Groupe de recherche en GÉNIE DES STRUCTURES

ÉCOLE POLYTECHNIQUE MONTRÉAL

Towards Displacement-Based Design of Isolated Bridges in Eastern North America

P. Daneshvar, Ph.D. Student

N. Bouaanani, Ing., Ph.D.

CSRN Workshop on Seismic Isolation and Damping of Bridge Structures

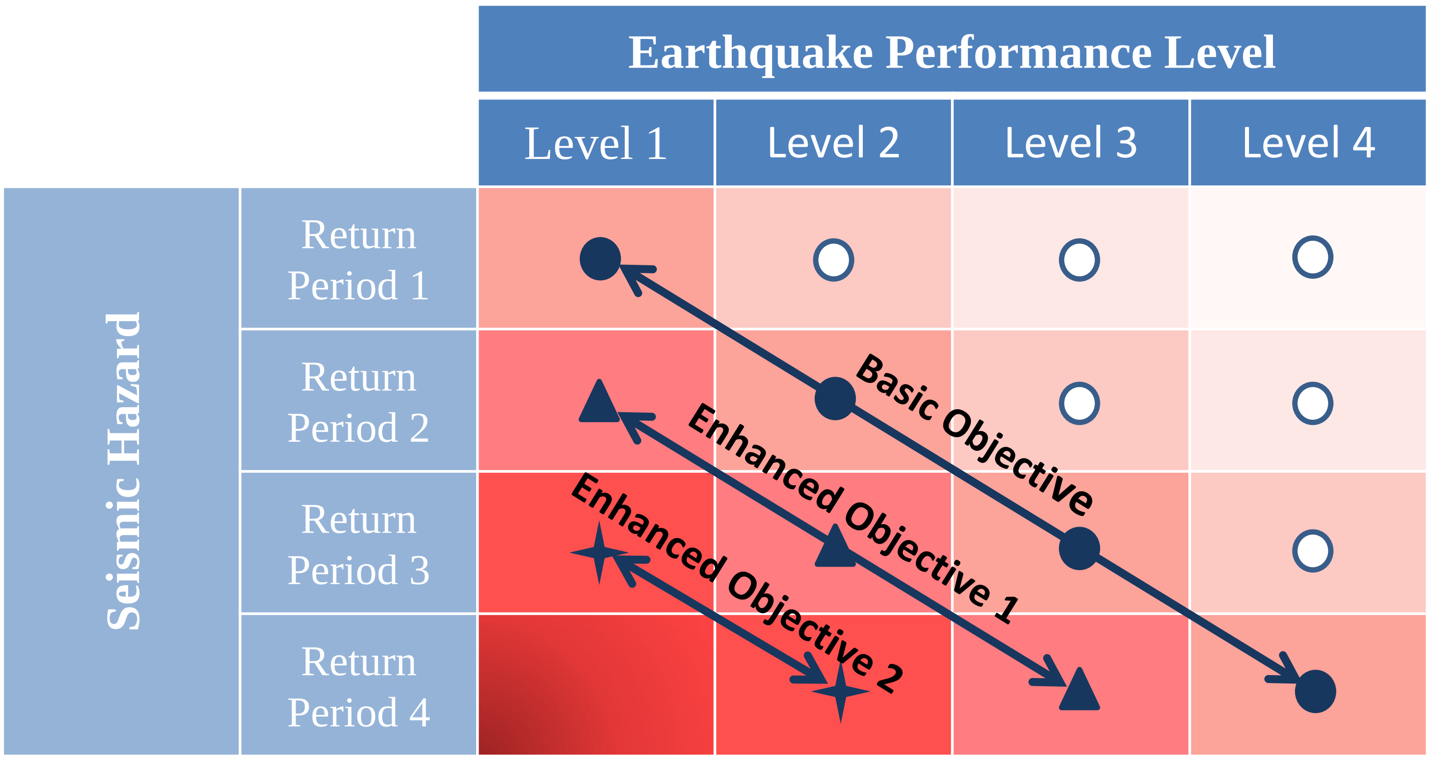
May 2011

Background

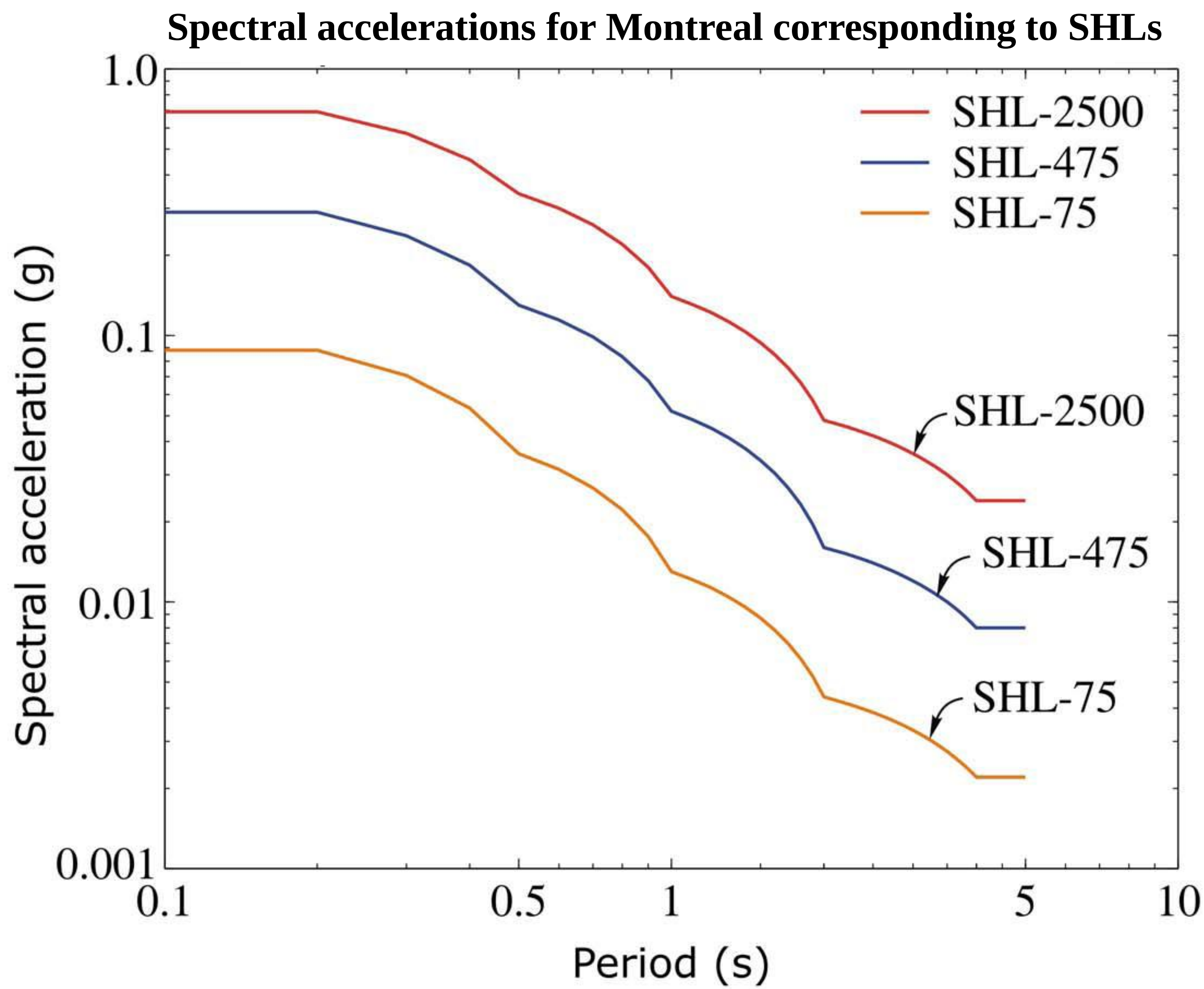
Destructive earthquakes of Loma Prieta (1989), Northridge (1994) and Kobe (1995) enhanced interest in Performance-Based Seismic Design (PBSD) as an alternative to the conventional approaches prescribed by the majority of the codes which depend on Force-Based Design (FBD).

