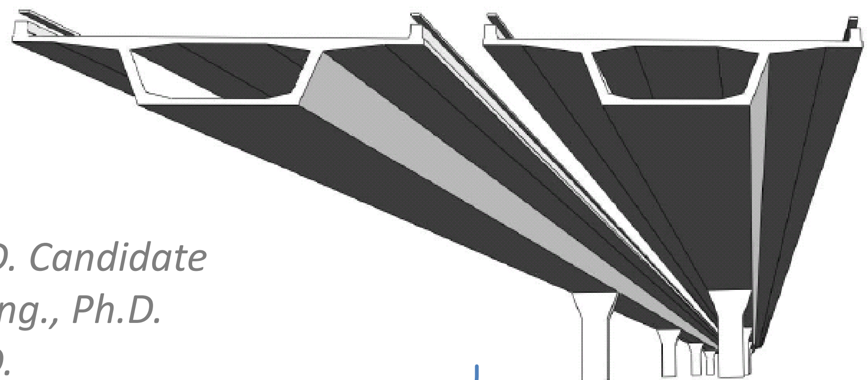
UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE & ENGINEERING

Design Guidelines for Isolated and Damped Bridges in Canada



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CSRN Canadian Seismic Research Network
RCRP Réseau canadien pour la recherche parasismique

Funded by NSERC / *Subventionné par le CRSNG*

26 Mai, 2011

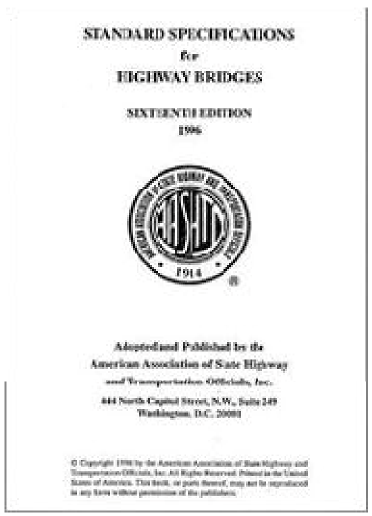
1. Introduction

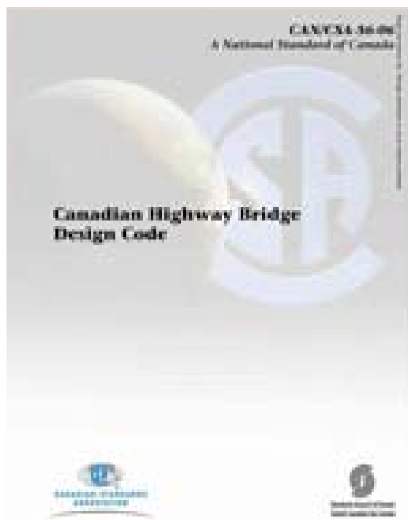
- Bridge Design Code:
  - CSA-S6;
  - 1994 AASHTO LRFD Highway Bridge Specification
- Design Performance Events:
  - 10%-50 years (475 years);
  - 2%-50 years (2500 years)
- Time-Histories for Eastern Canada:
  - Lack of Historical Records;
  - Artificial Records (e.g. Atkinson 2009);
  - Hybrid Records (e.g. McGuire 2001)

2. Problem Formulation and Project Goals

PROBLEM FORMULATION

- High risk of earthquake impact persists in Eastern Canada;
- Canadian Highway Bridge Design Code CSA-S6-06 is based on seismic ground motions adapted for western regions of Canada ;
- Assessment and Retrofit Update for existing bridges .





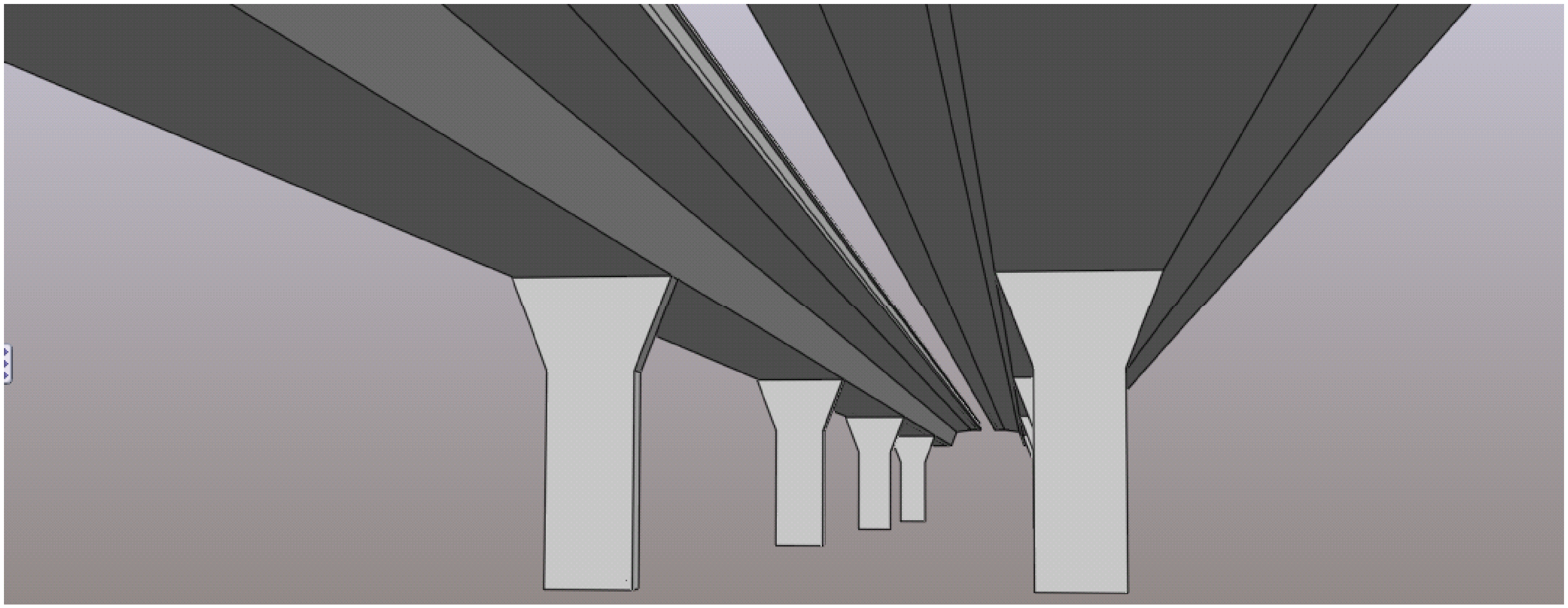
New Code
CAN/CSA-S6

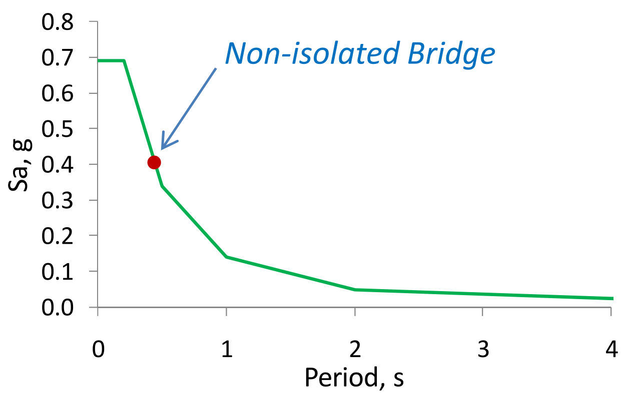
Retrofit Update
of
Existing Bridges

GOALS

- Updating Clause 4.10 of CSA-S6 Standard on isolated bridges;
- Development of an analytical tool for assessing isolated bridge behaviour under seismic demand.

3. Bridge Base Isolation





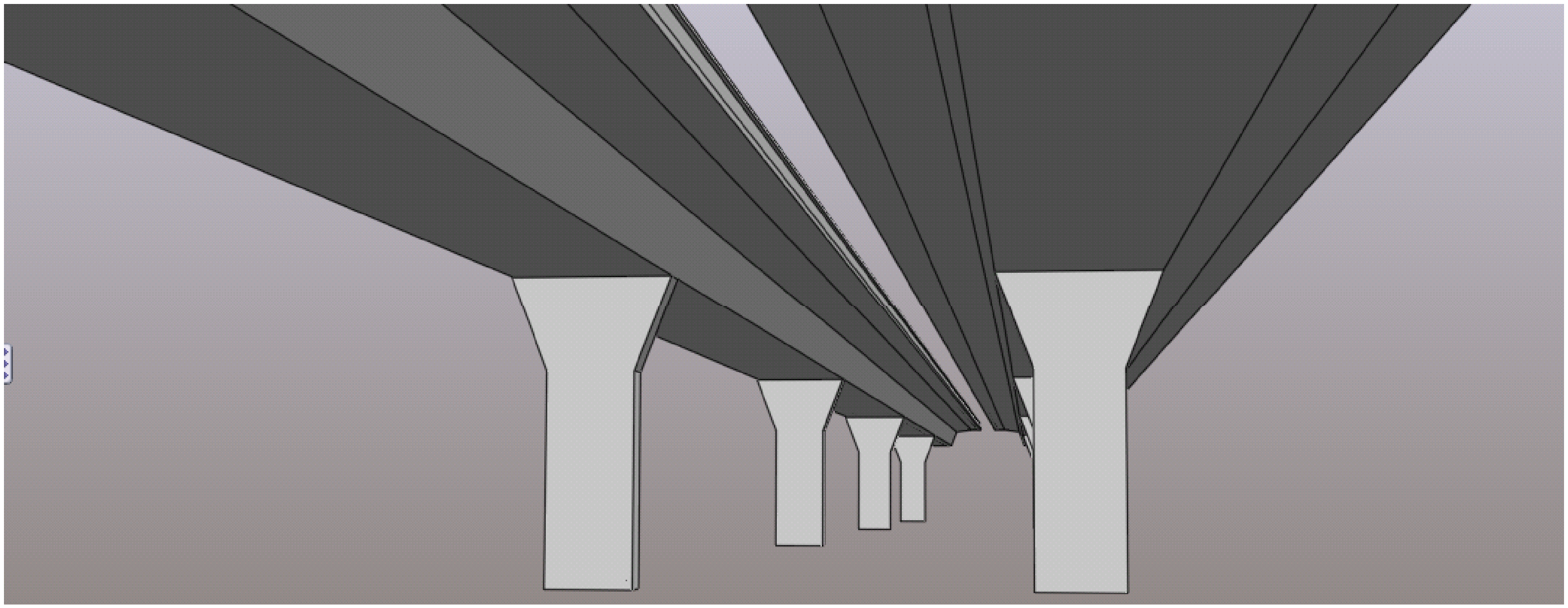
$$d_i = \frac{0.25 \cdot A \cdot S_i \cdot T_e}{B} \,(m)$$

⇩

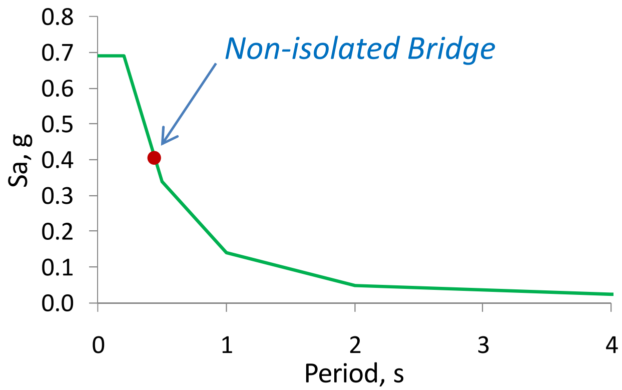
$$S_d = \frac{T_e^2}{4 \cdot \pi^2} \frac{A \cdot S_i}{B \cdot T_e} \cdot g$$

CAN/CSA-S6: Clause 4.10.6.2.1
(Statically Equivalent Force)
Displacement across isolation bearing

