Risk analysis of transmission lines systems to natural hazards with emphasis on earthquakes and extreme winds

Seismic Collapse Risk of a isolated Transmission Tower and Transmission line system

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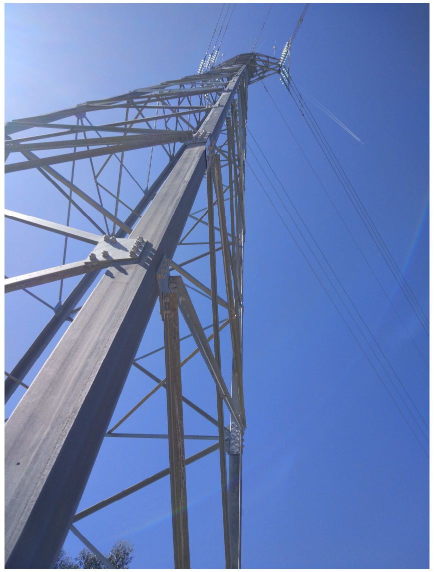


Outline

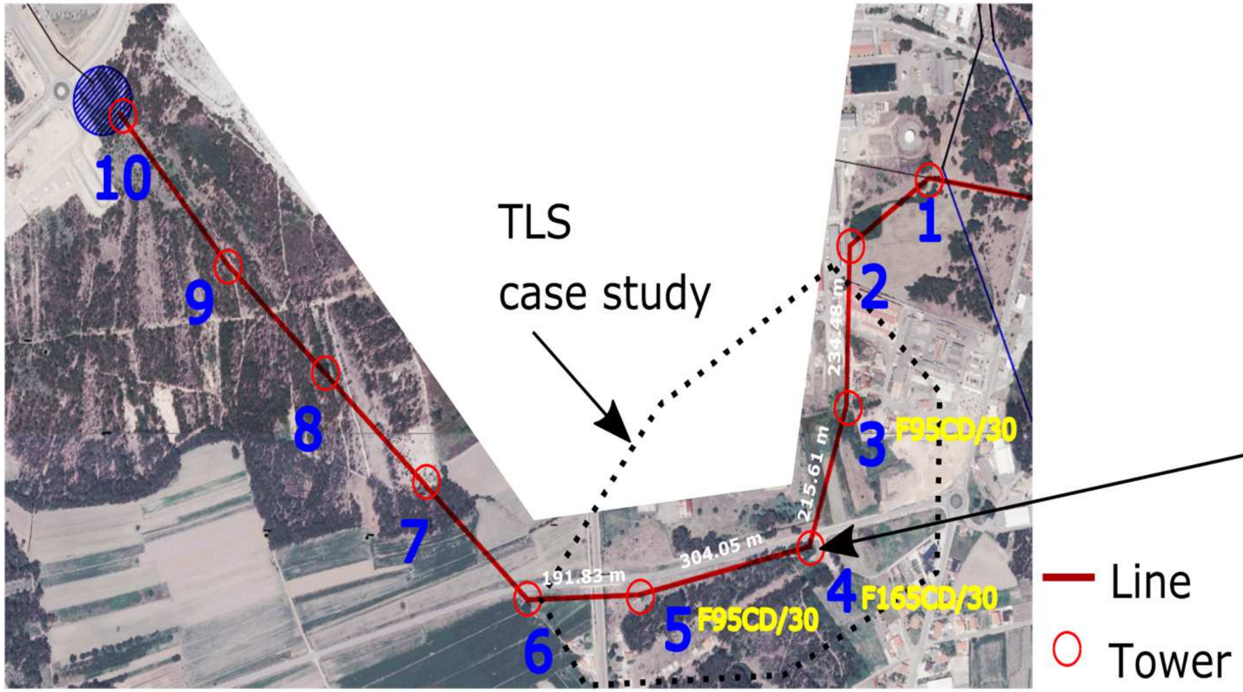
- Overhead Line System – Overview of the **Case study**;
  - Overhead Power Line Layout;
  - Lattice transmission tower (TT);
  - Transmission line system (TLS) components
- **Capacity assessment of a isolated TT and TT within the TLS**
  - Numerical modeling in OpenSees
  - Pushover analysis under different lateral load patterns
  - Dynamic analysis (IDA) for validation of pushover TT results
- **Seismic Collapse Risk assessment of a isolated TT and the TLS**
  - Selection of ground motion records for each system
  - Assessment of the annual frequency of collapse as a risk metric
- Conclusions

Case Study Presentation – Line Layout

Overhead High Voltage Line - Sub-transmission **<u>60 kV Line</u>** from EDP,DISTRIBUIÇÃO located in the North of Portugal

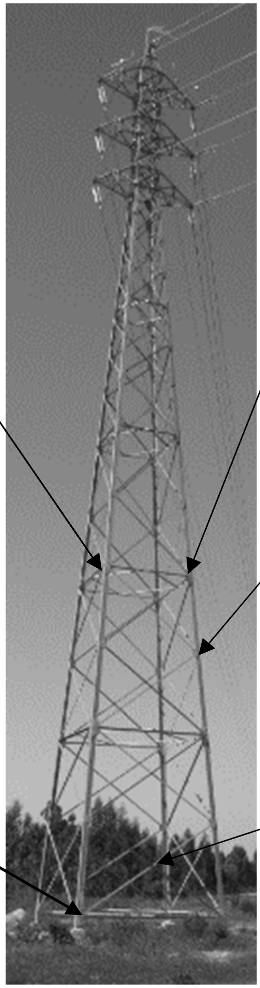
Overhead Power-Line Layout

a)



