Introduction to seismic analysis of irregular bridges

Introduction of the thesis objectives and description of the work plan

Comparison of nonlinear static procedures with nonlinear dynamic analysis for irregular bridges

Introduction to the subject of seismic design optimization

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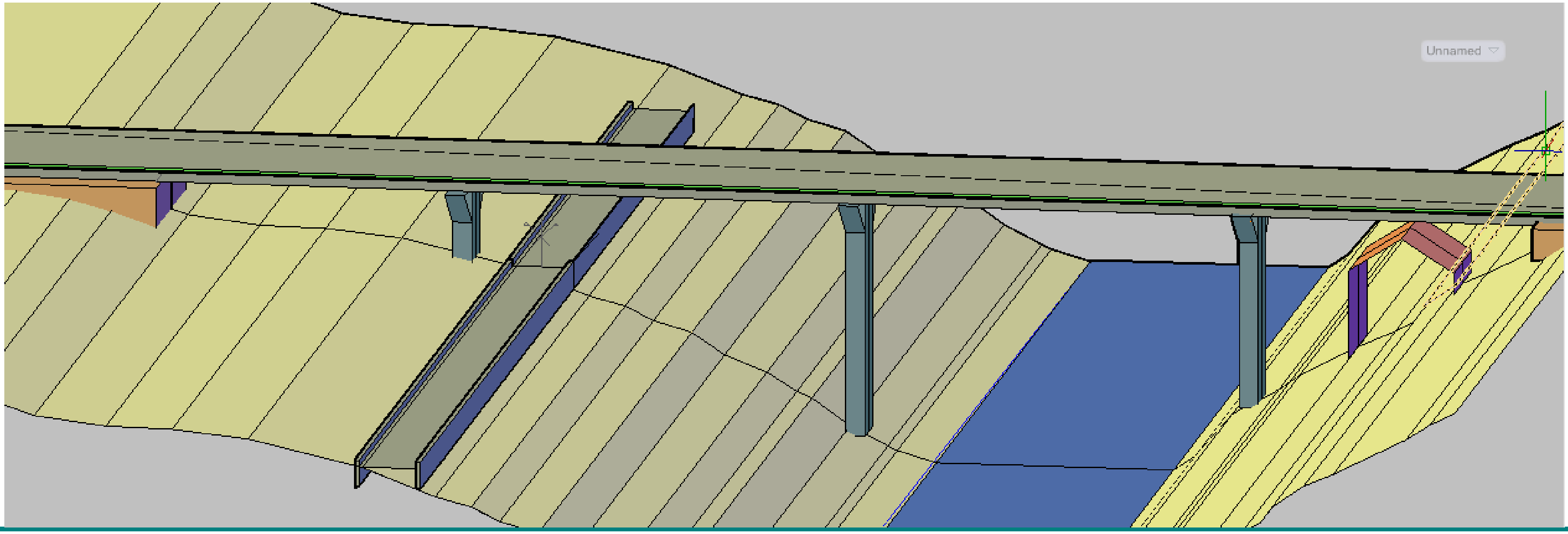


Seismic action and the importance of ductility

- Seismic action is often defined as an equivalente applied force, in part because the grand majority of actions on structures are defined as applied forces.

- However, seismic action has an inherent duality. It should not be only seen as an applied force, and should not be seen only as an imposed displacement. It should be seen as both.

- For that reason, providing ductility to structures is very importante for the structure's seismic performance. Ductility allows the structure to sustain imposed displacements, and allows the energy dissipation associated to most of the equivalent damping of the seismic response.

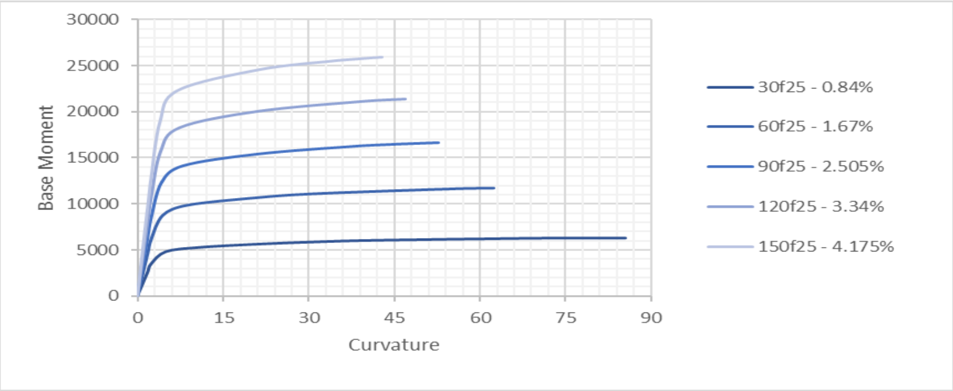
Ductility

Factors that influence the ductility of a concrete section:

- Concrete confinement
- Form and dimension of the concrete section
- Strength capacity of the materials
- Distribution of the steel flexural rebar and ratio between the compressive and tensile amounts of steel reinforcement.
- Axial force level
- Relation between the ultimate stress and yield stress of the steel reinforcement and the post yield stiffness
- Shear force
- Slope of the decreasing part of the constitutive relationship of the concrete

Effect of the amount of flexural steel and axial force on ductility

5m long column fixed at the bottom node and free at the top. Horizontal displacements were imposed on top node.