3. Bridge Base Isolation

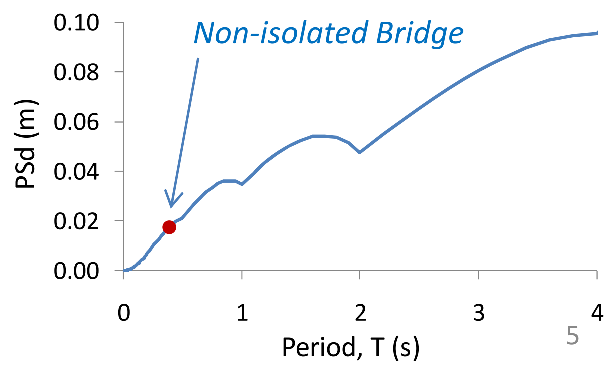


CAN/CSA-S6: Cl. 4.10.6.2.1



$$S_d = \frac{T_e^2}{4 \cdot \pi^2} \cdot \frac{A \cdot S_i}{B \cdot T_e} \cdot g$$

$$PS_d = \frac{S_a}{w^2}$$



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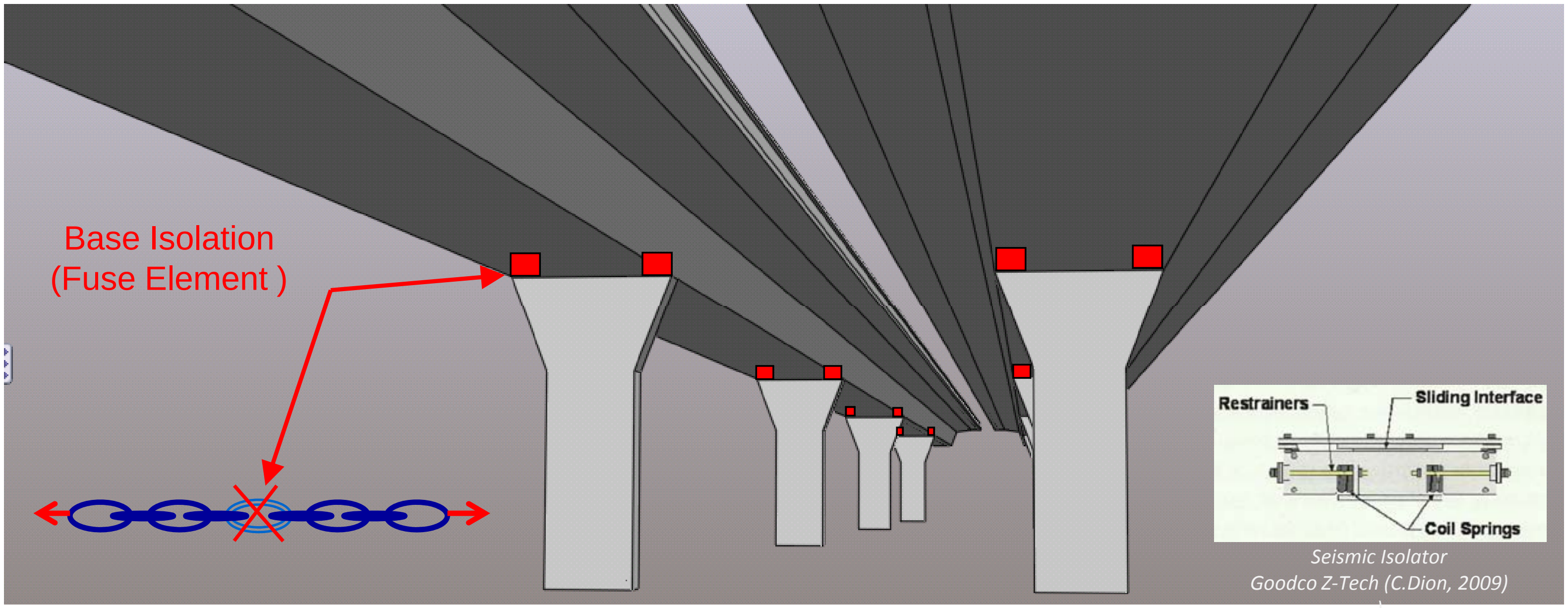
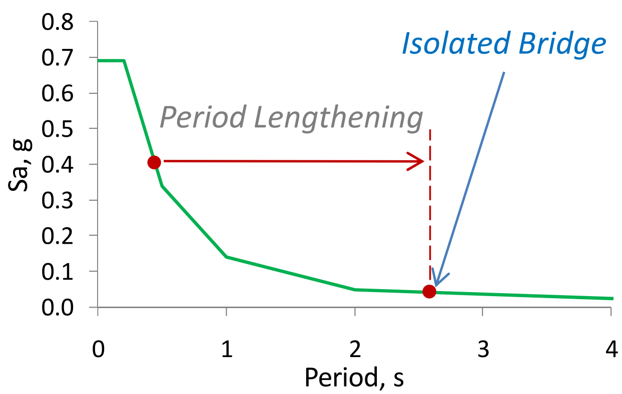
3. Bridge Base Isolation

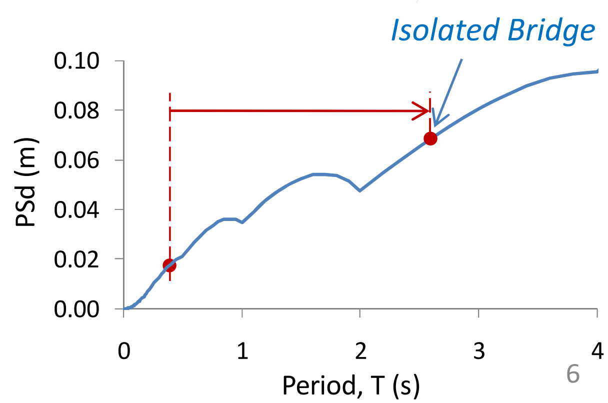




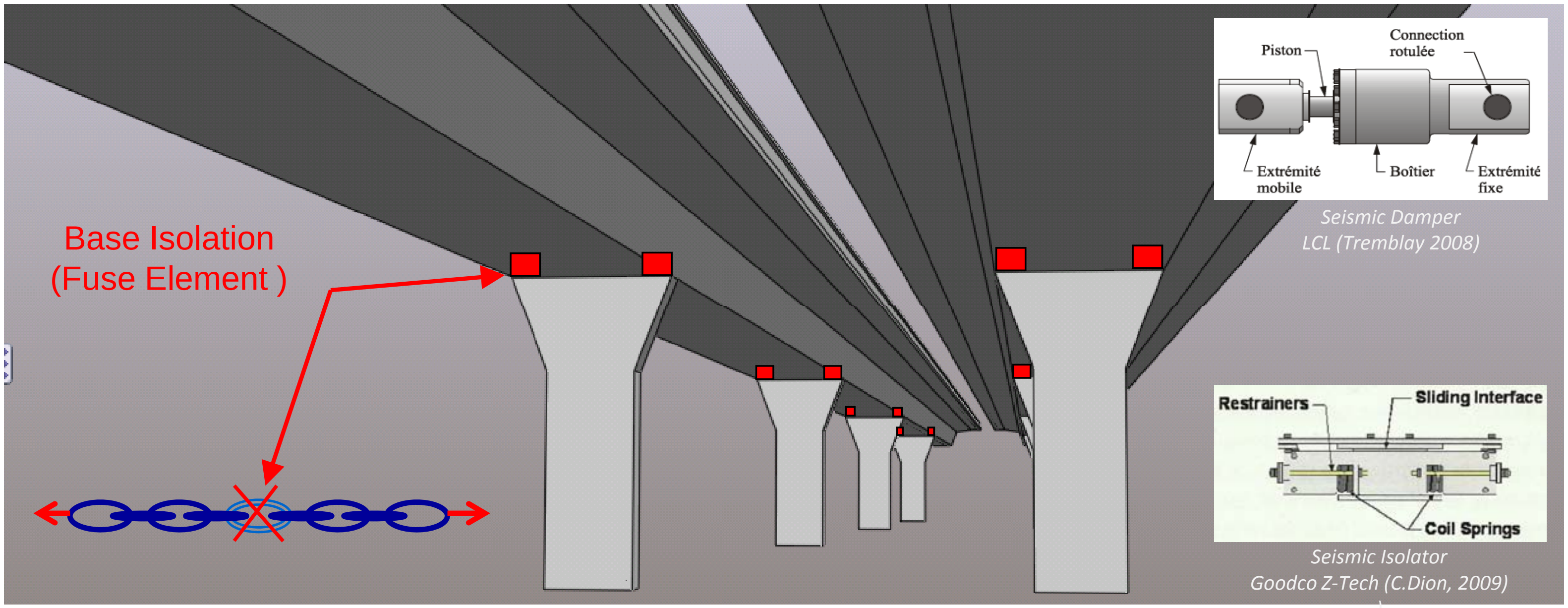
$$S_d = \frac{T_e^2}{4 \cdot \pi^2} \frac{A \cdot S_i}{B \cdot T_e} \cdot g$$

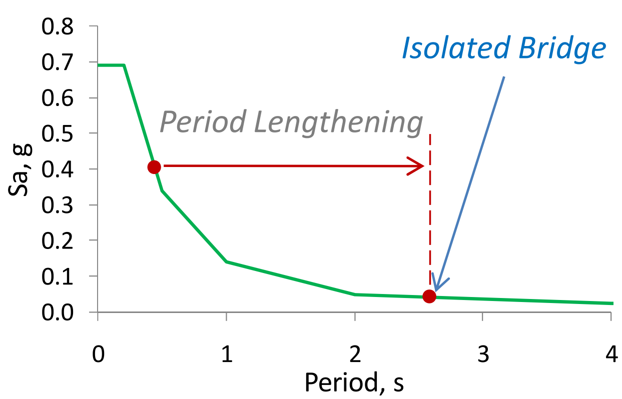
⇩

$$S_d = \frac{S_a}{w^2}$$



3. Bridge Base Isolation

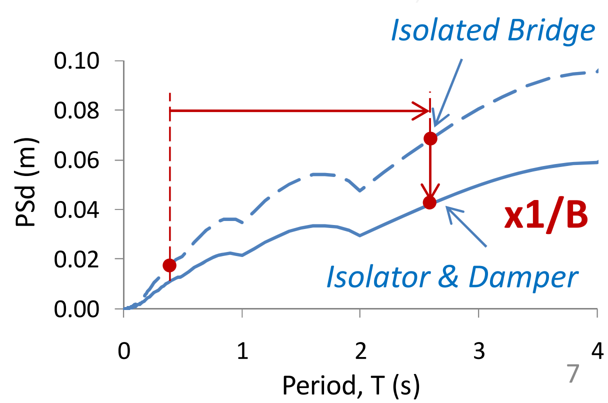




$$S_d = \frac{T_e^2}{4\cdot\pi^2}\cdot\frac{A\cdot S_i}{B\cdot T_e}\cdot g$$

⇩

$$S_d = \frac{S_a}{w^2}$$



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4. Damping Reduction Coefficient, B

Different Code Provisions

CAN/CSA-S6-06

Table 4.8
Damping coefficient, *B*
(See Clauses 4.10.6.2.1 and 4.10.11.2.)

