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

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17th June 2015
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Analysis and control of cable-stayed bridges under strong earthquakes

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

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

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

Earthquake: $M_W = 6.4$ (June 2008)
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 $\rightarrow$ 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** → demand of the studied earthquake
Modal Pushover Analysis (Chopra & Goel 2002)

- **i-mode Load pattern 2D**: modal force $s_i = \Gamma_i m \phi_i$

- **i-mode Target displacement**:

  - $s_n^j = \Gamma_n^j m \phi_n$
  - MPA → 2D
  - $s_n^X = s_n^Z = 0$

Seismic response of cable-stayed bridges
Novelty

3D Pushover analysis for each mode

\[ s_n^j = \Gamma_n^j m\phi_n \]
Extended Modal Pushover Analysis

Mathematical background

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

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

\[
\frac{F_{sn}}{M_n} = \sqrt{\left( \frac{F^X_{sn}}{M_n} \right)^2 + \left( \frac{F^Y_{sn}}{M_n} \right)^2 + \left( \frac{F^Z_{sn}}{M_n} \right)^2}
\]

\[
\ddot{q}_n = \sqrt{(q^X_n)^2 + (q^Y_n)^2 + (q^Z_n)^2}
\]
EMPA: Results

- If the modes are governed by one direction → EMPA ≈ MPA
- EMPA: Better prediction of the \textbf{axial force} for small-medium bridges
The transverse and longitudinal response \textit{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 → **FAST**
- Modes different than governing ones considered elastic → **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)
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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 → 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; $P_{\text{max}}$

**Viscous fluid Damper (VD)**

![Diagram of Viscous fluid Damper (VD)]
Proposed deck-tower dampers:

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

**Metallic yielding Damper (MD)**

![Diagram of metallic yielding damper with dimensions and labels](image)

Seismic response of cable-stayed bridges
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

\[ \varepsilon_{tot} = \max(\varepsilon_A, \varepsilon_B, \varepsilon_C, \varepsilon_D) \]

Concrete softening

Concrete cracking
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:
  - more efficient if the main span is below 500 m
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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

- Modes 1 and 2: $f = 4.4\text{Hz}$
  - Global bending modes

- Mode 3: $f = 6.2\text{Hz}$
  - Local bending modes

- Mode 9: $f = 9.2\text{Hz}$
  - Torsion mode
Further studies: advanced Pushover methods

- Application to long bridges under asynchronous earthquakes

Animation (deformation amplified)
Further reading


Acknowledgements

- Ashraf Ayoub (CUL)
- Miguel A. Astiz Suárez (UPM)
- Eleftheria Efthymiou (CUL)
- Roberto Cristantielli (PUB/CUL)

... and thank you all!

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