Accurate Collapse Capacity Quantification for Infilled RC Frame Buildings

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- Simplified Tool for Collapse Assessment
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- Conclusions

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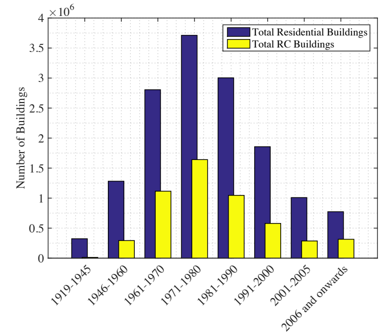
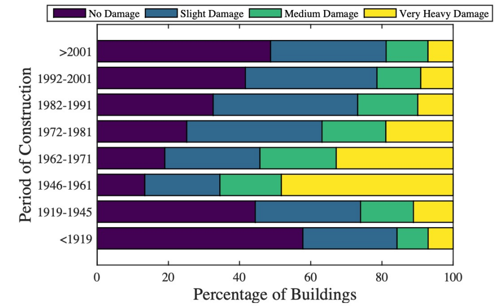
Motivation

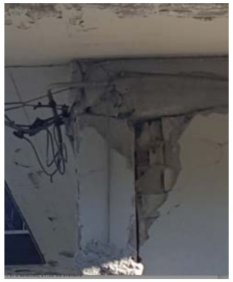
- The prevalence of RC-URM in the Italian/European building stock and observed damaged



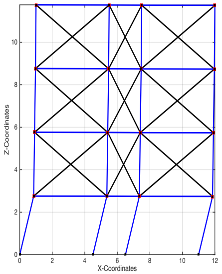


- Insufficient or poor detailing of structural members, inadequate solution to frame-panel interaction



- The global effect of URM infill panel addition: increase in initial stiffness and sudden drop in lateral strength capacity after the rupture of infills

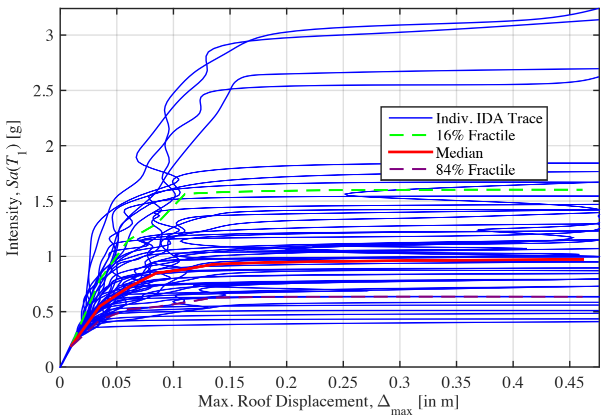


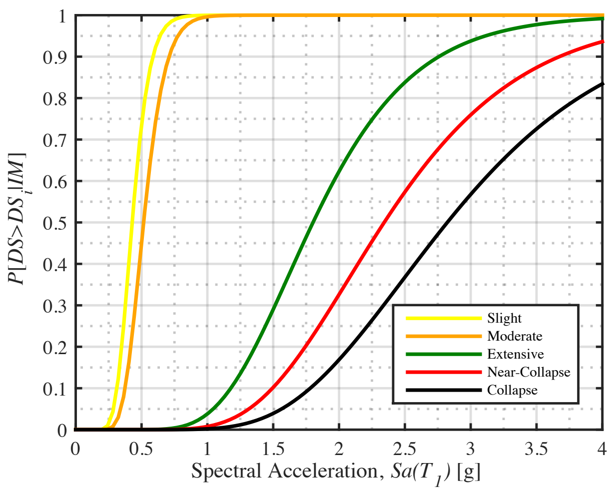

Motivation

- The exceedance of the structural demand-based performance level through fragility curves

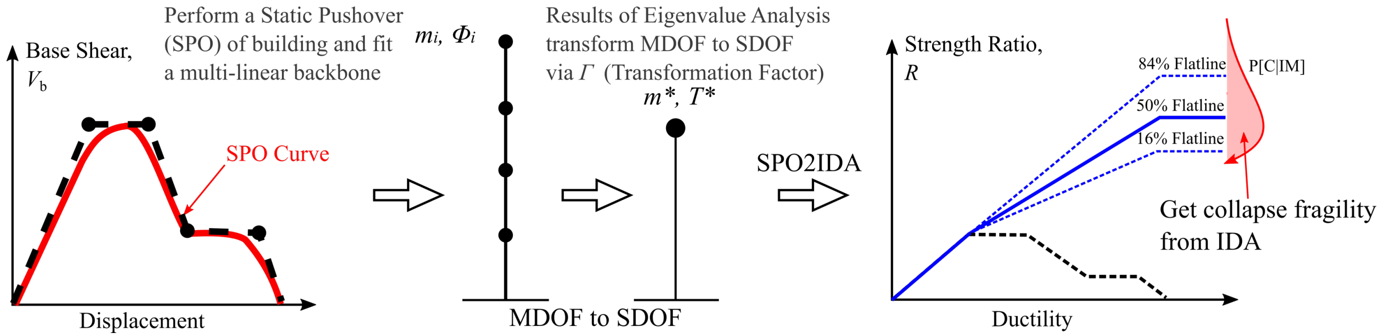
- Computation time-and-effort-extensive analyses (i.e. numerical modelling, ground-motion selection, non-linear dynamic analysis)

- Necessity for simplified methods based on SDOF oscillators (e.g. SPO2IDA, ExtendedSPO2IDA, SPO2FRAG) and R-μ-T relationships

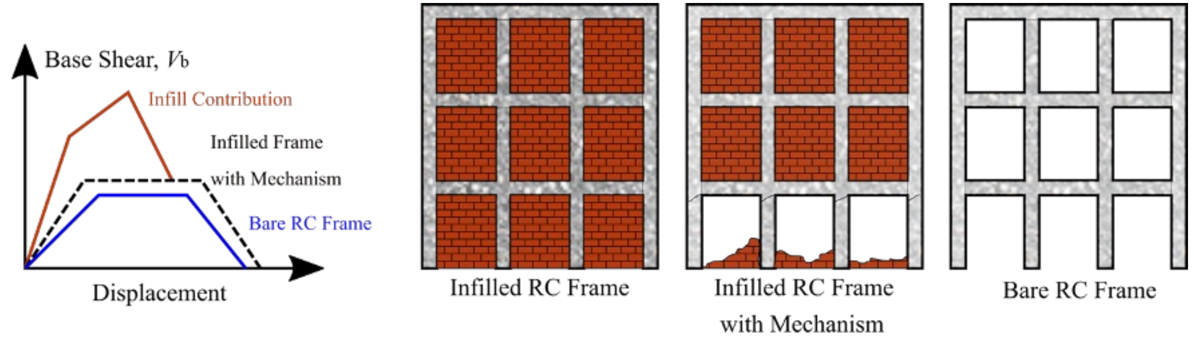




- SPO2IDA (Vamvatsikos & Cornell 2002) and other similar tools offer the ability to relate the force-deformation capacity of a frame structure to its dynamic counterpart through IDA curves