Equivalent viscous damping, β (% of critical)	Damping coefficient, B
≤2	0.8
5	1
10	1.2
20	1.5
30	1.7
40	1.9
50	2

Note: *The percentage of critical damping shall be verified by a test of the isolation system's characteristics as specified in Clause 4.10.11.3.3. The damping coefficient shall be based on linear interpolation for damping levels other than those specified in this Table. For isolation systems where the effective damping exceeds 30% of critical, a three-dimensional non-linear time-history analysis shall be performed using the hysteresis curves of the system, unless B is limited to 1.7.*

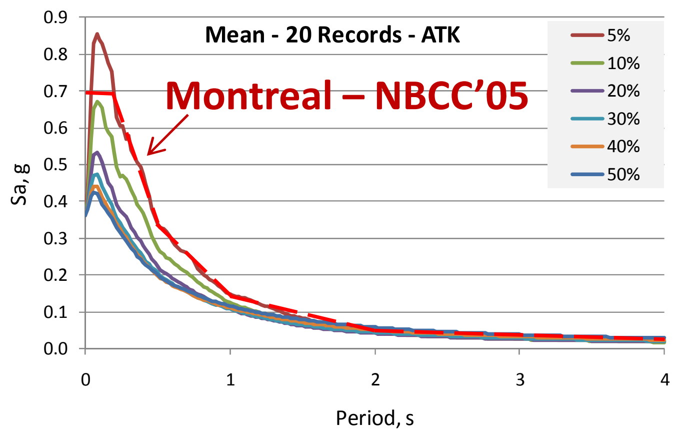
β	AASHTO (1994)	AASHTO (2009)	EUROCODE 8	FEMA 273 (1997) FEMA 356 (2000)	FEMA 273 (1997) FEMA 356 (2000)
(%)	B	B	1/μ	B_s	B_1
2	0.8	0.76	0.84	0.8	0.8
5	1.0	1.00	1.00	1.0	1.0
10	1.2	1.23	1.22	1.3	1.2
20	1.5	1.52	1.58	1.8	1.5
30	1.7	1.71	1.87	2.3	1.7
40	1.9	1.87	2.12	2.7	1.9
50	2.0	2.00	2.35	3.0	2.0

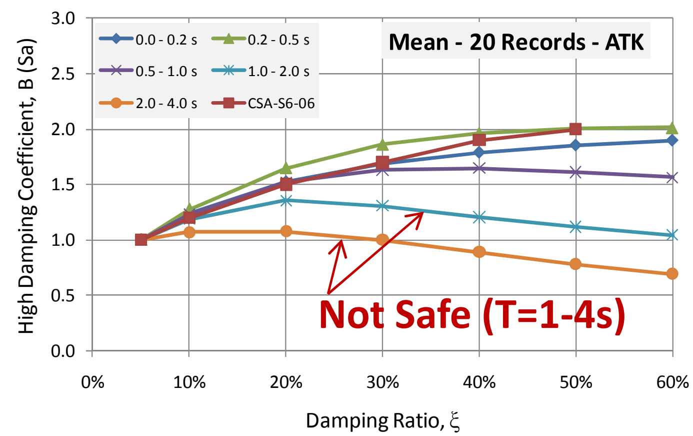
β	UBC (1994)	ATC-40 (1996)	ATC-40 (1996)	Newmark & Hall (1982)		
(%)	B	B_s	B_1	A Region	V Region	D Region
2				0.77	0.81	0.85
5	1.00	1.00	1.00	1.00	1.00	1.00
10	1.19	1.30	1.22	1.29	1.20	1.16
20	1.56	1.82	1.54	1.81	1.53	1.38
30	1.89	2.38	1.82			
40		3.03	2.08			
50						

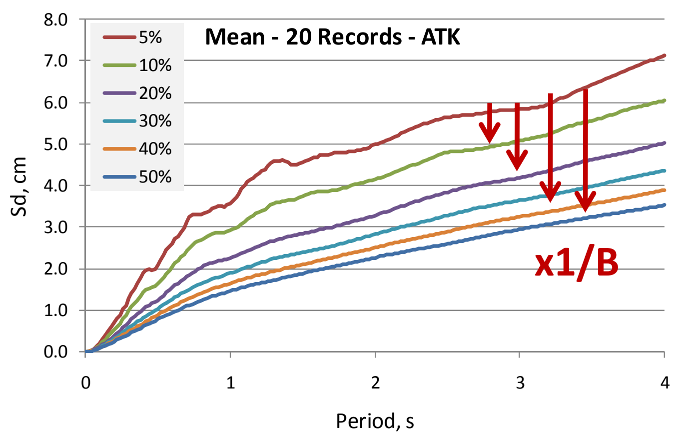
T=0.50s T=3.33s

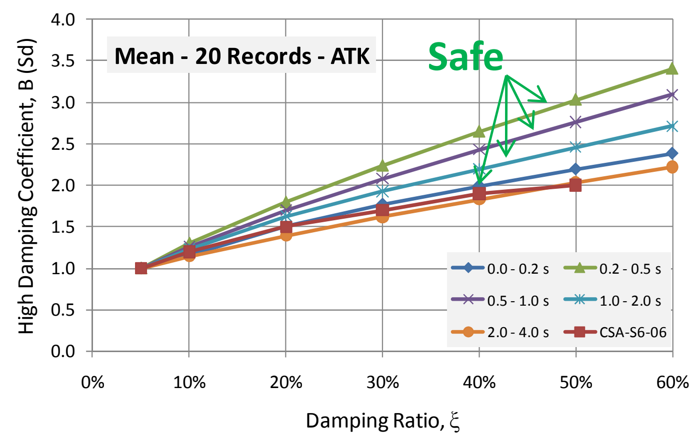
4. Damped Elastic Response Spectra

Mean of 20 Artificial Records (Atkinson 2009)
Montreal – 2% in 50 years – Soil Class C



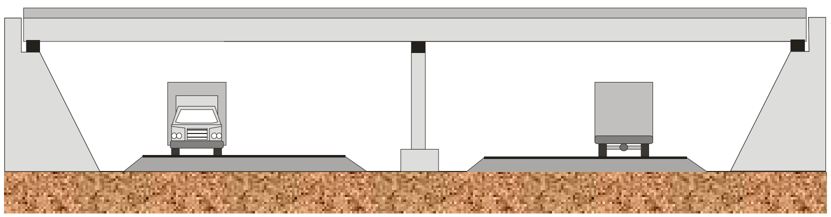




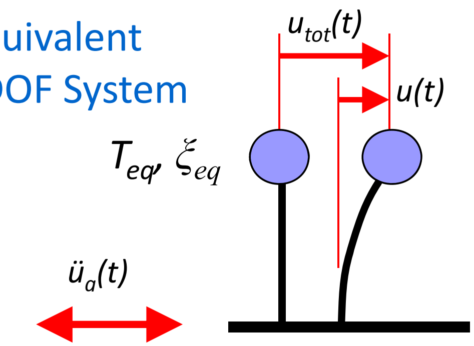


5. Existing Isolated Bridge – Linear Equivalent System

Isolated Bridge – Nonlinear Behaviour



Equivalent SDOF System



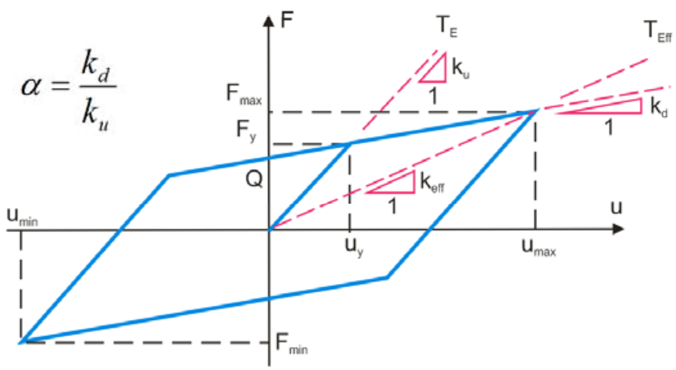
$$\beta_{eff} = \frac{1}{4\pi}\cdot\frac{Eh}{Es} = \frac{2}{\pi}\cdot\frac{Q\cdot(u_{max}-u_y)}{k_{eff}\cdot u_{max}^2} = \frac{2}{\pi}\cdot\frac{(\mu-1)\cdot(1-\alpha)}{\mu\cdot(1+\alpha\mu-\alpha)}$$

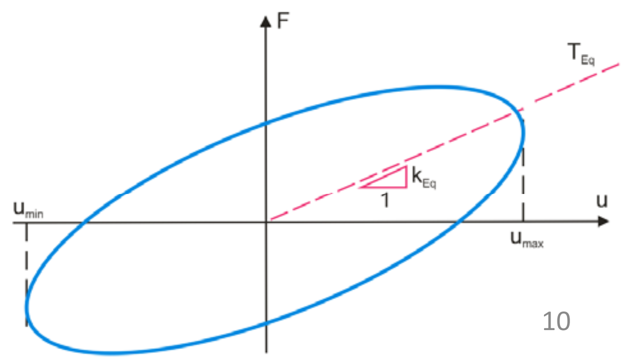
$$T_{eff} = T_e\cdot\sqrt{\frac{\mu}{1+\alpha\mu-\alpha}}$$

$$\xi_{eq} = \beta_{eff}$$

$$T_{eq} = T_{eff}$$

$$\alpha = \frac{k_d}{k_u}$$





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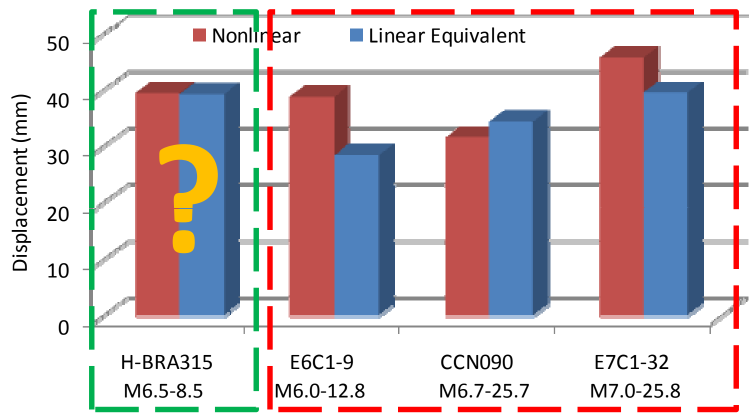
5. Equivalent System

Bridge Response under 4 earthquake records

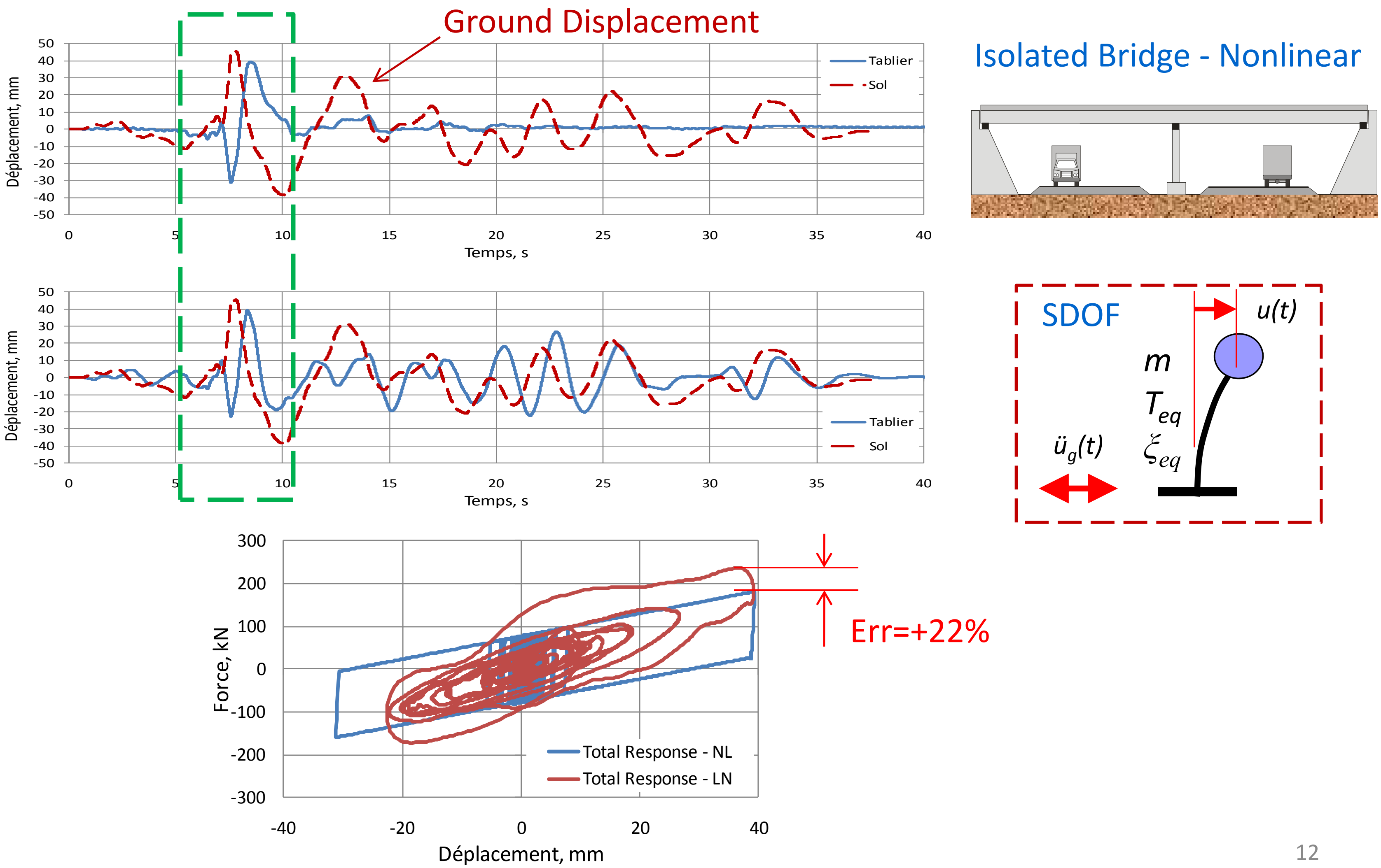
Analysis Type and Parameters	Hybrid H-BRA315 M 6.5 R 8.5km	Artificial E6C1-9 M 6.0 R 12.8 km	Hybrid CCN090 M 6.7 R 25.7 km	Artificial E7C1-32 M 7.0 R 25.8 km
Nonlinear (α=kd/ku=0.01)				
Elastic Period, Te (s)	0.34	0.34	0.34	0.34
Added Damping, ξ (%)	0	0	0	0
Effective Damping, β (%)	26.6	26.8	30	24.3
Effective Period, Teff (s)	2.6	2.6	2.5	2.7
Displacement Response (mm)	***39***	***39***	***32***	***46***
Linear Equivalent				
Equivalent Damping, ξ (%)	26.6	26.8	30	24.3
Equivalent Period, Teq (s)	2.6	2.6	2.5	2.7
Displacement (mm)	***39***	***28***	***35***	***40***



