Innovative strategies for the analysis and control of cable-stayed bridges under strong earthquakes

Dr Alfredo Camara

Lecturer in Structural Engineering
City University London

Research Centre for Civil Engineering Structures

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Index

Index

Scope

Analysis and control of cable-stayed bridges under strong earthquakes

The Tatara bridge, Japan

Why?

- High social and economical relevance
- Large flexibility + reduced damping → seismic behaviour?

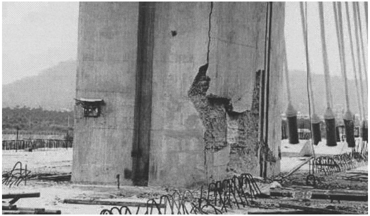
- The scientific approach began in the 1990's
- The research is focused on:
  - Spatial variability
  - Cable-structure interaction
  - Connections along the deck
  - Multi-span bridges
  - Curved decks

Prof. Abdel-Ghaffar

Lack of studies on the towers $\rightarrow$ key elements

Good seismic response of cable-stayed bridges, however ...

Ji-Lu bridge (Taiwan)
Chi-Chi earthquake
$(1999,\ M_W = 7.3)$

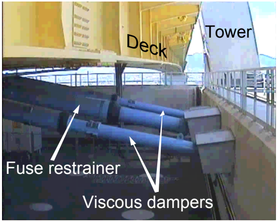


Trend in constructed cable-stayed bridges

Floating deck-tower connections with anti-seismic devices

Paradigmatic bridge: Rion-Antirion

- Greece, 2004
- Multi-span
- $286 + 3 \times 560 + 286$
- Seismic area: $a_g = 0.48$ g



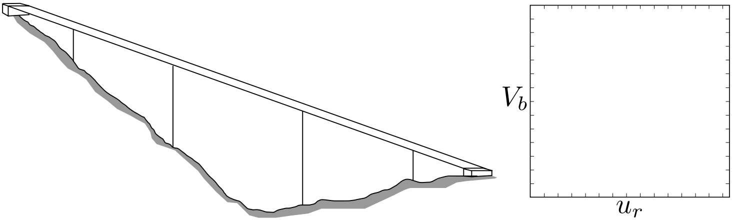
Earthquake: $M_W = 6.4$ (June 2008)

- Deck-tower connection: only transversely
- 4 nonlinear viscous dampers: $\alpha_d = 0.15$
- Fuse restrainer (no dissipation under wind loads)

Index

Scope of Pushover analysis

Pushing statically using load patterns representing the inertia forces

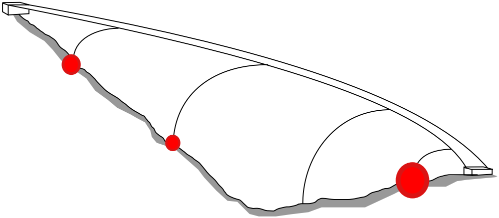


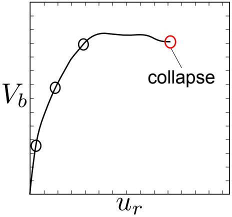
Purpose

- To expose possible structure weaknesses

Scope of Pushover analysis

Pushing statically using load patterns representing the inertia forces





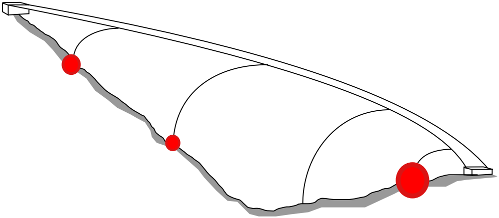
Purpose

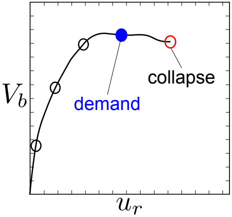
- To expose possible structure weaknesses
- To estimate the seismic response under large earthquakes

