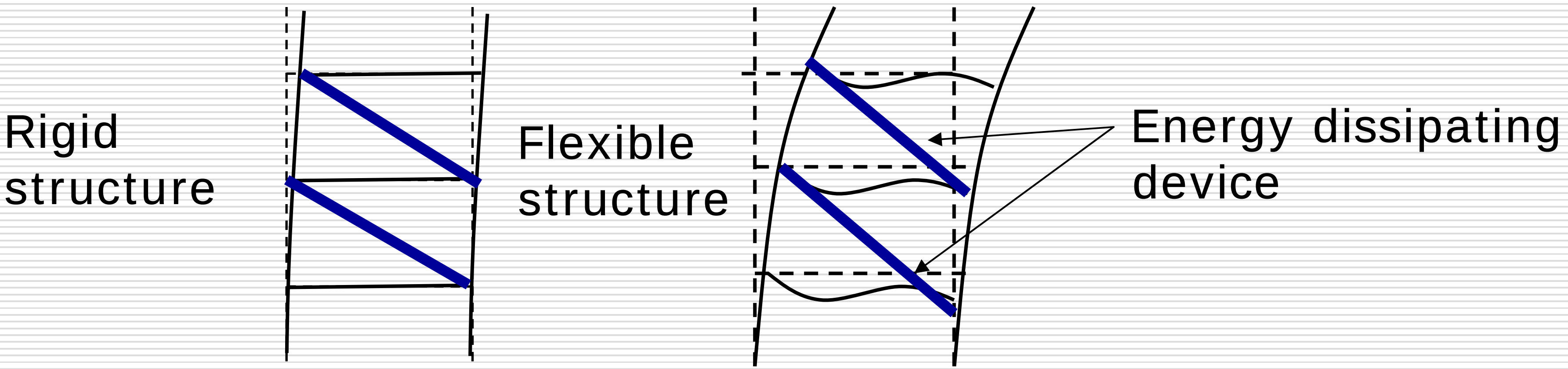
Response Modification of Urban Infrastructure
都市施設の免震設計
Chapter 3 Response Control
3章　制震設計

Kazuhiko Kawashima
Tokyo Institute of Technology
東京工業大学
川島一彦

3.1 Response Control

1) What structures are favorable for implementation of response control?

- Response control is one of the passive control algorithms. Structural response is controlled by installing energy dissipaters.
- Response control is effective for flexible structures which deforms considerably resulting in large relative velocity or relative displacement between nodal points. Energy dissipaters are installed between those nodal points.



1) What structures are favorable for implementation of response control? (contd.)

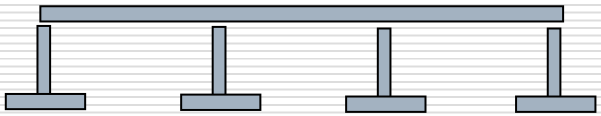
a) Building application

- Energy dissipaters cannot dissipate energy if a structure is rigid. Therefore, the response control is generally used in tall and steel frame buildings.
- Reinforced concrete buildings are nor favorable for implementation of response control.

b) Bridge application

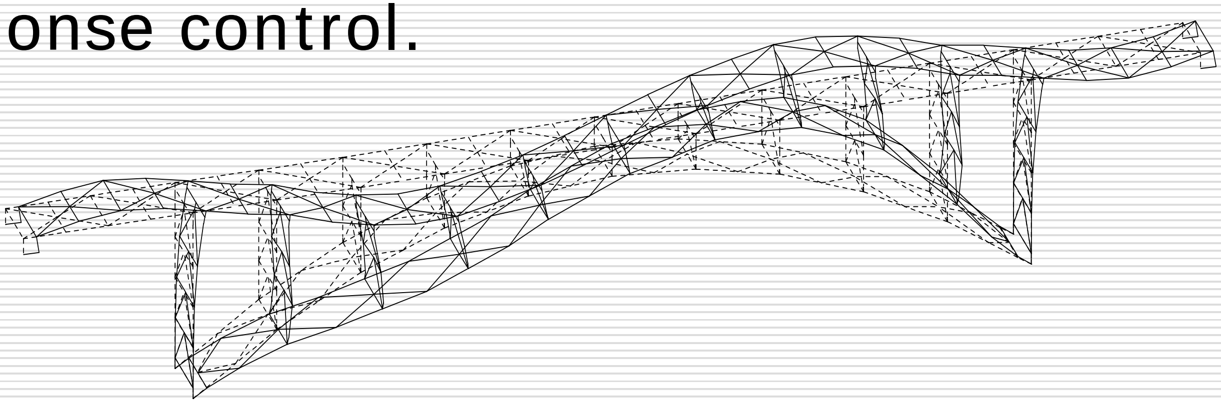
Because substructures of a bridge are not generally flexible, the response control can be effective for controlling flexible superstructures. However, the following points have to be considered.