- ExtendedSPO2IDA was developed (Nafeh et al. 2019) to incorporates the representative behaviour of infilled RC frames



- $Sa(T_1)$ is optimal IM at lower intensities, but the associated uncertainty increases at higher levels of intensity

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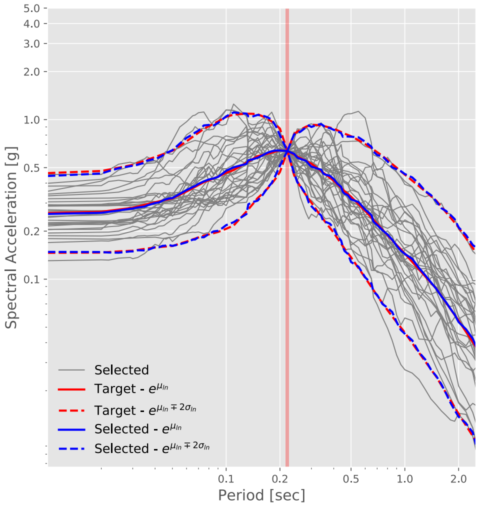
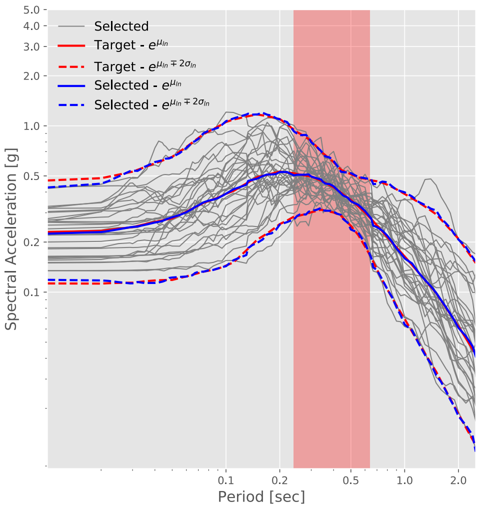
Suitable Choice of Intensity Measure

- Average Spectral Acceleration (Sa_{avg}) introduced by Eads et al. (2015)
- $Sa_{avg} = \left(\prod_{i=1}^{N} Sa(c_i T_1)\right)^{1/N}$
- T ranges from $[0.2T_1; 3.0T_1]$
- Efficiency: accurate prediction of the response given an EDP
- Sufficiency: Independence of the structural response value from seismological parameters
- Unbiased by ground-motion velocity-based characteristics as shown by O'Reilly et al. (2021)
- Stable collapse risk estimates across various ground-motion sets highlighted by Eads et al. (2015).
- Adequacy for infilled RC frame structures at high intensities when inelastic mechanisms form highlighted in O'Reilly et al. (2021)





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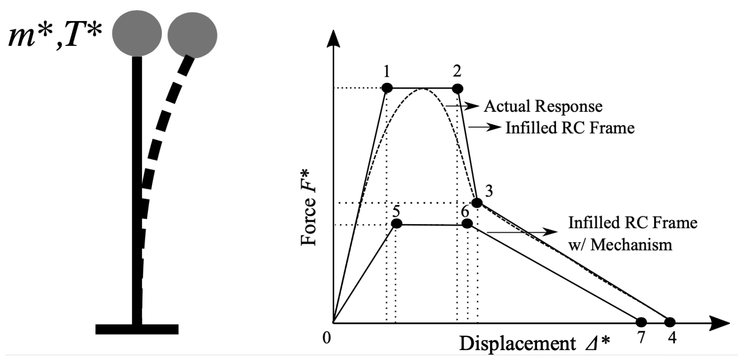
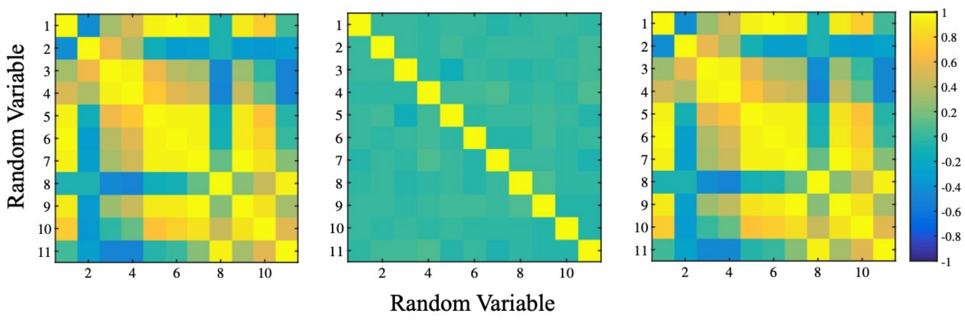
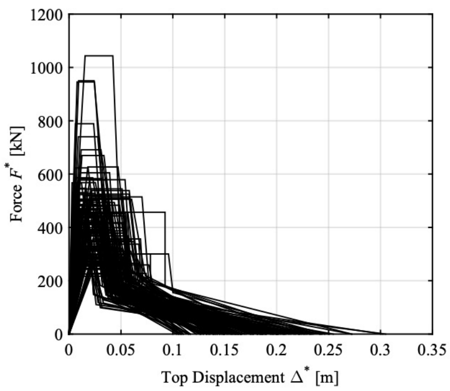
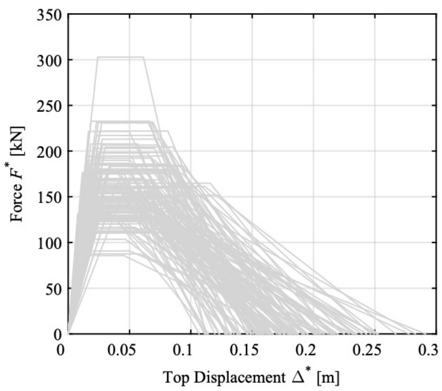
- A dataset of single-degree-of-freedom (SDOF) oscillators with varying backbone parameters is developed through correlation controlled Latin hypercube sampling (CLHS) (Nafeh et al. 2019)