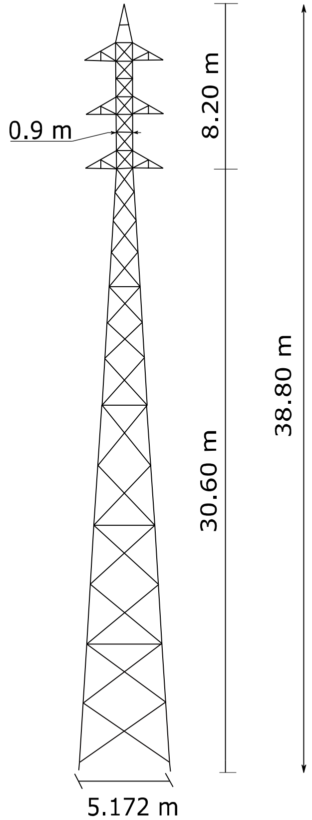
Previously RADAR Monitored Tower

Case Study Presentation – TT 3D View

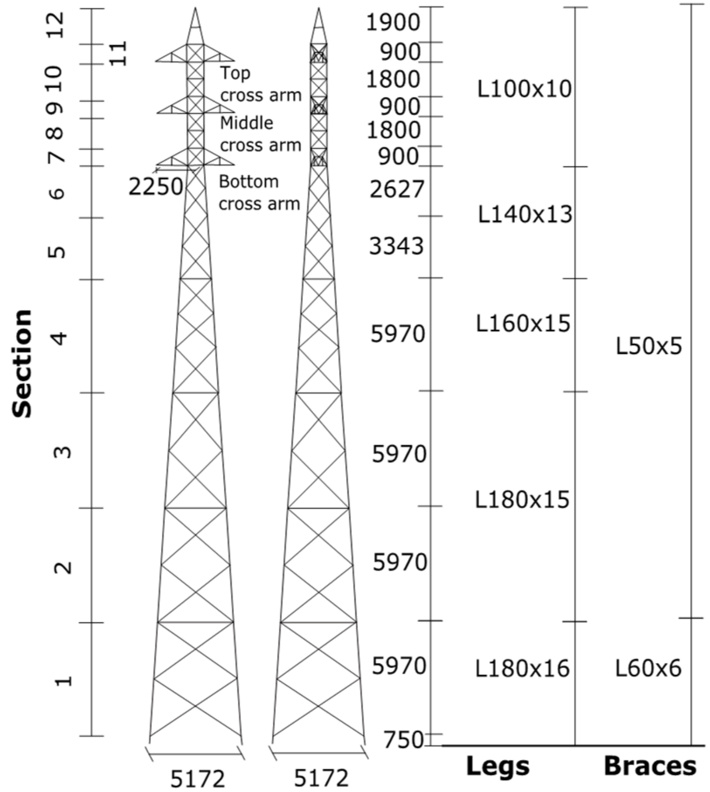


Brace connection

Pinned joint in brace intersection

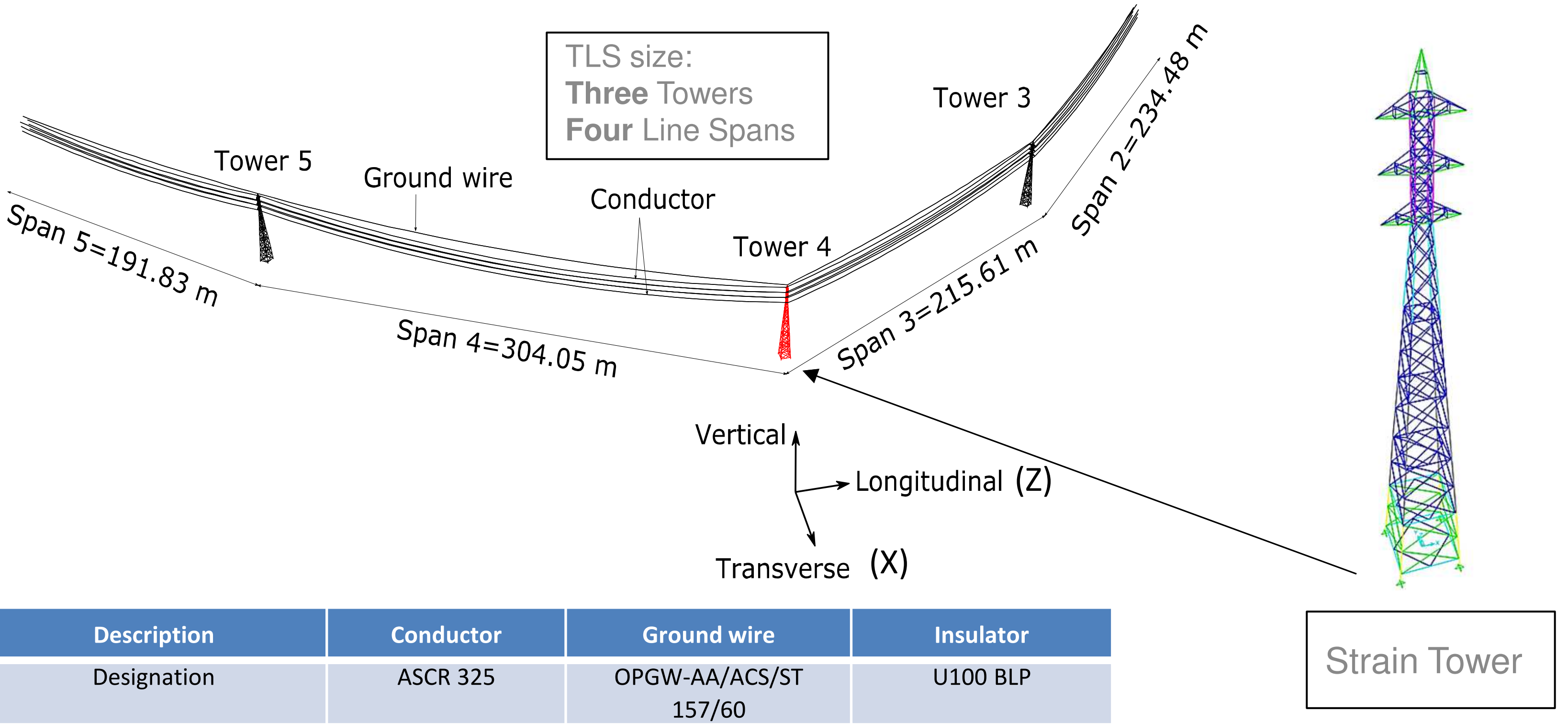


Equal steel angles



Steel class - S275

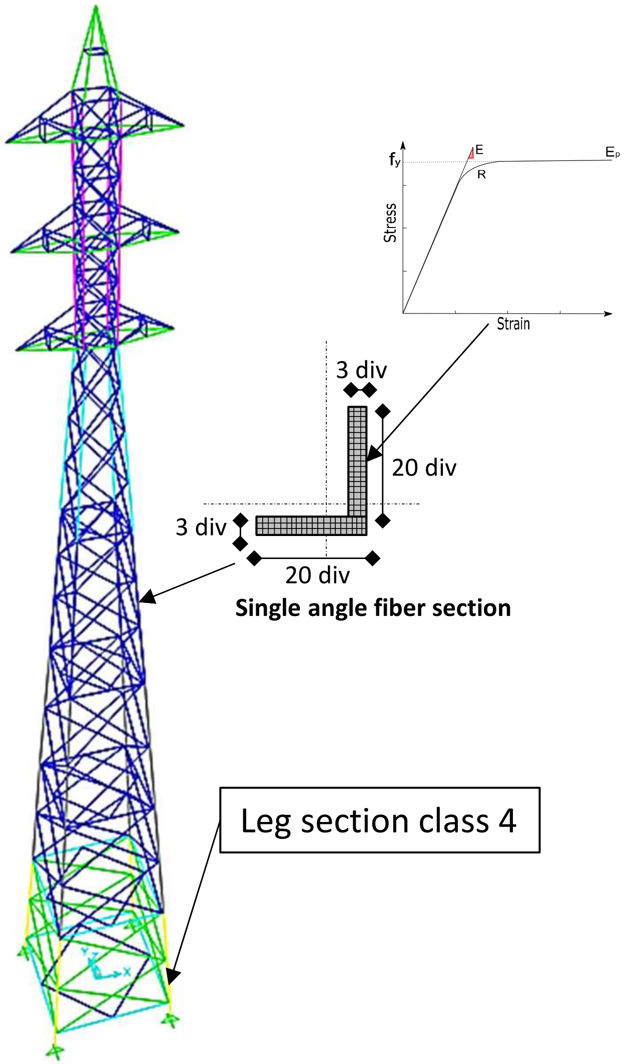
Case Study Presentation – TLS 3D View



Description	Conductor	Ground wire	Insulator
Designation	ASCR 325	OPGW-AA/ACS/ST 157/60	U100 BLP
Outside Diameter (mm)	23,45	19,60	-
Modulus of Elasticity (GPa)	79,5	84,5	76,5
Cross-sectional area (mm^2)	325	219,66	-
Mass per unit length (kg/Km)	1260	868	30 (total mass)
Nominal breaking load (kN)	109,38	112,6	100

Capacity assessment of a isolated TT and TT within the TLS

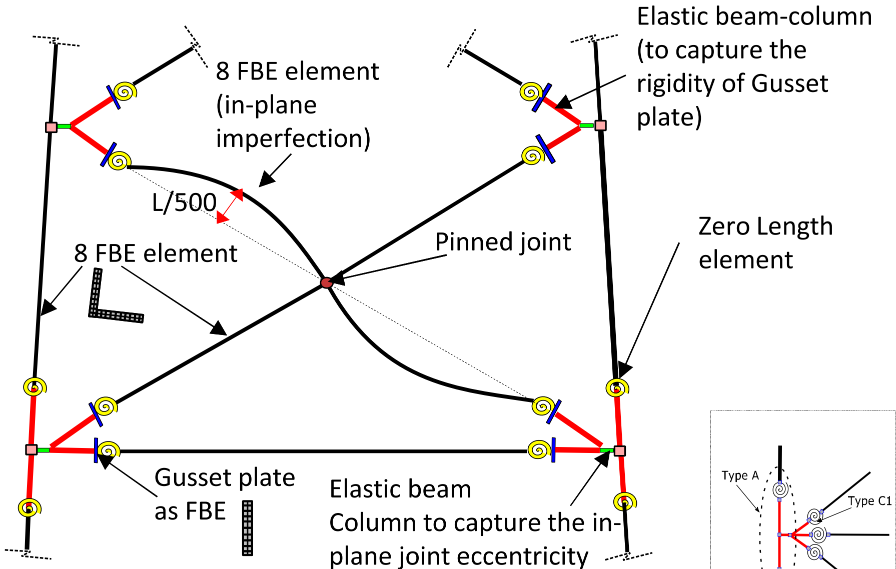
Numerical modeling in OpenSees of a Lattice Tower