● Because there is a requirement for limiting the minimum stiffness (the maximum deflection of a superstructure under dead load is limited), bridge superstructures are not generally flexible. In particular, plate girder bridges, box girder bridge, and PC bridges are not appropriate for the response control

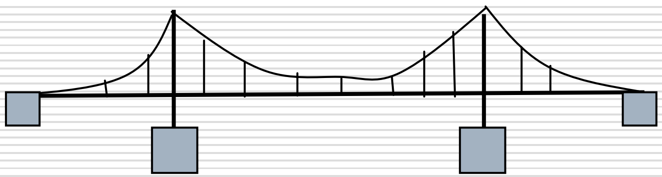


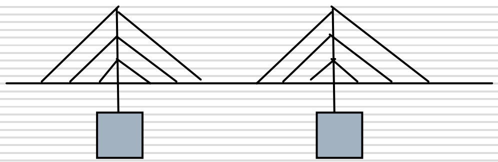
b) Bridge application (contd.)

- Since the whole structural members deform in an arch bridge, it is favorable for implementation of response control.



- Superstructures of cable stayed bridges and suspension bridges (long span bridges) are flexible. Thus, when the seismic performance of bridges can be enhanced by response control, it is feasible.





What energy dissipaters are available for response control?

Typically the following two devices are widely used for energy dissipaters in response control.

- viscous dampers including nonlinear viscous dampers
- unbond brace dampers

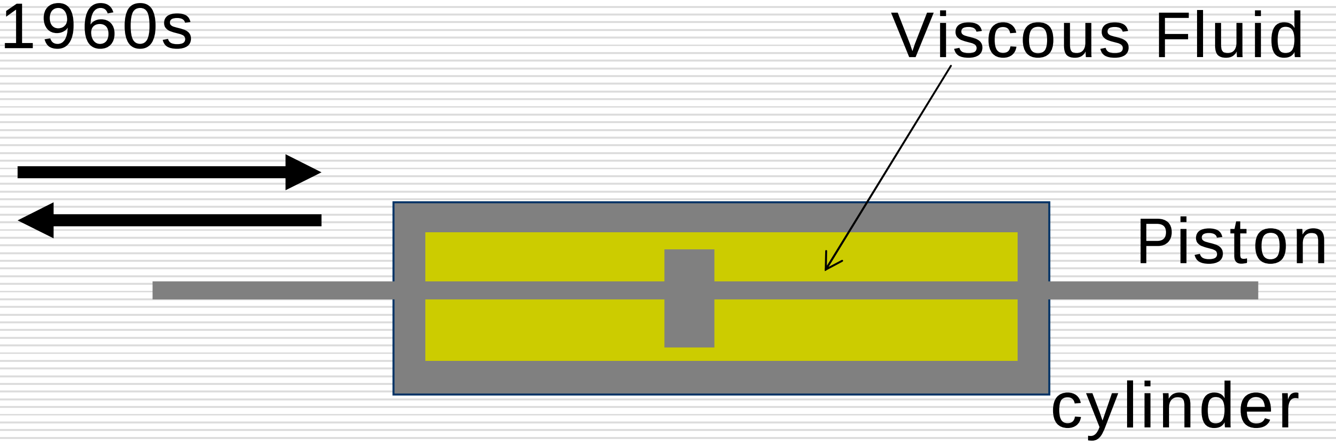
Requirements for dampers in response control

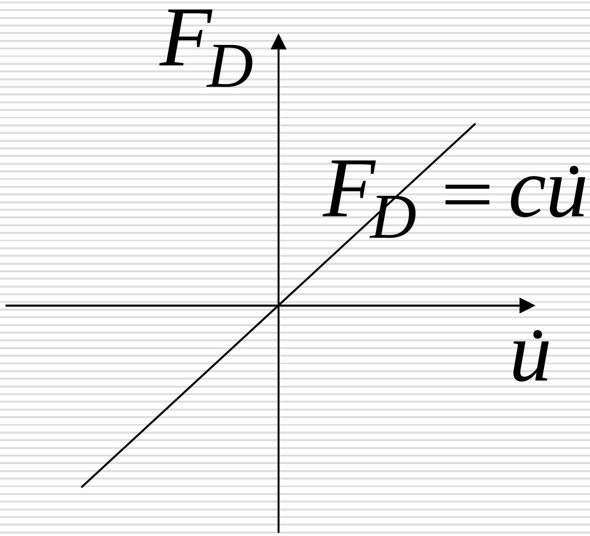
- Dampers must be long enough for connecting two nodal points
- Dampers must produce large damping forces