Find the target displacement → demand of the studied earthquake

Scope of Pushover analysis

Pushing statically using load patterns representing the inertia forces





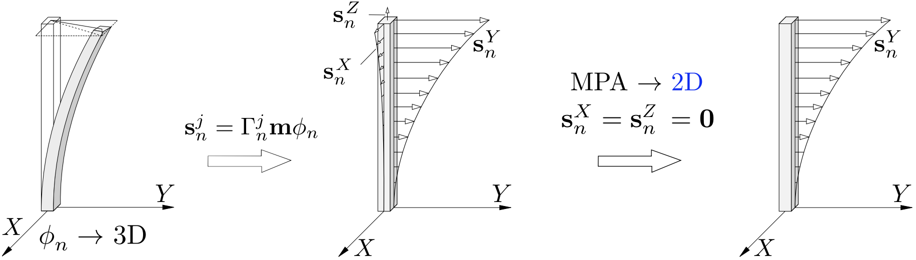
Purpose

- To expose possible structure weaknesses
- To estimate the seismic response under large earthquakes

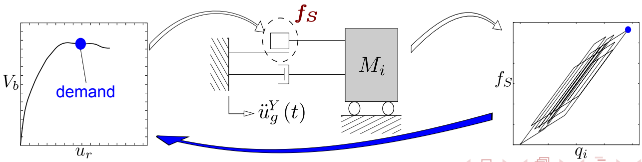
Find the target displacement $\rightarrow$ demand of the studied earthquake

Modal Pushover Analysis (Chopra & Goel 2002)

- i-mode **Load pattern** 2D: modal force $\mathbf{s}_i = \Gamma_i \mathbf{m} \boldsymbol{\phi}_i$



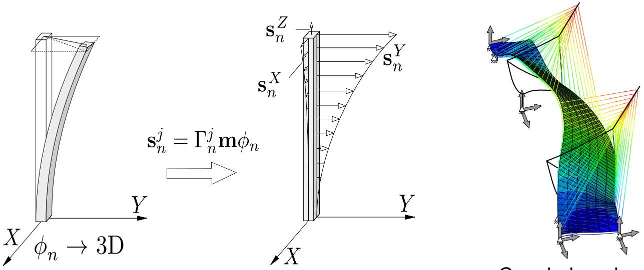
- i-mode **Target displacement**:



Extended Modal Pushover Analysis

Novelty

3D Pushover analysis for each mode



Coupled mode

Extended Modal Pushover Analysis

Mathematical background

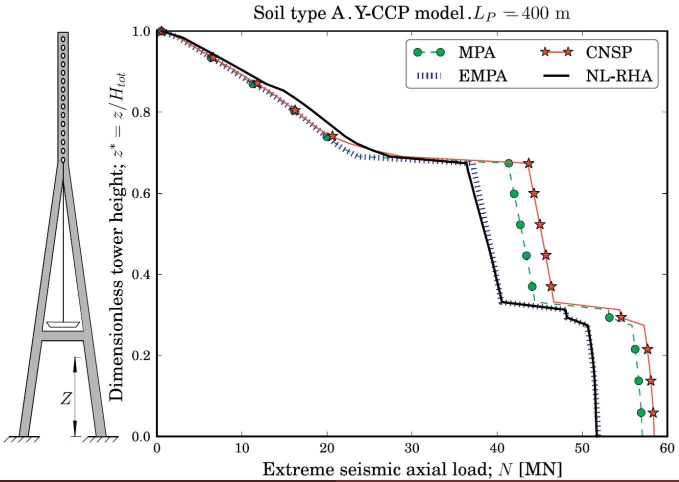
$$\phi_n^T \mathbf{m}\ddot{\mathbf{u}} + \phi_n^T \mathbf{c}\dot{\mathbf{u}} + \phi_n^T \mathbf{f}_S(\mathbf{u}, \dot{\mathbf{u}}) = -M_n \underbrace{\left(\Gamma_n^X \ddot{u}_g^X(t) + \Gamma_n^Y \ddot{u}_g^Y(t) + \Gamma_n^Z \ddot{u}_g^Z(t)\right)}_{\ddot{u}^*_{g,n}(t)}$$

