CAPACITY ASSESSMENT OF A HIGH-VOLTAGE LATTICE TOWER UNDER DIFFERENT LOADING PATTERNS

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Outline

- Overhead Line System - **Case study description**;
    - Overhead Power Line Layout;
    - Lattice tower description;

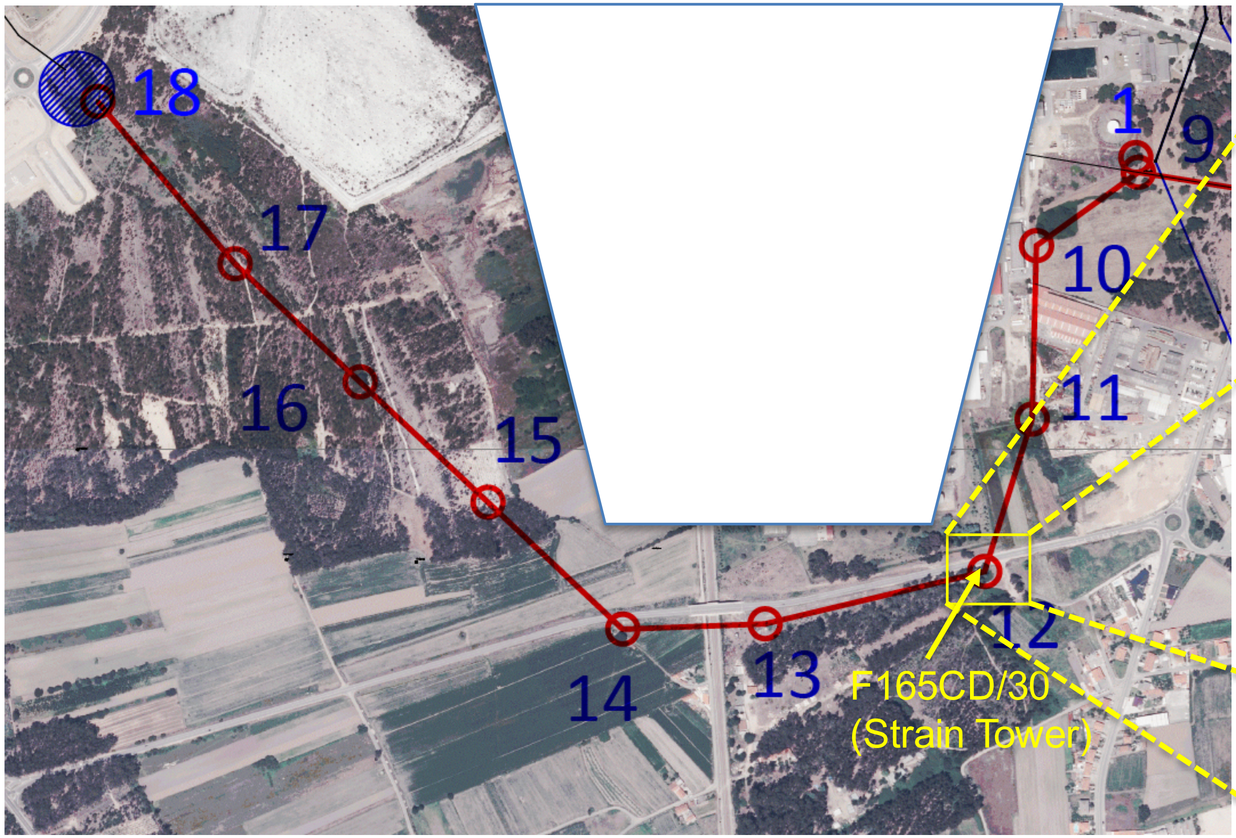
- **Capacity assessment of a high-voltage lattice tower** under different loading patterns
    - Numerical modeling in OpenSees of a Lattice Tower
    - Model validation in elastic range (SAP2000 vs OpenSees)
    - Pushover analysis for different model assumptions under different loading patterns (Uniform, Rectangular, Inverted Triangular and Modal)