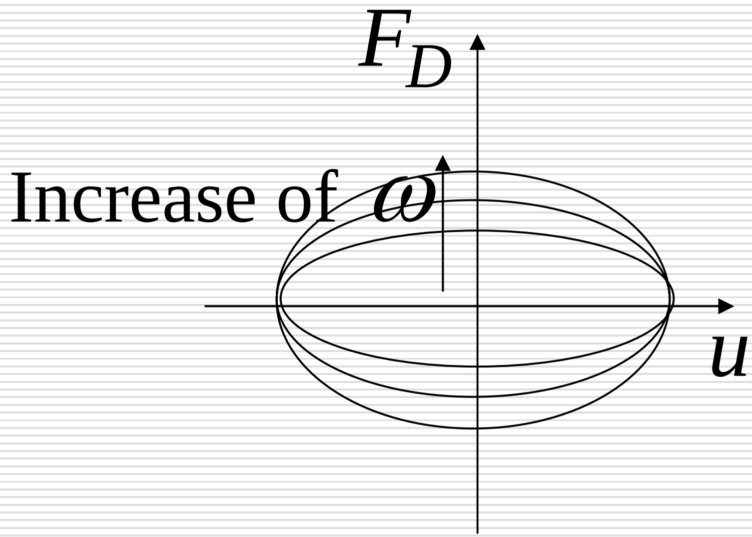
3.2 Viscous dampers

1) Structure of viscous damper

Started to be used since the late 1960s







2) Property of viscous dampers

a) Thermal effect and damper stopper or lock up damper

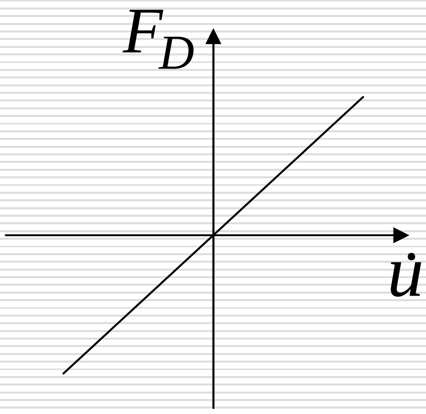
- At the early days, fluid which is insensitive to thermal change was not available.
- Consequently, damping ratio of a damper changed depending on temperature. Thus, if viscosity of fluid is determined so that the energy dissipation can be maximum in summer, the energy dissipation cannot be the maximum in winter.
- Thus, viscous dampers are often used as damper stoppers or lock-up dampers -→ See 3.3
- Now dampers with damping force fee of thermal change (nonlinear viscous dampers) are available.

b) Nonlinear dampers

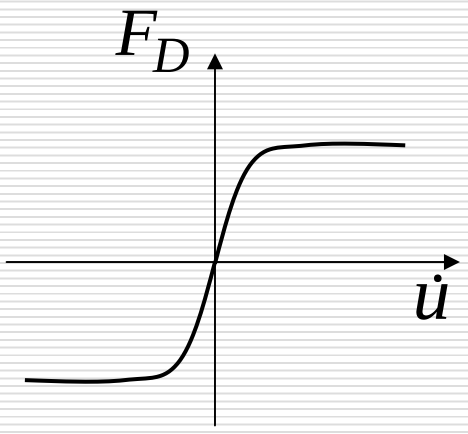
● If response velocity becomes excessively larger, the damping force builds up. This leads to failure of dampers or structural members connected to dampers.

● Nonlinear dampers were developed such that the damping force saturates to a certain level under high response velocity.