Ok! **-28%** **+9%** **-13%**

5. Equivalent System

Comparison – Displacement Response (EQ: H-BRA315)



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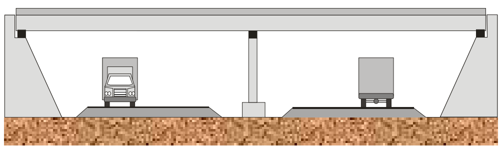
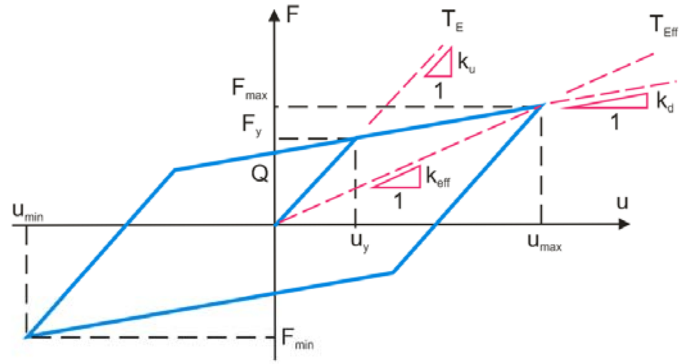
5. Equivalent System

Code - Bilinear Hysteretic Systems

Isolated Bridge - Nonlinear





CAN/CSA-S6-06

4.10.11.3.3 Design properties of the isolation system

The following requirements shall apply to the design properties of the isolation system:

(a) The minimum and maximum effective stiffness of the isolation system shall be determined as follows:
   (i) The value of k_{min} shall be based on the minimum effective stiffnesses of individual isolator units as determined by the cyclic tests of Clause 4.10.11.2(c)(ii) at a displacement amplitude equal to the design displacement.
   (ii) The value of k_{max} shall be based on the maximum effective stiffnesses of individual isolator units as determined by the cyclic tests of Clause 4.10.11.2(c)(ii) at a displacement amplitude equal to the design displacement.

(b) The equivalent viscous damping ratio, β, of the isolation system shall be calculated as follows:

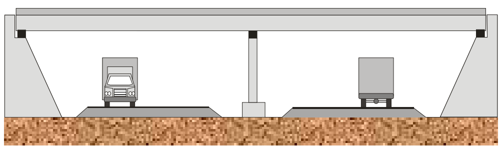
$$\beta = \frac{1}{2\pi} \bullet \frac{\text{Total area}}{\Sigma k_{max} d_i^2}$$

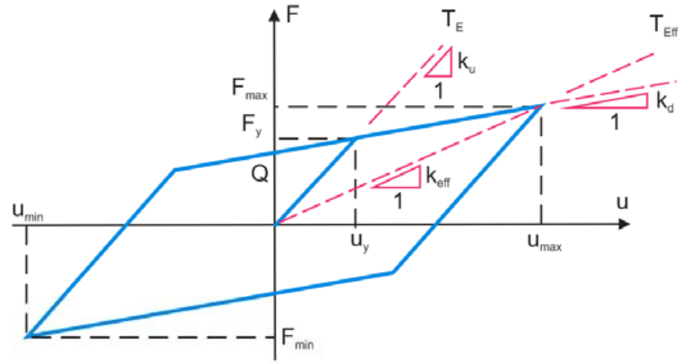
where the total area represents the energy absorbed by the isolation system in one cycle and shall be taken as the sum of the areas inside the hysteresis loops of all isolators. The hysteresis loop area of each isolator shall be taken as the minimum area of one cycle obtained from the three hysteresis loops established by the cyclic tests of Clause 4.10.11.2(c)(ii) at a displacement amplitude equal to the design displacement.

5. Equivalent System

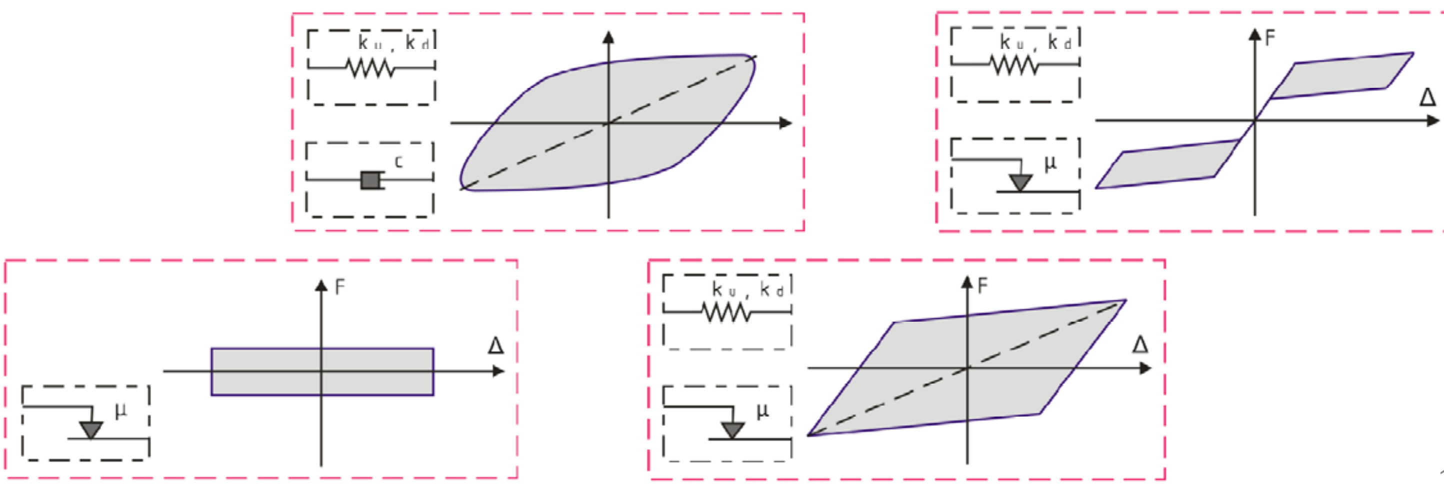
to prepare... provisions for variety of existing Isolation and Damping Systems

Isolated Bridge - Nonlinear

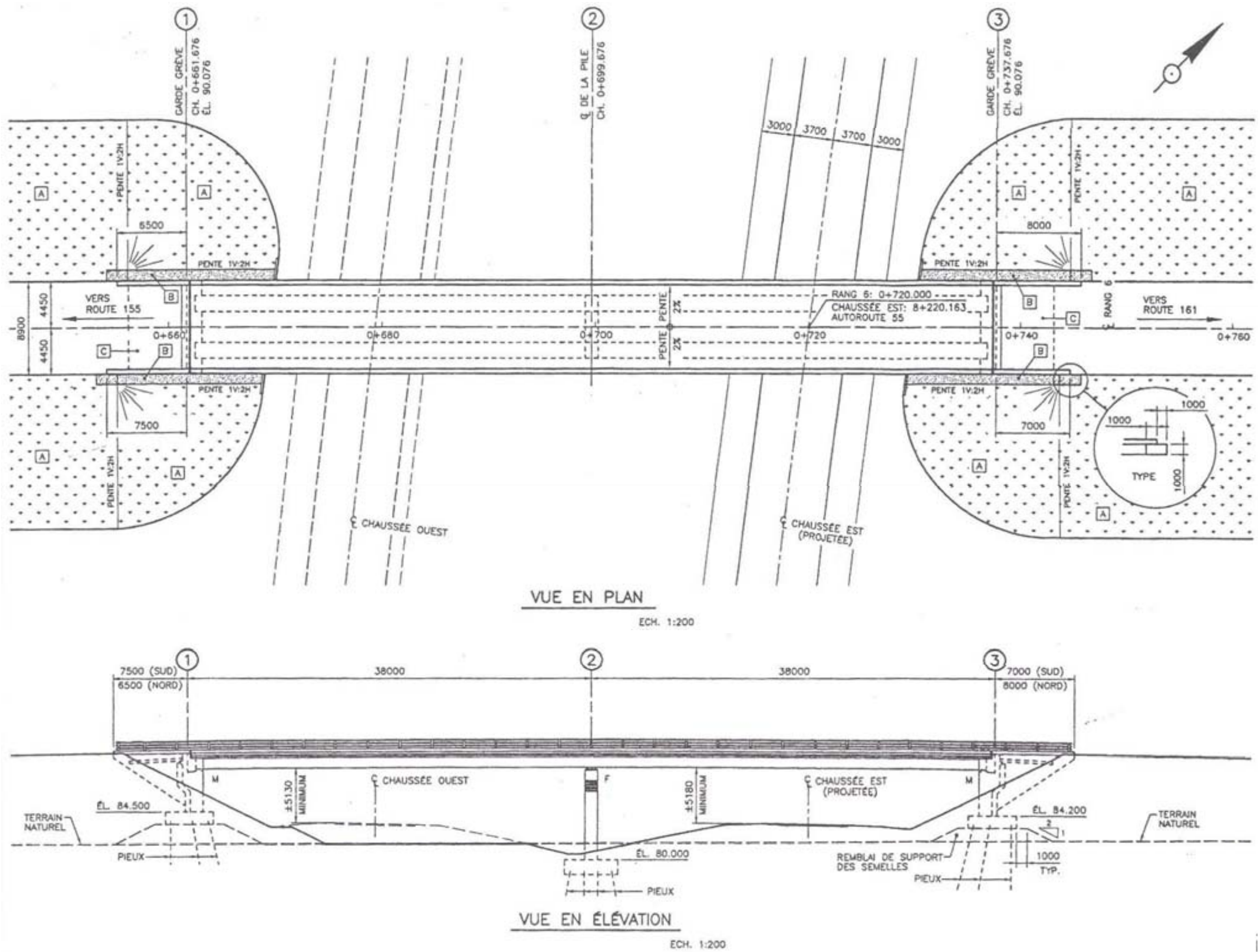




Combined Response of Existing Systems

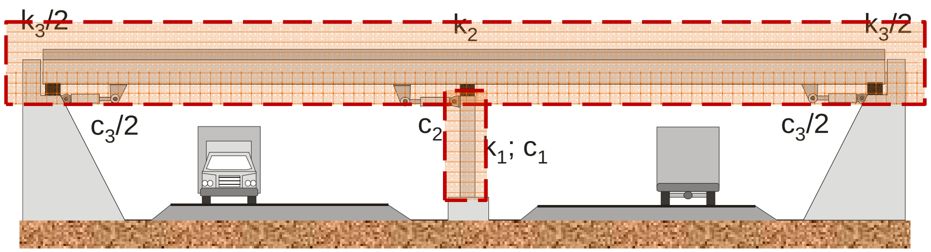


4. Analytical Tool - Existing Bridge (CSA-S6-88)



4.1 Isolated Bridge - Modeling

Analytical Tool – Model Assumptions

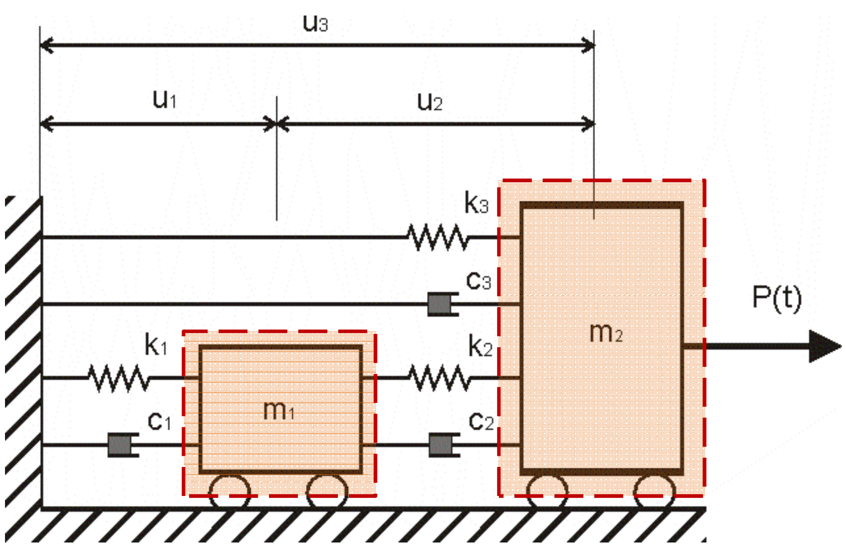


Deck Mass:

m_2 = 1 574 000 kg

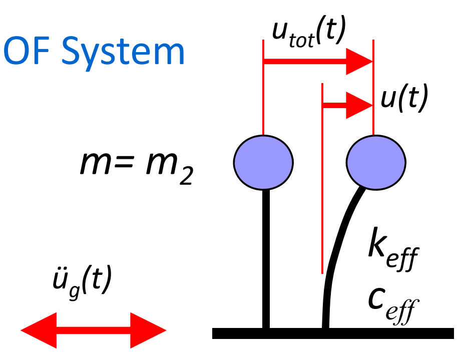
Pier Mass:

$m_1 \cong 0$ kg



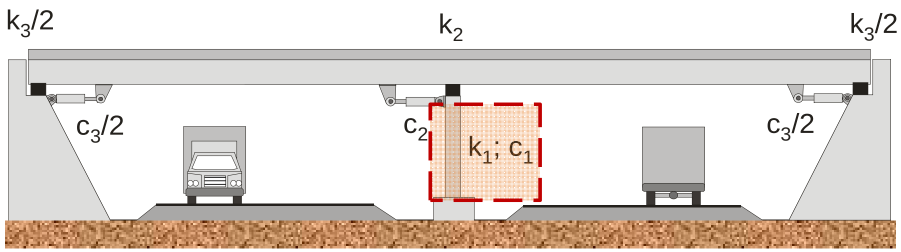
SDOF System

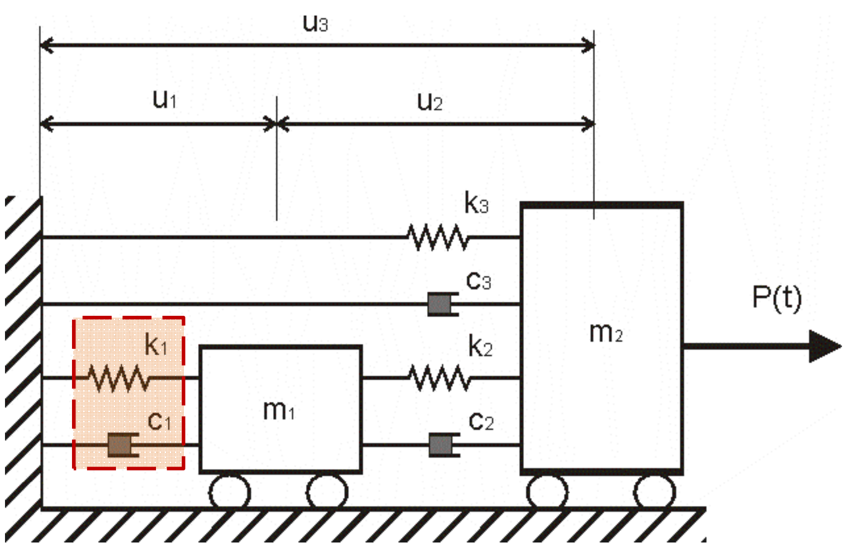
$m = m_2$

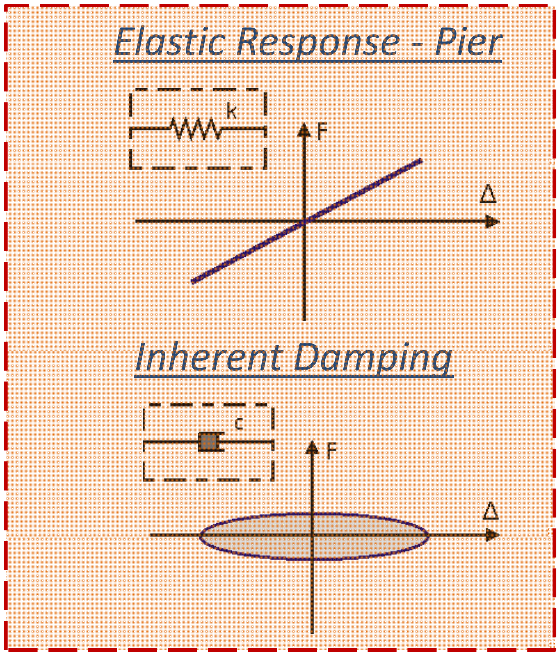


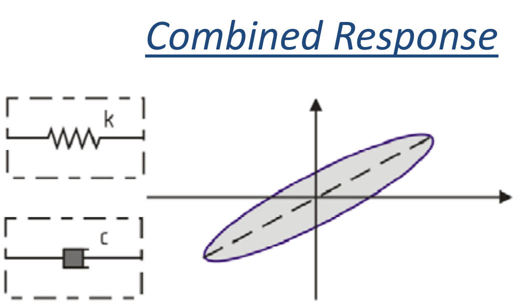
4.1 Isolated Bridge - Modeling

Analytical Tool – Model Assumptions





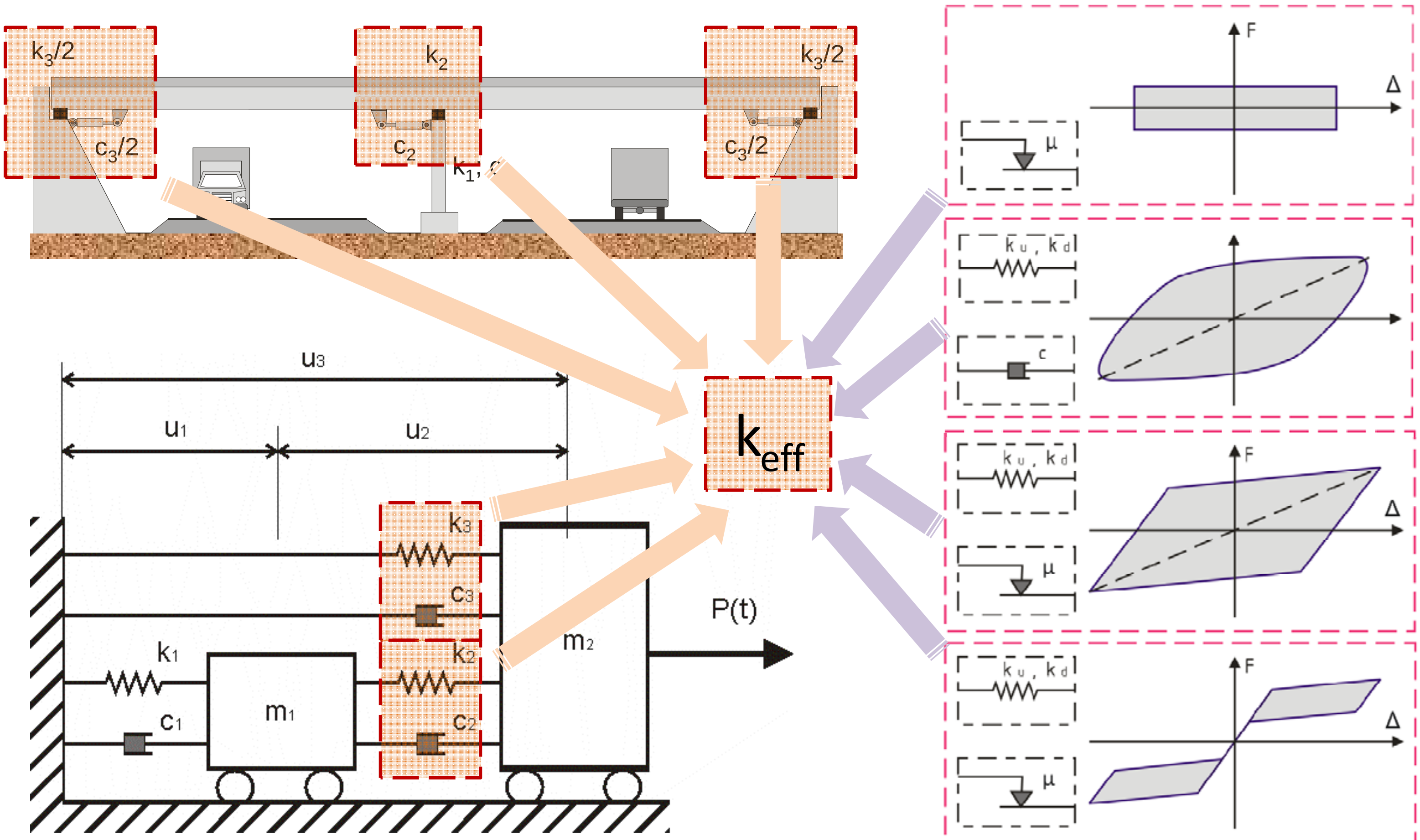




4.1 Isolated Bridge - Modeling

Analytical Tool – Model Assumptions

Isolator Response



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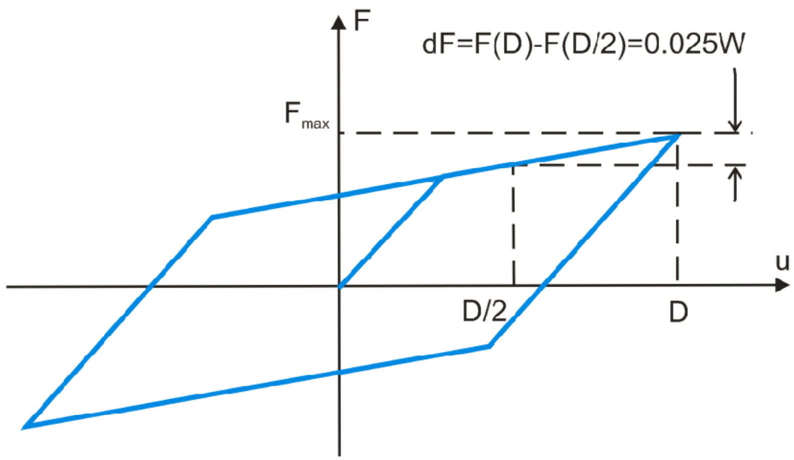
5. Isolator Restoring Force (CSA-S6-06 Cl.4.10.10.2)



CAN/CSA-S6-06

4.10.10.2 Lateral restoring force

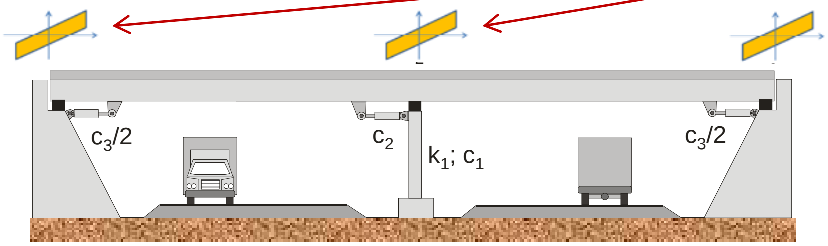
The isolation system shall be configured to produce a lateral restoring force such that the lateral force at the design displacement is at least 0.025*W* greater than the lateral force at 50% of the design displacement.