$$\ddot{\bar{q}}_n + 2\xi_n\omega_n\dot{\bar{q}}_n + \frac{\overline{F}_{sn}}{M_n} = -\ddot{u}^*_{g,n}(t) \rightarrow \text{SDOF}$$

$$\begin{cases} \dfrac{\bar{F}_{sn}}{M_n} = \sqrt{\left(\dfrac{F_{sn}^X}{M_n}\right)^2 + \left(\dfrac{F_{sn}^Y}{M_n}\right)^2 + \left(\dfrac{F_{sn}^Z}{M_n}\right)^2} \\ \bar{q}_n = \sqrt{(q_n^X)^2 + (q_n^Y)^2 + (q_n^Z)^2} \end{cases}$$

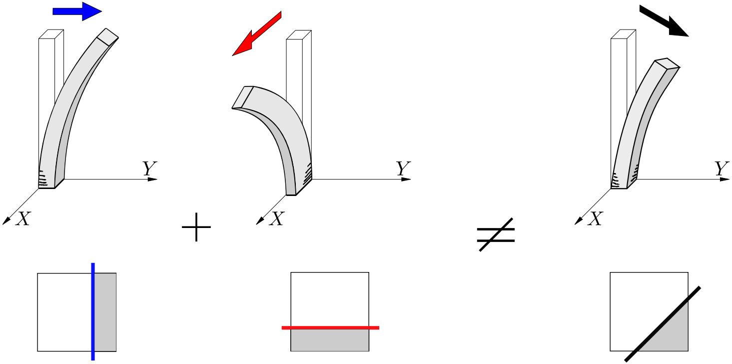
EMPA: Results

- If the modes are governed by one direction $\rightarrow$ EMPA $\approx$ MPA
- EMPA: Better prediction of the **axial force** for small-medium bridges



Coupled Nonlinear Static Pushover

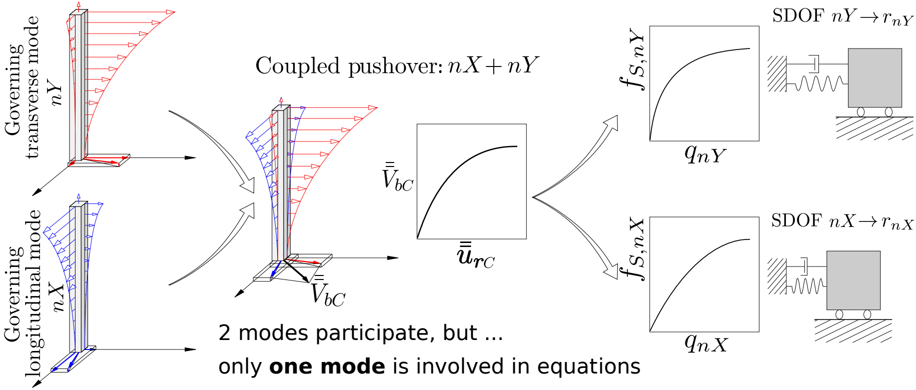
The transverse and longitudinal response **interact** in nonlinear range



Novelty

3D Pushover combining the dominant modes in transverse and longitudinal directions

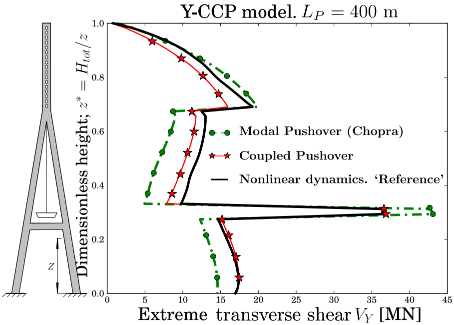
Coupled Nonlinear Static Pushover: approach

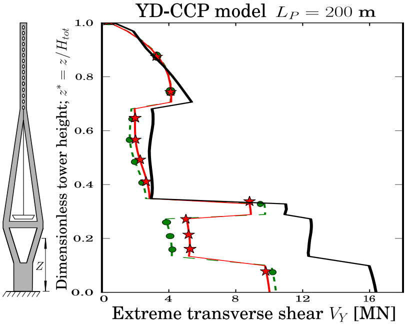


2 modes participate, but ...
only **one mode** is involved in equations

- One nonlinear static analysis $\rightarrow$ **FAST**
- Modes different than governing ones considered elastic $\rightarrow$ **SAFE**