Normal dampers



Nonlinear dampers



3) Response control by viscous dampers

- Viscous dampers are widely used for response control of tall steel buildings.
- In bridges, viscous dampers are not widely installed to superstructure, except arch bridges and cable supported bridges, because
  - ✓Superstructures are not generally vulnerable to seismic effects, because dead load and traffic load are predominant in design.
  - ✓Enhancement of energy dissipation capacity of a superstructure does not generally mitigate seismic response of piers, columns, abutments and foundations.
  - ✓Dislike building application, viscous dampers installed in bridges are exposed to weathering.
- Viscous dampers are widely installed between a superstructure and substructures

4) Design Requirements of Viscous Dampers

The following points have to be considered in design of viscous dampers

- Amount of energy dissipation, or equivalent damping ratio required
- Stroke
- Maximum damping force which depends on the maximum velocity of dampers. The design damping force is set depending on the design velocity and design displacement (stroke).
- Dampers have to be used so that the velocity and displacement should be smaller than the design velocity and design displacement.

5) Extensive use of viscous dampers to bridges

5) Extensive use of viscous dampers to bridges (contd.)

Courtesy of Oiles Corporation

5) Extensive use of viscous dampers to bridges (contd.)

Courtesy of Oiles Corporation

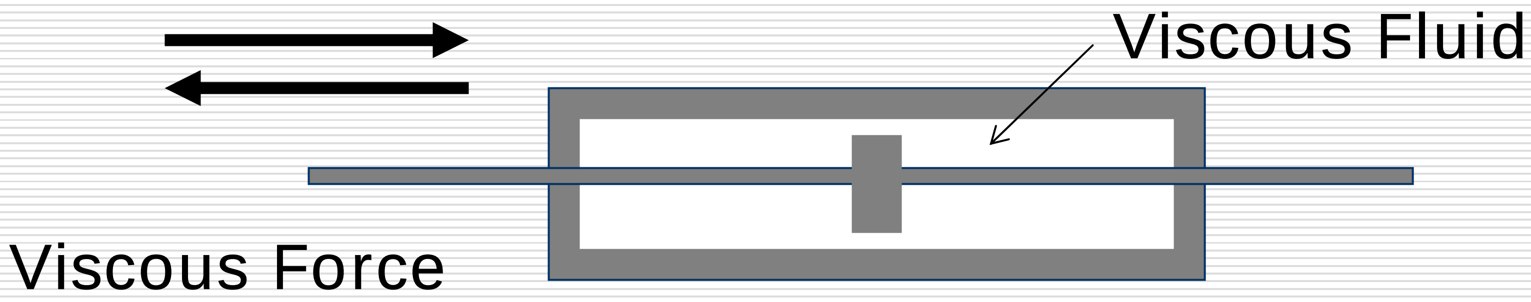
6) Viscous Dampers in Italy

7) Large viscous damper installed in Rion AntiRion Bridge, Greece

3.3 Viscous Damper Stoppers or Lock-up dampers

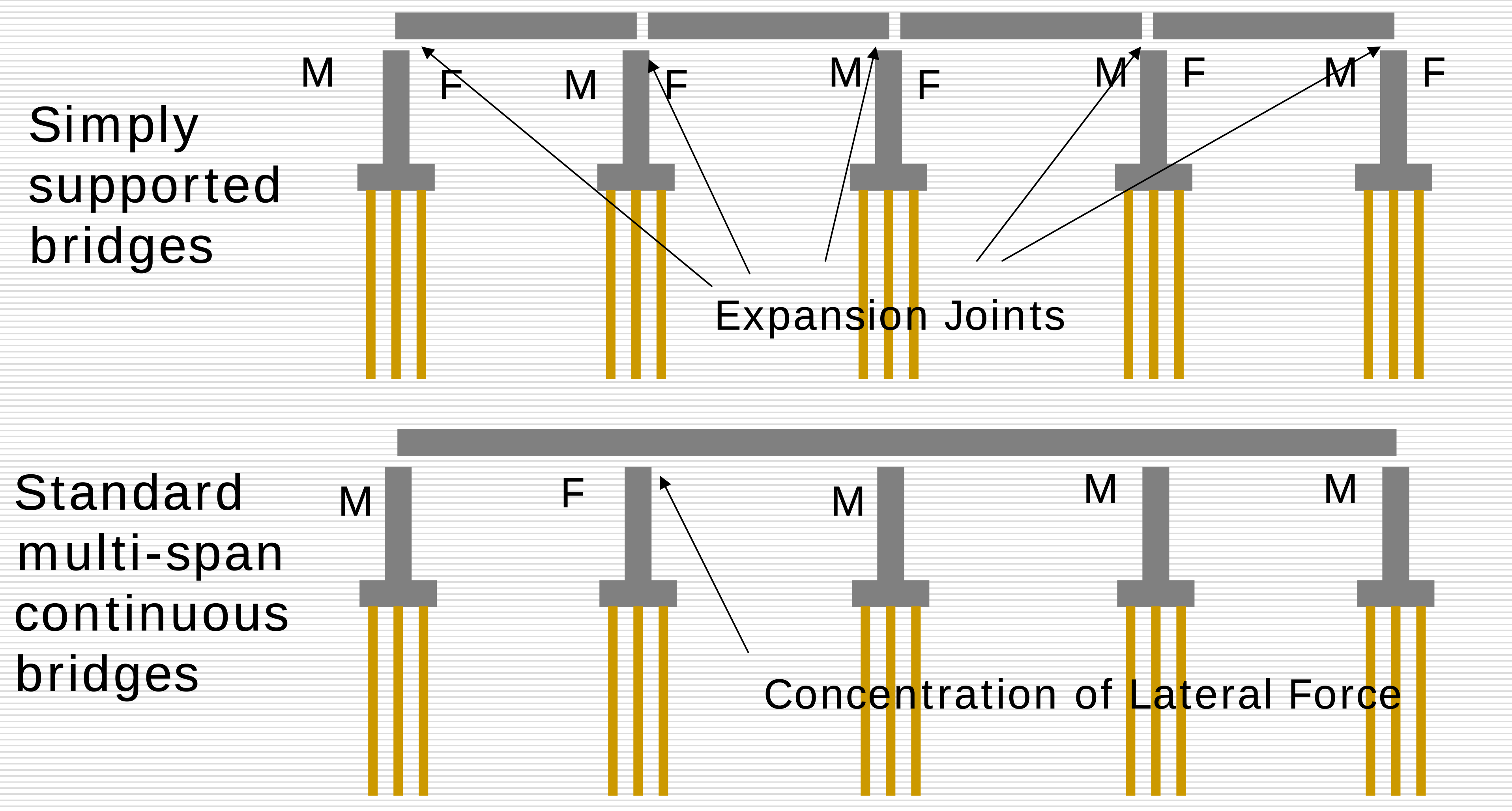
1) Viscous dampers are widely used for “viscous damper stoppers” in bridges