Background

The purpose of PBSD is to ensure the performance of structures, under frequent and rare earthquakes, to be in accordance with the diverse needs of the society. PBSD provides more flexibility to meet target performance and economic objectives.



Seismic Hazard vs. Design Spectra



Seismic Hazard in CHBDC

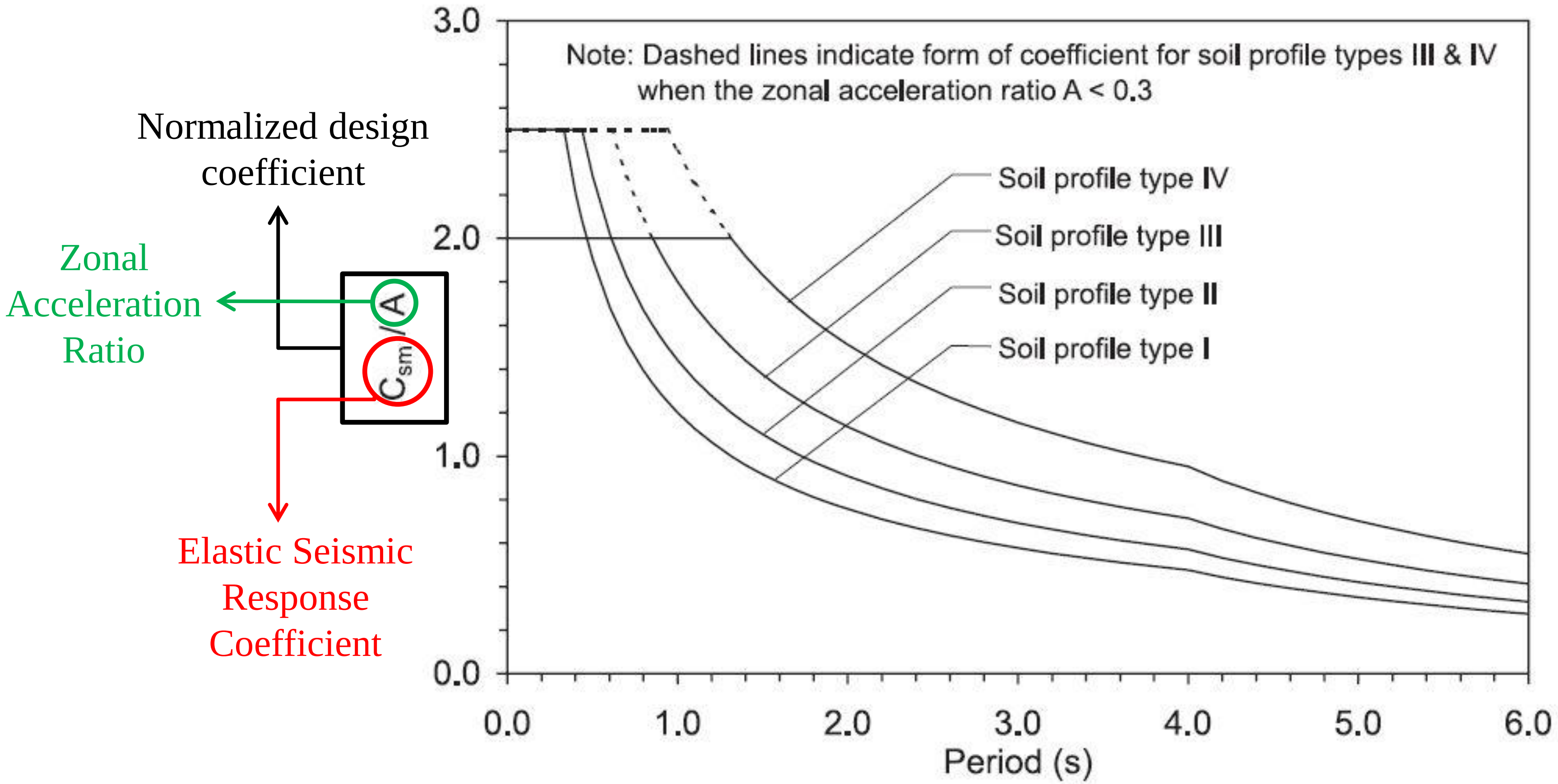
- The design earthquake in the recent Canadian Highway Bridge Design Code (CHBDC) has a return period of 475 years.
- Lifeline and emergency bridges need to remain open to all traffic after the design earthquake.
- Lifeline bridges also need to be open to emergency vehicles after a 1000-year return period event.
- NBCC's change from a 475 to a 2500 year return period to achieve uniform reliability across Canada had a significant impact on regions with moderate seismic activity such as eastern Canada (Roy et al., 2010).

An example of the results of changes in SHLs in Quebec (Roy et al., 2010)

Quebec	NBCC 1995 CHBDC	Geological Survey Canada	NBCC 2005
Return Period	475 years	475 years	2500 years
Peak Ground Acceleration (g)	0.12	0.18	0.40

Design Spectrum of CHBDC

Earthquake Load (P_e) = C_{sm} × Equivalent Weight of the Bridge (W)



Normalized seismic response coefficient for various soil profiles (CHBDC, 2006)

Displacement-Based Design

- Displacements are the primary design parameters in DBD methods.

- Structural damage could be directly related to displacement demands and therefore, damage could be controlled most efficiently by imposing displacement (or drift) limits rather than strength limits.