- Forced-based elements (FBE) were used for the tower members (with a fiber cross section)
  - **Eight FBE** per member to capture the initial imperfection (assumed in plane L/500-parabolic shape)
- The **material model steel02** uniaxial Giuffre Menegotto-Pinto material is used for steel fibers
- Only **in-plane joint eccentricities** were considered in the modelling
- **Corotational geometric transformation** was adopted to take into account geometric nonlinearities
- The study ignored possible **local buckling effects** in the leg member cross sections

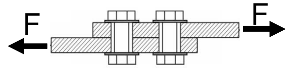
Capacity assessment of a isolated TT and TT within the TLS

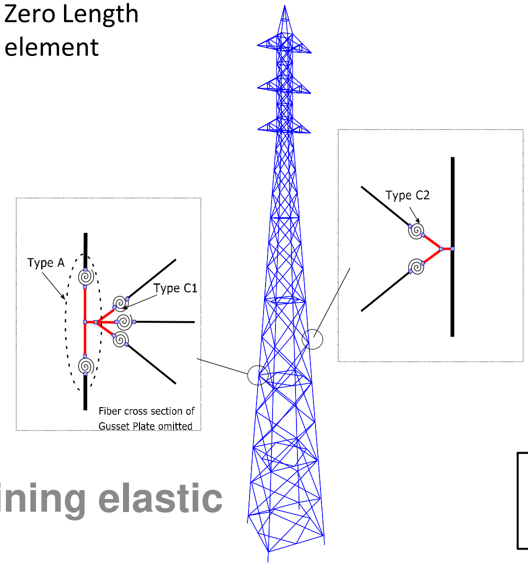
Numerical modeling in OpenSees of a Lattice Tower

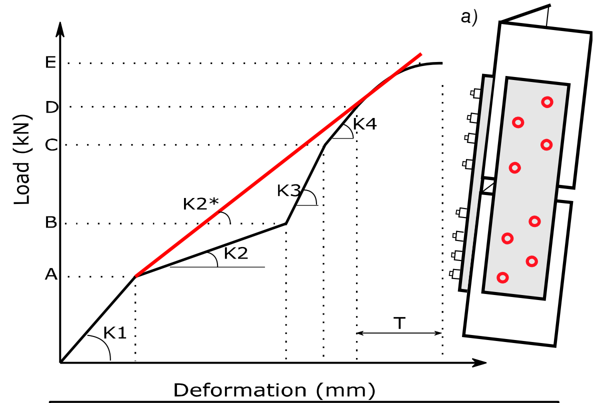


Panel Numerical model

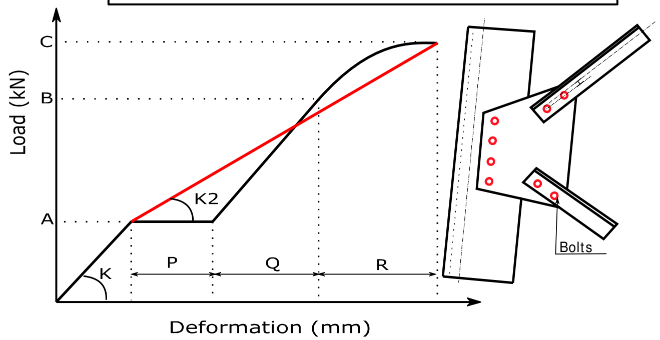
Bolted joint –
Slippage model







Lap-splice bolted joint-Type A



Lapped bolted joint- Type C1 and C2

- Gusset plates were modeled **combining elastic Beam-Column** and **FBE**
- Cross brace joint, modelled with **Equal dof constraints** (translation and torsional dof)
- Zero length elements were used to simulate the **slippage joint behavior** for the **axial d.o.f.**
- For the **rotational d.o.f**. a linear behavior (empirical formulation) was defined

Capacity assessment of a isolated TT

Isolated Tower - Lateral Load Patterns

Loading patterns:

- **Uniform**

$$F_i = W_i$$

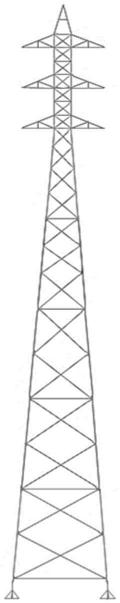
- **Inverted-Triangular**

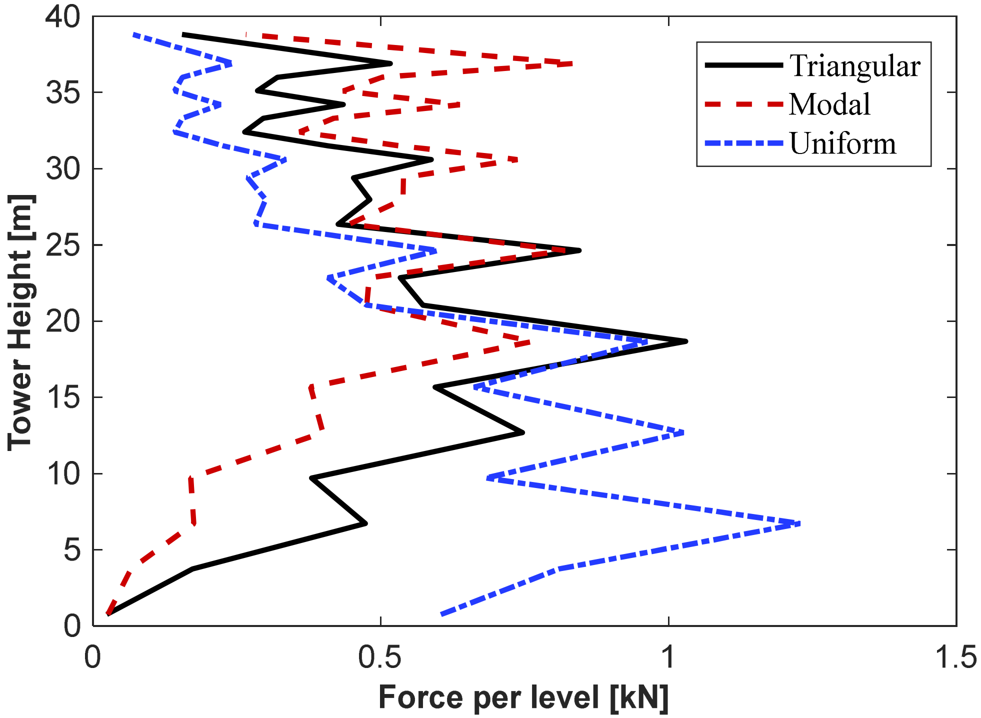
$$F_i = \frac{W_i h_i}{\sum_{l=1}^{n} W_l h_l}$$

- **Modal**

$$F_i = W_i \phi_{ij}$$

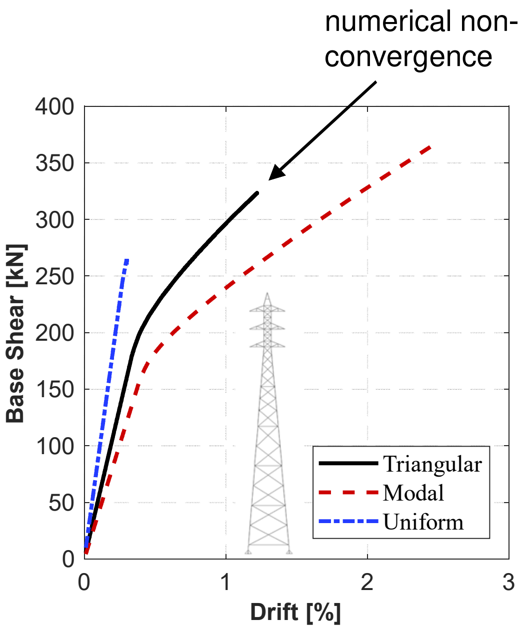
Total force applied to the tower scaled to: $\sum F_i = 10$ kN