- Conclusions and future developments

Case Study Presentation – Line Layout

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

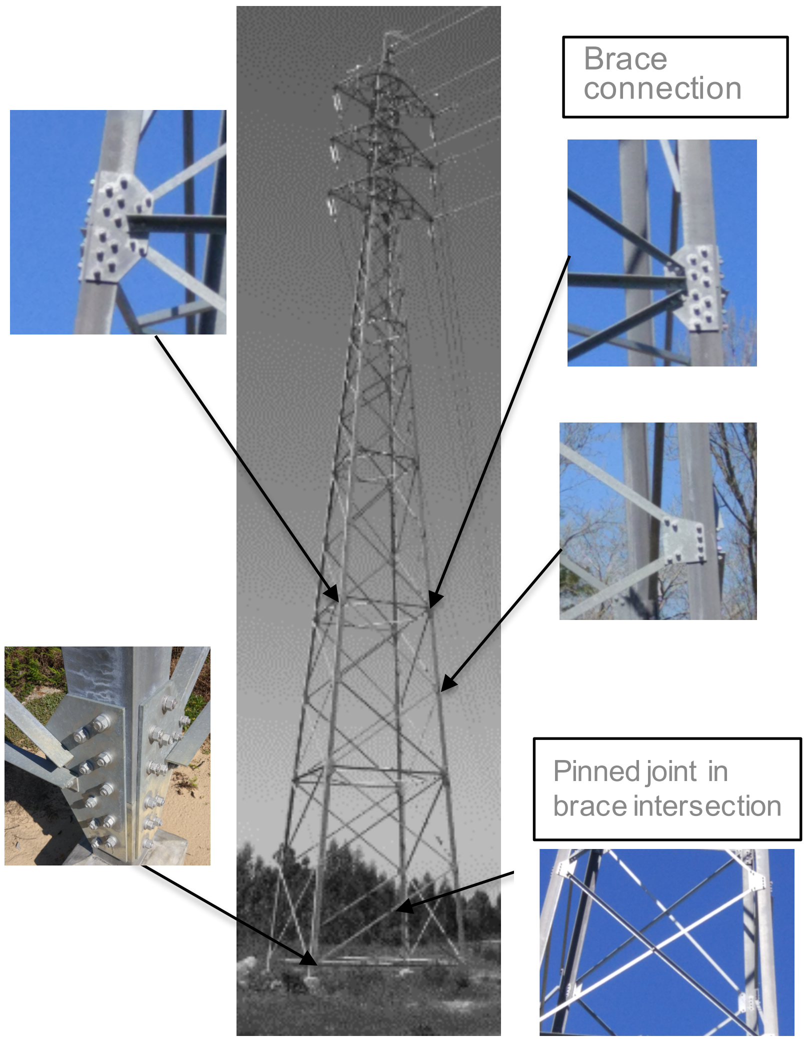
Overhead Power-Line Layout

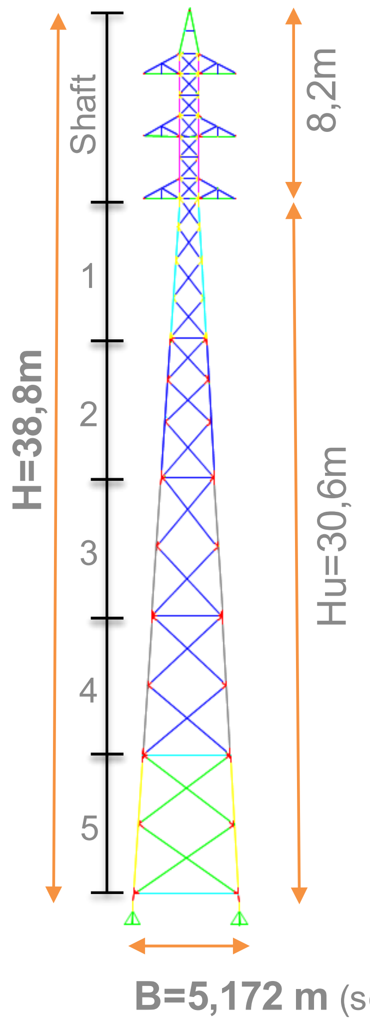


Previously RADAR Monitored Tower

Case Study Presentation – 3D View

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





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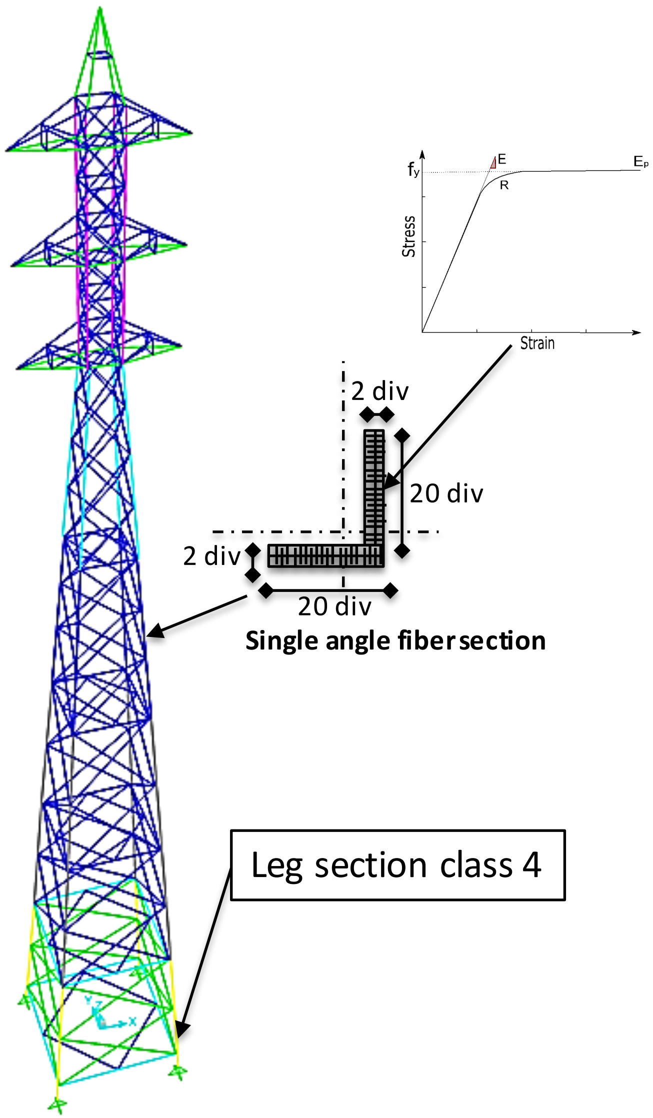
Tower Member	Sections (angle)
Leg	L180x16 (yellow) L180x15 (grey) L160x15 (blue) L140x13 (cyan) L100x10 (magenta)
Diagonal Bracing	L60x6 (green) L50x5 (blue)
Horizontal Bracing	L70x7 (cyan) L50x5 (blue)
Cross arm (L=1,8 m)	L50x5 (blue) sup. chord L60x6 (green) inf. chord

Steel class - S275

Capacity assessment of a high-voltage lattice tower under different loading patterns

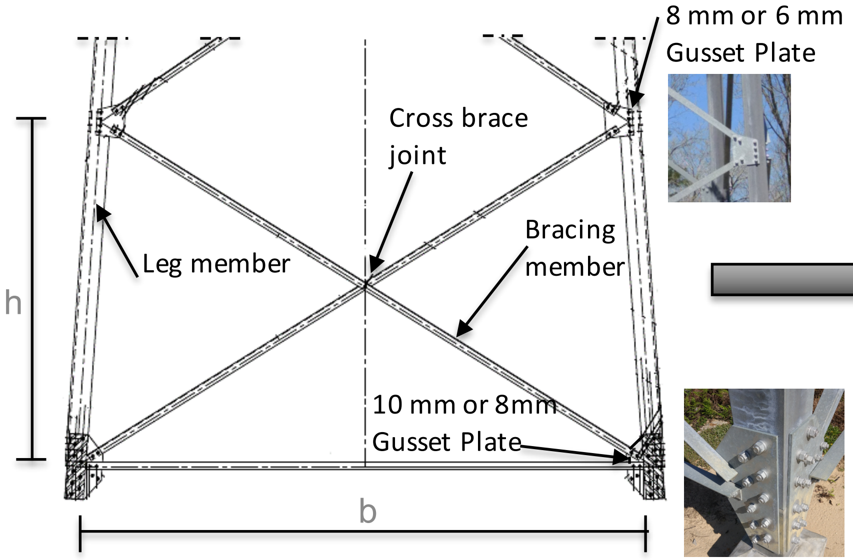
Numerical modeling in OpenSees of a Lattice Tower