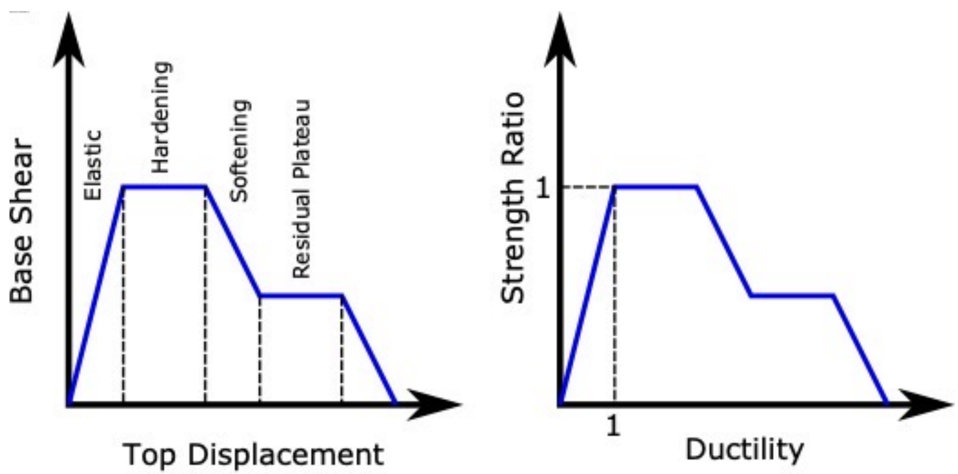


- Methodology

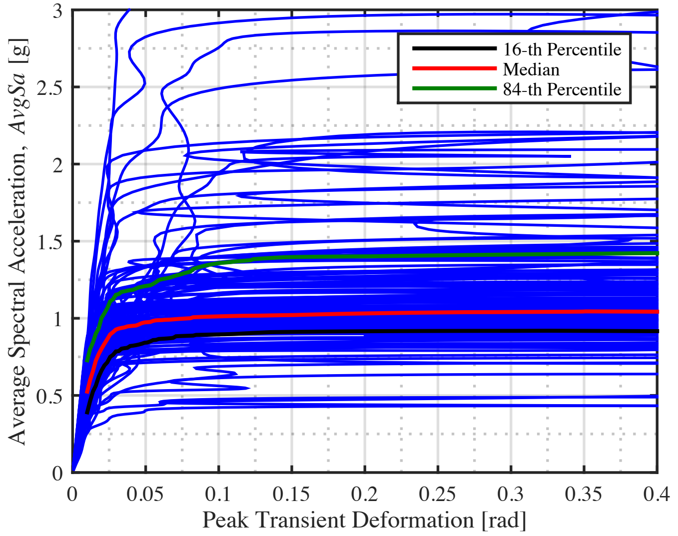
1. Normalise the static backbone parameters to strength ratio and ductility at each response branch *i* ($R_{st,i}$, $\mu_{st,i}$) for each SDOF system

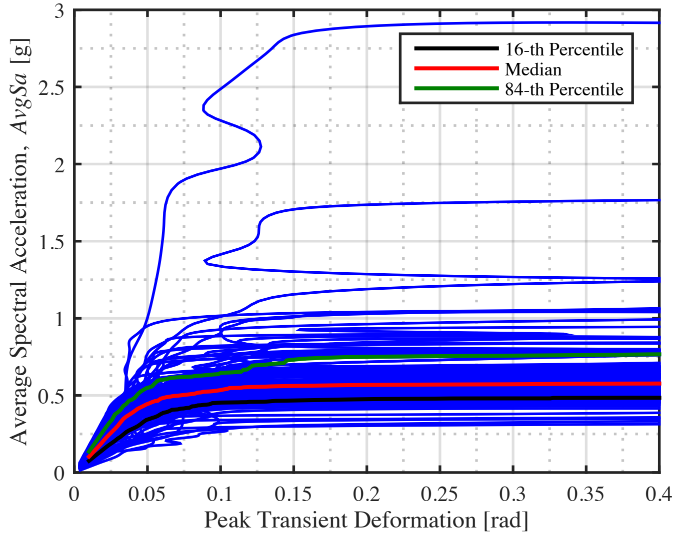
$$R_{st,i} = \frac{V_{b,i}^*}{V_{b,y}^*}$$

$$\mu_{st,i} = \frac{\Delta_i^*}{\Delta_y^*}$$



2. Perform IDAs on SDOF dataset and process the IDA results (16%, 50% and 84%). The INNOSEIS record sets (Vamvatsikos 2019) for medium and high seismicity were used.