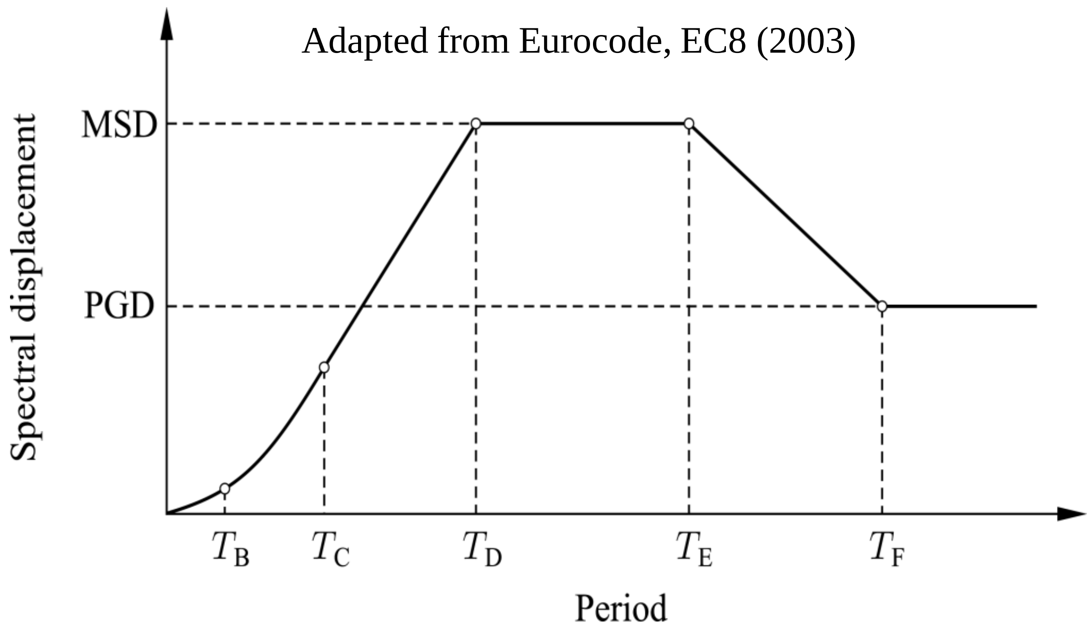
- DBD offers the ability to control explicitly the displacement demand in each member rather than assigning a single, force-based behavior factor to the entire structure.

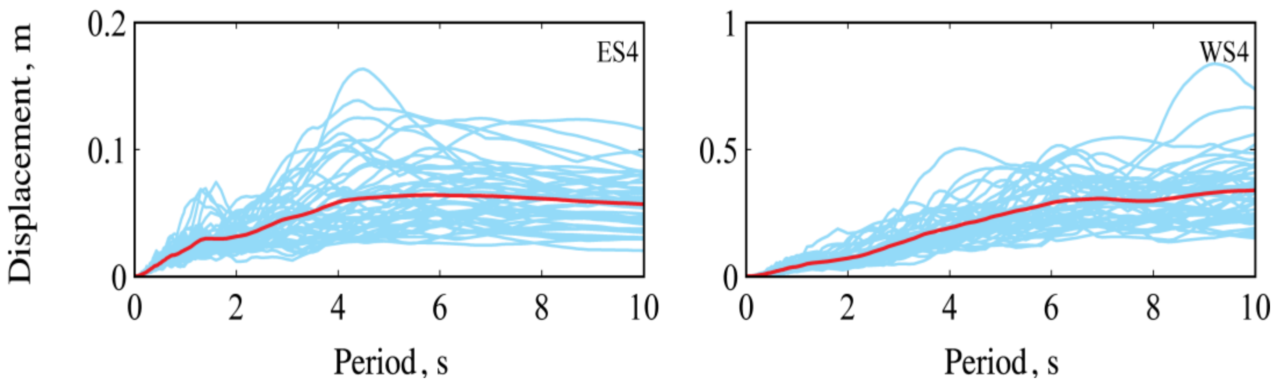
- Several DBD procedures have been developed so far.
  - Direct Displacement-Based Design (DDBD) (Priestley and Kowalsky, 2000)

DDBD Procedure

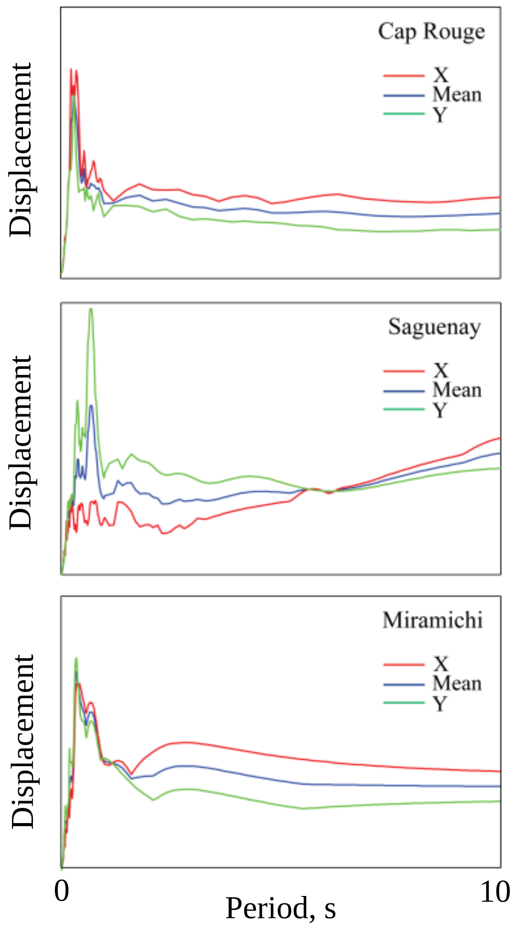
- DDBD procedure requires defined seismic hazard levels.
- It designs a structure to satisfy a pre-defined drift limit.
- For buildings, various seismic hazard levels have been proposed and the current code prescribes inter-storey drift limits.
- For bridges, there is a need for data related to seismic hazard levels as well as appropriate definition of displacement limits.