5.1 Restoring Force - Examples

Bridge Assessment: 3 Isolation Configurations

Restoring Force

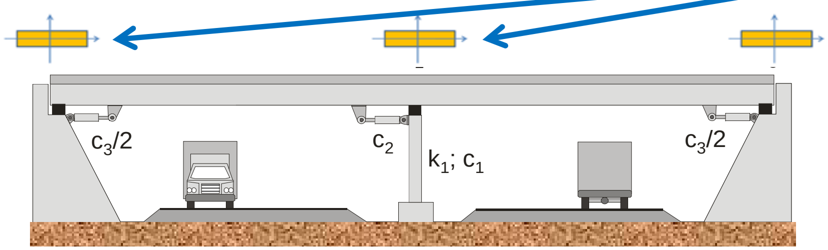
Configuration A:



Isolator	k_u (kN/m)	$\alpha=k_d/k_u$
Abutment	534 300	0.1
Pier	534 300	0.1

Sliding

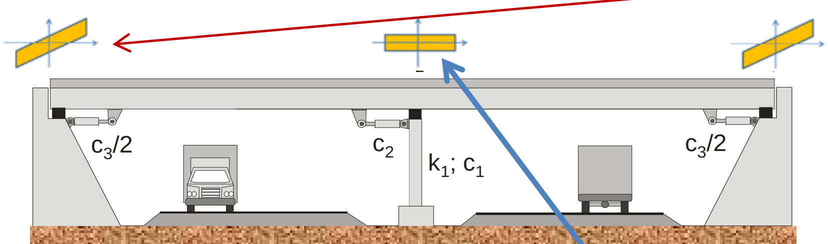
Configuration B:



Isolator	k_u (kN/m)	$\alpha=k_d/k_u$
Abutment	534 300	0.0
Pier	534 300	0.0

Restoring Force

Configuration C:



Isolator	k_u (kN/m)	$\alpha=k_d/k_u$
Abutment	534 300	0.1
Pier	534 300	0.0

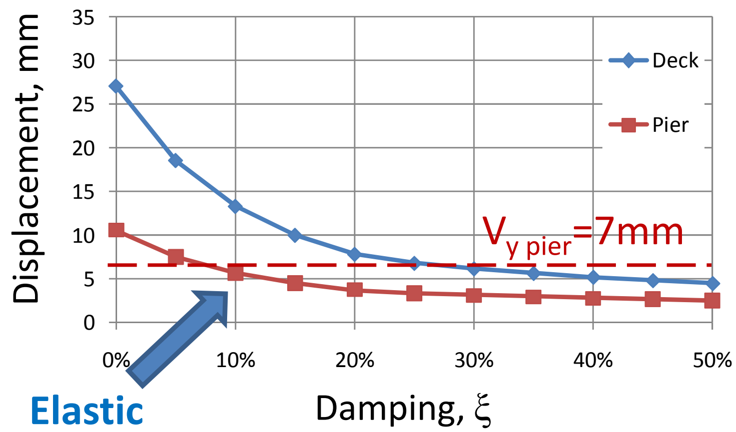
Sliding

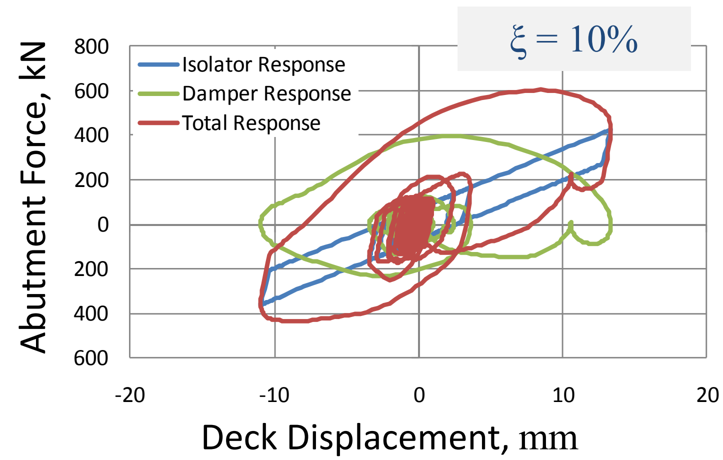
5.1 Restoring Force - Examples

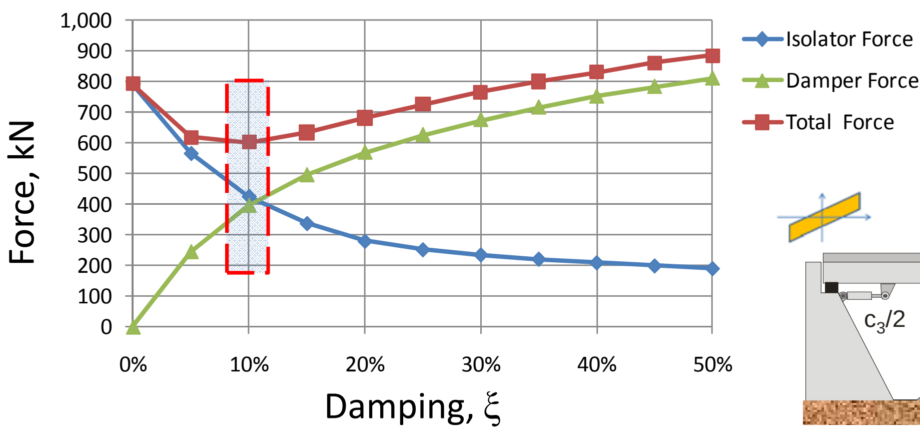
Seismic Isolation Deck-Abutment and Deck-Pier

Configuration A: Responses

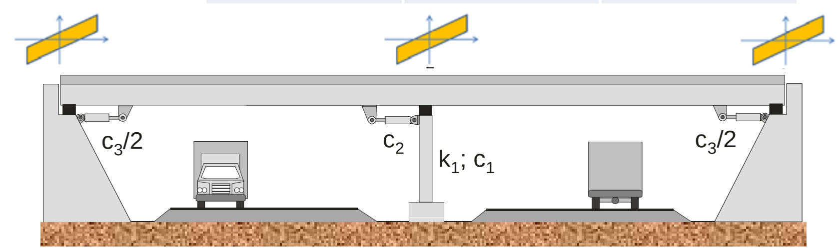
Configuration A: $\alpha_{(abutm)} = 0.1$ and $\alpha_{(pier)} = 0.1$







Isolator	k_u (kN/m)	$\alpha = k_d/k_u$
Abutment	534 300	0.1
Pier	534 300	0.1



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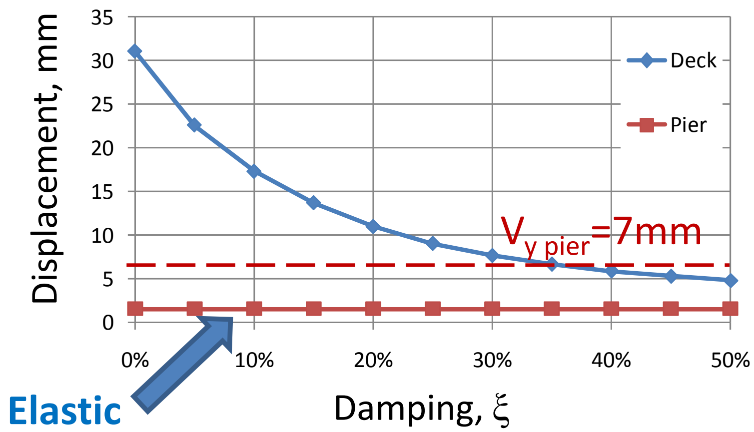
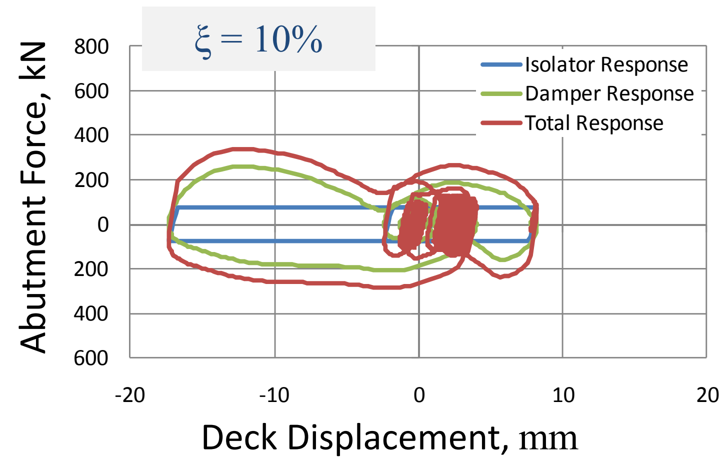
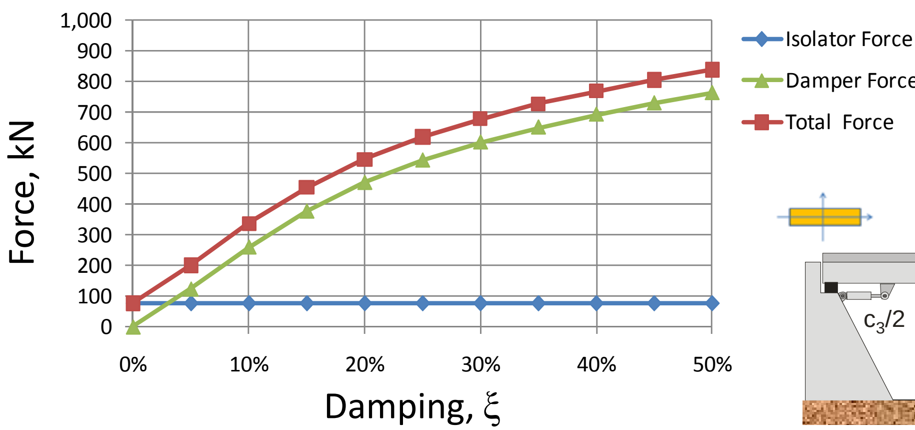
5.1 Restoring Force - Examples

Configuration B: Responses

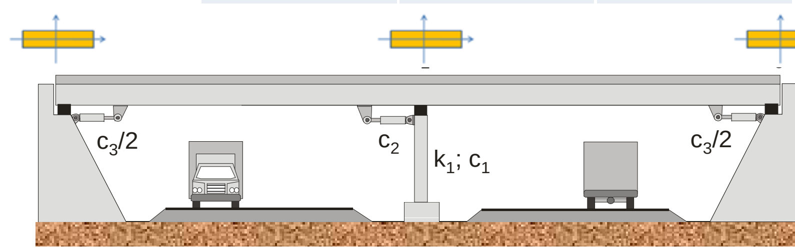
Seismic Isolation Deck-Abutment and Deck-Pier Configuration B: $\alpha_{(abutm)} = 0.0$ and $\alpha_{(pier)} = 0.0$







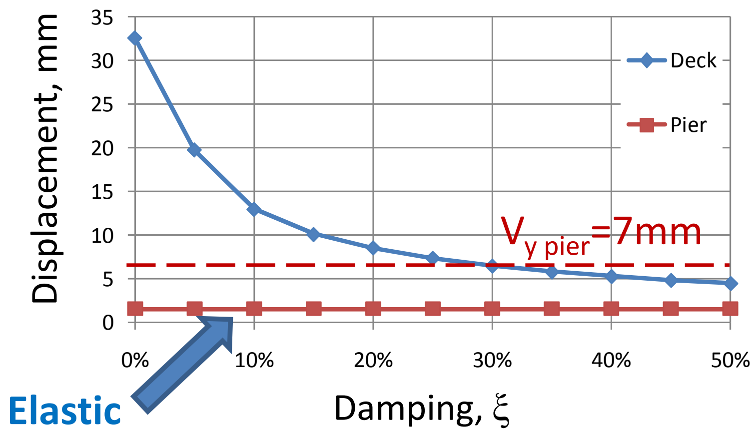
Isolator	k_u (kN/m)	$\alpha = k_d/k_u$
Abutment	534 300	0.0
Pier	534 300	0.0