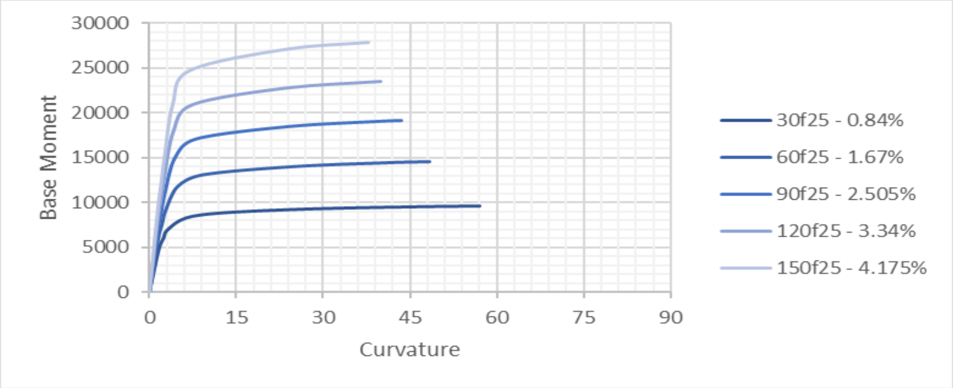


Section Diameter = 1.5m

N = 0 kN

µN = 0%

Confinement reinforcement = 2ϕ16//10cm

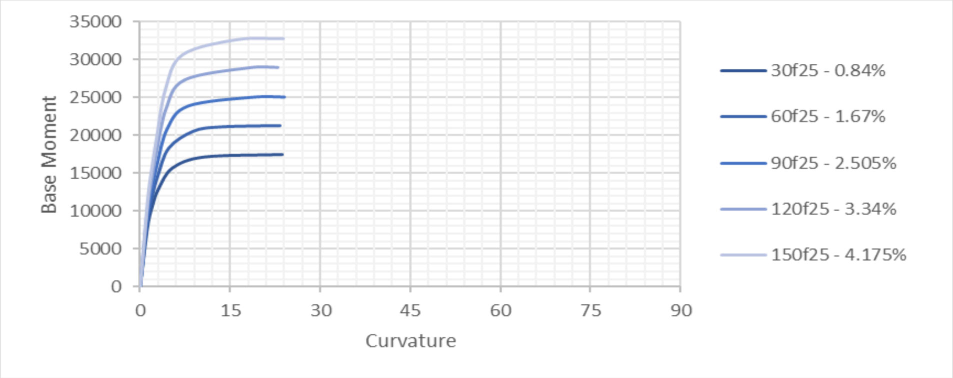


Section Diameter = 1.5m

N = -6715 kN

µN = 10%

Confinement reinforcement = 2ϕ16//10cm



Section Diameter = 1.5m

N = -33576 kN

µN = 50%

Confinement reinforcement = 2ϕ16//10cm

Objectives of the thesis project

- Take advantage of the real non-linear behavior of the materials, which allows to obtain more efficient designs of bridges, by allowing to redistribute the loads between the vertical structural elements. In turn, this allows to optimize and normalize design and construction.
- Case for seismic design in the transverse direction: develop a design process that simplifies the work of the structural engineer, both in cases of irregular bridges, where the transverse horizontal displacement profile of the deck (THDPD) is complex, as in regular bridges where the THDPD is simpler.
- The goal is to obtain a generic design method of the structural vertical elements that integrates the work performed for both directions.

Work plan description – case studies

- several types of bridges will be analyzed, both in the transverse direction and longitudinal direction, falling into these categories:
  - Short bridges - due to the ratio between the stiffness of the superstructure and the stiffness of the piers, the superstructure controls the displacements.
  - Long bridges – both regular and irregular, in terms of pier geometry.

Work plan description – methodology of analysis

- Through non-linear dynamic analysis the transverse horizontal displacement profile of the deck (THDPD), for each bridge, will be ascertained, as will be the ductility demand in each pier, with special emphasis given to piers with higher ductility demand.
- These analyses will be performed both for the case with normalized/optimized design as for bridges designed through current/traditional methodologies.
- The evaluation of the seismic performance of the optimized solution is done by comparison with the seismic performance of the current/traditional design solution, for each bridge model case. For this purpose, the ratio between available ductility and ductility demand of the critical piers will be compared.
- All of this will be done in a stochastic framework, where the material properties will introduce uncertainty into the model. Particular attention will be given to the calculation of the constitutive relations and especially the concrete's ultimate compressive strain.

Work plan description – topics/tasks

1. Longitudinal model designed for constant shear strength of the piers.
2. Longitudinal model designed for constant flexural strength at the base of the piers.
3. “Regularity Index” and “Relative Stiffness Index” – Choosing of the case studies.
4. Transverse analysis - Short bridges.
5. Transverse analysis – Long regular bridges.
6. Transverse analysis – Long irregular bridges.

Work plan description – topics/tasks

In the remainder of the presentation the results for the work done so far for topics/tasks 1 and 2 are presented:

1. Longitudinal model designed for constant shear strength of the piers.
2. Longitudinal model designed for constant flexural strength at the base of the piers.

Task 2 has already been addressed in the Masters' thesis, however the study and analyses were repeated with new software, FEM program, that was developed this year during the curricular part of the PhD program.