Displacement Spectra



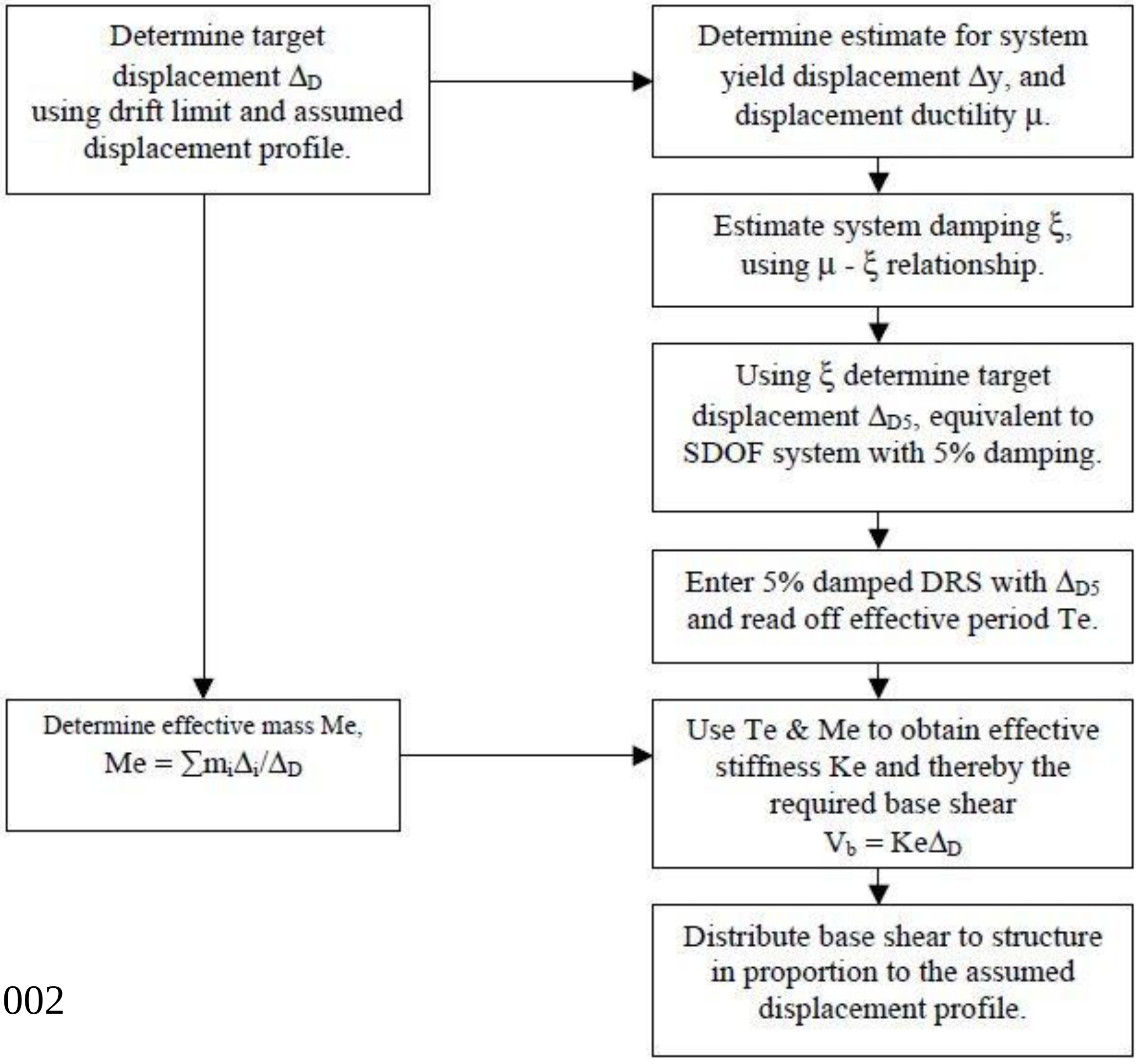


Simulated Data



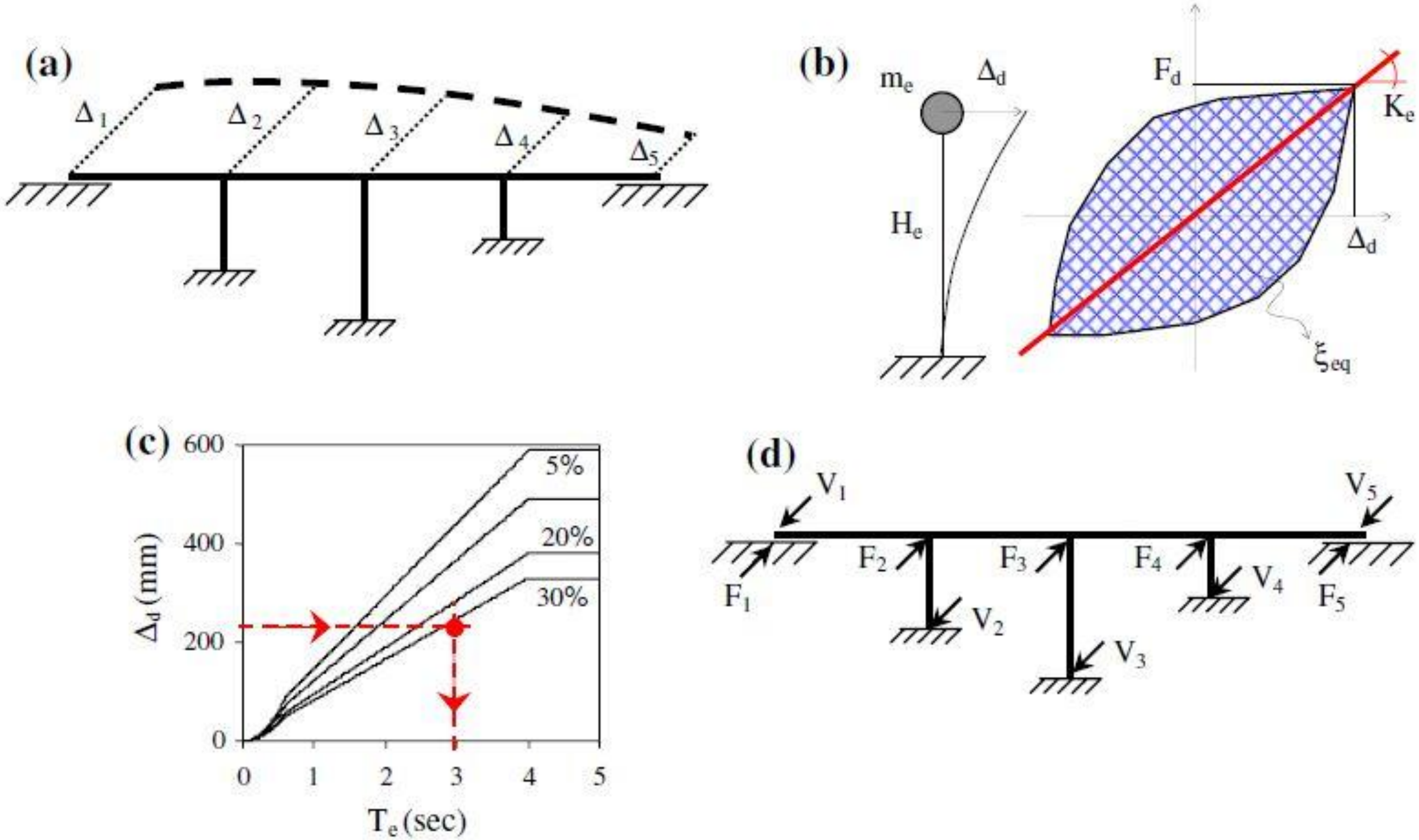
Historical Data

DDBD Procedure



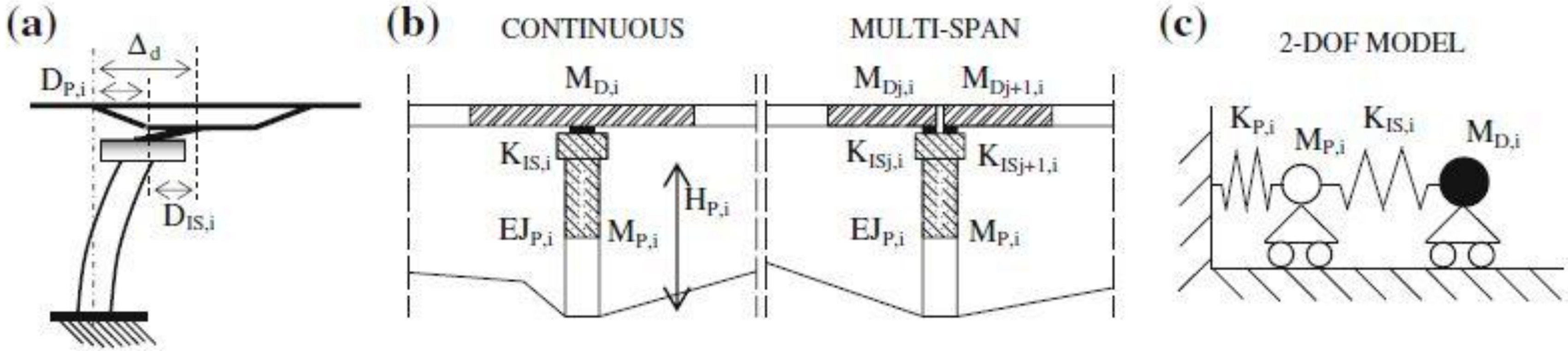
Sullivan, 2002

DDBD Procedure

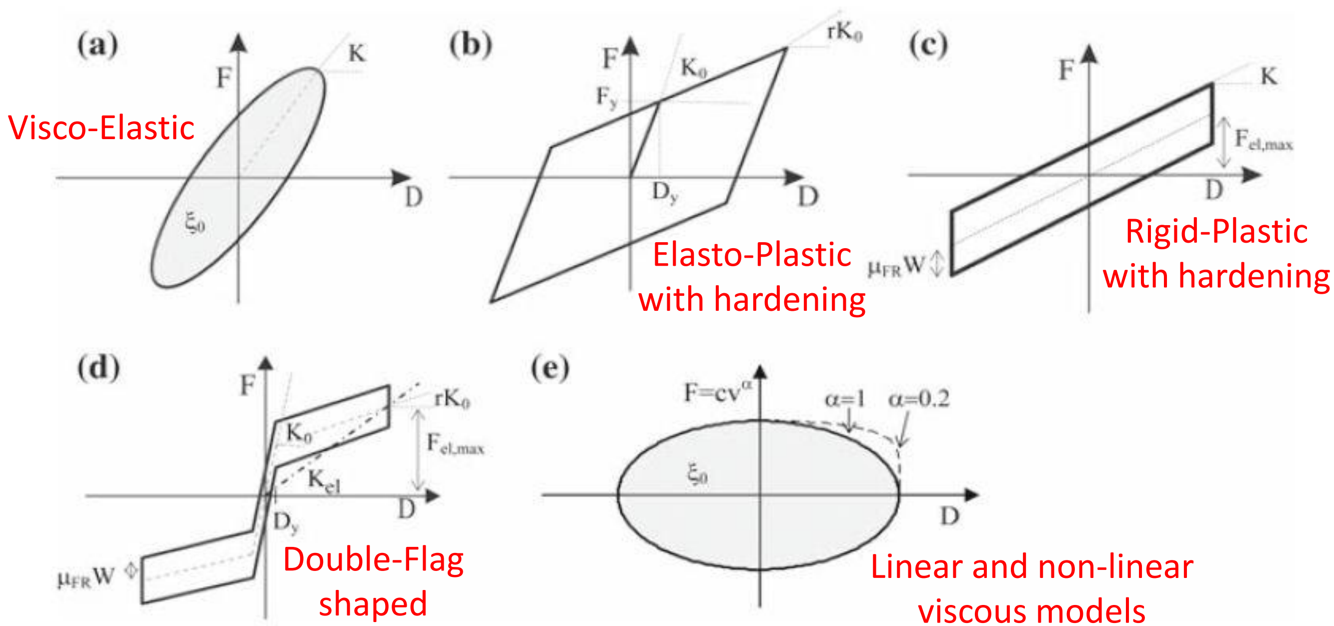