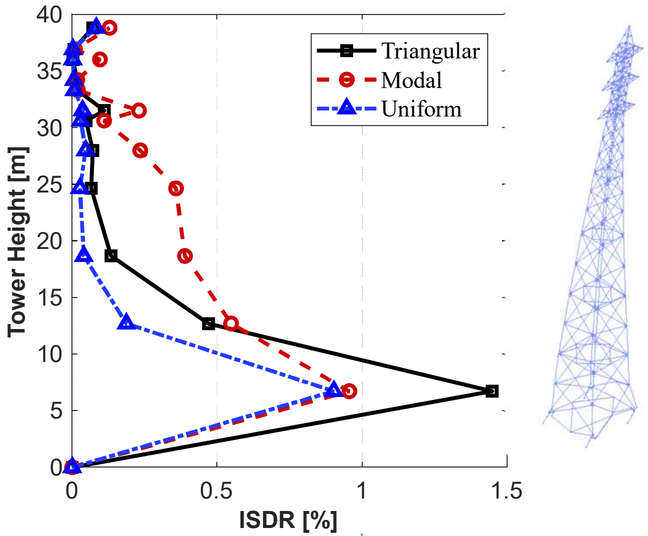


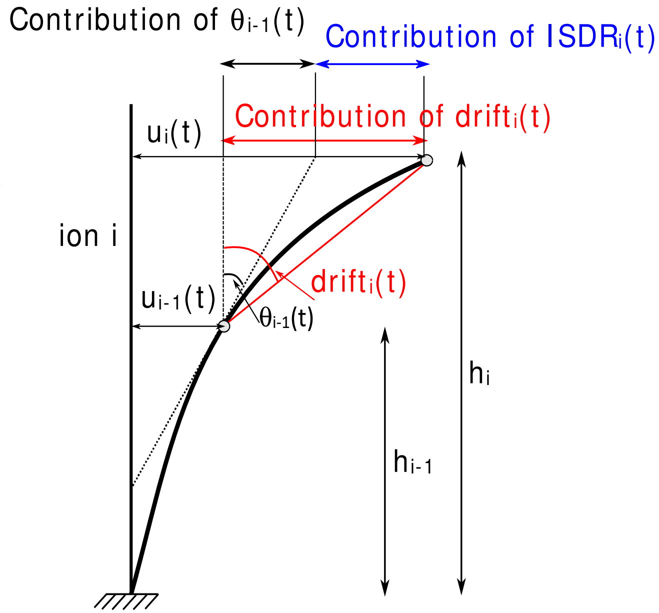


Capacity assessment of a isolated TT

Pushover Curves– Model A- Tower **without initial member imperfections**







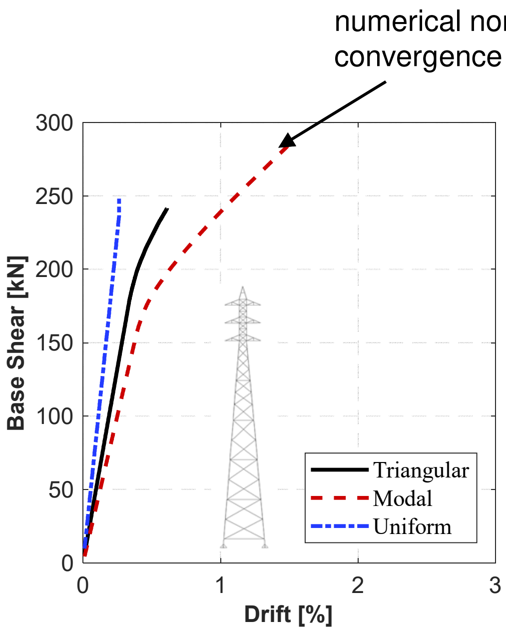
$$ISDR_i = max[drift_i(t) - \theta_{i-1}(t)] = max\left[\frac{u_i(t) - u_{i-1}(t)}{h_i - h_{i-1}} - \theta_{i-1}(t)\right]$$

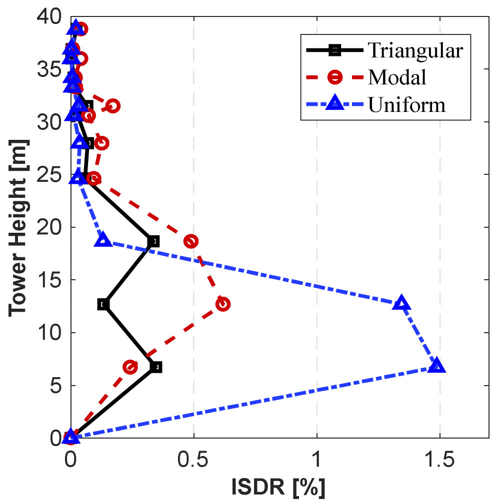
	Load Patterns Modal	Triangular	Uniform
V_b (kN)	366.4	323.3	266.5
ISDR (%)	0.97	1.45	0.95
$Driftx_{max}$ (%)	2.47	1.22	0.30

- **Bottom of the tower section is not as rigid as floor system in buildings**
- **Height/width aspect ratio much higher than buildings**

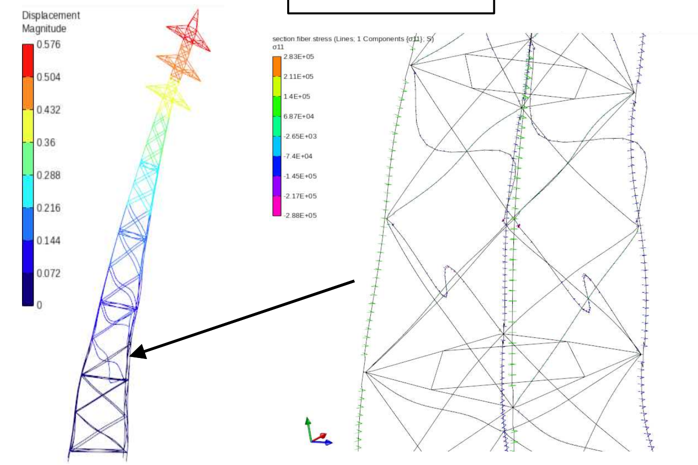
Capacity assessment of a isolated TT

Pushover Curves– Model B- Tower with **initial member imperfections**

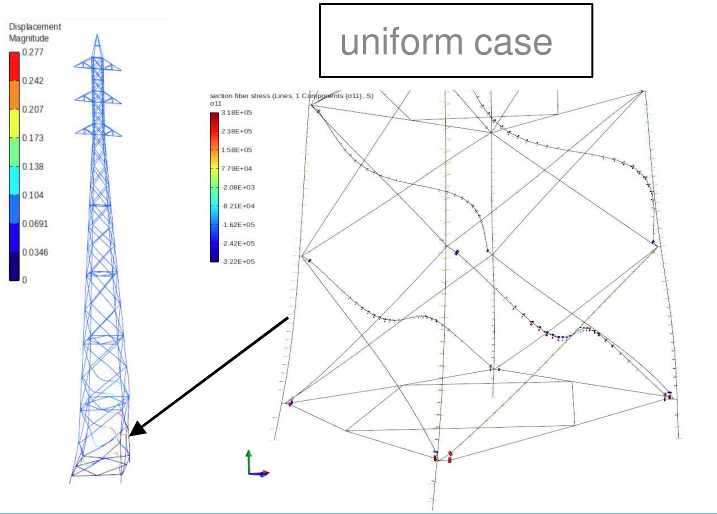




Modal case



uniform case



	Load Patterns		
	Modal	Triangular	Uniform
V_b (kN)	283.6	241.5	248.1
ISDR (%)	0.61	0.43	1.5
$Driftx_{max}$ (%)	1.48	0.61	0.26

Capacity assessment of a isolated TT

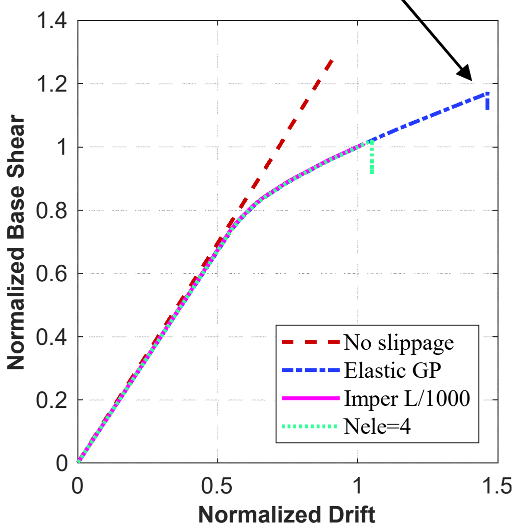
Pushover Curves– Model B- Tower with initial member imperfections