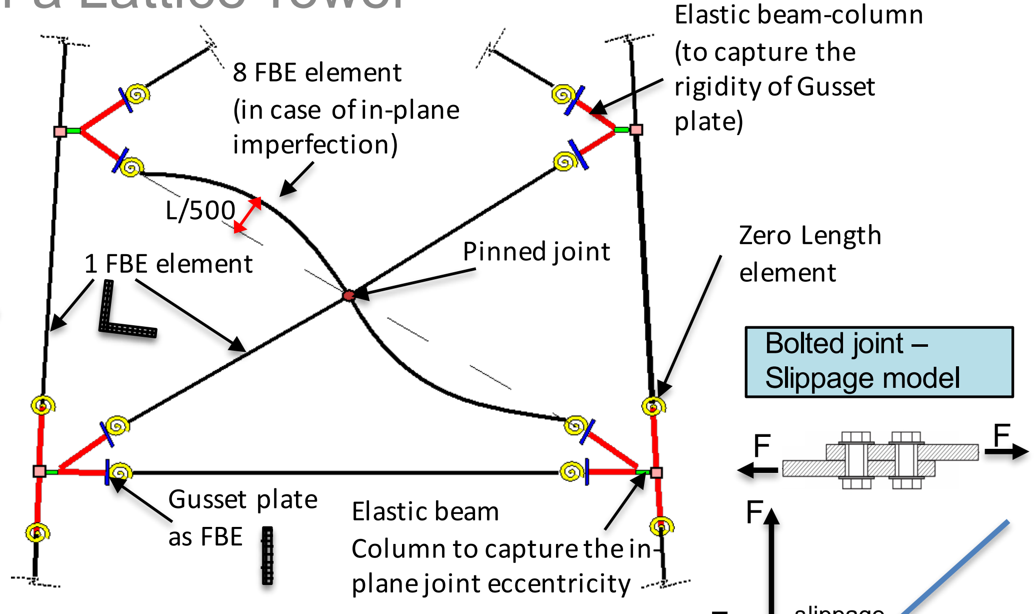
- Forced-based elements (FBE) were used (plasticity spread along the element length) for the main members (leg, braces and arms);
  - Fiber section were considered to generate the cross section with two rectangular patches (20x2 per patch)
  - Three integration points per element
  - Element torsional properties have been added to the fiber nonlinear beam element with the section aggregator command
  - **One FBE per member** and **eight FBE** when modelling in-plane imperfection (L/500-parabolic shape)
- Gusset plates were modeled combining elastic Beam-Column and FBE (two integrations points per element)
- The **material model steel02** uniaxial Giuffre Menegotto-Pinto material is used for steel fibers with extensions included for kinematic and isotropic hardening
- The **MinMax material model** wrapped around steel02 is used for leg members with **class section 3/4** (to ensure elastic behavior)
- **Corotational geometric transformation** was adopted to take into account the geometric nonlinearities
- Only **in-plane joint eccentricities** were considered in the modelling

Capacity assessment of a high-voltage lattice tower under different loading patterns

Numerical modeling in OpenSees of a Lattice Tower



Tower Elevation



Structural model

- Cross brace joint, modelled with **Equal dof constraints** (translation and torsional dof)
- Gusset Plates (GP) connection modelled as:
  - Assumed as “rigid” elastic beam-column element with 10*A,10*I of the connected member;
  - The **GP modeled** with a FBE of **length** 2*thickness_plate and **width** based on Whitmore width (to capture out-plane resistance of the GP);
- Zero length elements to simulate the **slippage joint behavior** (ignored at the moment in the present results) for the **axial d.o.f.**

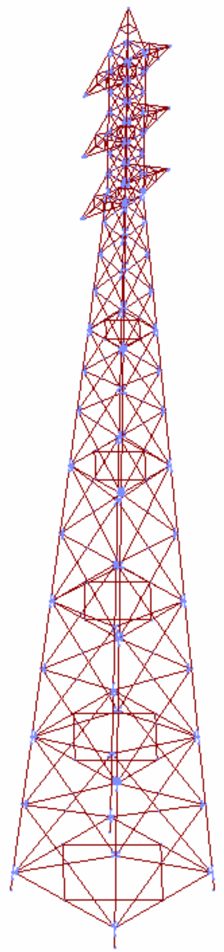
Capacity assessment of a high-voltage lattice tower under different loading patterns

Numerical modeling in OpenSees of a Lattice Tower

Model A – "Tower"

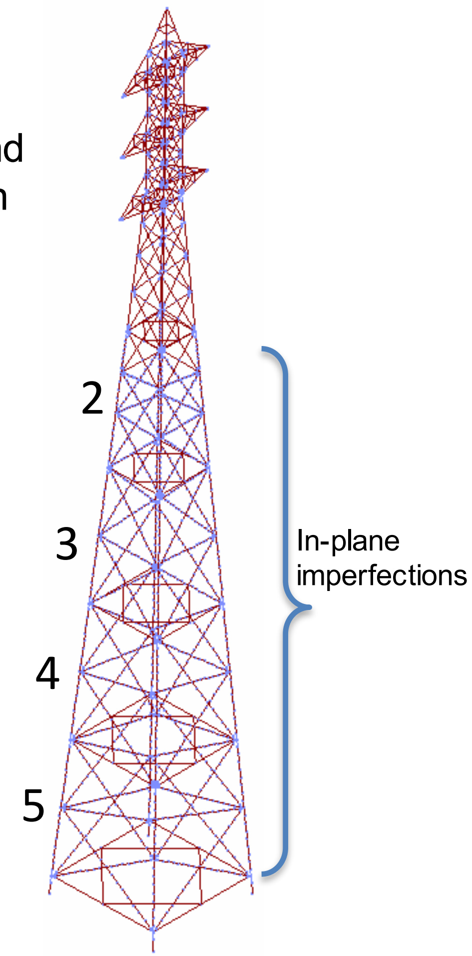
Model B – Model A + in-plane imperfections

Model	A	B
Nº of FBE (member)	642	**1902 (≈x3)**
Nº of FBE (Gusset Plate)	460	460
Nº elastic beamcolumns	620	620
Nº Zerolength elements	540	540



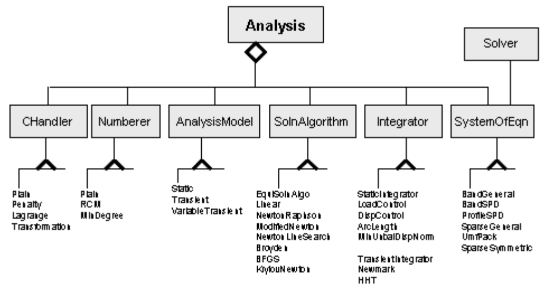
Effects considered:

- In-plane imperfections (w/ parabolic shape and **8 FBE per member**) in legs and diagonal braces between **sections 5 to 2**



Capacity assessment of a high-voltage lattice tower under different loading patterns

Pushover analysis in OpenSees of a Lattice Tower



Analysis Strategy

- Because of the **material and geometrical nonlinearities**, an iterative solution is required:
  - **Newton method with line search solution algorithm** was selected to achieve rapid convergence, determines the sequence of steps taken to solve the non-liner eq. at the current step;
  - solution algorithm uses an **energy increment test**, which checks the positive force convergence if half of the inner-product of the displacement increment and the unbalanced force is smaller than a tolerance equal to Tol=10^{-4}
  - The equations are formed using a **Umf pack scheme** (a sparse system of equations SOE), within the solution algorithm, it specifies how to store and solve the SOE in the analysis
  - A **reverse Cuthill-McKee degree-of-freedom numbering object** to provide the mapping between the degrees-of-freedom at the nodes and the equation number, in order to reduce the storage bandwidth.
  - The constraints determines how the constraint equations are enforced in the analysis, in this study a **Transformation constraint** handler was used
- **Gravity analysis** : ten load steps are performed by using a **load control integrator** for the vertical loads: self-weight of the structure
  - Elements (legs and brace) in tower model were subjected only to end forces
- **Pushover analysis**: a tentative 1000 displacement steps are performed by using a **displacement control integrator** of the tower top node up to 1% of tower height