Tasks 1 and 2: Bridge Design – Longitudinal direction

Current methodology

The design of the bending reinforcement for each pier is done in accordance to each pier's stiffness.

The result is, the stiffer the pier, (case of shorter piers) the more steel is assigned to it, which in turn increases the stiffness even more.

The outcome is that the stiffer elements have less ductility due to having more flexural steel, when stiffer elements should have more ductility due to having more ductility demand.

This methodology of design has disadvantages:

- there are a lot of piers with different lengths – each pier has a different design.

Normalization/Optimization

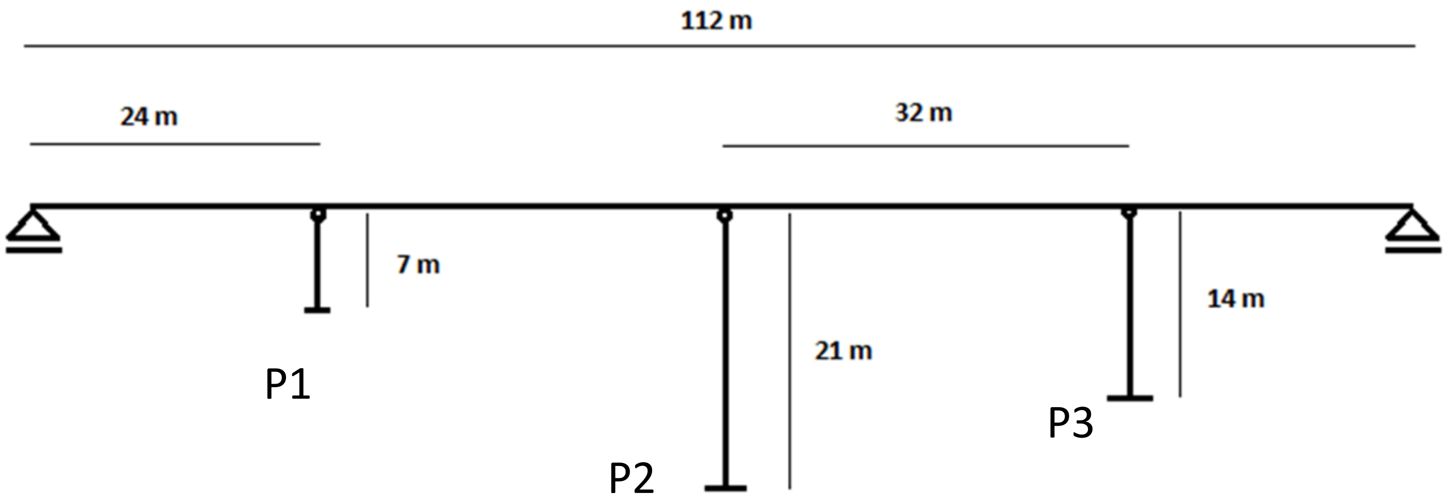
Can the piers be designed with arbitrary amount of bending steel reinforcement, without jeopardizing the seismic performance?

Instead of dividing the flexural steel reinforcement between the piers in accordance to their stiffness, the steel reinforcement can be assigned to each pier in a way that allows normalization of the design project, for instance:

- Equal steel reinforcement for all the piers – Design normalization

- Stiffer pier, less steel, more ductility – Design optimization

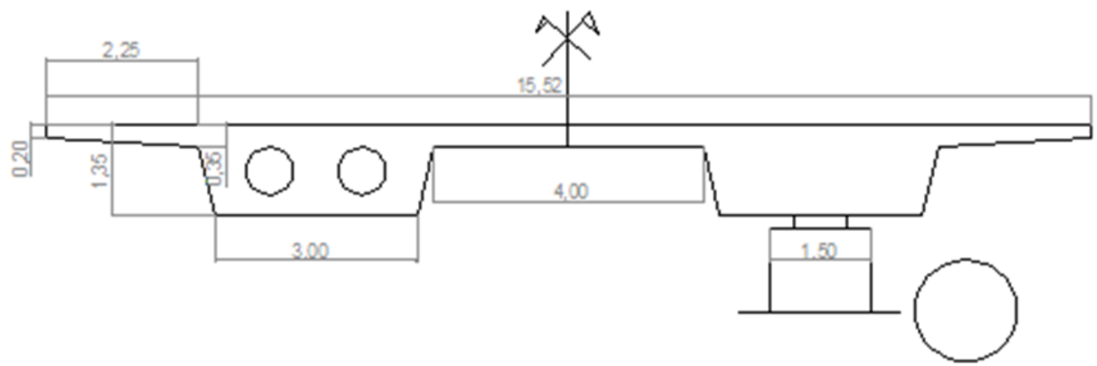
Bridge Geometry – case study for tasks 1 and 2