Results



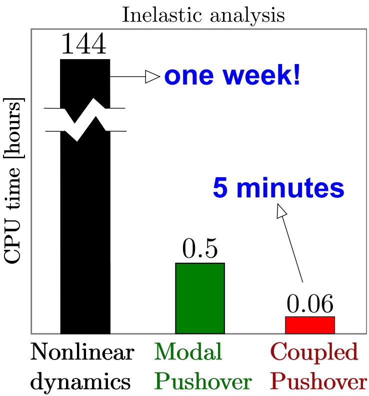


- Good estimation with advanced Pushover: errors typically below 20%
- Coupled Pushover yield very accurate solutions

However:

- Pushover results could be misleading if the tower damage is very large

Computational cost



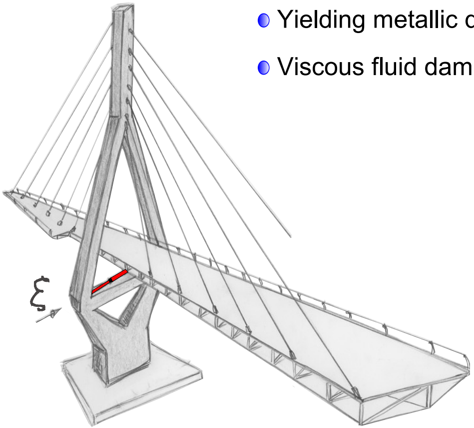
Cable-stayed bridges under strong earthquakes, beyond the elastic range:

- Analysis: Advanced Pushover
- Verification: Nonlinear dynamics (HHT)

Index

Without anti-seismic devices:

- Extensive cracking in key tower sections,
  especially small bridges on soft soil with central cable-system
- Reaction of the deck against the towers $\rightarrow$ large damage
- Proposed: **transverse dampers between deck and towers**

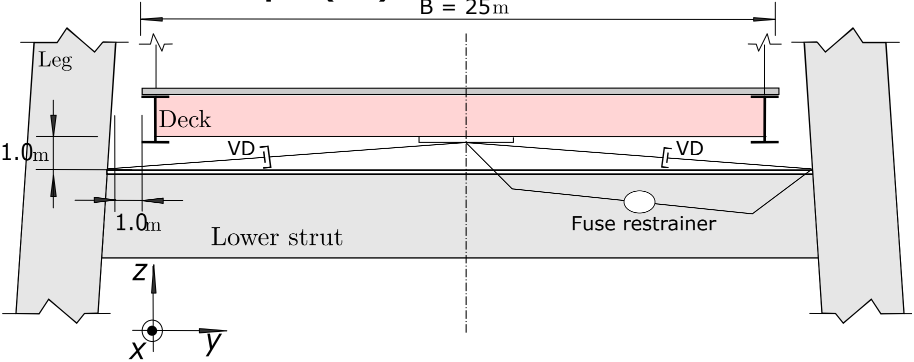


- Yielding metallic dampers
- Viscous fluid dampers

Proposed deck-tower dampers:

- Pushover $\rightarrow$ force starting the damage in the tower; $P_{\max}$

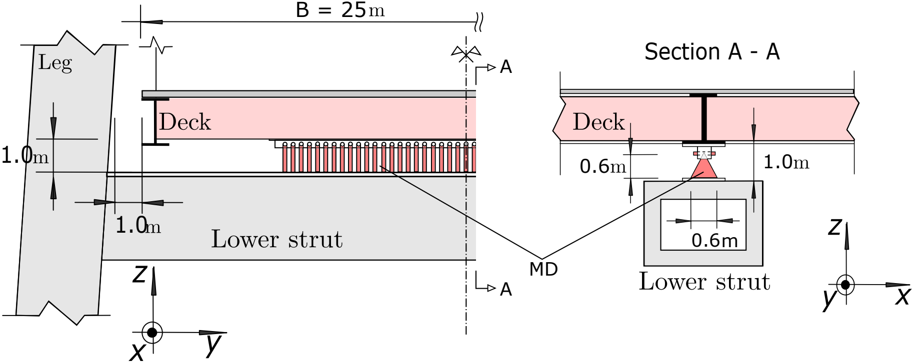
Viscous fluid Damper (VD)



