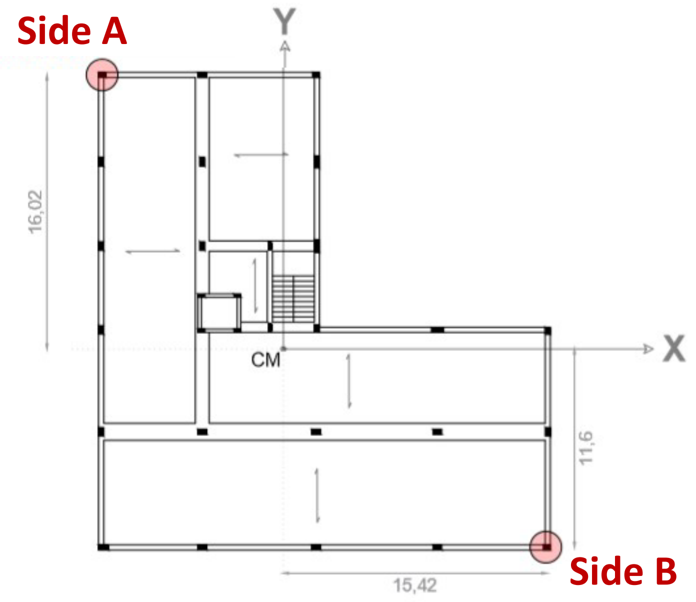
- All displacement demands obtained from NLSAs in the strong structural direction are conservative with respect to the corresponding results of NLTHAs.
- Conversely, the pushover displacements on the weak direction (Fig. d) are lower than NLTHAs results obtained with natural records probably due to the ground motion variability.
- The results provided by generated records are closer to those obtained from NLSAs.





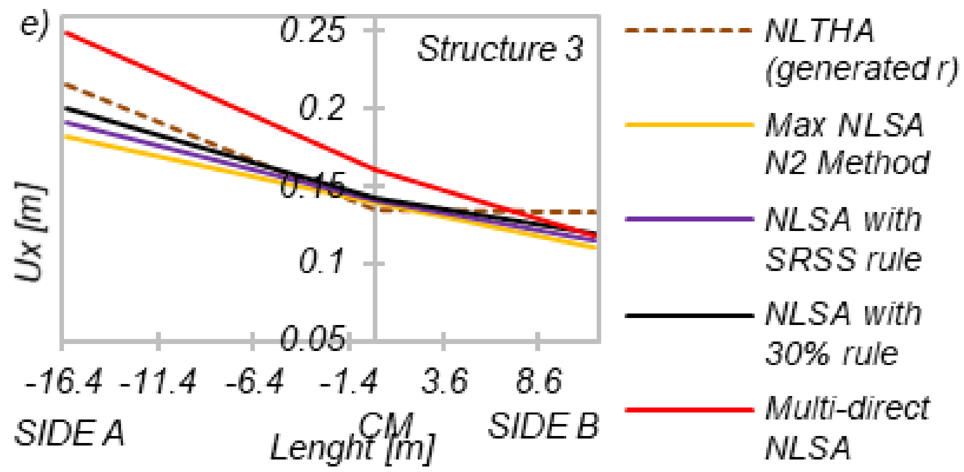
Analysis and Discussion of Results

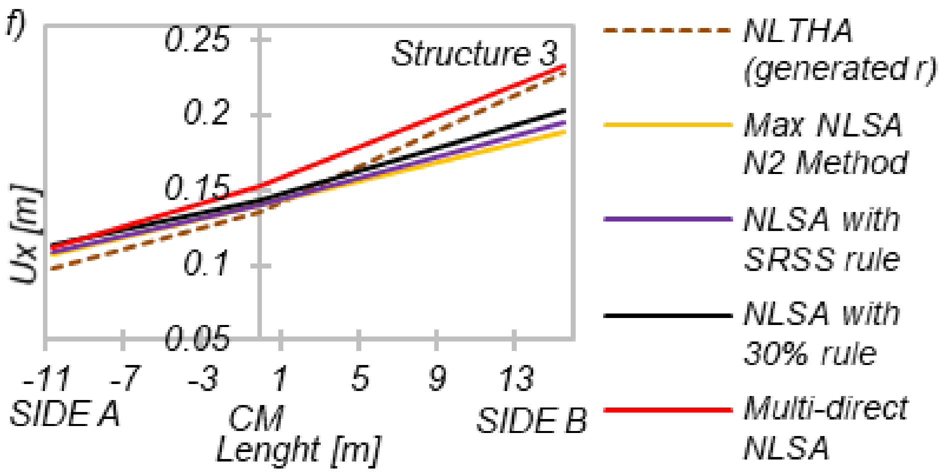
Structure 3



Displacement demands (on the top floor)

- NLS analyses provide unconservative displacements in x-direction (except for multi-directional NLSAs, which produce conservative results on side A).
- In y direction, N2 results are conservative with respect to NLTHAs only on side A, probably due to the strong torsion of the deck. By contrast, multi-directional NLSAs are in this case always conservative and very close to NLTHAs. All NLSAs of Fig. e and Fig. f refer to the mass proportional load pattern.