B35 Concrete

A500 Steel

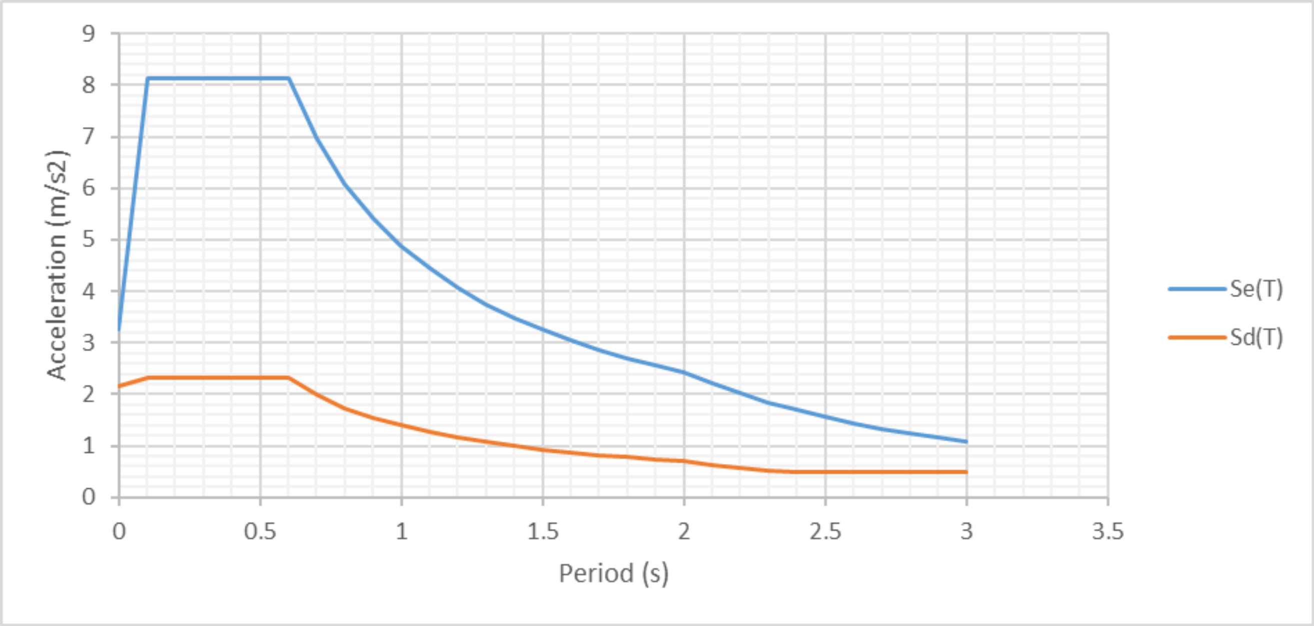
6 circular piers – Diameter 1.5m



Seismic spectra

Portuguese code earthquake:

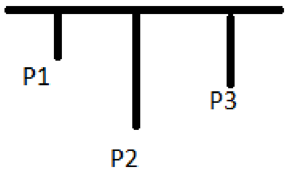
Earthquake 1, zone 1, terrain type C



Tasks 1 and 2: Bridge Design – Longitudinal direction

The concept of effective stiffness from EC8-2 is used for the design:

$$E_c J_{eff} = \frac{\nu M_{Rd}}{\phi_y} \qquad \nu = 1.2 \; e \; \phi_y = 2{,}25.\frac{\varepsilon_{sy}}{d}$$



ϕy	εsy	D(m)	Ec(GPa)	M (ton)
0.0032625	0.002175	1.5	32	3600

Current methodology

	P1	P2	P3
N (kN)	-4900	-5800	-5200
L(m)	7	21	14
Mrd(kN.m)	13505	4783	4564
Jeff(m^4)	0.1552	0.0550	0.0525
K(kN/m)	43447.5	569.9	1835.3
2.K (2 piers)	86895.0	1139.8	3670.7

K total	91705.4
f(Hz)	0.803
T(s)	1.245

F Inertia (kN)
4027.87

	P1	P2	P3
Faction	1908.29	25.03	80.61
Maction	13358.05	525.65	1128.55
Mstrength	13505.38	4783	4564
%Steel reinf	**2.80%**	**0.40%**	**0.40%**

Normalization/Optimization

	P1	P2	P3
N (kN)	-4900	-5800	-5200
L(m)	7	21	14
Mrd(kN.m)	5194	5515	5303
Jeff(m^4)	0.0597	0.0634	0.0610
K(kN/m)	16709.36	657.11	2132.50
2.K (2 piers)	33418.72	1314.22	4265.00

Ktotal	38997.95
f(Hz)	0.524
T(s)	1.909

Finertia (kN)
2626.63

	P1	P2	P3
Faction	716.4	238.8	358.2
Maction	5014.5	5014.5	5014.5
Mstrength	5194	5515	5303
%Steel reinf	**0.60%**	**0.60%**	**0.60%**

	P1	P2	P3
N (kN)	-4900	-5800	-5200
L(m)	7	21	14
Mrd(kN.m)	4450	8826	6043
Jeff(m^4)	0.0511	0.1014	0.0695
K(kN/m)	14315.87	1051.63	2430.08
2.K (2 piers)	28631.75	2103.26	4860.16

Ktotal	35595.17
f(Hz)	0.500
T(s)	1.998

Finertia (kN)
2509.42

	P1	P2	P3
Faction	418.2	418.2	418.2
Maction	2927.7	8783.0	5855.3
Mstrength	4450	8826.1	6043
%Steel reinf	**0.40%**	**1.50%**	**0.80%**