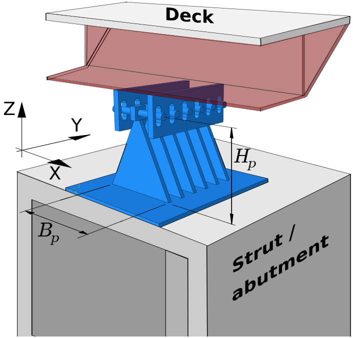
Proposed deck-tower dampers:

- Pushover $\rightarrow$ force starting the damage in the tower; $P_{\max}$

Metallic yielding Damper (MD)



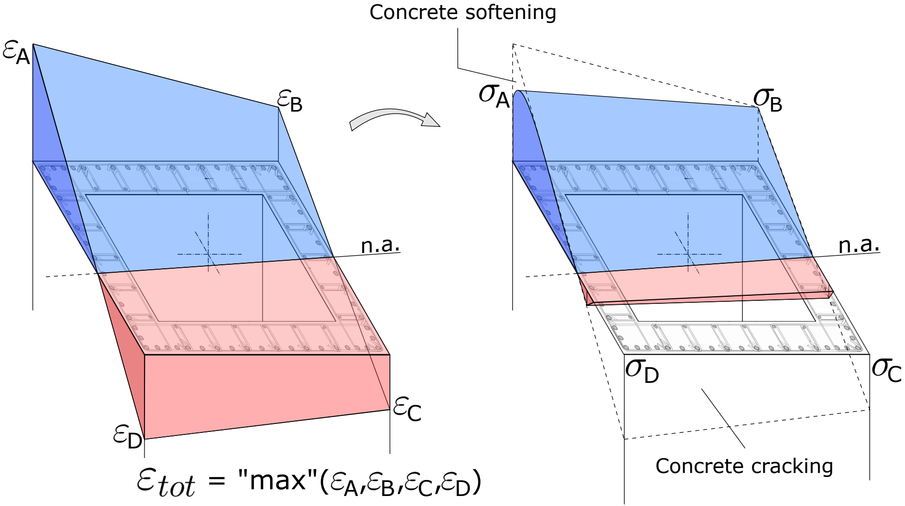
Yielding metallic dampers: triangular plates



- Fixed plate dimensions. Number of plates defined to yield prior to the tower damage (no control on the ductility)

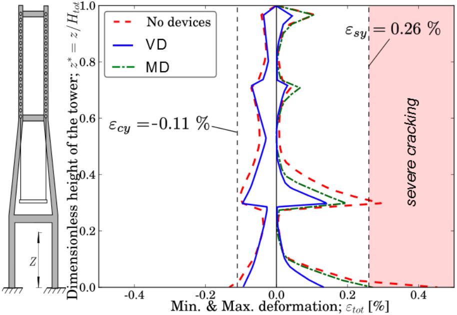
$$P_y = 0.85 \cdot 0.9 \cdot P_{\max} \rightarrow \text{Number of plates}$$

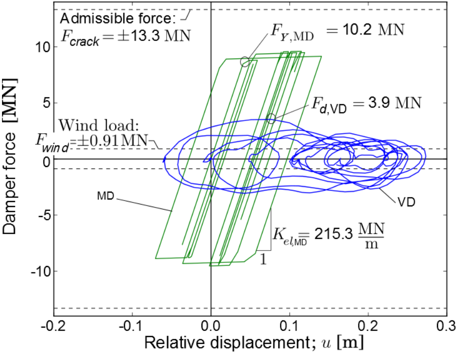
Peak deformations along the tower



$$\varepsilon_{tot} = \text{"max"}(\varepsilon_A, \varepsilon_B, \varepsilon_C, \varepsilon_D)$$

Response with dampers between deck and towers





- Typically **Viscous dampers** are more efficient than **Triangular plates**
- Care should be taken with the low-cycle fatigue in Yielding dampers
- Dampers in deck-tower connection:

  $\rightarrow$ more efficient if the main span is below 500 m

Index

Conclusions

Regarding the analysis strategies ...