Fundamentals of DDBD with specific reference to bridge structures (Cardone et al., 2008)

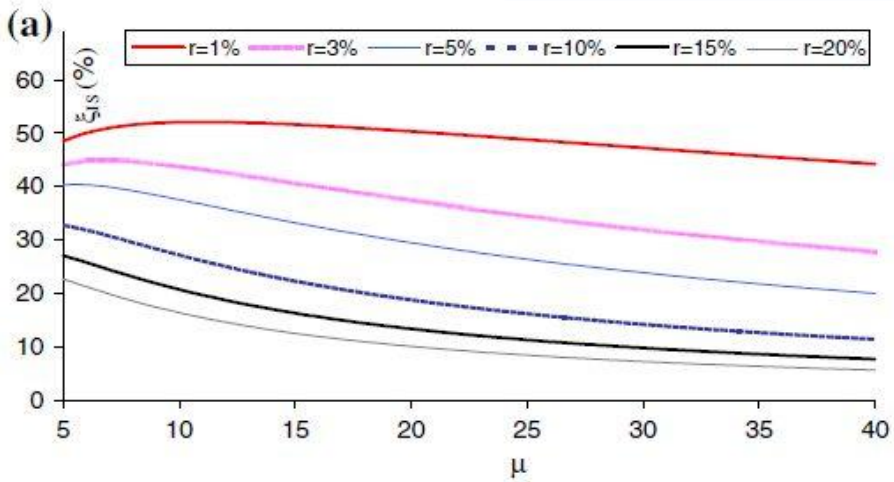
DDBD Procedure Including Seismic Isolation



Considerations for deck, pier and **IS** in proposed DDBD procedure (Top); Behavior of isolation systems (**IS**) and auxiliary viscous dampers (Bottom) (Cardone et al., 2008)