- Use a fluid with sufficiently high viscousity

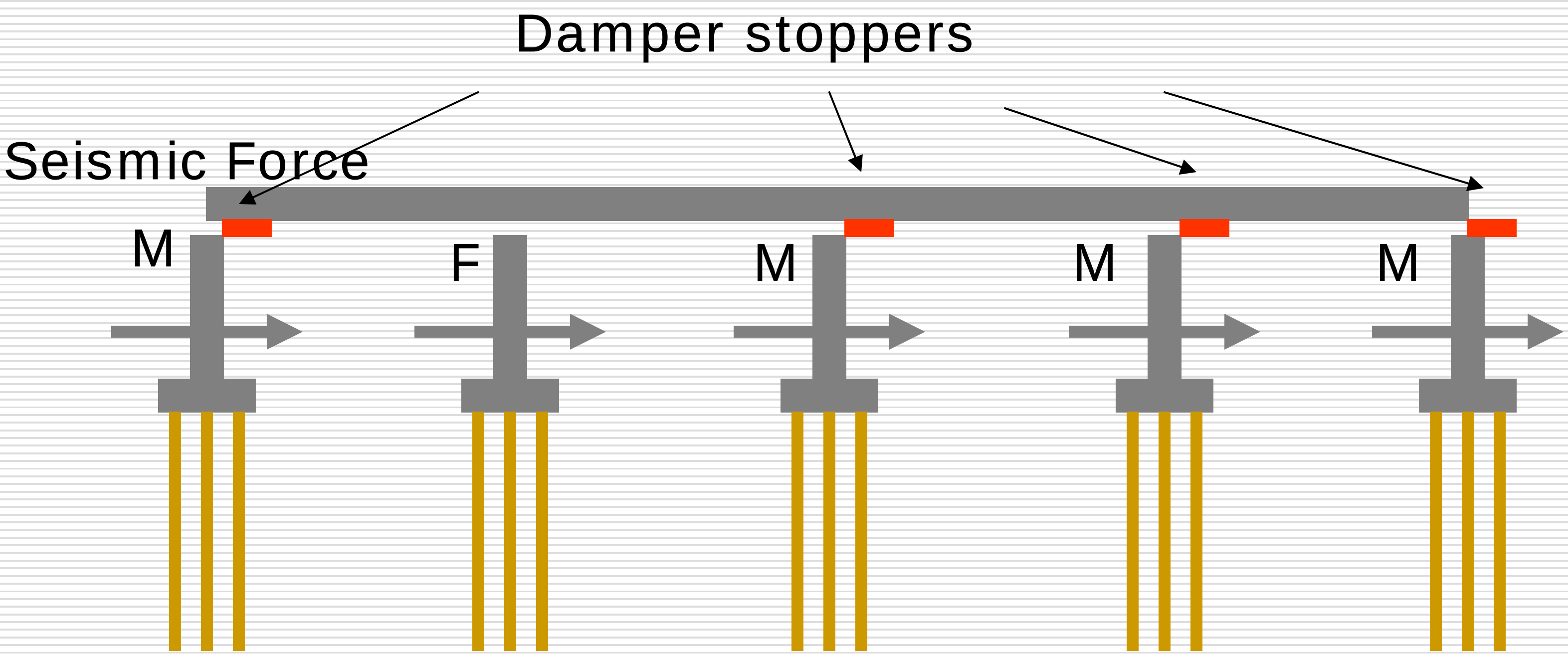


- Viscous force is very small under a low rate movement resulting in an extremely small resistance to thermal deformation
- Viscous force increases under high rate movements resulting in strong resistance to seismic response

2) Viscous damper stoppers are effectively used to distribute lateral seismic force transferred from spans to columns in multi-span continuous bridges



2) Viscous damper stoppers are effectively used to distribute lateral seismic force transferred from spans to columns in multi-span continuous bridges (contd.)



3) Example of Damper Stoppers

Ueno Viaduct, Metropolitan Expressway

3) Example of Damper Stoppers (contd.)

3.4 Unbond Brace Damper

1) Structure of unbond brace damper

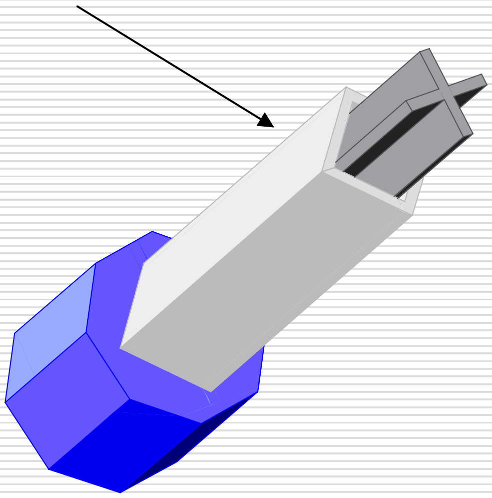
- An unbond brace damper consists of a mild steel rod, casing and inject material.
- A mild steel rod (low yielding steel) is encased in a casing so that the mild steel rod cannot be buckled under compression. The inject material assists preventing buckling of mild steel rod inside the casing.
- Energy is dissipated by plastic deformation of the mild steel bar.
- Casing is effective to set an unbond brace damper between two nodal points with a long distance (5-20 m)

1) Structure of unbond brace damper (contd.)

Brace

Buckling constraint casing of plastic bar

Mild steel (low yielding steel) rod



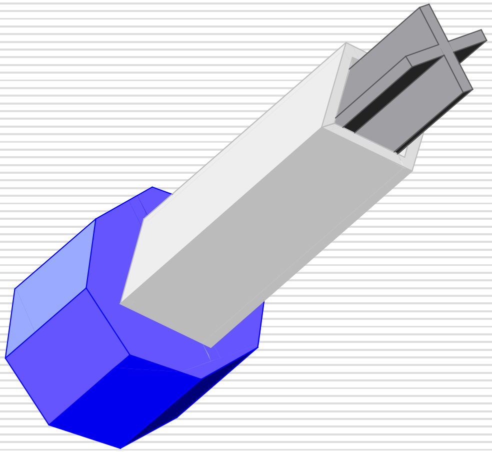
Morishita et al (2004)