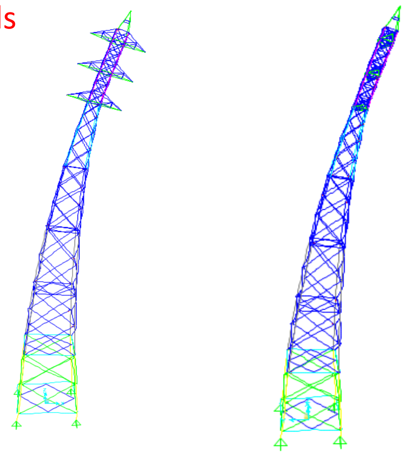
Capacity assessment of a high-voltage lattice tower under different loading patterns

Model validation in elastic range (SAP2000 vs OpenSees – Model A)

Modal Analysis

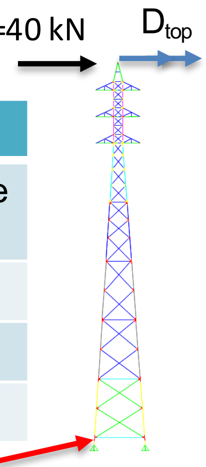
Frequency	Model		
	SAP2000	OpenSees	Difference (%)
f_1 (Hz)	3,53	3,47	1,7%
f_2 (Hz)	3,53	3,47	1,7%
f_3 (Hz)-local	5,66	5,66	0,0%
f_4 (Hz)-local	6,83	6,79	0,6%
f_5 (Hz)-local	7,65	7,58	0,9%

Not the final models



Mode Shapes
SAP2000 f1,f2

Static Analysis



Static analysis	Model		
	SAP2000	OpenSees	Difference (%)
D_{top} (mm)	92	93	1,1%
$N_{leg,Support}$(kN)	150,67	150,65	0,1%
$\sigma_{leg\_max,support}$ (MPa)	27,3	27,3	0,0%

Control section

	Analysis options (10 load steps are performed)			
	Default	A	B	C
Constraints	Transf.	Tranf.	Tranf.	Tranf.
Numberer	RCM	RCM	RCM	RCM
System	**UmfPack**	**BandGeneral**	**BandSPD**	**ProfileSPD**
Test	EnergyIncr	EnergyIncr	EnergyIncr	EnergyIncr
Algorithm	NewtonLine Search	NewtonLine Search	NewtonLine Search	NewtonLine Search
Integrator	Load control	Load control	Load control	Load control
Run Time (s)	4	218 (x54,5)	88 (x22)	22 (x5,5)

Capacity assessment of a high-voltage lattice tower under different loading patterns

Loading Patterns Distributions considered for the Pushover Analysis

Loading patterns:

- **Uniform**

  $F_i = W_i$

- **Triangular**

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

  V_b=10 kN assumed

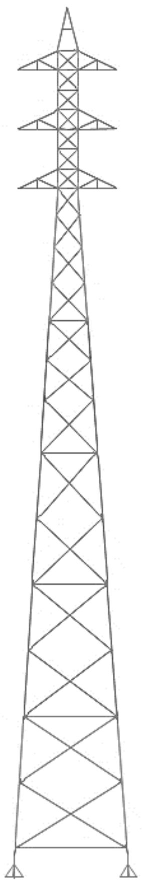
- **Rectangular**

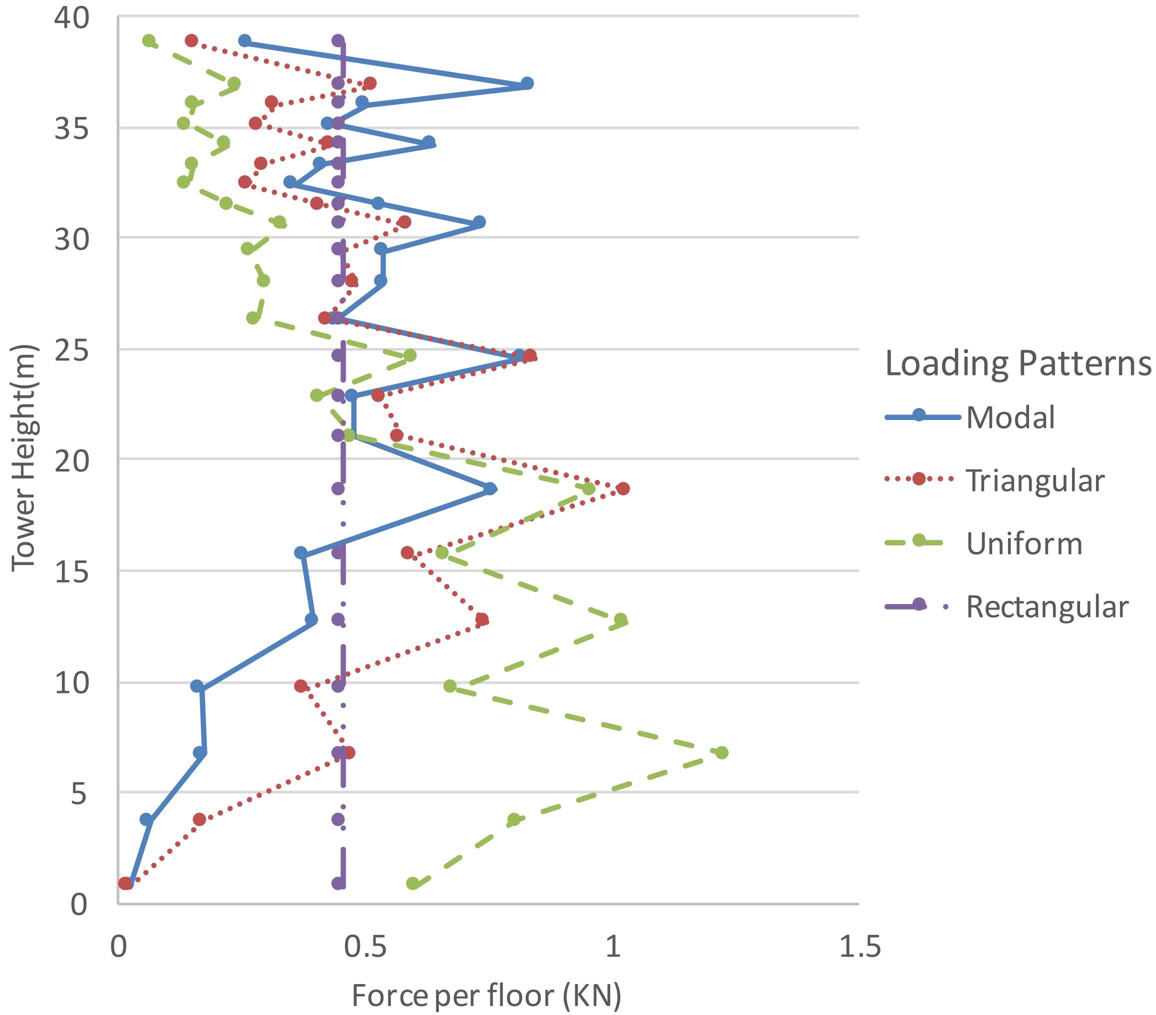
  →
  →
  →
  →

- **Modal (1st mode)**

  $F_i = W_i \phi_{ij}$

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

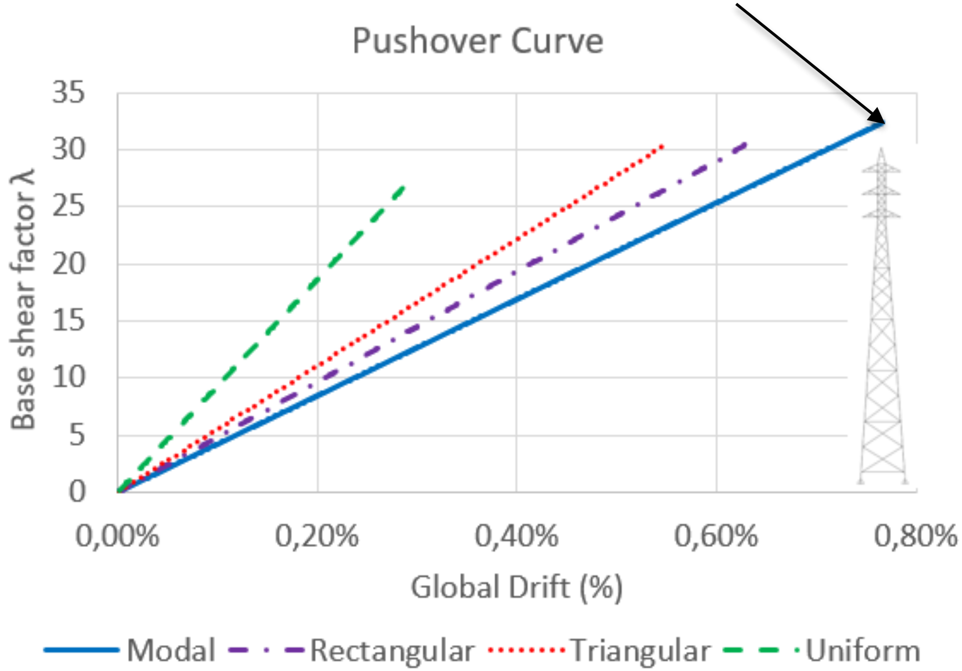




Capacity assessment of a high-voltage lattice tower under different loading patterns

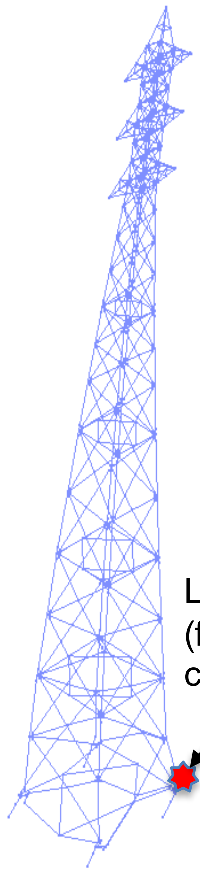
Pushover Curves– Model A (without imperfections)

Loss of numerical convergence

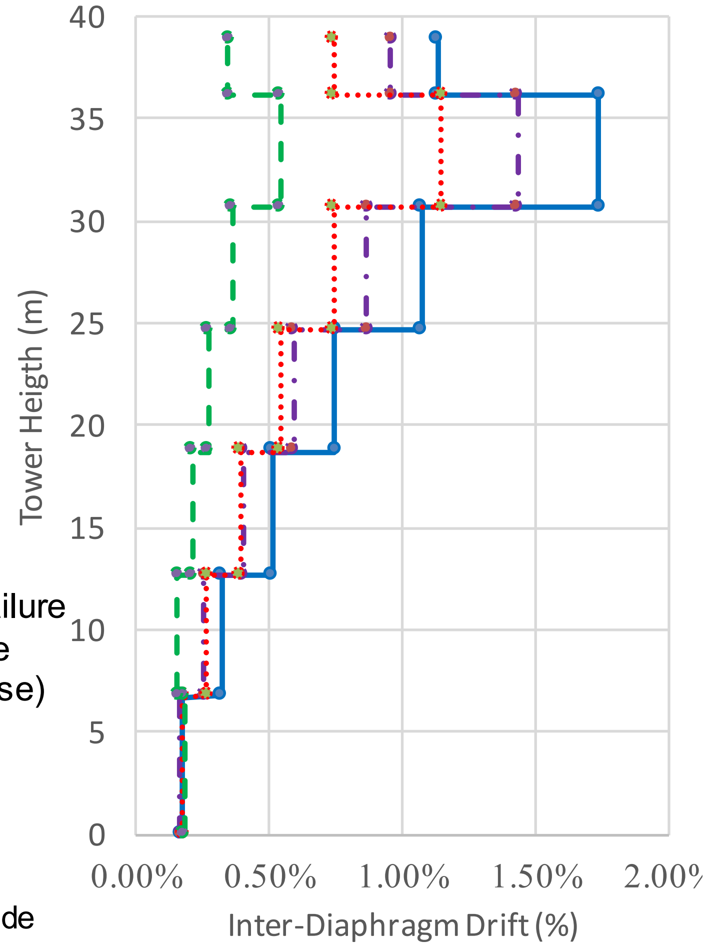


	Load Patterns			
	Modal	Rectangular	Triangular	Uniform
λ_{max}	32,35	30,40	30,32	27,03
$Drift_{max}$ (%)	0,77	0,63	0,55	0,29
Run Time (s)	389	347	301	120