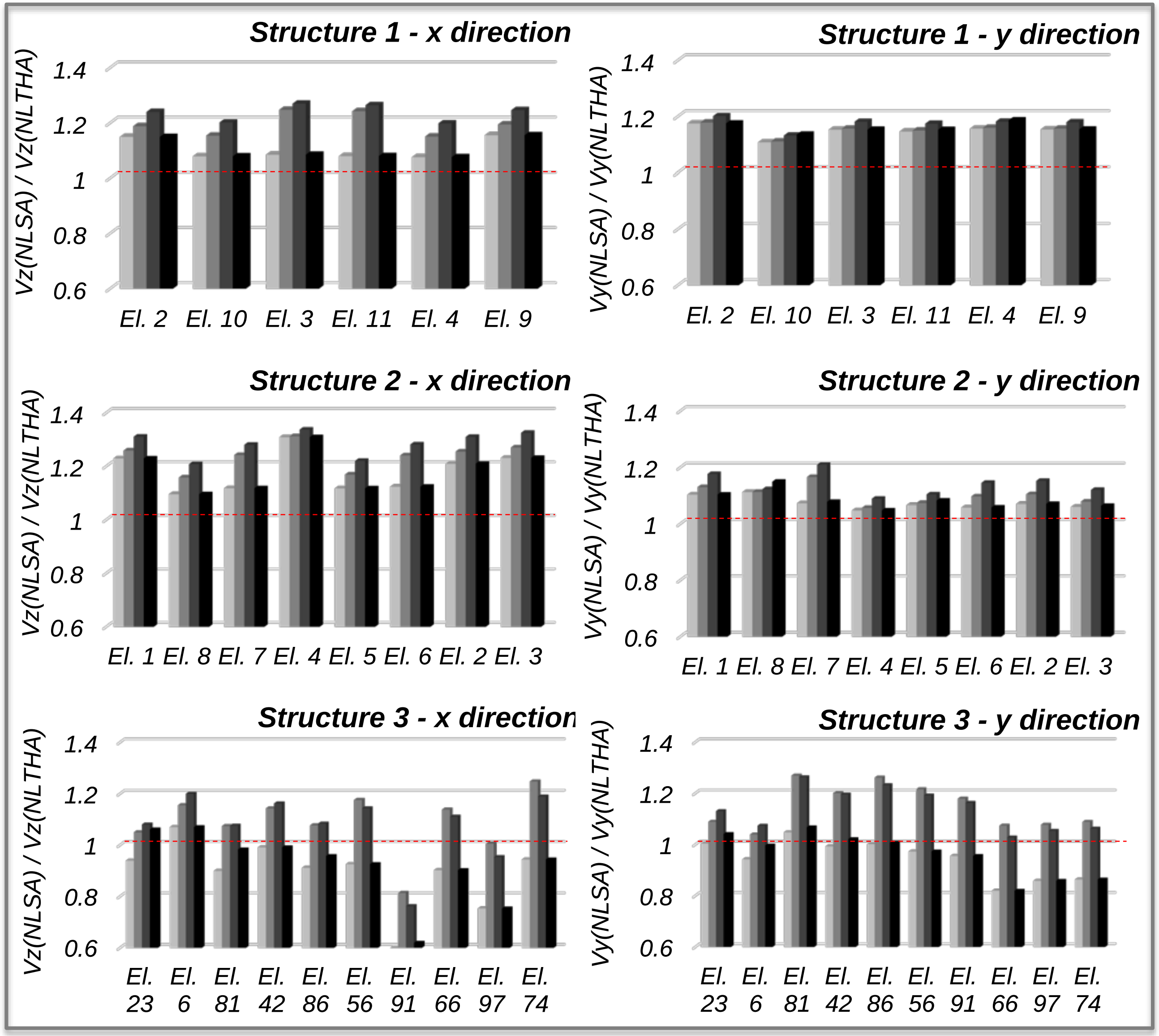
Analysis and Discussion of Results

Shear demands

- Ratios between the shear demands obtained from NLSAs and NLTHAs in the x and y structural directions.
- a) maximum shear values obtained from the application of the N2 method in the ±x and ±y structural directions,
- b) and c) application of the SRSS and 30% combination rules to the shear demands in the ±x and ±y structural directions and
- d) application of pushover forces at different incident angles θ_i and calculation of the maximum shear values obtained at each θ_i.

Legend

Max(NLSA/NLTHA) NLSA(30%)/NLTHA
NLSA(SRSS)/NLTHA Multi-direct-NLSA/NLTHA



Conclusions

- The combination rules applied on displacement demands of single-story buildings do not provide results very different from the conventional N2 method.
- The prediction of displacement demands obtained from multi-directional NLSAs is very performing for the multi-story building, where the method also provides accurate predictions of floor rotations.
- All pushover procedures provide an overestimation of shear demand in single-story structures, in both directions and for all columns. Conversely, for the multi-story structure, the shear demands in NLSAs are greater than the results of NLTHAs (and therefore conservative) only if combinations rules are applied.
- The adequacy and precision of the pushover procedures depend on the structural configuration and the degree of plan irregularity. Therefore, future research should further investigate the effects of different pushover procedures on further load patterns, EDPs and structural configurations.

Thank you for your attention