Capacity curves

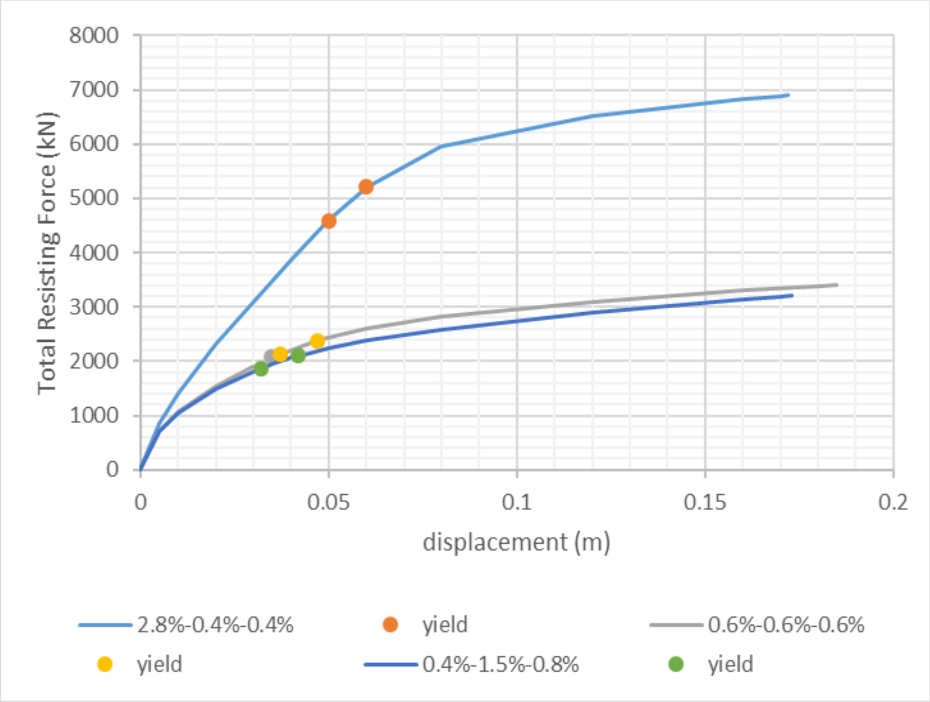
Mean Values

εcu = -16.8‰

2.8%-0.4%-0.4% – δu = 17.2cm

0.6%-0.6%-0.6% – δu = 18.5cm

0.4%-1.5%-0.8% – δu = 17.3cm



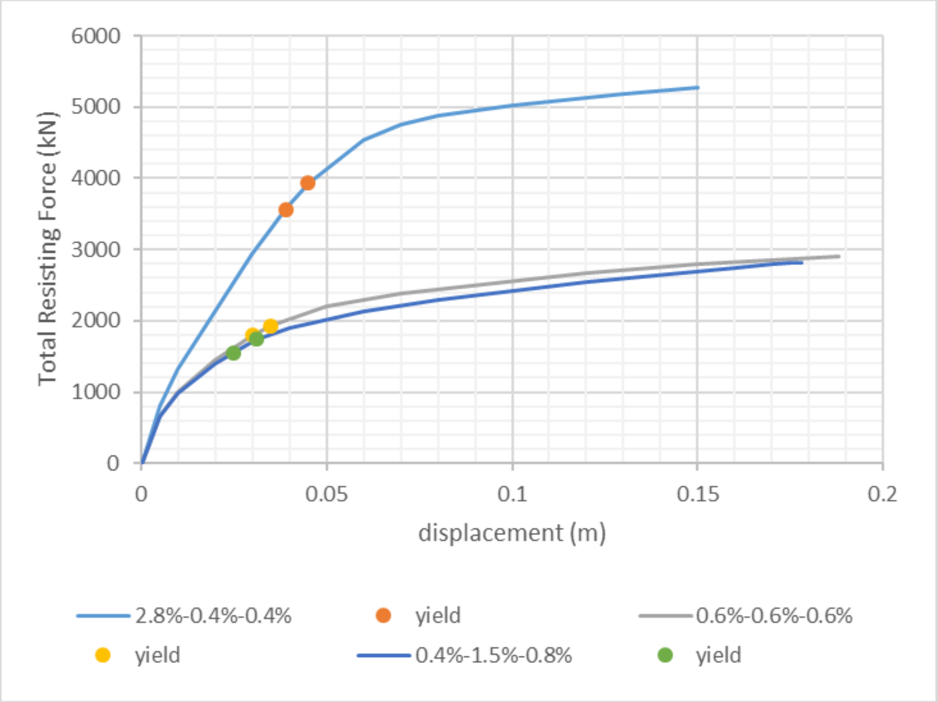
Design Values

εcu = -20.6‰

2.8%-0.4%-0.4% – δu = 15cm

0.6%-0.6%-0.6% – δu = 18.8cm

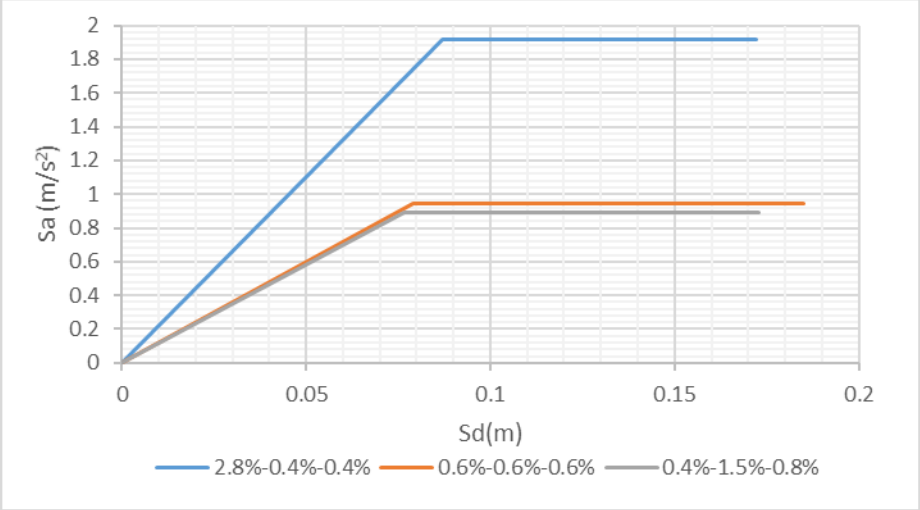
0.4%-1.5%-0.8% – δu = 17.8cm



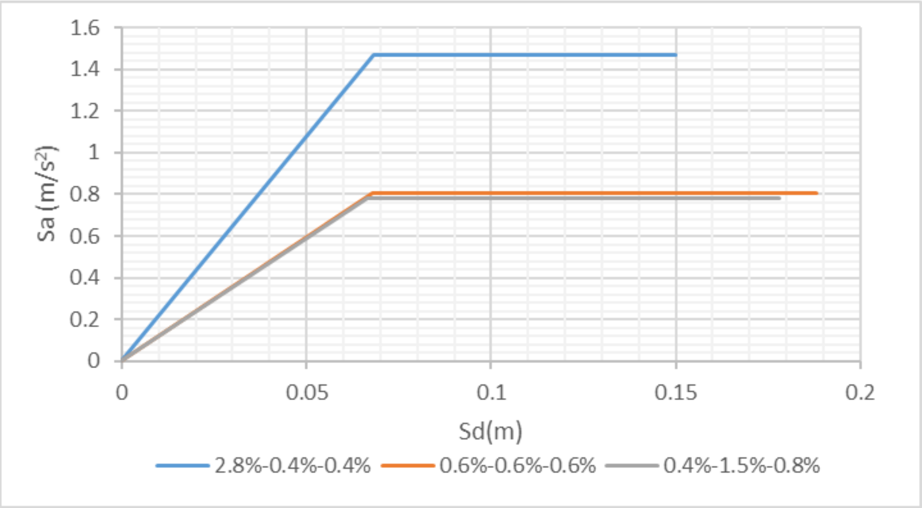
Seismic analysis - N2 method

Bi-Linearization N2 method

Mean Values



Design Values

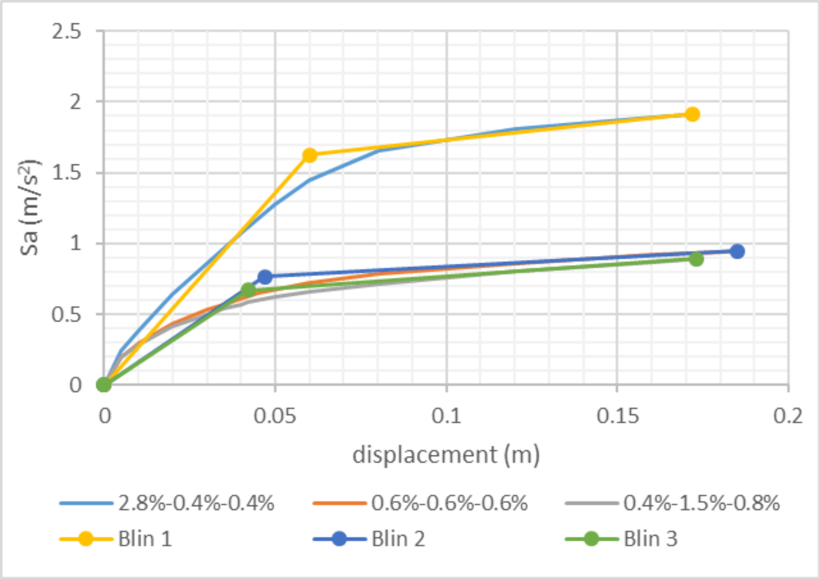


N2 method results

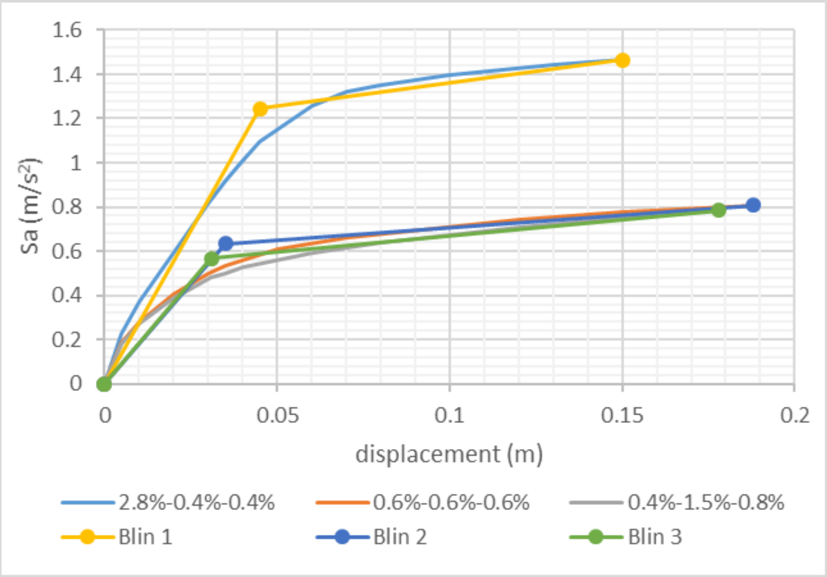
	Sdy	Say	Sdu	ag	Ty (s)	μ	$sa_e(TC;ag)$	TC (s)	Sde(Ty)	Rμ	μp	**Sd_t**
Mean Values												
2.8%-0.4%-0.4%	8.70	1.91	17.20	2.50	1.34	1.98	2.80	0.60	12.72	1.46	1.44	**12.72**
0.6%-0.6%-0.6%	7.91	0.95	18.50	2.50	1.81	2.34	2.07	0.60	17.24	2.18	1.44	**17.24**
0.4%-1.5%-0.8%	7.65	0.89	17.30	2.50	1.84	2.26	2.04	0.60	17.49	2.29	1.41	**17.49**
Design Values												
2.8%-0.4%-0.4%	6.80	1.47	15.00	2.50	1.35	2.21	2.77	0.60	12.85	1.89	1.53	**12.85**
0.6%-0.6%-0.6%	6.79	0.81	18.80	2.50	1.82	2.77	2.06	0.60	17.31	2.55	1.58	**17.31**
0.4%-1.5%-0.8%	6.65	0.78	17.80	2.50	1.83	2.68	2.05	0.60	17.39	2.62	1.55	**17.39**