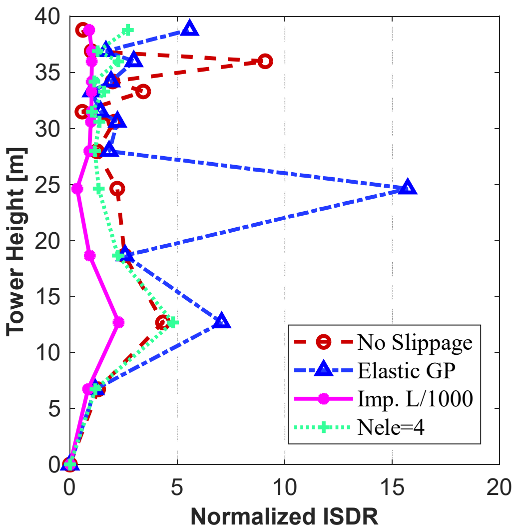
Impact of modelling uncertainty

Model B (default model)	Modelling effect
Model B-1	Ignores slippage effects
Model B-2	Assumes gusset plates as elastic
Model B-3	Initial member Imperfection at L/1000
Model B-4	Nº of FBE per member with imperfection 4

Model Modification	Base Shear (kN)	$Drift_{max}$ (%)	Difference (%) to default model B Base shear	Driftmax
Model B (Default)	241,5	0,611	-	-
Model B-1 (no slippage)	306,9	0,553	27,08%	-9,49%
Model B-2 (elastic Gusset plate)	283,6	0,894	17,43%	46,32%
Model B-3 (Imper. L/1000)	244,2	0,62	1,12%	1,47%
Model B-4 (Nele=4)	247,0	0,642	2,28%	5,07%

numerical non-convergence



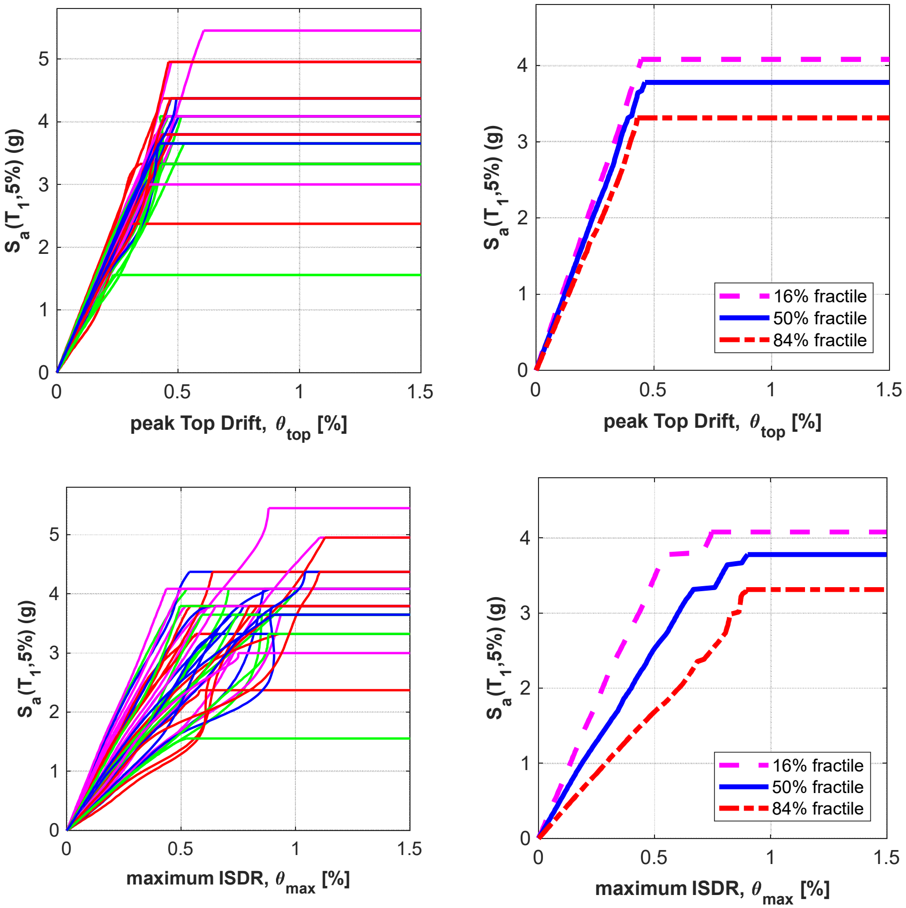


Capacity assessment of a isolated TT

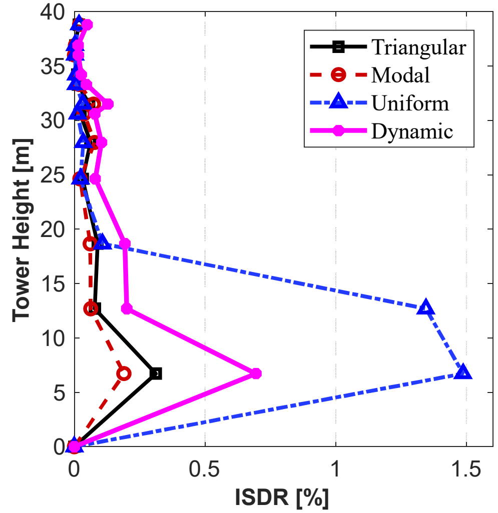
Pushover Curves– Model B- Tower with initial member imperfections

Evaluation of pushover analysis for isolated TT

- IDA (with for forty single X horizontal component records)



IM=Sa(T$_1$)=3,65g



Total error

$$error = \frac{\sqrt{\sum_{i=1}^{n} e_i}}{n}$$

$$e_i = \left(\frac{\Delta_{iD} - \Delta_{iP}}{\Delta_{iD}}\right)^2$$

Total error shape

$$error_\sigma = \frac{\sqrt{\sum_{i=1}^{n} (e_i - \bar{x}_i)^2}}{n}$$

$$\bar{x}_i = \frac{\sum_{i=1}^{n} e_i}{n}$$

	Modal	Triangular	Uniform
Total error (%)	18.4	18.3	52.3
Total error shape (%)	4.4	2.1	7821

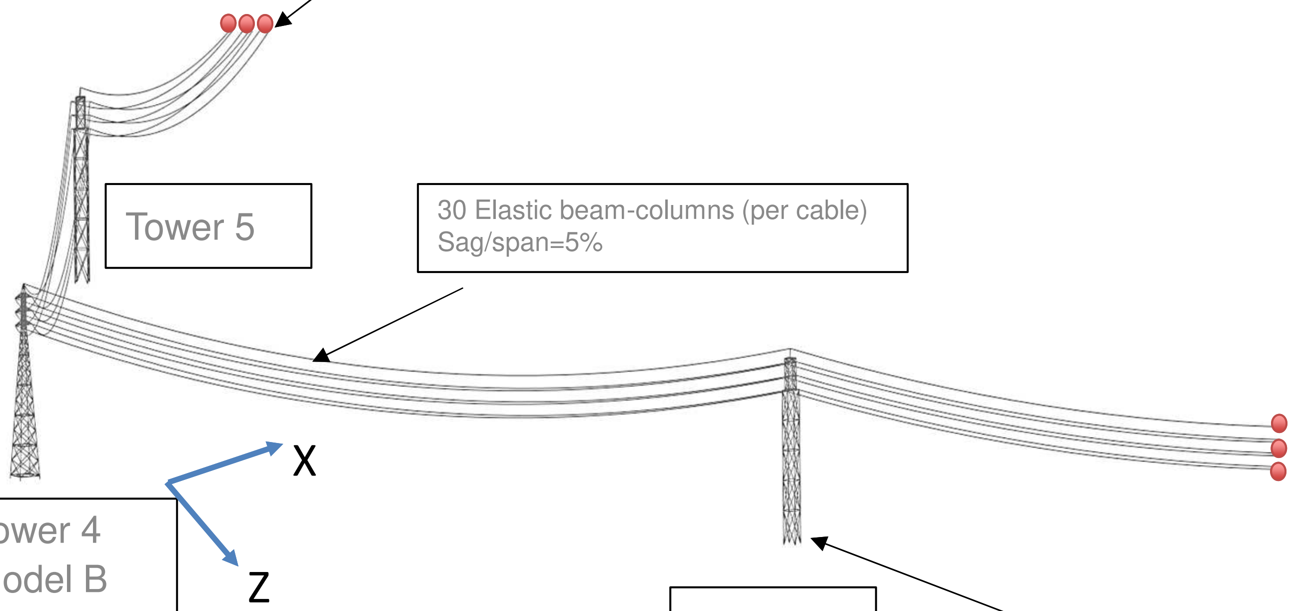
Capacity assessment of a TT within the TLS