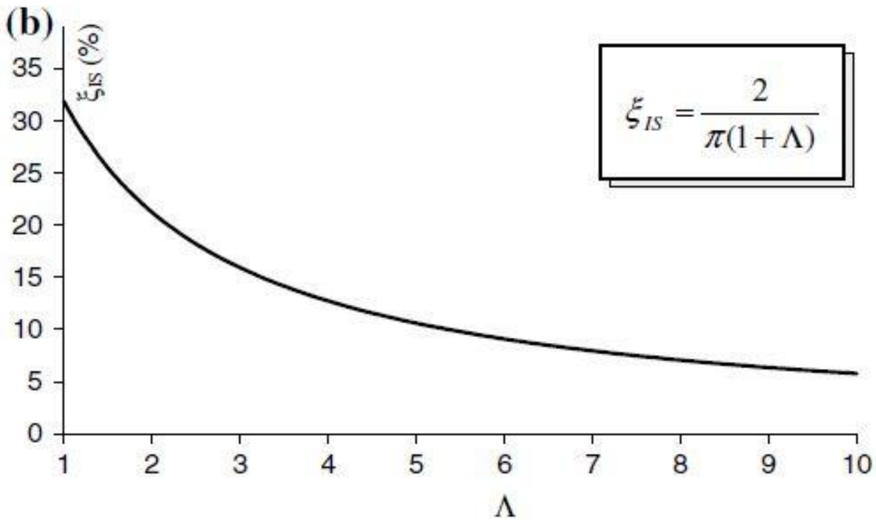


DDBD Procedure Including Seismic Isolation



$$\xi_{IS} = \frac{2(\mu-1)(1-r)}{\pi\mu(1+r(\mu-1))}$$

	HDRB	LRB	SYD
μ	<15	<40	var.
r	$15-25\%$	$5-15\%$	$1-5\%$
ξ_{IS}	$15-25\%$	$20-30\%$	$>30\%$

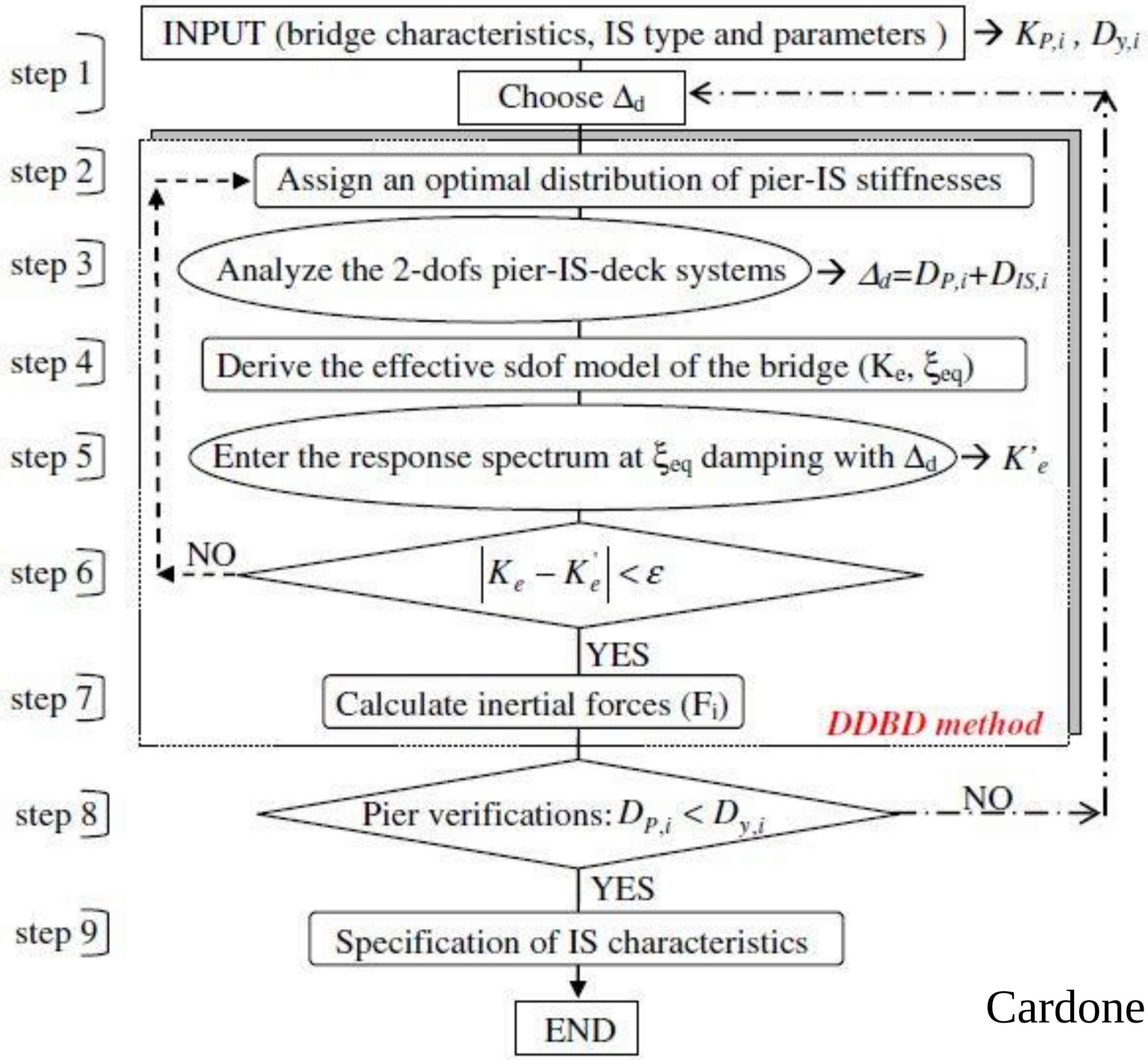


$$\xi_{IS} = \frac{2}{\pi(1+\Lambda)}$$

FPB	SMA+FSB
$\Lambda = \frac{D}{R\mu_{FR}}$	$\Lambda = \frac{4D}{\mu_{FR} T_{el}^2}$
$\frac{D}{R} \cong 7.5-15\%$ $\mu_{FR} \cong 2-5\%$	$\mu < 50$ $r \cong 5-10\%$ $\mu_{FR} \cong 2-5\%$
$\Lambda \cong 1.5-7.5$	$\Lambda \cong 1.3-10$
$\xi_{IS} \cong 7.5-25\%$	$\xi_{IS} \cong 5-27\%$

Mechanical properties and damping ratios of **(a)** Elasto-Plastic with hardening ISs and **(b)** Rigid-Plastic with hardening and Double-Flag shaped ISs