Damage concentration
Collapse mechanism



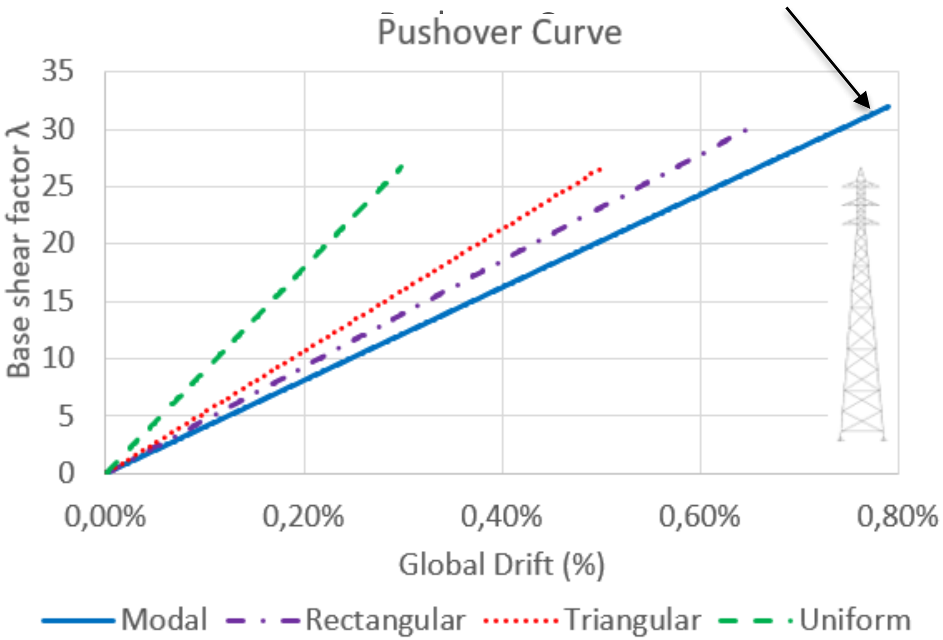
Uniform - collapse mode



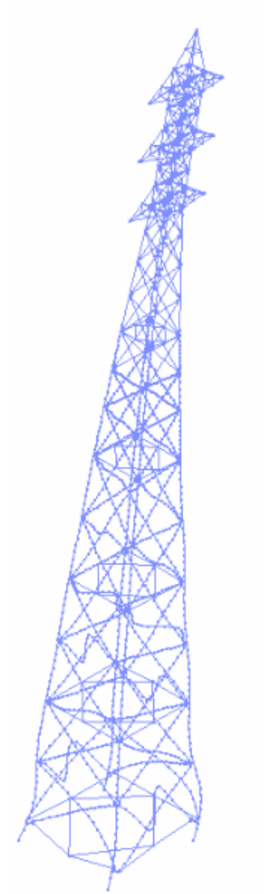
Capacity assessment of a high-voltage lattice tower under different loading patterns

Pushover Curves– Model B (with imperfections)

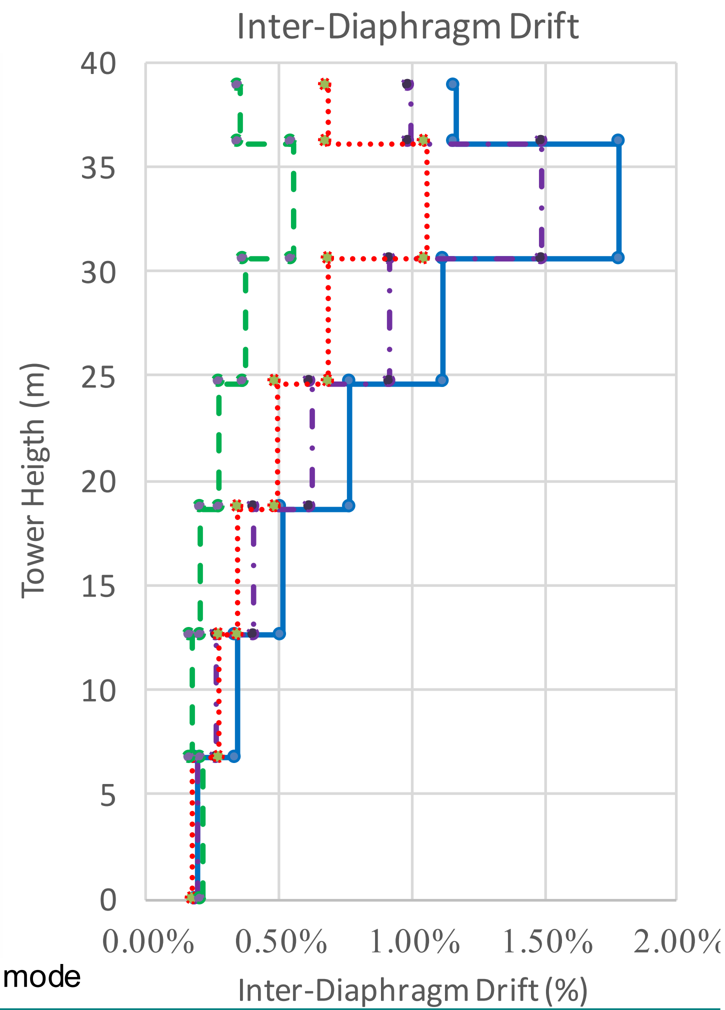
Loss of numerical convergence



	Load Patterns			
	Modal	Rectangular	Triangular	Uniform
λ_{max}	31,96	30,34	26,93	26,67
$Drift_{max}$ (%)	0,79	0,66	0,51	0,29
Run Time (s)	736	484	364	399



Uniform - collapse mode



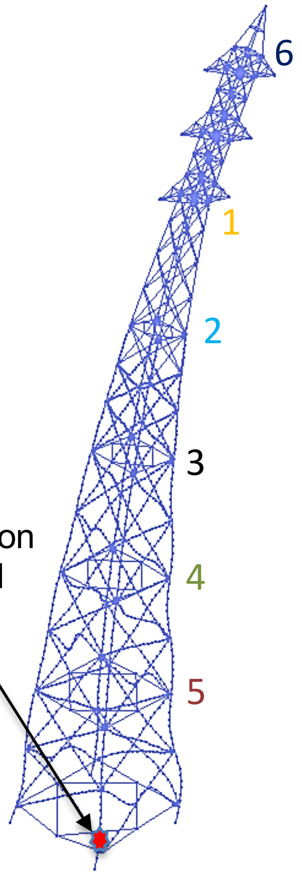
Capacity assessment of a high-voltage lattice tower under different loading patterns

Pushover Curves– Model B (with imperfections)