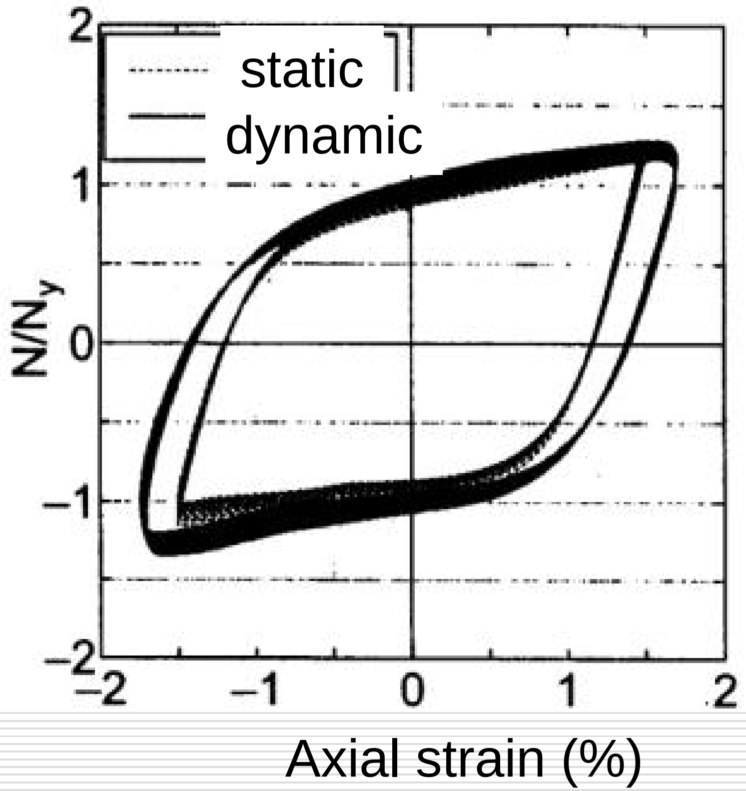
森下邦宏他、土木学会論文集、No. 766/I-68、2004

Unbond Brace Dampers

Morishita et al (2004)

2) Large and Stable Hysteretic Energy Dissipation by a Damper Brace



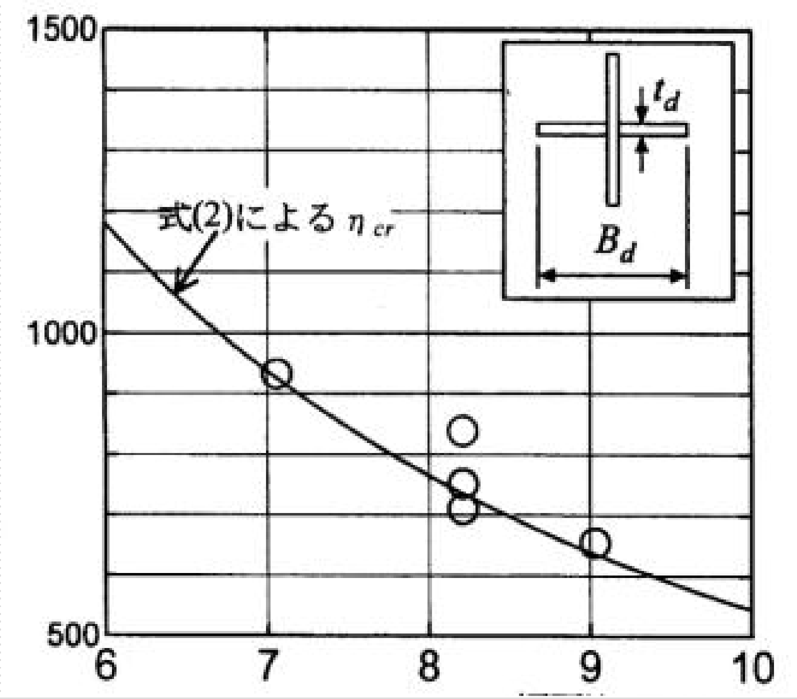


Morishita et al (2004)

3) Thickness of Plates and Fatigue has to be properly considered in design

- Width-thickness ratio

$$r = \frac{B_d}{2t_d}$$



Width/Thickness Ratio

- Accumulated plastic deformation

$$\eta = \sum_i \frac{\delta_{pi}}{\delta_y}$$

where,

δ_{pi} : plastic displacement of i-th loading

δ_y : yield displacement

$$\eta_{cr} = 17{,}800 r^{-1.52}$$

Morishita et al (2004)