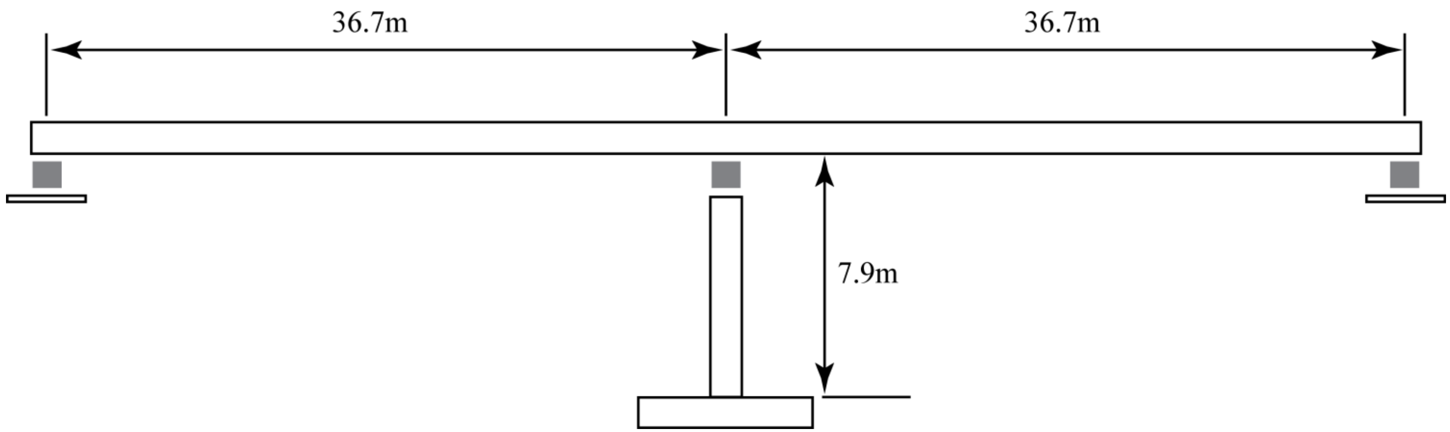
DDBD Procedure Including Seismic Isolation

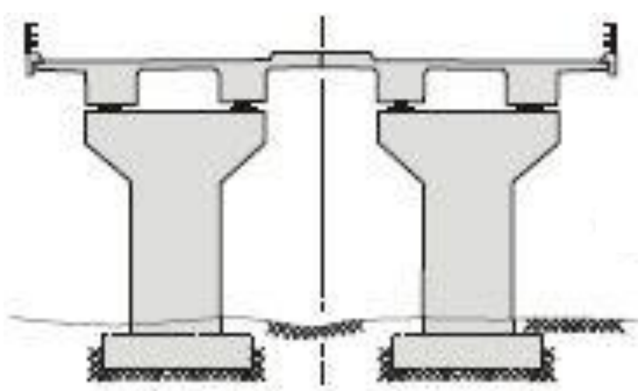


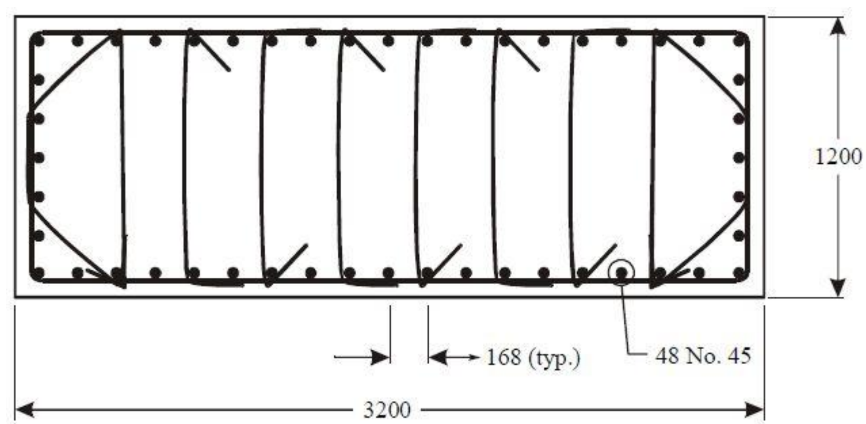
Cardone et al., 2008

Simplified Example of the Application of DDBD Method

Isolation Design of a Two-Span Bridge







Simplified Example of the Application of DDBD Method

Bridge Deck	
Bridge length	73.4 m
Span length	36.7 m
Weight of Bridge Deck	349 kN/m

Single Column	
Column width	3.2 m
Column height	7.9 m
Column length	1.2 m
Column weight	90.24 kN/m

Axial Loads	
$P_{top,\ Column}$	6404.15 kN
$P_{bot,\ Column}$	7117.046 kN
$P_{abutment}$	6404.15 kN

F_y = 350 Mpa

Simplified Example of the Application of DDBD Method

Strain penetration length:

$$(f_{ye} = 1.1 \times f_y)$$

$$L_{SP} = 0.022\ f_{ye}\ d_{bl} = 370.14\ \text{mm}$$

Yield displacement:

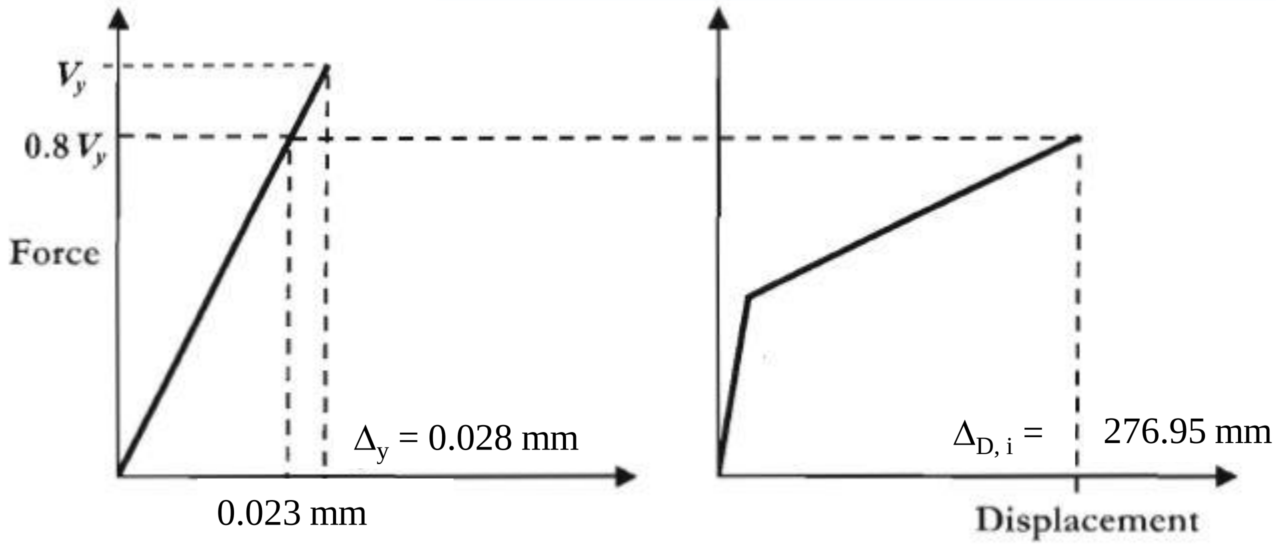
$$\Delta_y = [\Phi_y\ (H + L_{SP})^2] / 3 = 28.8\ \text{mm}$$

There is no defined limit on the displacement (as a performance objective) in CHBDC. Therefore, a maximum total displacement of 300mm is assumed for the pier and the device:

$$\Delta_{D,\ Total} = 0.3\ \text{m}$$

It is assumed that the equivalent viscous damping of the isolation system is approximately 20% and also the isolators will be designed for a force level equal to 0.8 times the design strength of the corresponding pier.