Numerical modeling in OpenSees of a TLS

Zero-length elements to simulate remote end span conditions

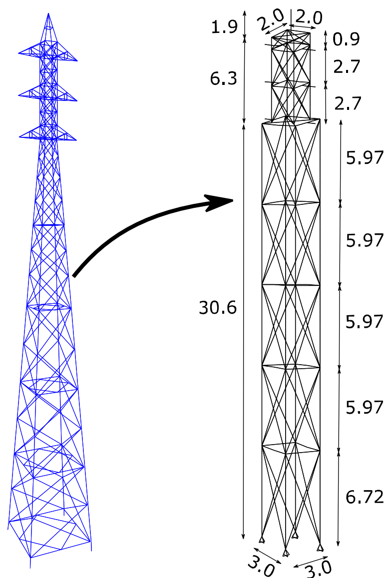
Tower 5

30 Elastic beam-columns (per cable)
Sag/span=5%



Tower 4
Model B

Tower 3

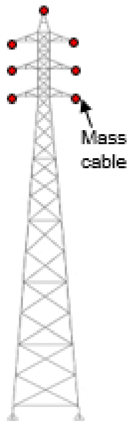


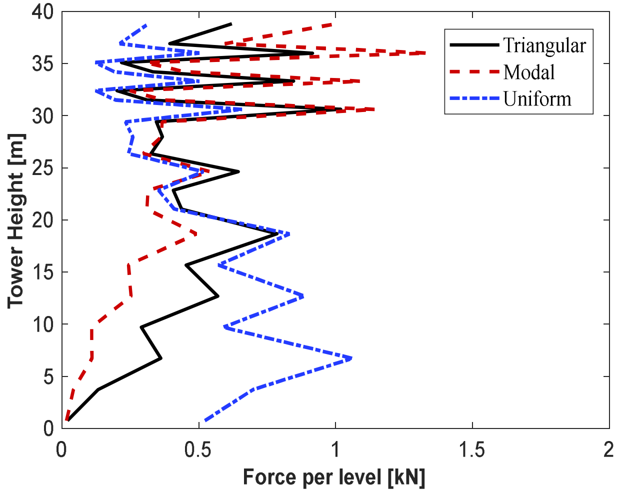
Simplified model

T_1 (X or transverse direction)=0,40 s

T_1 (Z or longitudinal direction)=0,44 s

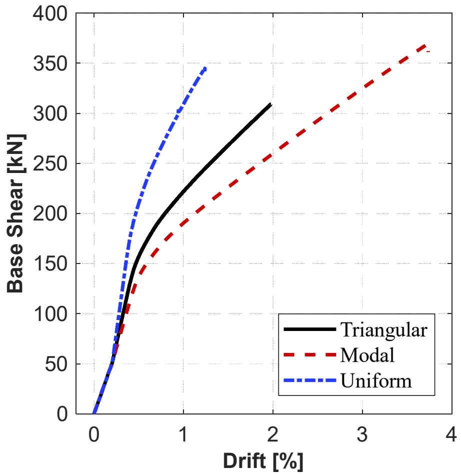
Capacity assessment of a TT within the TLS

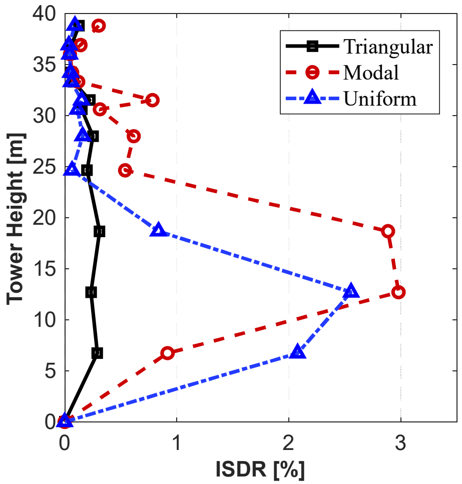




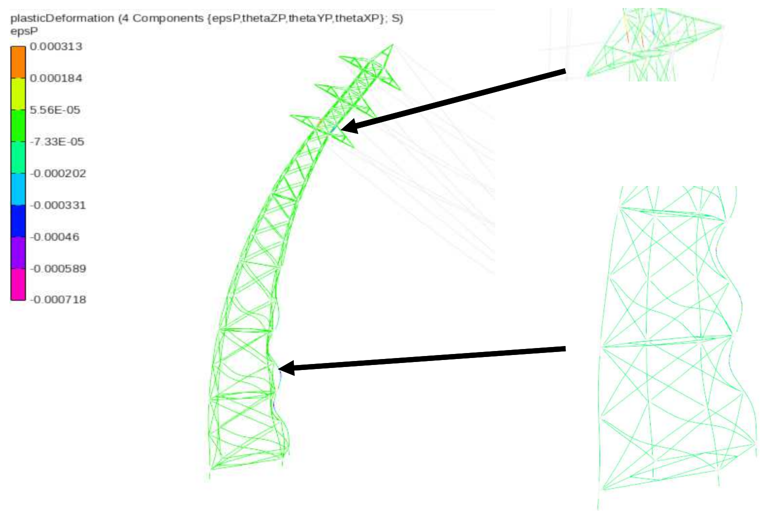
		Loading Patterns Modal	Triangular	Uniform
Base Shear (kN)	X positive	366.9	308.7	341.8
	Isolated TT (model B) positive	283.6	241.5	248.1
Drift$_{max}$ (%)	X positive	3.71	1.97	1.21
	Isolated TT (model B) positive	1.48	0.611	0.26

X Direction (positive)





Modal case- Collapse mechanism



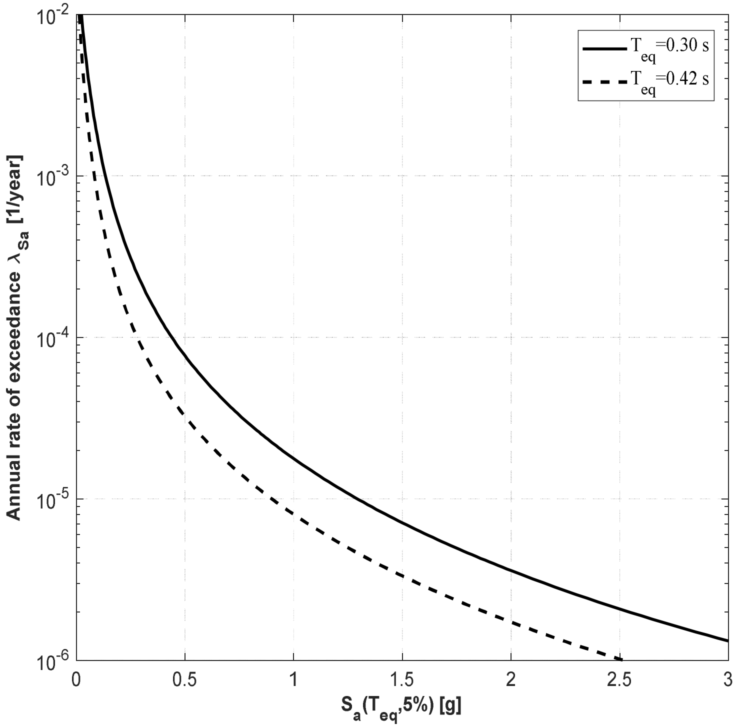
Seismic Collapse Risk assessment

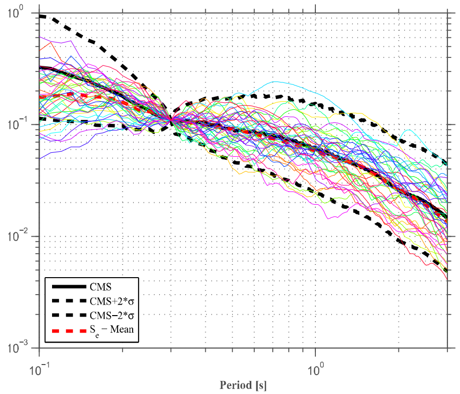
Selection and Scaling of Ground Motion Records