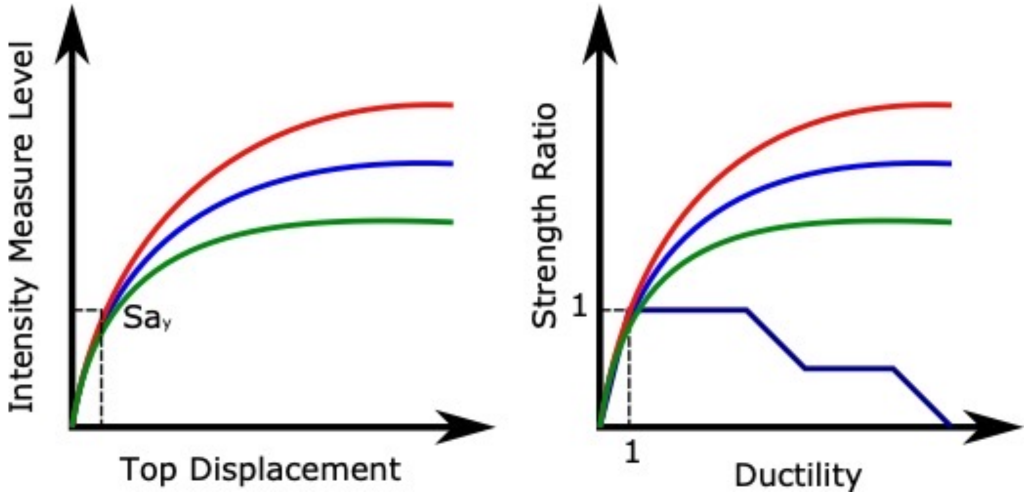


3. Interpolate and normalise the IM-EDP values at each response branch *i* ($R_{dyn,i}$, $\mu_{dyn,i}$)

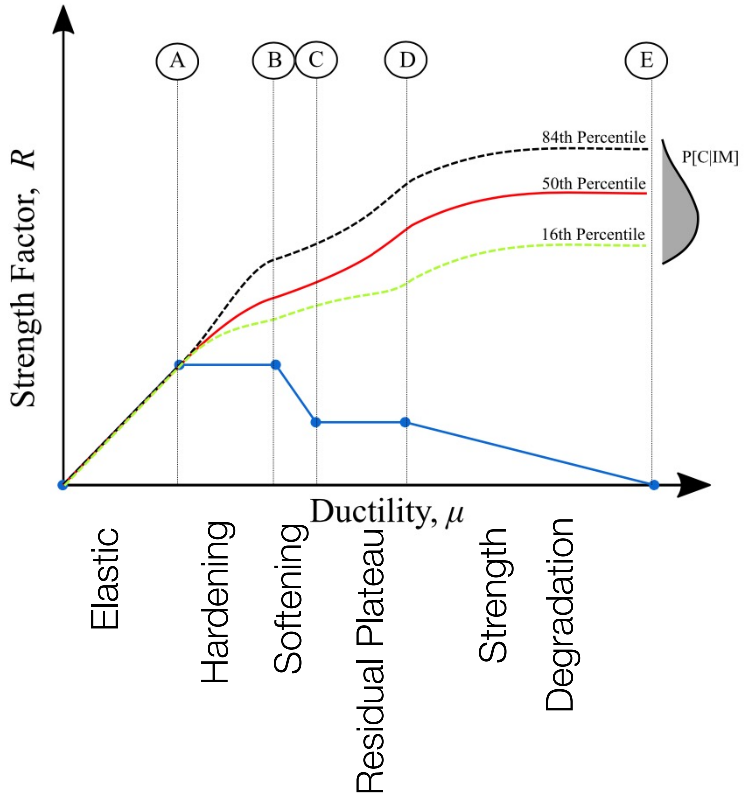
$$R_{dyn,i} = \rho = \frac{Sa_{avg}(T^*[a,b])}{Sa_y}$$

$$\mu_{dyn,i} = \frac{\Delta^*_{dyn,i}}{\Delta^*_y}$$

$$Sa_y = \frac{4\pi^2 \Delta^*_y}{T^{*2}}$$



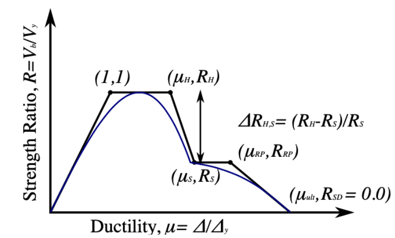
5. Perform two-step regression analysis
    i. Fit a functional form at each response branch relating the static and dynamic response parameters (e.g. coefficients of a polynomial fit)
    ii. Relate the chosen functional form parameters to the fundamental period and relevant capacity parameters (i.e. relate the coefficients of the polynomial fit to strength variables)



Simplified Tool for Collapse Assessment

- Fitted Functions

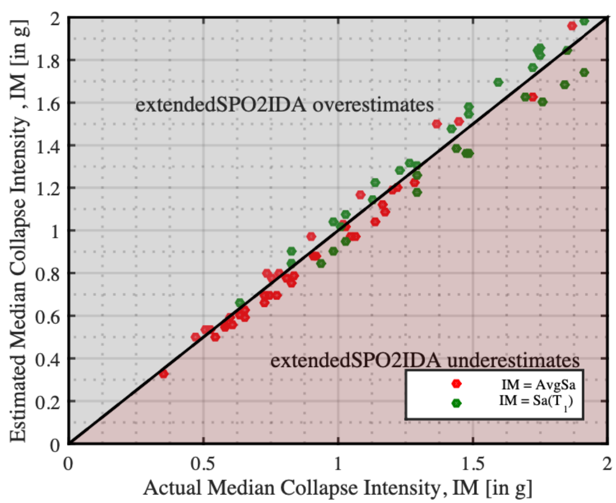
Response Branch	1st Step Regression	2nd Step Regression
Hardening (H)	$R_{dyn,H} = \alpha_{1,qt}\mu_H + \beta_{1,qt}$ Where $\mu_H \in (1; \mu_H]$	$\alpha_{1,16} = -0.5563T^{*2} + 0.711T^* + 0.0115$ $\beta_{1,16} = 0.5563T^{*2} - 0.711T^* + 0.9885$ $\alpha_{1,50} = -0.634T^{*2} + 0.9239T^* + 0.08742$ $\beta_{1,50} = 0.634T^{*2} - 0.9239T^* + 0.9126$ $\alpha_{1,84} = -1.053T^{*2} + 1.509T^* + 0.1239$ $\beta_{1,84} = 1.053T^{*2} - 1.509T^* + 0.8761$
Softening (S)	$R_{dyn,S} = \alpha_{2,qt}\mu_s + \beta_{2,qt}$ Where $\mu_S \in (\mu_H; \mu_S]$	$\alpha_{2,16} = 0.2186(\frac{T^*}{\Delta R_{H,S}})^{0.34}$ $\beta_{2,qt} = 0.7782(\frac{T^*}{\Delta R_{H,S}})^{-0.08327}$ $\alpha_{2,50} = 0.377(\frac{T^*}{\Delta R_{H,S}})^{0.2951}$ $\beta_{2,50} = 0.6189(\frac{T^*}{\Delta R_{H,S}})^{-0.1445}$ $\alpha_{2,84} = 0.5857(\frac{T^*}{\Delta R_{H,S}})^{0.2825}$ $\beta_{2,84} = 0.4087(\frac{T^*}{\Delta R_{H,S}})^{-0.3045}$
Residual Plateau (RP)	$R_{dyn,RP} = \alpha_{3,qt}\mu_{RP} + \beta_{3,qt}$ Where $\mu_{RP} \in (\mu_S; \mu_{RP}]$	$\alpha_{3,16} = 0.07401T^{*2} + 0.04584T^* - 0.00548$ $\beta_{3,16} = -2.158R_{RP}{}^2 + 2.196R_{RP} + 0.9244$ $\alpha_{3,50} = 0.04537T^{*2} + 0.08579T^* - 0.01045$ $\beta_{3,50} = -1.549R_{RP}{}^2 + 1.754R_{RP} + 1.288$ $\alpha_{3,84} = 0.06217T^{*2} + 0.2534T^* - 0.0286$ $\beta_{3,84} = -2.174R_{RP}{}^2 + 2.179R_{RP} + 1.552$
Strength Degradation (SD)	$R_{dyn,SD} = \alpha_{4,qt}\mu_{SD} + \beta_{4,qt}$ Where $\mu_{SD} \in (\mu_{RP}; \mu_{ult}]$	$\alpha_{4,16} = 0.01552T^* - 0.001861$ $\beta_{4,16} = -1.662T^{*2} + 2.049T^* + 1.173$ $\alpha_{4,50} = 0.02035T^* - 0.002569$ $\beta_{4,50} = -2.008T^{*2} + 2.541T^* + 1.405$ $\alpha_{4,84} = 0.02875T^* - 0.003179$ $\beta_{4,84} = -3.886T^{*2} + 4.641T^* + 1.553$