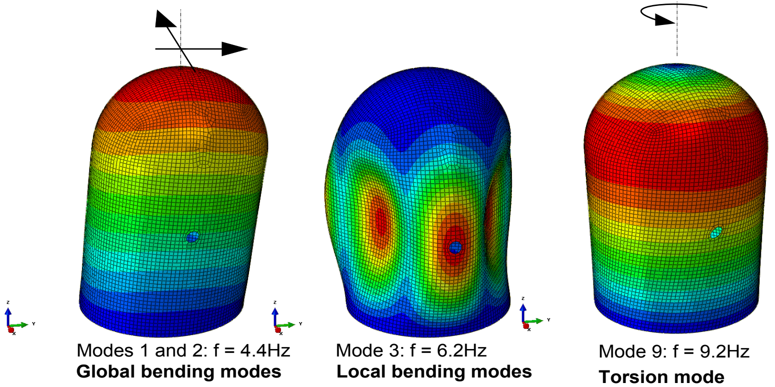
- **Extension of 'Modal Pushover'** to consider the 3D nature of vibration modes
- Proposal of a **Coupled Pushover** which combines the dominant modes in one nonlinear static analysis

Regarding the anti-seismic devices ...

- Dampers connecting the deck and the towers are more efficient if the main span is below 500 m:
  - Improved control with Viscous Dampers, but maintenance?
  - The low-cycle fatigue is important in yielding Metallic Dampers

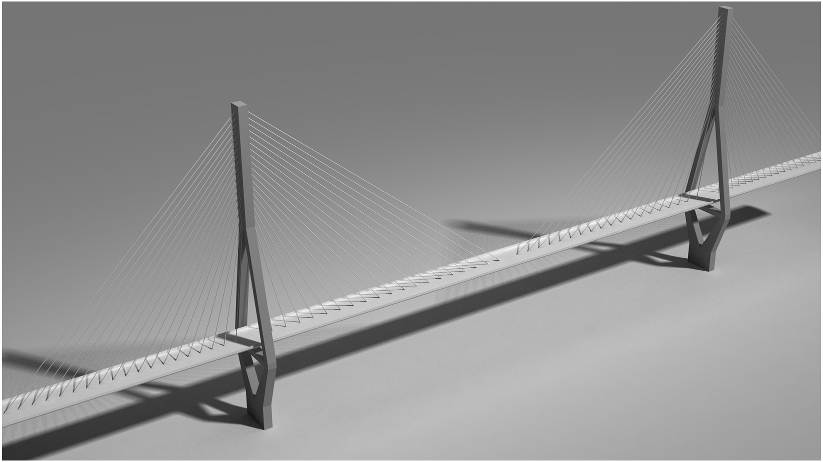
Further studies: advanced Pushover methods

- Application to Prestressed Concrete Containment Vessels



Further studies: advanced Pushover methods

- Application to long bridges under asynchronous earthquakes



Animation (deformation amplified)

Further reading

- Camara A and Astiz MA (2012). Pushover analysis for the seismic response prediction of cable-stayed bridges under multi-directional excitation. *Engineering Structures*, **41**:444-455.

- Camara A and Astiz MA (2014). Analysis and control of cable-stayed bridges subjected to seismic action. *Structural Engineering International*, **24**(1):27-36.

- Camara A and Astiz MA (2014). Applicability of the strategies for the elastic seismic analysis of cable-stayed bridges. *International Journal for Numerical Methods in Analysis and Engineering Design* (in Spanish) **30**(1):42-50.

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alfredo.camara@city.ac.uk

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