Simplified Example of the Application of DDBD Method



Force-displacement diagrams for pier and corresponding isolation system

Displacement of the isolator:

$$\Delta_{D,\ \text{isolator}} = \Delta_{D,\ \text{Total}} - (0.8 \times \Delta_{y,\ \text{pier}}) = 276.95\ \text{mm}$$

Equivalent viscous damping corresponding to the pier-isolator system:

$$\xi_{\text{pier-isolator}} = [(0.2 \times \Delta_{D,\ \text{isolator}}) + (0.05 \times 0.8 \times \Delta_{y,\ \text{pier}})] / \Delta_{D,\ \text{Total}} = 0.188$$

Simplified Example of the Application of DDBD Method

Displacement of the abutments:
(assuming rigid abutment structure)

$$\Delta_{D,\text{ abutment isolator}} = \Delta_{D,\text{ Total}} = 300 \text{ mm}$$

Equivalent viscous damping corresponding to the abutment-isolator system:

$$\xi_{\text{abutment-isolator}} = 0.2$$

To calculate the global equivalent system damping, it is assumed to distribute the total base shear in proportion to the weight supported by each abutment or pier:

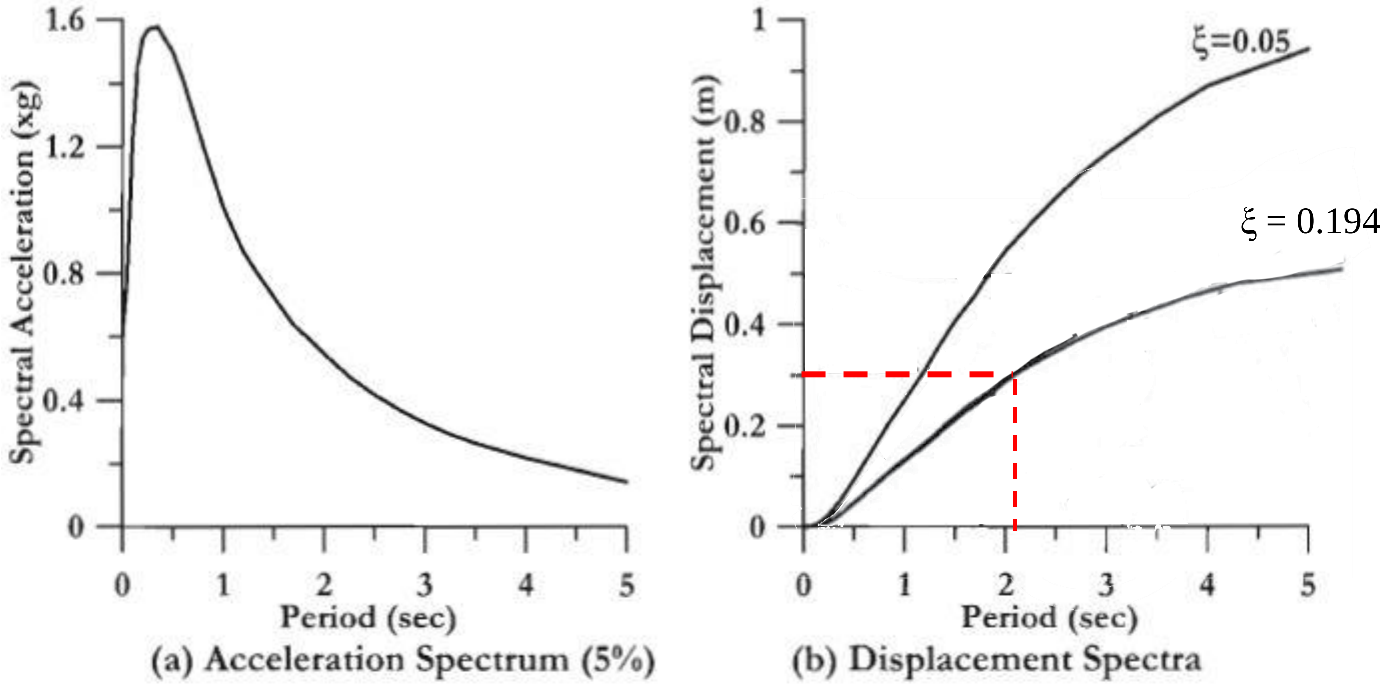
$$\xi_{\text{system}} = [(2 \times P_{\text{abutment}} \times \xi_{\text{abutment-isolator}}) + (2 \times P_{\text{pier}} \times \xi_{\text{pier-isolator}})] / [2 \times P_{\text{abutment}} + 2 \times P_{\text{pier}}]$$

$$\xi_{\text{system}} = 0.194$$

A spectral reduction factor (proposed in European codes such as Eurocode EC8 (2003)) should be applied to the 5% damped spectrum corresponding to the site:

$$R_{\xi} = [0.07/(0.02 + \xi_{\text{system}})]^2 = 0.57$$

Simplified Example of the Application of DDBD Method



Design Spectra for medium ground condition from ATC3 (after Priestley et al., 2007)

The displacement spectrum (the reduction factor having been applied) is entered with a displacement equal to 0.3m and a response period is obtained:

$$T_e = 2.1s$$

Simplified Example of the Application of DDBD Method

Taking the effective weight as 25600 kN, the equivalent stiffness is calculated:

$$K_e = (4\,\pi^2\, m_e)/\, T_e^{\,2} \;= 23.3\ \text{MN/m}$$

The total base shear is thus calculated:

$$V_{\text{base, Total}} = K_e\, \Delta_{D,\ \text{Total}} = 7.01\ \text{MN}$$

The base shear is now distributed to the columns in proportion to the supported weight:

$$V_{\text{abutment}} = V_{\text{base}} \times P_{\text{abutment}} \,/\, W_e = 1.751\ \text{MN}$$

$$V_{\text{pier}} = V_{\text{base}} \times P_{\text{pier}} \,/\, W_e = 1.751\ \text{MN}$$

$$M_{\text{pier}} = V_{\text{pier}} \times H = 13.8\ \text{MN-m}$$

Isolation over strength factor = 1.25

$$M_{\text{Total}} = M \times \phi^{\circ} = 17.29\ \text{MN}$$

Conclusions

- Performance-Based Design is an alternative to the current Force-Based Design and ensures that the performance of a bridge would meet rational target structural and economic criteria.

- Direct Displacement-Based Design procedure is relatively fast, easy to apply and more rational.

- However, in order to apply this procedure to design and retrofit of bridges, certain ingredients such as data related to seismic hazard levels, design displacement spectra and displacement limits have to be provided.