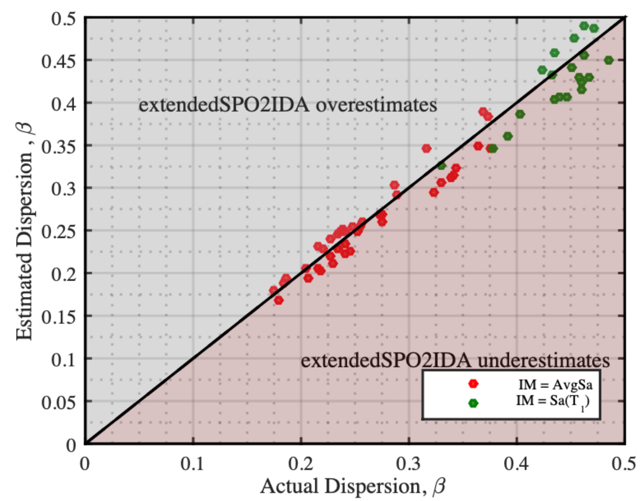


- The tool can be downloaded from (https://github.com/gerardjoreilly/InfilledRC-SPO2IDA)

Simplified Tool for Collapse Assessment

- Verification of Simplified Tool:
  - Additional set of 40 SDOFs
  - Incremental dynamic analysis with INNOSEIS record sets
  - Better estimate in terms of median collapse intensity (Sa_{avg} and $Sa(T_1)$)
  - Lower dispersion at collapse when Sa_{avg} is used in comparison to $Sa(T_1)$

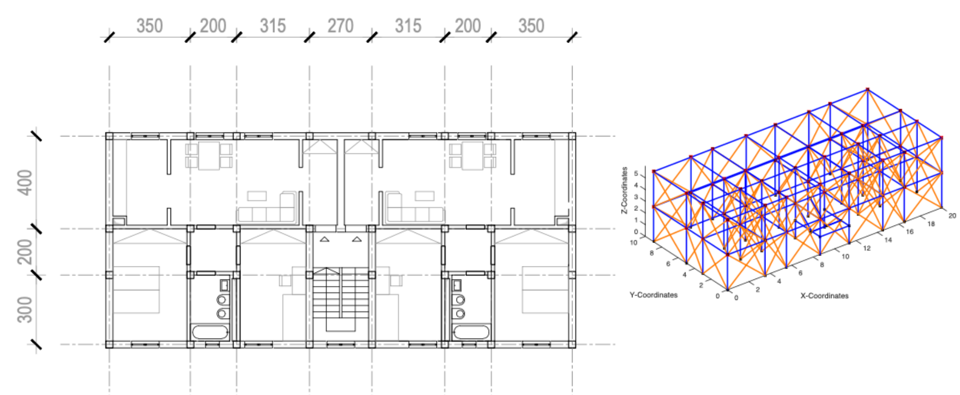




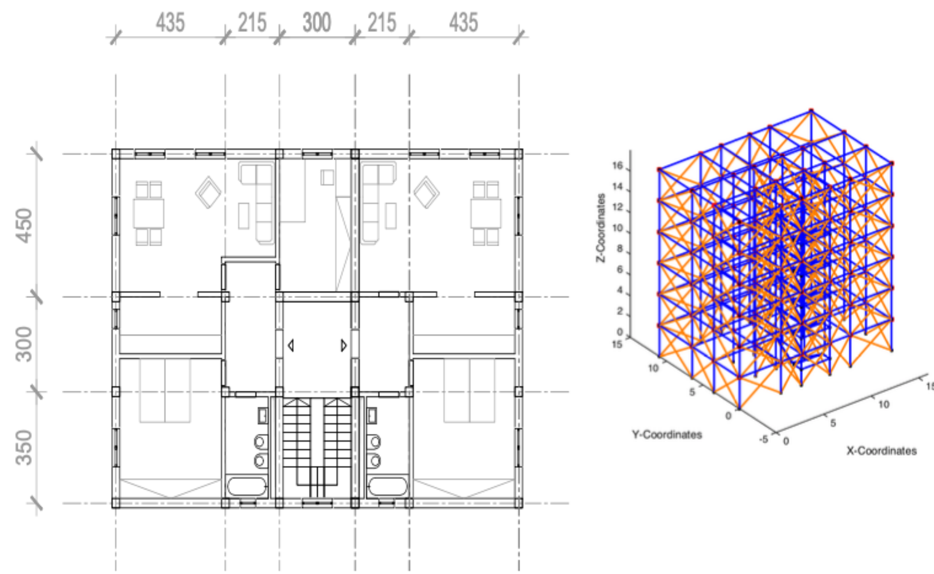
Contents

Case Study Validation (Case Study Layouts)

- 2-Storey Infilled Building (Pre-Code Structure)



- 6-Storey Infilled Building (Pre-Code Structure)