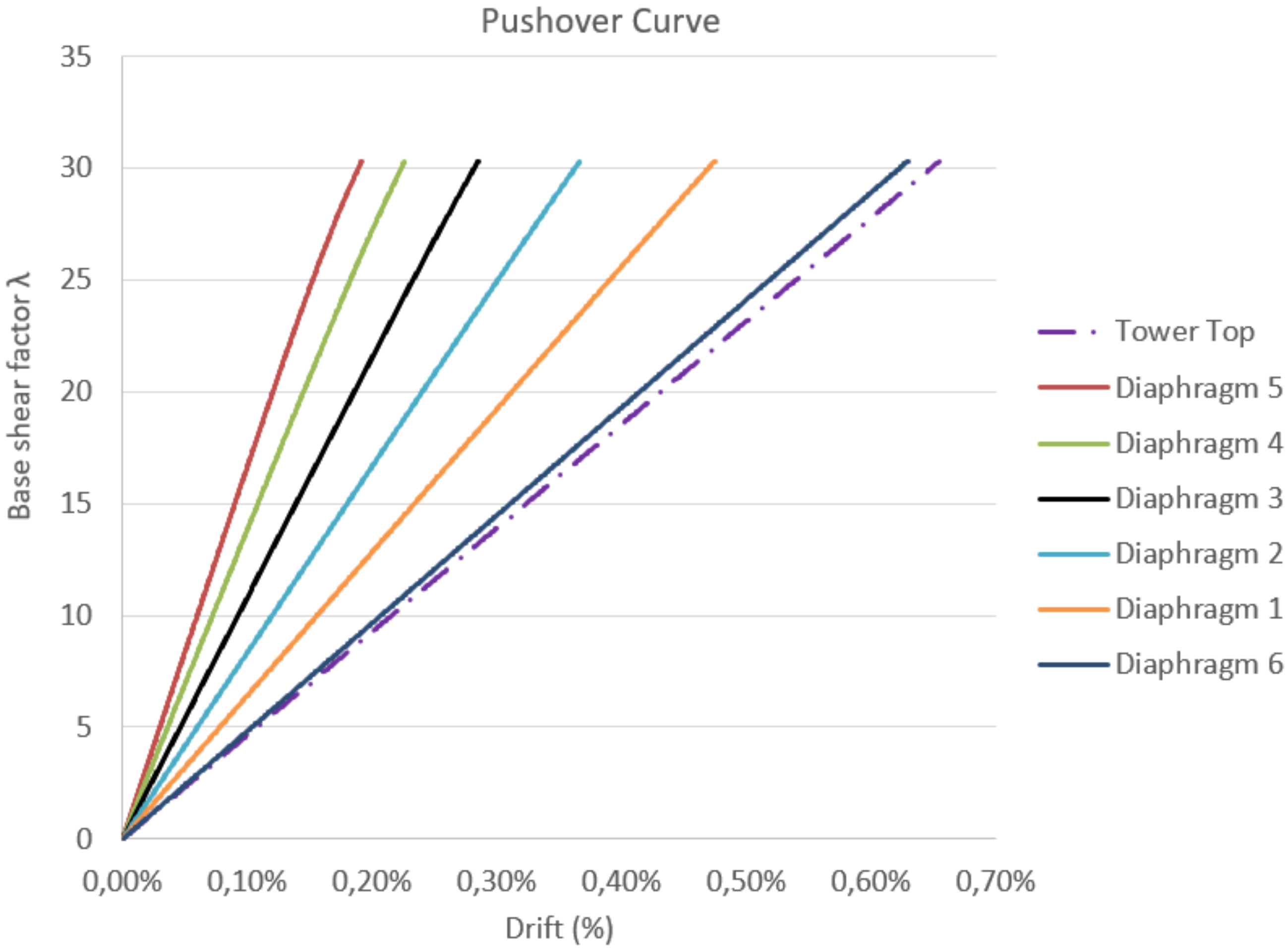
Collapse mechanism

Modal and Rectangular - collapse mode are similar

Defined by loss of numerical convergence



Tension Leg failure – section yielding: N+M

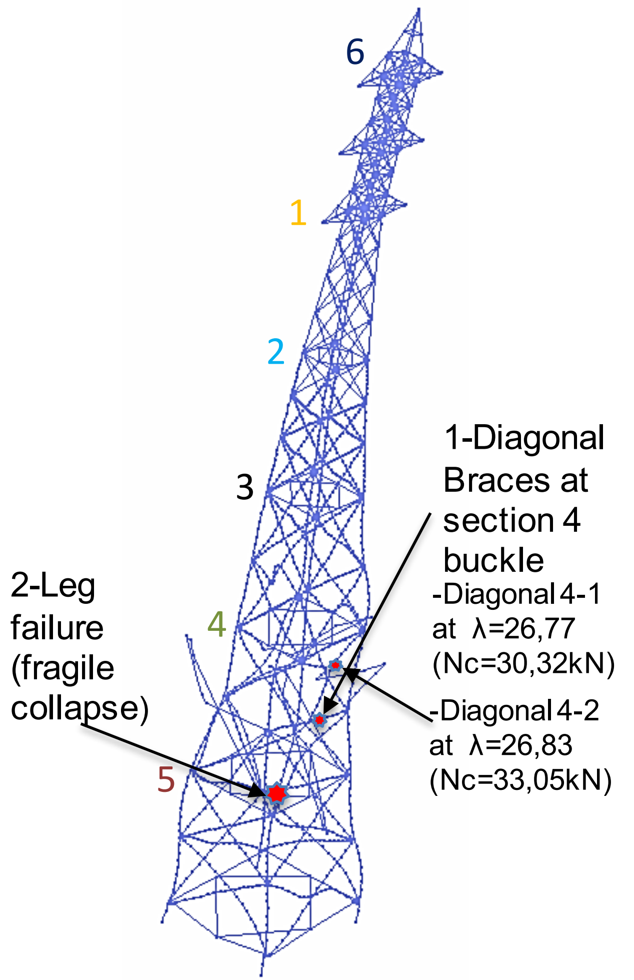


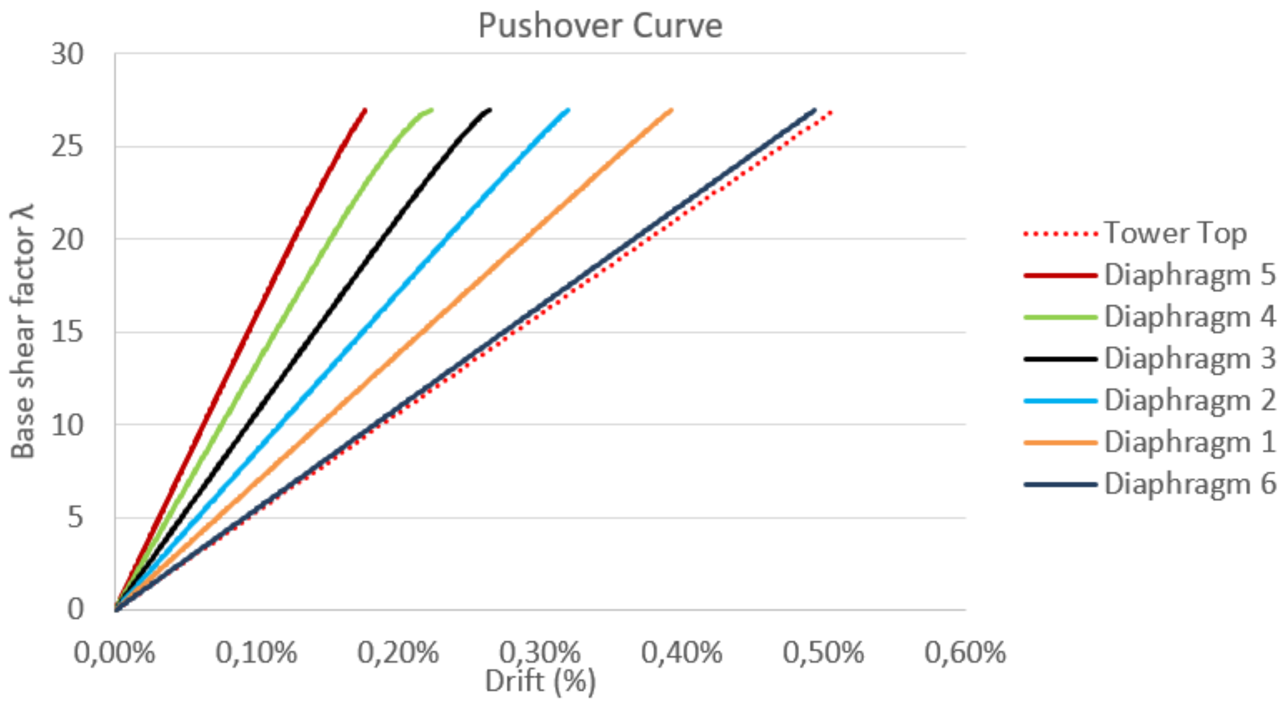
Capacity assessment of a high-voltage lattice tower under different loading patterns