- Assess the **annual frequency of collapse**

$$\lambda_c = \int \phi\left(\frac{\ln(IM_i/\mu)}{\beta}\right) |d\lambda_{IM}(x)|$$

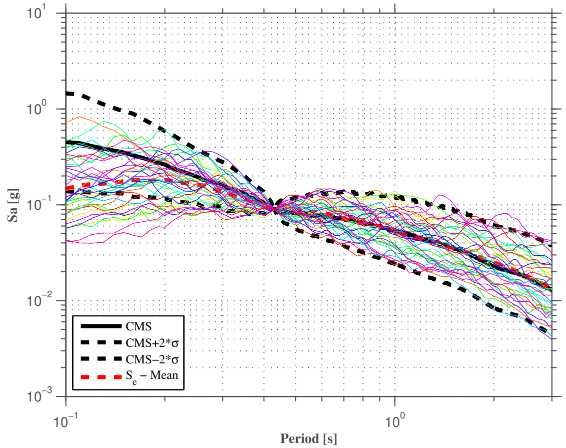
- Selection and Scaling of GM records based on Conditional Mean Spectrum (SelEQ Framework, Macedo 2017)





S_{ag}(T=0.30s ,5%)

S_{ag}(T=0.42s ,5%)



IM=$S_{ag}(T_{eq}, 5\%) = \sqrt{S_{ax}(T_{eq}) \cdot S_{az}(T_{eq})}$

$$T_{eq} = \sqrt{T_{1x} T_{1z}}$$

- Conditional Mean Spectrum for $S_{ag}(T_{eq}$,5%);
- Probability of exceedance **10% in 50y** →T=475 y;
- Soil Type C assumed
- A total of **40 GM with 2 components (NGA West2)**

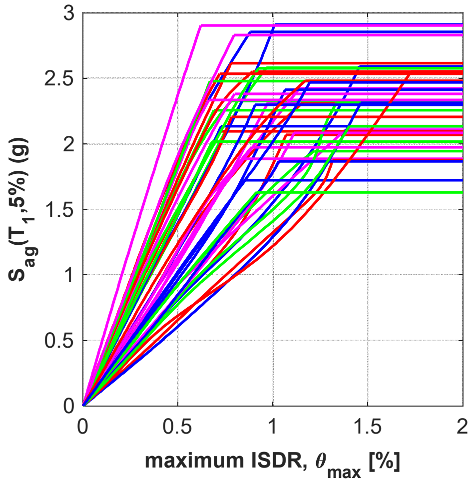
Seismic Collapse Risk assessment of a Isolated Transmission Tower

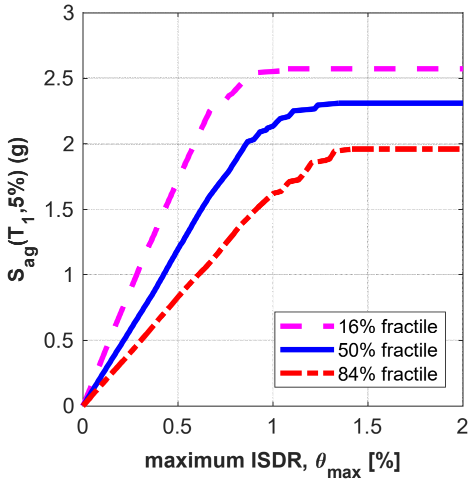
Collapse data obtained through an Incremental Dynamic Analysis

Selected IM:
$S_{ag}(T_{eq}=T_1=0.30s\ ,5\%)$

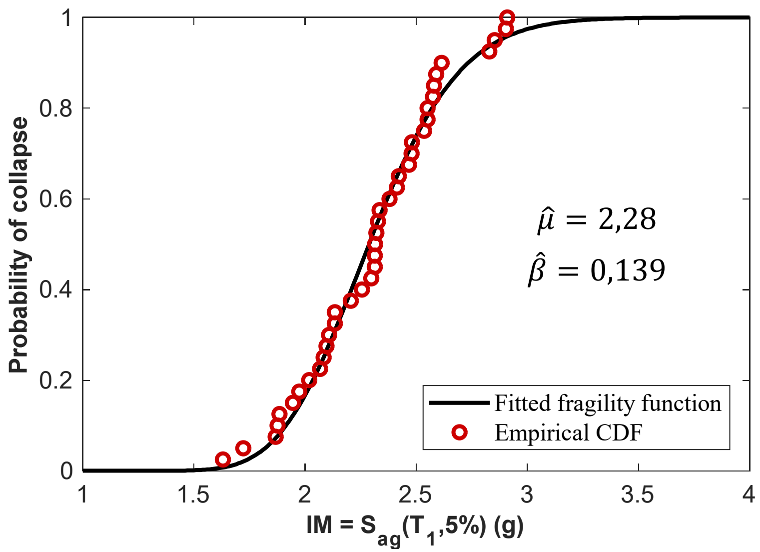
Selected EDP:
Maximum Inter-Section drift:

$$\theta_{max} = \max\left[\sqrt{ISDR_{i,x}(t)^2 + ISDR_{i,z}(t)^2}\right]$$





Other considerations for the **Dynamic Analysis:**
- Mean properties (JCSS Probabilistic Model code)
- Rayleigh Damping model ($C = \alpha M + \beta K_{ini}$)
  - ξ=5% viscous damping
  - α and β (f_1=3,27 Hz and f_2=13.01Hz)



- Fragility function fitting with the **method of moments**
- Assumed a lognormal distribution

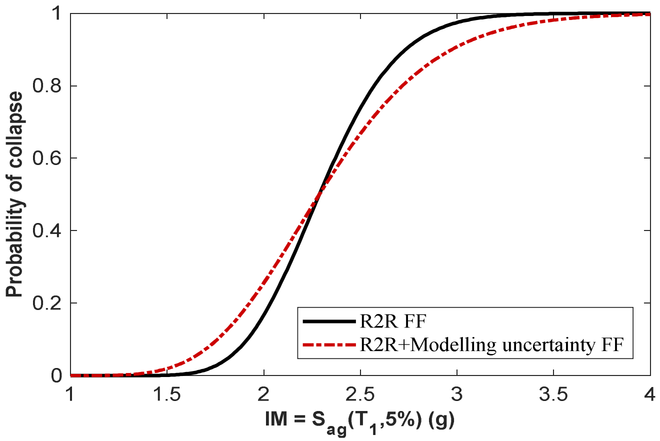
$$Pcollapse = \phi\left(\frac{\ln(IM_i/\mu)}{\beta}\right)$$

Seismic Collapse Risk assessment of a lattice Transmission Tower

Collapse data obtained through an Incremental Dynamic Analysis

- Fragility function considering additional source of uncertainty
- **Model uncertainty** assumed at $\beta_{model} = 0.15$ based on paper Full scale tests of Transmission Towers Riera, J.D .et al. (1990) – Cigre document

$$\lambda_c = \int \phi(\frac{\ln(IM_i/\mu)}{\beta})\ |d\lambda_{IM}(x)|$$

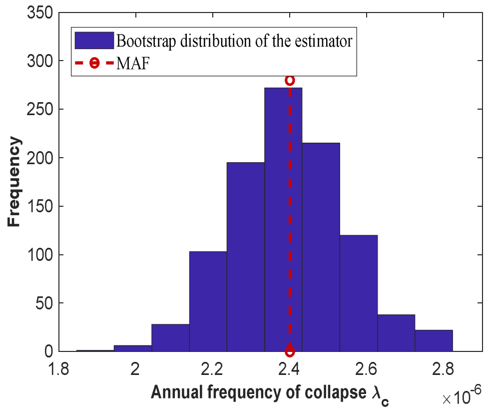


Model	$\hat{\lambda}_c$ (1/year)	$\hat{P}_{c,50y}$(%)	$\hat{\beta}_{1y}$	$\hat{\beta}_{50y}$
R2R	$2.41*10^{-6}$	0.012%	4.57	3.67
R2R+ Modelling uncertainty	$2.59*10^{-6}$	0.013%	4.55	3.65

Estimation risk uncertainty due to R2R (Parametric Bootstrap)
1000 parametric simulations

$$Pcollapse = \phi(\frac{\ln(IM_i/\mu)}{\beta})$$

Model	$E[\hat{\lambda}_c]$ (1/year)	$Var[\hat{\lambda}_c]$	$C.o.v[\hat{\lambda}_c]$
R2R-Parametric Bootstrap	$2.39*10^{-6}$	$2.14*10^{-14}$	6%