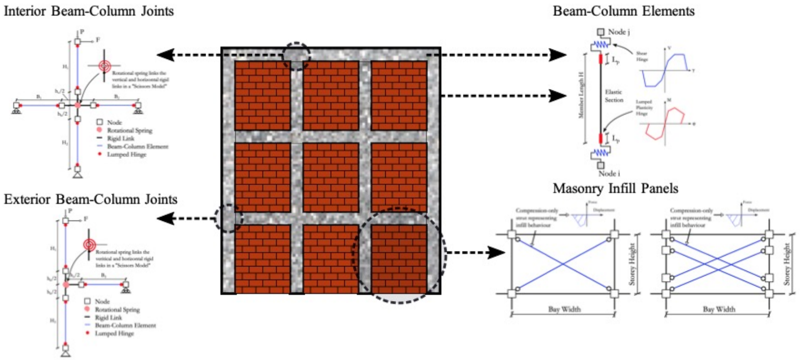
Case Study Validation (Case Study Layouts)

- Buildings were designed for gravity-loads (GLD) only according to Regio-Decreto 1939 with no consideration for ductile detailing
- The allowable stresses were generally assumed to be equal to 29.2% and 33.3% for compression and tension respectively
- The value for allowable shear stress necessary for the calculation of transverse reinforcement is taken as 0.4 N/mm^2 for normal-weight concrete and 0.6 N/mm^2 for high-strength concrete
- Frames span in one direction only
- Permanent loads of 500 kg/m^2 and 450 kg/m^2 were considered for typical and roof slabs respectively
- Accidental loads of 200 and 150 kg/m^2 were considered for typical and roof slabs respectively

ID	Number of Frames			Column Sections (mm)	Beam Sections (mm)	Longitudinal Reinforcement Ratios (%)	Transverse Reinforcement (diameter/spacing)	Material Characteristics
GLD#1	Dir-X	Exterior	2	250x250mm	500x300mm	C: 0.89% - 0.98% (ϕ14 - ϕ16) B: 0.21% - 0.31% (ϕ14)	C: ϕ6 @150mm B: ϕ6 @200mm	Smooth Rebars (Aq42, σ=140 MPa); Concrete (σ=5 MPa);
		Interior	2					
	Dir-Y	Exterior	2					
		Interior	0					
GLD#2	Dir-X	Exterior	2	250x250mm 300x300mm	500x300mm	C: 0.89% - 0.98% (ϕ14 - ϕ16) B: 0.40% - 0.67% (ϕ16)	C: ϕ6 @150mm B: ϕ6 @200mm	
		Interior	2					
	Dir-Y	Exterior	2					
		Interior	0					

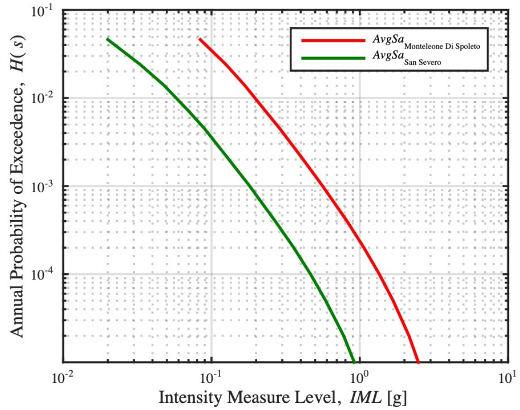
Case Study Validation (Numerical Modelling)

- Three-Dimensional Lumped Plasticity Model in OpenSees
- Interior Beam-Column Joints: “zero-Length” elements with rigid-offsets in transformation + “Hysteretic” Material to account for flexural and axial behaviour O’Reilly & Sullivan (2019)
- Exterior Beam-Column Joints: “zero-Length” elements with rigid-offsets in transformation + “Hysteretic” Material to account for flexural and axial behaviour, O’Reilly & Sullivan (2019), De Risi et al. (2017)
- Beam-Column Elements: “*Force Beam-Column*” Element with Finite Plastic Hinge Length coupled with “*zero-Length*” Elements + “*Pinching4*” Material + Shear Hinges for stair elements, O’Reilly & Sullivan (2019), Di Domenico et al. (2021)
- Masonry Infill Panels: Equivalent single strut models to account for the IP response, Crisafulli & Carr (2000) , Decanini (2005)



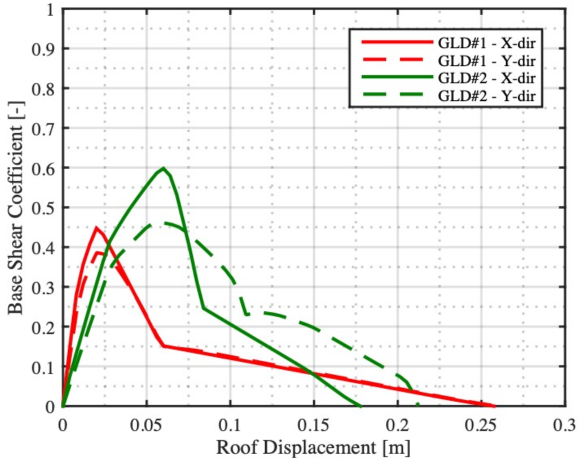
Case Study Validation (Hazard and Record Selection)

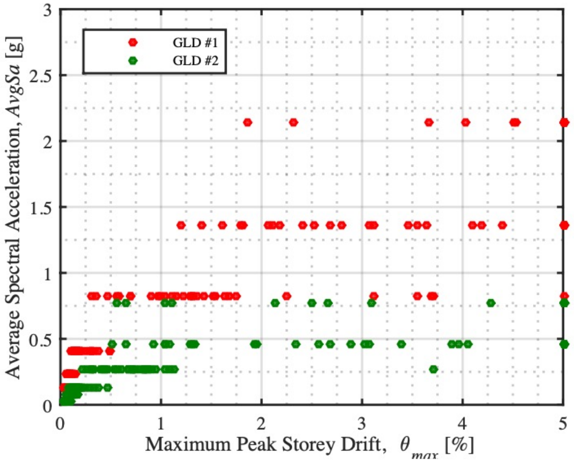
- Two locations representing medium (San Severo) and high seismicity (Monteleone di Spoleto)
- Hazard analysis for record selection using OpenQuake
- Site Characteristics (i.e. Vs30) from **Mori et al.** (2020)
- Record selection from PEER-NGA database using Conditional Mean Spectrum with modifications suggested by **Kohrangi et al.** (2017)
- Correlation model by **Baker & Jayaram** (2008) for spectral values
- The geometric mean of the two components was selected



Case Study Validation (Results)