Pushover Curves– Model B (with imperfections)

Collapse mechanism

Triangular - collapse mode





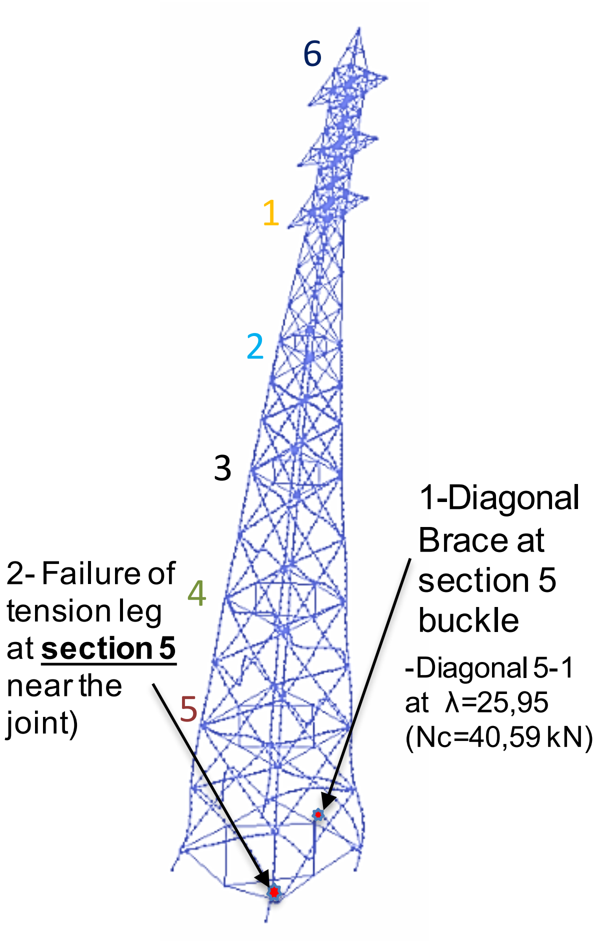
Diagonal	Nc,Rd (kN)		
	EC3-3-1 (Towers)	OpenSees	Difference (%)
4-1	21,0	30,3	30,6%
4-2	23,4	33,0	29,1%

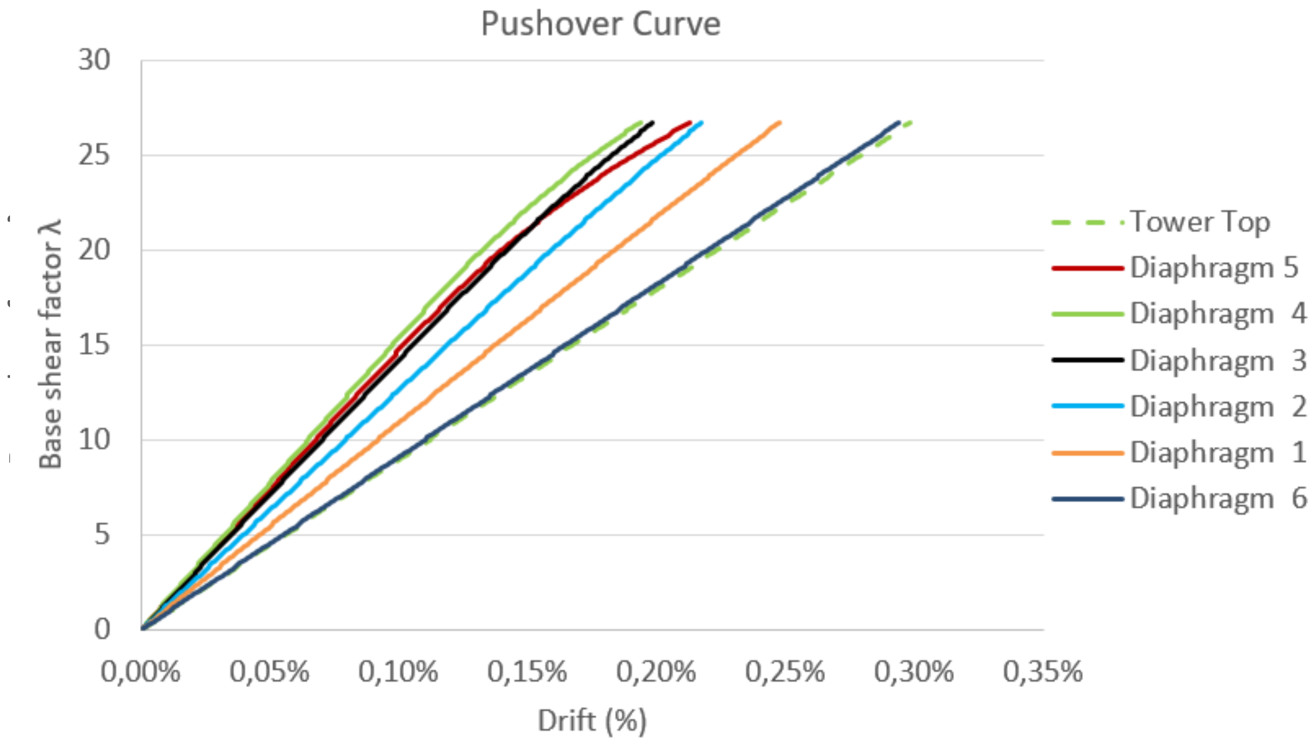
Capacity assessment of a high-voltage lattice tower under different loading patterns

Pushover Curves– Model B (with imperfections)

Collapse mechanism

Uniform - collapse mode





Diagonal	Nc,Rd (kN)		
	EC3-3-1 (Towers)	OpenSees	Difference (%)
5-1	33,05	40,6	18,7%

Conclusion and Future Developments

Main Conclusions

*The **Model B** (Tower with imperfections) simulates more closely the potential collapse behavior mode of the isolated lattice tower. Although the model A (Tower without imperfections) in terms **total base shear** and **global drift** provides almost the **same results as model B** (except for the triangular load pattern) it **cannot represent the actual sequence of collapse**.*

*For the present structure the **uniform load pattern** serves as a **upper bound** and the **modal load pattern** as a **lower bound** of the induced base shear.*

*Diagonal Braces contribution to the **energy dissipation of the system** seems **insignificant** (the structure shows a near-elastic behavior up to collapse, ductility capacity μ=1), meaning that the tower still has important strength reserves to explore.*

Future Developments

Experimental characterization of typical **joint slippage** behavior in lattice towers in Portugal through laboratory testing

*Development of **fragility curves** for Earthquake and Wind Hazards (more focus given to the Wind Hazard)*

*Computation of the **seismic and wind risk** (defined as a annual probability of failure) of the isolated tower and a simplified "tower+cable" system*

Thank you!