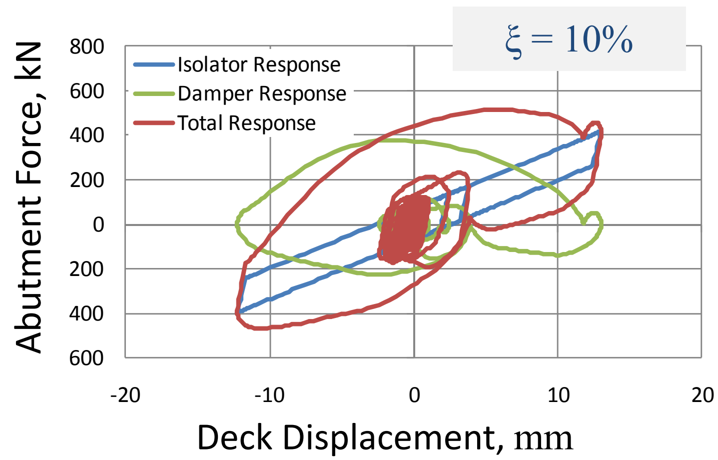


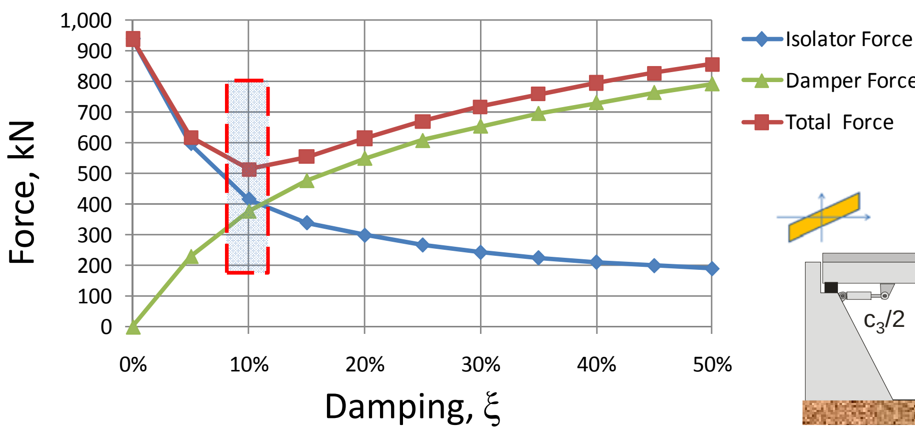
5.1 Restoring Force - Examples

Configuration C: Responses

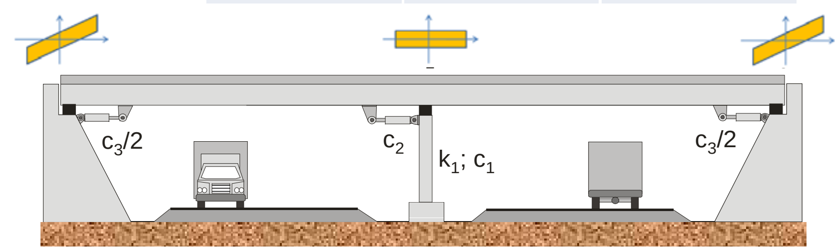
Seismic Isolation Deck-Abutment and Deck-Pier Configuration A+B: $\alpha_{(abutm)} = 0.1$ and $\alpha_{(pier)} = 0.0$







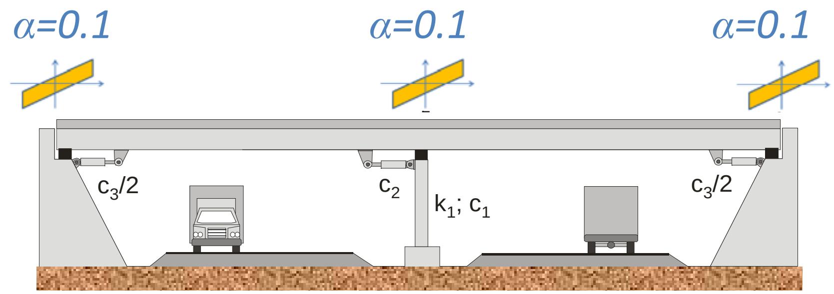
Isolator	k_u (kN/m)	$\alpha = k_d/k_u$
Abutment	534 300	0.1
Pier	534 300	0.0

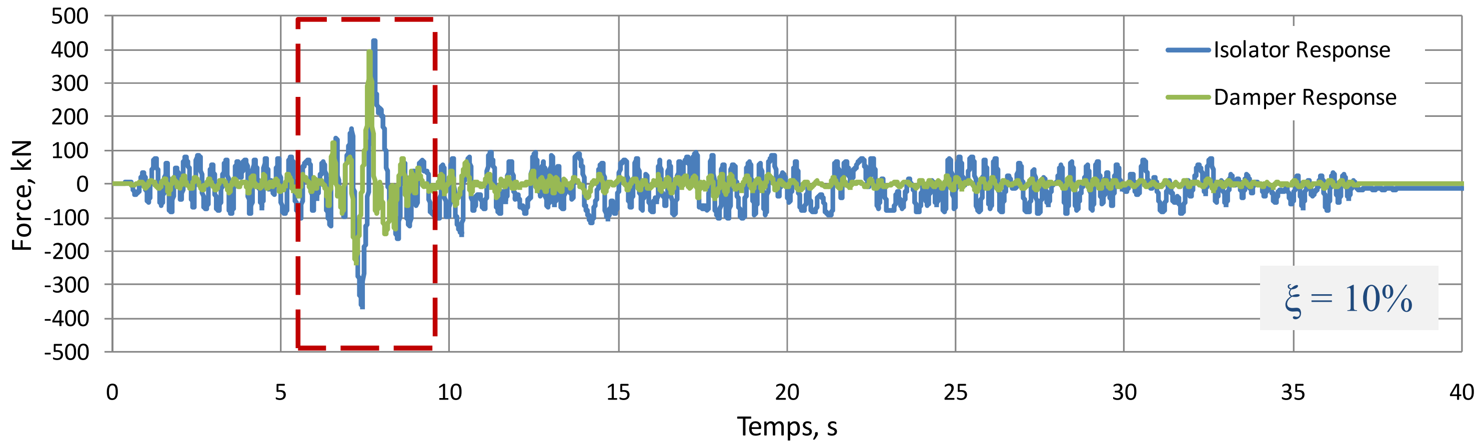


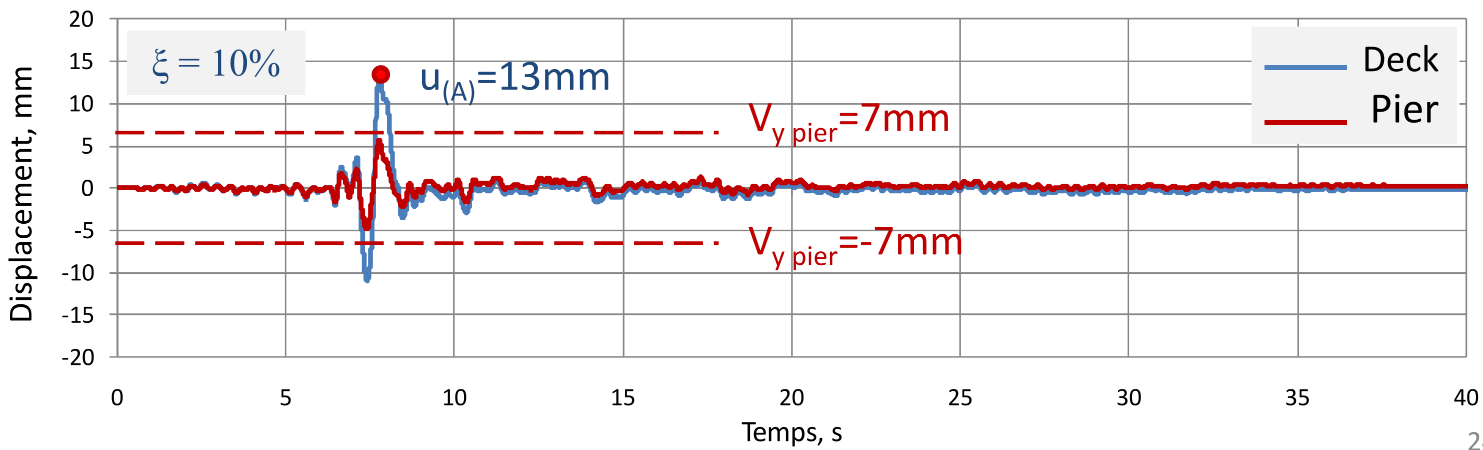
5.1 Restoring Force - Examples

Configuration A:

Time-history responses



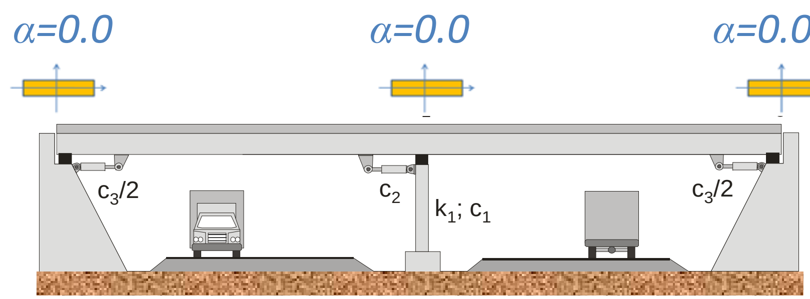


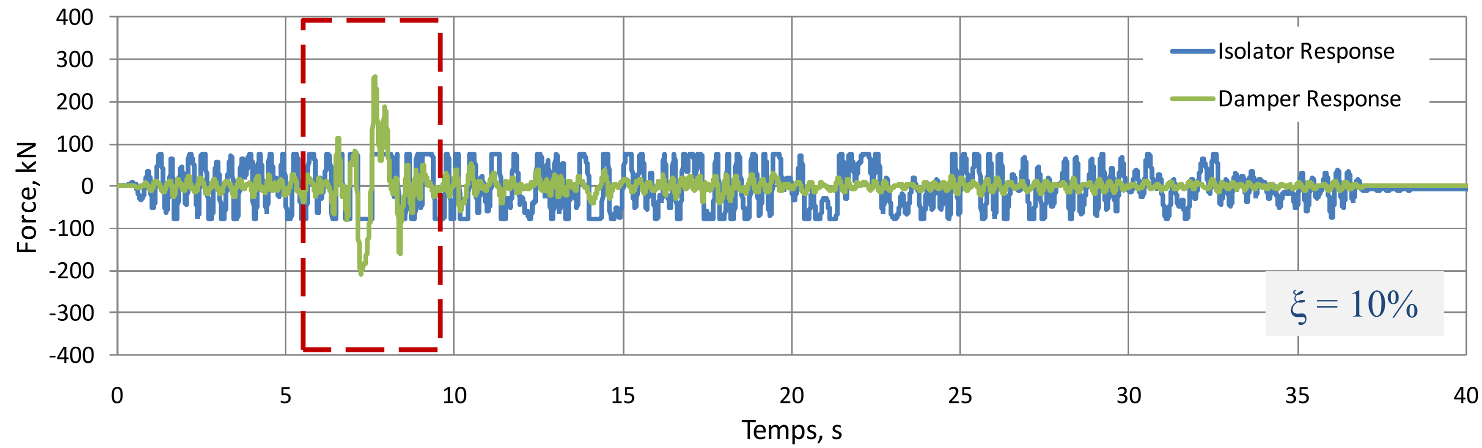


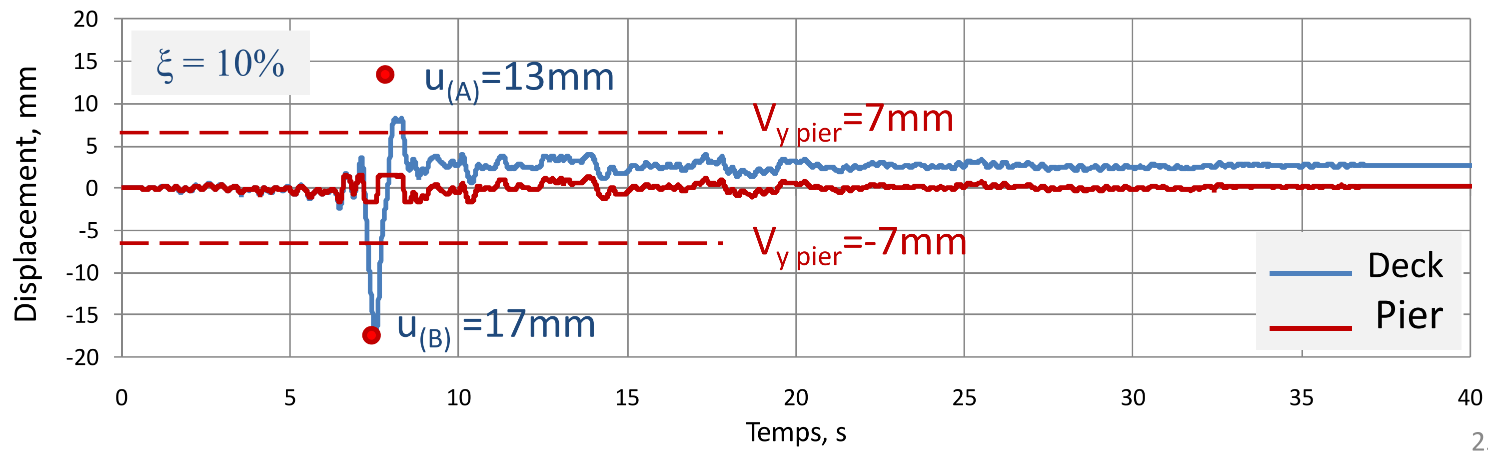
5.1 Restoring Force - Examples

Configuration B:

Time-history responses



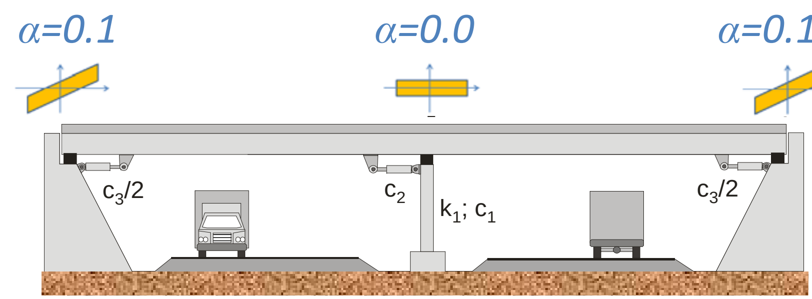


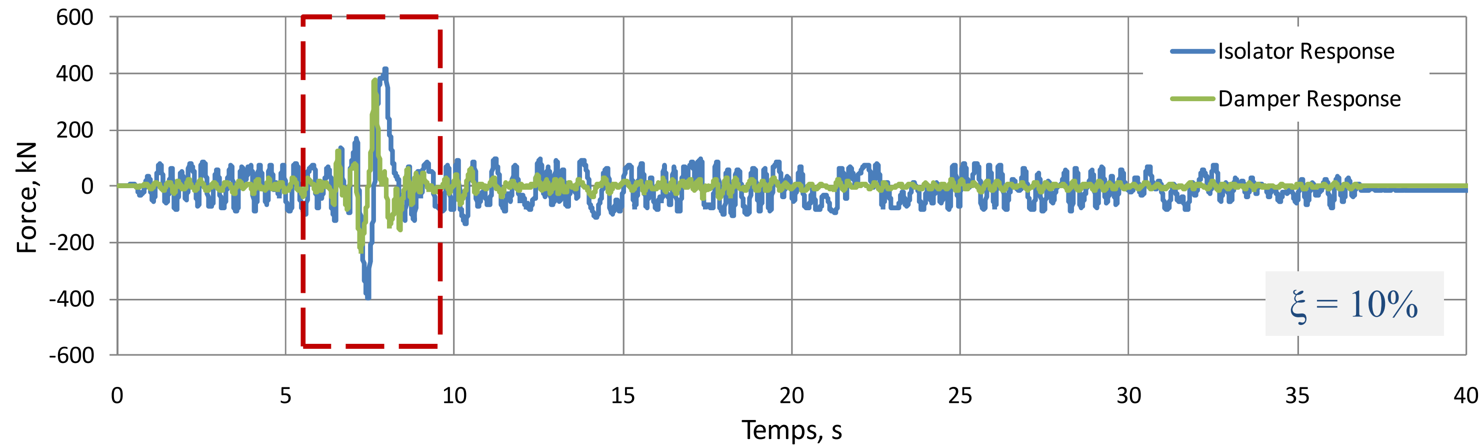


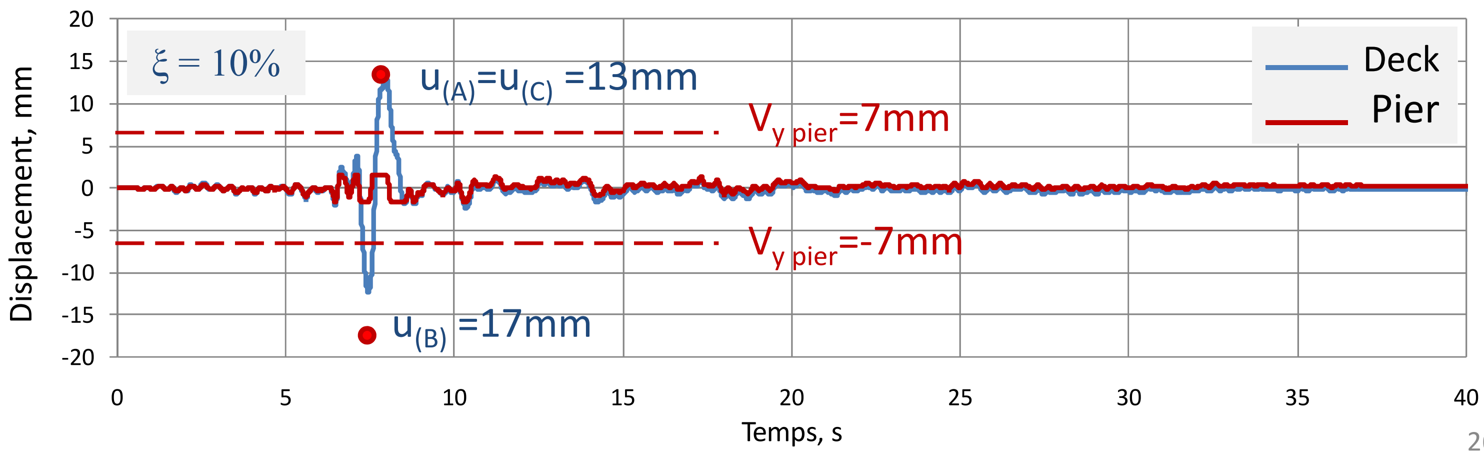
5.1 Restoring Force - Examples

Configuration C:

Time-history responses

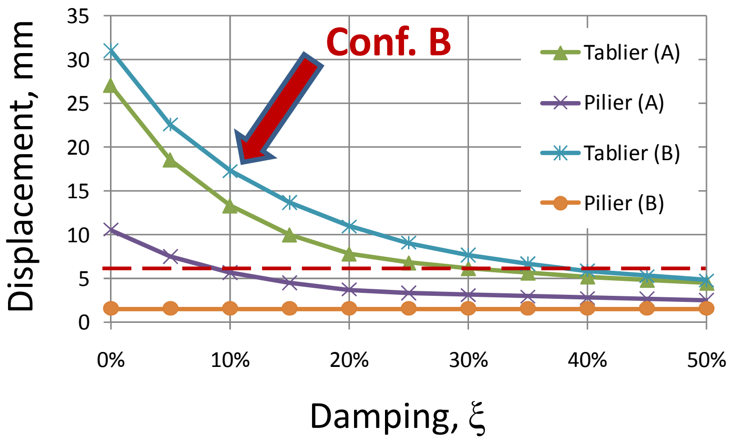


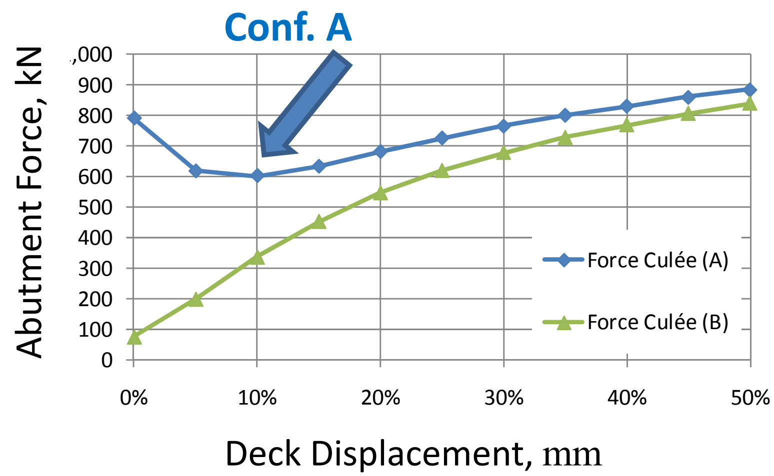




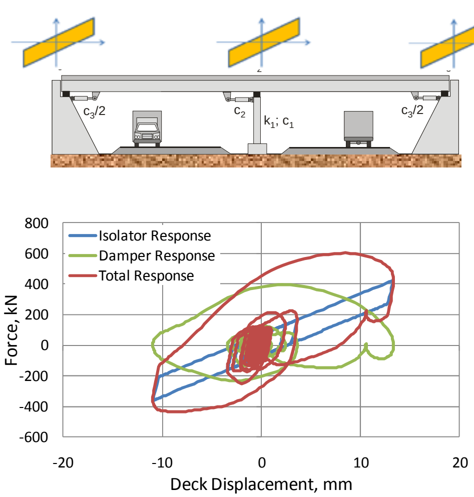
5.2 Restoring Force - Comparison

Results Discussion

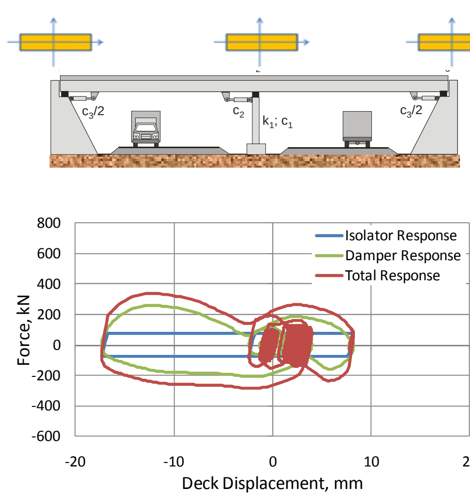




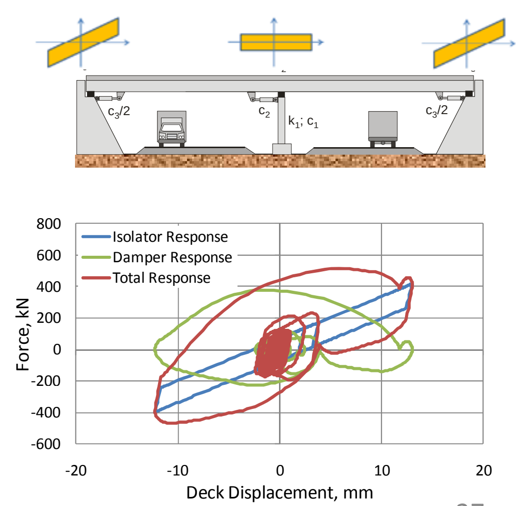
Configuration A:



Configuration B:



Configuration C:



Conclusions

1. Proposed Analytical Tool makes it possible to predict the response of Isolated Bridge under seismic demand
2. Existing in the Code S6 high damping coefficients, B, do not provide reliable response transformation for nonlinear systems and must be re-evaluated for Eastern Canadian regions.
3. Simplified model of a bilinear isolation system presented in the current Code S6 does not cover a variety of existing devices and must be complemented.
4. Existing in the Code S6 provision for required Isolator Restoring Force does not reflect combined effect of existing isolation and damping devices and must be re-examined for the new code edition.