- Eigenvalue analysis was conducted to obtain the first-mode shape
- Static Pushover (SPO) analysis was conducted to obtain the global force-displacement behaviour
- The SPO results corresponding to both principal directions were considered





- Eigenvalue + SPO results are inserted as input in the ExtendedSPO2IDA tool.
- Multiple Stripe Analysis conducted to compare the predictive capacity of the tool in a hazard-consistent scenario

Case Study Validation (Results)

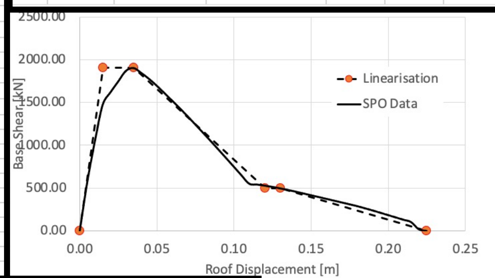
- Step 1: Insert results of SPO (base shear vs roof displacement)
- Step 2: Insert results of the modal analysis
- Step 3: Fit the multi-linear model to the SPO curve

Pushover Curve Data

		Base Shear V_b [kN]	Roof Displacement Δ [m]
3	1	0	0.000
4	2	571.671	0.005
5	3	1051.331	0.010
6	4	1475.543	0.015
7	5	1620.169	0.020
8	6	1746.025	0.025
9	7	1871.373	0.030
10	8	1905.271	0.035
11	9	1848.175	0.040
12	10	1779.491	0.045
13	11	1699.916	0.050
14	12	1612.684	0.055
15	13	1524.394	0.060
16	14	1435.147	0.065
17	15	1342.447	0.070
18	16	1246.327	0.075
19	17	1149.533	0.080
20	18	1051.848	0.085
21	19	952.602	0.090
22	20	852.352	0.095
23	21	751.347	0.100
24	22	649.680	0.105
25	23	551.574	0.110
26	24	542.211	0.115
27	25	529.470	0.120
28	26	514.508	0.125
29	27	497.365	0.130
30	28	479.354	0.135
31	29	459.212	0.140
32	30	438.279	0.145
33	31	417.145	0.150
34	32	395.952	0.155
35	33	374.749	0.160
36	34	353.543	0.165
37	35	332.332	0.170
38	36	311.041	0.175
39	37	289.475	0.180
40	38	264.461	0.185
41	39	239.023	0.190
42	40	212.013	0.195
43	41	184.766	0.200
44	42	157.517	0.205
45	43	130.085	0.210
46	44	102.335	0.215
47	45	18.335	0.220
48	46	0.000	0.225

Input data

		Equivalent Linearisation		Normalisation		Checks	Description
		Base Shear V_b [kN]	Roof Displacement Δ [m]	R	μ		
1		0.00	0.000	0.00	0.00	-	Zero point just for plotting
2	*Yielding*	1905.27	0.015	1.00	1.00	#DIV/0!	Force is taken as max of SPO. Displacement set to match the initial stiffness of SPO
3	*Hardening*	1905.27	0.035	1.00	2.33	Ok	Force is equal to point 1. Displacement set visually by user
4	*Softening*	500.00	0.120	0.26	8.00	Ok	Both set visually by user
5	*Residual*	500.00	0.130	0.26	8.67	Ok	Both set visually by user
6	*Degradation*	0.00	0.225	0.00	14.99	Ok	Force is taken as zero. Displacement taken as point of zero force.



Notes:
Cells highlighted in yellow are to be inputted by the user
Ensure that all of the checks are satisfied
Modal analysis are used for the MDOF to SDOF conversion
Mode shape should be normalised with top=1 since EDP is roof displacement
Choose % to find secant but careful it is still finding a value in intial branch
Modal analysis should be updated manually along with the formulas in cells O8, O9 and O10

Example of 3 storey infilled frame (weak single leaf) from O'Reilly & Sullivan (2018)

Modal Analysis

Level	Mass [t]	Φ[-]
0	-	0.00
1	200	0.16
2	200	0.32
3	200	0.48
4	200	0.64
5	200	0.80
6	200	1.00

Case Study Validation (Results)

- Equivalent SDOF properties
- Median collapse intensity ($Sa(T_1)$) and associated dispersion (previous version)
- Median collapse intensity (Sa_{avg}) and associated dispersion (current version)
- IDA curves corresponding to median, 16% and 84% percentiles

Results

% of $V_{b,max}$ to take secant =	20%	
Initial stiffness (SPO) =	0	kN/m
Initial stiffness (Linearisation) =	95264	kN/m
Difference	#DIV/0!	
Yield displacement, Δ_y =	0.020	m
Yield base shear, $V_{b,y}$ =	1905.3	kN
Total mass, m =	660.0	t
SDOF mass, m^* =	583.00	t
Transformation factor, Γ =	1.12	
SDOF Yield displacement, Δ_y^* =	0.018	m
SDOF Yield force, F_y^* =	1705.8	kN
SDOF period, T^* =	0.49	s
SDOF yield acceleration, Sa_y =	0.33	g

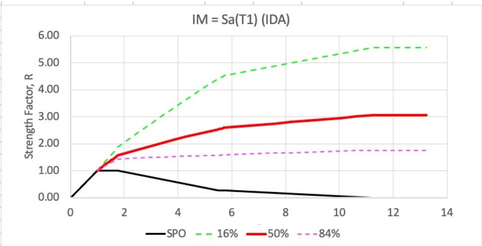
Make sure to have small steps for the pushover curve, else errors might pop up