$P_{collapse}$ in 50 years = 0.010 % - 0.013 %

associated 2 standard deviation

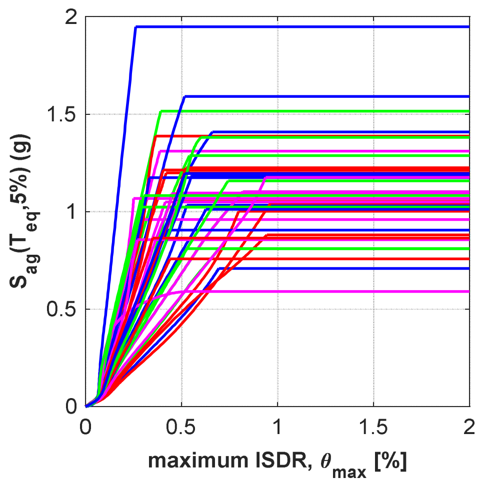
Seismic Collapse Risk assessment of a TLS

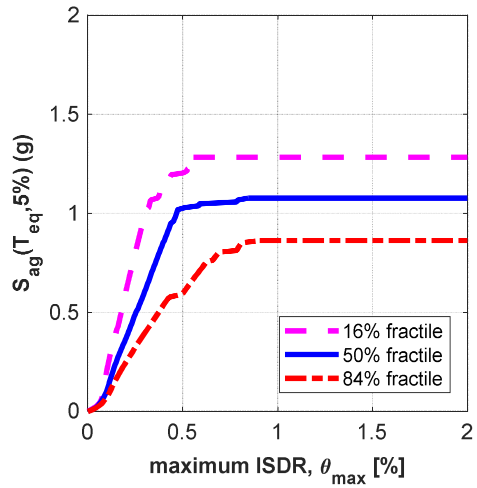
Collapse data obtained through an Incremental Dynamic Analysis

Selected IM:
$S_{ag}(T_{eq}$=0.42 s ,5%)

Selected EDP:
Maximum Inter-Section drift:

$$\theta_{max} = \max\left[\sqrt{ISDR_{i,x}(t)^2 + ISDR_{i,z}(t)^2}\right]$$

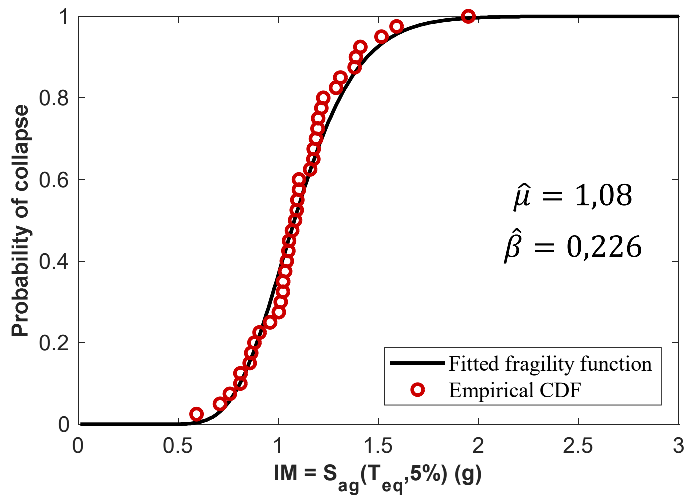




Other considerations for the **Dynamic Analysis:**

- Mean properties (JCSS Probabilistic Model code)
- Rayleigh Damping model ($C = \alpha M + \beta K_{ini}$)
    - ξ=5% viscous damping (Towers)
    - α and β (f_i=2,27 Hz and f_j=11.3Hz)
    - ξ=1% viscous damping (Cables)
    - α and β (f_i=0,14 Hz and f_j=0,98Hz)

$$Pcollapse = \phi\left(\frac{\ln(IM_i/\mu)}{\beta}\right)$$

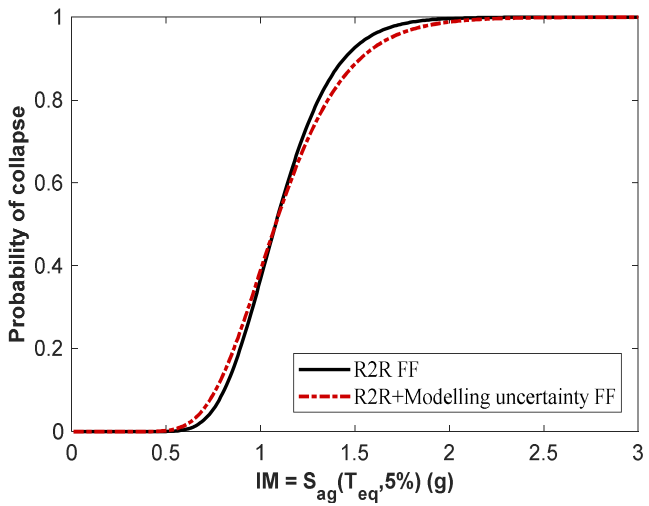


Seismic Collapse Risk assessment of a TLS

Collapse data obtained through an Incremental Dynamic Analysis

- Fragility function considering additional source of uncertainty
- **Model uncertainty** assumed at $\beta = 0.15$ based on paper Full scale tests of Transmission Towers Riera, J.D .et al. (1990) – Cigre document

$$\lambda_c = \int \phi(\frac{\ln(IM_i/\mu)}{\beta})\ |d\lambda_{IM}(x)|$$



Model	$\hat{\lambda}_c$ (1/year)	$\hat{P}_{c,50y}$(%)	$\hat{\beta}_{1y}$	$\hat{\beta}_{50y}$
R2R	$6.91*10^{-6}$	0.034%	4.34	3.39
R2R+ Modelling uncertainty	$2.59*10^{-6}$	0.037%	4.32	3.36

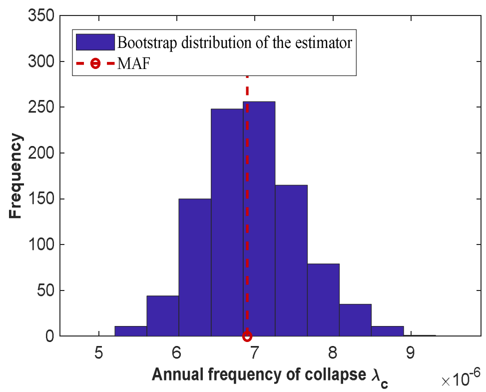
Estimation risk uncertainty due to R2R (Parametric Bootstrap)
1000 parametric simulations

$$Pcollapse = \phi(\frac{\ln(IM_i/\mu)}{\beta})$$

Model	$E[\hat{\lambda}_c]$ (1/year)	$Var[\hat{\lambda}_c]$	$C.o.v[\hat{\lambda}_c]$
R2R-Parametric Bootstrap	$6.95*10^{-6}$	$3.86*10^{-13}$	9%

$P_{collapse}$ in 50 years = 0.028 % - 0.041 %

associated 2 standard deviation



Conclusion

Main Conclusions

The behavior of TT under consideration is that of a brittle system with a low overstrength ratio (1,09) and ductility level (1.25).

Conclusions based on Pushover analysis:

-Different lateral load patterns induce specific failure mechanism.

*-The **triangular load pattern** has shown the better prediction in the obtained ISDR profile when compared to the dynamic analysis results (high intensity levels).*

-High sensitivity of the TT ultimate behavior to the modelling effects.

-Existence of different failure mechanisms between the isolated TT and TLS.

Conclusions based on nonlinear dynamic analysis:

- Indicate that most of damage is always concentrated in section 1.

- Median collapse capacity of isolated TT is more than double of TLS.

- Probability of collapse in 50 year of TLS is approximated 3x the isolated TT.

- When compared with acceptable historical failure rates of TT (0.25% in 50y) for wind or ice events or proposed target reliability index for TLS industry (0.15% in 50y risk category III)**, both systems display a very low seismic collapse risk*

*Reliability of Transmission Towers under Extreme Wind and Ice Loading (Eidinger,2012)

**Question: What is an acceptable target reliability for high-voltage transmission lines? (Kempner,2018)

Thank you!