Seismic analysis - ATC-40 method

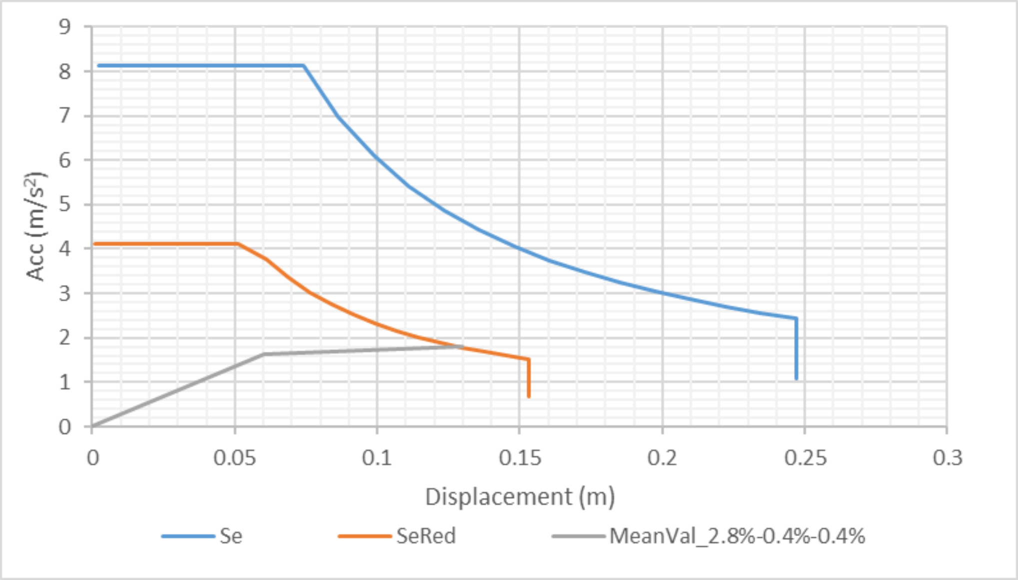
Mean Values



Design Values



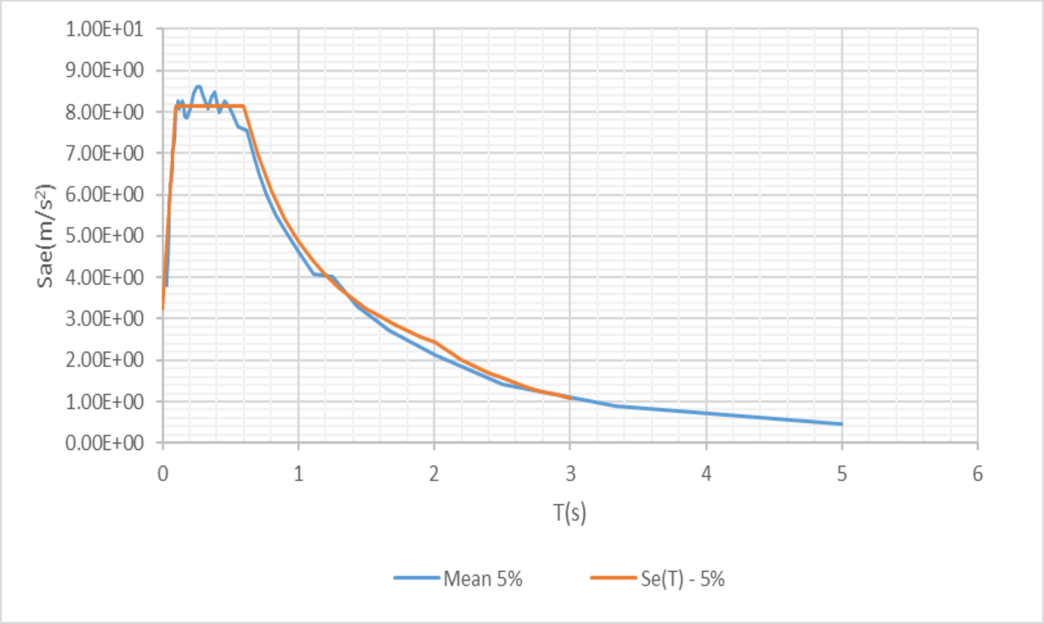
Seismic analysis - ATC-40 method



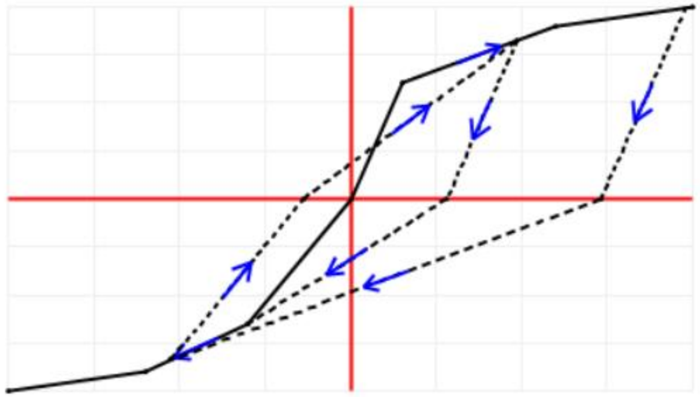
Mean Values	**Sdt**
2.8%-0.4%-0.4%	0.13
0.6%-0.6%-0.6%	0.147
0.4%-1.5%-0.8%	0.149
Design Values	**Sdt**
2.8%-0.4%-0.4%	0.14
0.6%-0.6%-0.6%	0.144
0.4%-1.5%-0.8%	0.146

Seismic analysis - Dynamic Time-History

20 Artificial accelerograms, designed to be compatible with the Eurocode response spectrum of the type 1, zone 1, terrain type C earthquake, were used.



Multilinear Plastic - Takeda



Mean Values	
ζ	0.02
	Mean dmax(cm)
2.8%-0.4%-0.4%	12.34
0.6%-0.6%-0.6%	14.84
0.4%-1.5%-0.8%	15.15

Design Values	
ζ	0.02
	Mean dmax(cm)
2.8%-0.4%-0.4%	12.8
0.6%-0.6%-0.6%	15.36
0.4%-1.5%-0.8%	15.63

Comparison N2, ATC-40, Non-linear dynamic

MeanValues	Sdu	Sdt N2	Sdt ATC40	Sdt DinNLin
2.8%-0.4%-0.4%	0.172	0.127	0.13	0.1234
0.6%-0.6%-0.6%	0.185	0.172	0.147	0.1484
0.4%-1.5%-0.8%	0.173	0.175	0.149	0.1515
DesignValues	**Sdu**	**Sdt N2**	**Sdt ATC40**	**Sdt DinNLin**
2.8%-0.4%-0.4%	0.15	0.129	0.14	0.128
0.6%-0.6%-0.6%	0.188	0.173	0.144	0.1536
0.4%-1.5%-0.8%	0.178	0.174	0.146	0.1563

“Current bridge”

“Normalized bridges”

- Results using design values are conservative in comparison with results using mean values. For the “normalized bridges” the results are similar but not for the “current bridge”.
- N2 method gives more accurate results for the stiffer bridge (current methodology) than for the “normalized bridges”.
- The arbitrary distribution of flexural reinforcement doesn’t jeopardize the seismic performance