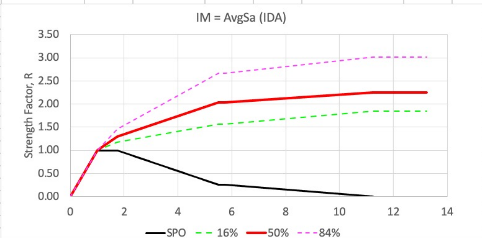
IDA - SaT

Median collapse intensity, $Sa(T_1)$ =	1.14	g
Dispersion, β_{RTR} =	0.58	

IDA - AvgSa

Median collapse intensity, AvgSa=	0.84	g
Dispersion, β_{RTR} =	0.20	

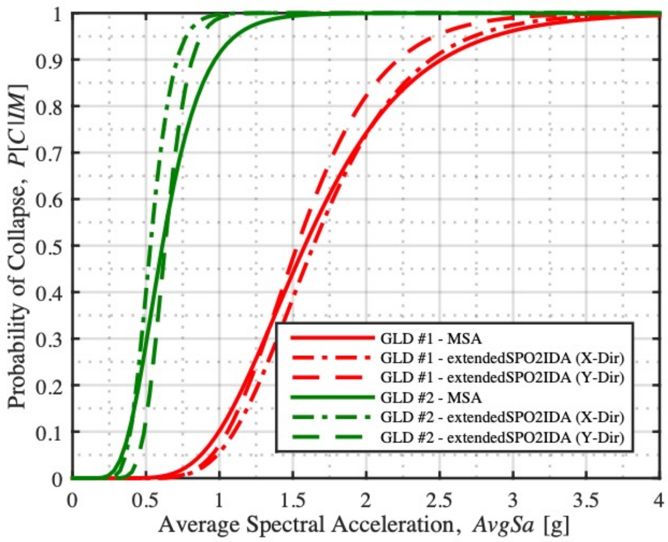




Case Study Validation (Results)

- Collapse fragility functions were obtained considering a lognormal distribution with median collapse intensities and dispersions from MSA and ExtendedSPO2IDA
- An excellent match is observed between the two sets of case study buildings
- The comparison illustrates the accuracy of the proposed tool for this typology considering different heights and across all seismicity levels

Case Study Building	Multiple Stripe Analysis		Extended SPO2IDA	
	$\widehat{Sa_{avg}}$	β	$\widehat{Sa_{avg}}$	β
GLD #1	1.58	0.36	1.53 (X) 1.64 (Y)	0.29 (X) 0.31 (Y)
GLD #2	0.61	0.39	0.63 (X) 0.53 (Y)	0.20 (X) 0.23 (Y)



Contents

Conclusions

- The seismic assessment of RC structures with masonry infills is important considering their prevalence in the regional building stock
- The characterisation of their behaviour up to global collapse is essential in risk-based analysis associated to PBEE
- Non-linear dynamic analysis are computationally expensive in terms of time and effort
- R-μ-T relationships considering the general response of the infilled RC typology were developed
- Behaviour characteristics such as period elongation and formation of inelastic mechanisms (e.g. soft-storey mechanism) are accounted
- Sa_{avg} was chosen as suitable IM for the study considering its inherent properties (i.e. low associated dispersions)
- The developed tool offers ease of applicability in terms of format, and information required
- The accuracy of the tool in predicting median collapse intensities and associated dispersions was highlighted

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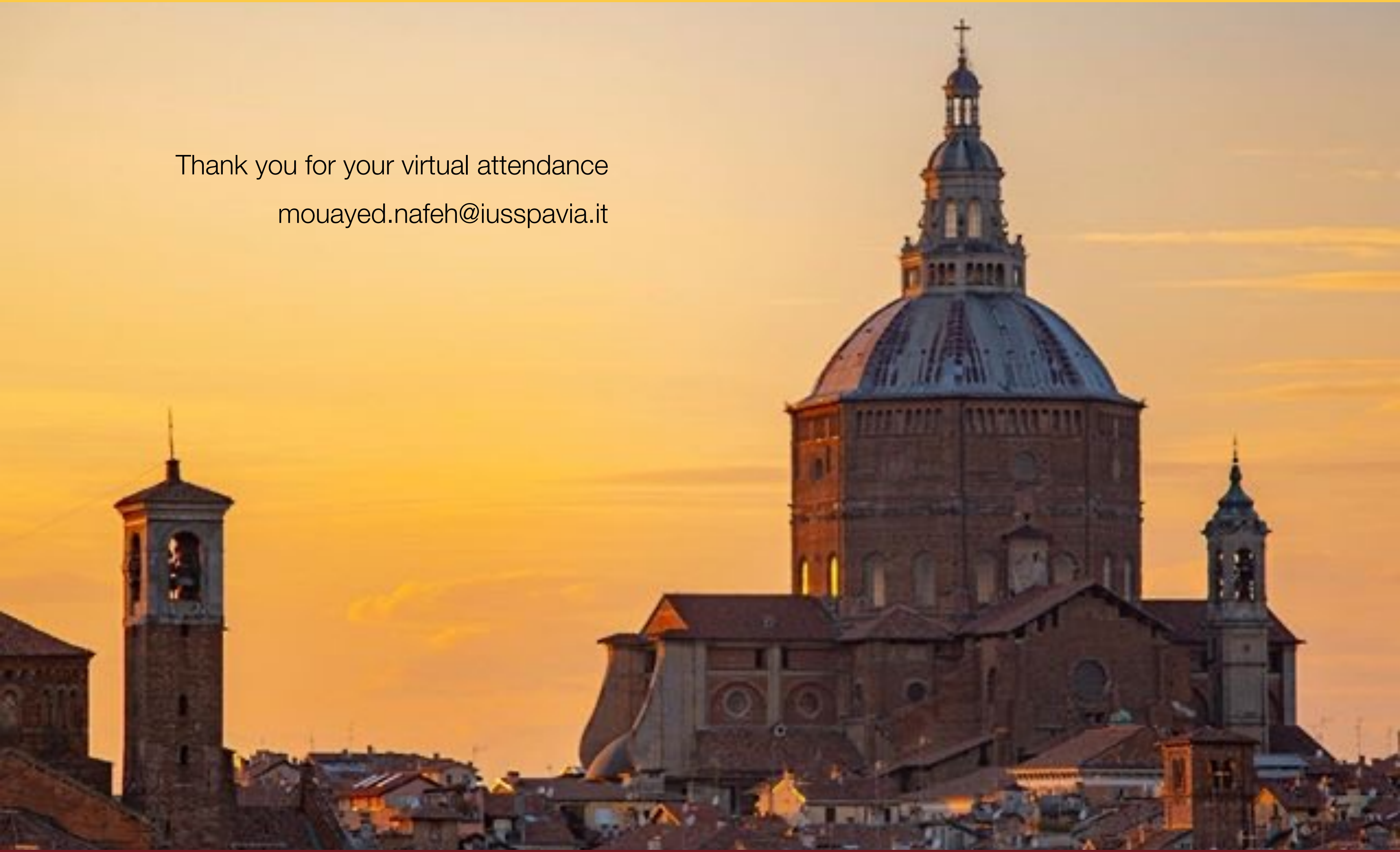

Thank you for your virtual attendance

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