MeanValues	Sdu/Sdt N2	Sdu/Sdt ATC40	Sdu/Sdt DinNLin
2.8%-0.4%-0.4%	1.352	1.323	1.394
0.6%-0.6%-0.6%	1.073	1.259	1.247
0.4%-1.5%-0.8%	0.989	1.161	1.142
DesignValues	**Sdu/Sdt N2**	**Sdu/Sdt ATC40**	**Sdu/Sdt DinNLin**
2.8%-0.4%-0.4%	1.167	1.071	1.172
0.6%-0.6%-0.6%	1.086	1.306	1.224
0.4%-1.5%-0.8%	1.024	1.219	1.139

Conclusions

- About the design methodology:
  - The bridges designed with the optimization/normalization methodology seem to have good seismic performance
  - It is possible to arbitrarily distribute the bending reinforcement between the piers without jeopardizing the seismic performance
  - Nevertheless, special care should always be given to the design of the confinement steel reinforcement to make sure that the structures have enough ductility to withstand the seismic action, for both current and normalized design.

- About the seismic analysis:
  - The use of design values is usually conservative in relation to the mean values, more so when the piers are stiffer (have larger amounts of flexural reinforcement) or have higher axial forces.
  - The higher the ductility demand, the more the choice of design or mean values has to be studied carefully.
  - Both the N2 method and the ATC-40 give good results. However the ATC-40 seems to give better results for the lower frequency structures, while the N2 method seems better for the higher frequency structures.

Future Developments for tasks 1 and 2

- Develop and introduce a stochastic model. The stochastic model will contemplate the material properties, since it has been shown that strength and ductility are differently affected by the material properties.

Thank you!