4) Unbond brace dampers widely used for buildings 座屈拘束ブレースダンパー

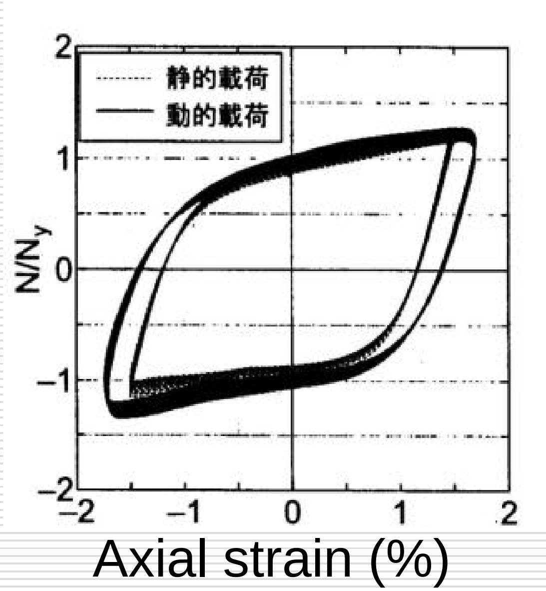
Courtesy of Shin-Nippon Steel Co. Ltd

3.5 Evaluation of Equivalent Damping Ratio

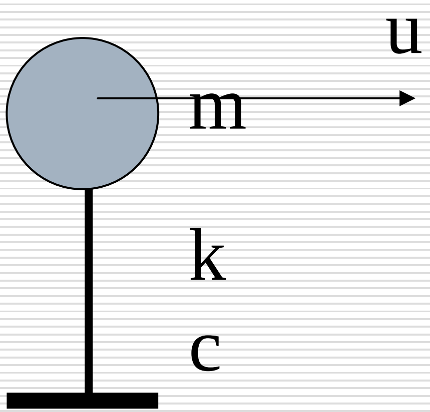
1) Why the equivalent damping ratio is required?

- Damping force by a viscous damper can be directly evaluated by “viscous damping force” in analysis.
- However energy dissipation by any devises other than viscous dampers cannot be directly evaluated in terms of the “viscous damping force”.

- For example, damping force by an unbond brace damper is independent of velocity and is generally represented as



2) Energy dissipation by viscous dampers



Equation of motion of a SDOF system subjected to a viscous damping force

$$m\ddot{u} + c\dot{u} + ku = F(t)$$

$$F_D = c\dot{u}$$

If F(t)=0, the equation of motion of free oscillation becomes

$$\ddot{u} + 2h\omega\dot{u} + \omega^2 u = 0$$

If u is a harmonic motion,

$$u = A\sin(\omega t - \varphi)$$

$$\dot{u} = A\omega\cos(\omega t - \varphi)$$

2) Energy dissipation by viscous dampers (contd.)

Energy dissipation by the damping force per cycle F_D is

$$W_d = \oint F_D du = \oint c\dot{u} du$$

Because, $c\dot{u} \cdot du = c\dot{u} \frac{du}{dt} dt = c\dot{u} \cdot \dot{u} dt$

the energy dissipation of a damper per cycle is

$$W_d = \int_0^{2\pi/\omega} c\dot{u} \cdot \dot{u} dt$$

Substituting

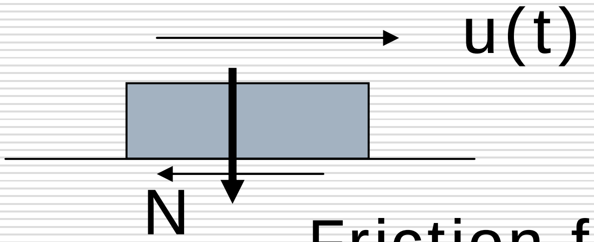
$$\dot{u} = A\omega \cos(\omega t - \varphi)$$

$$W_d = c\int_0^{2\pi/\omega} \omega^2 A^2 \cos^2(\omega t - \varphi) d(\omega t) = c\omega A^2 \pi$$

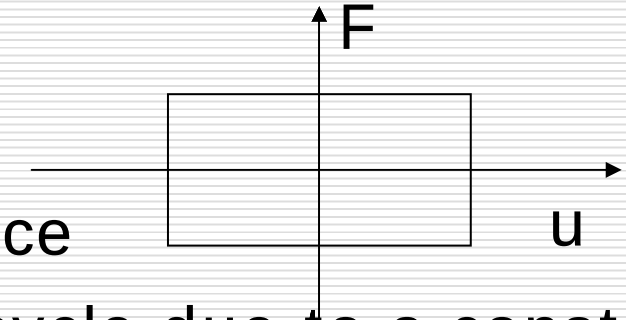
3) Equivalent damping coefficient

For simplicity, let consider energy dissipation by a friction force.

$$F_f = \mu N$$



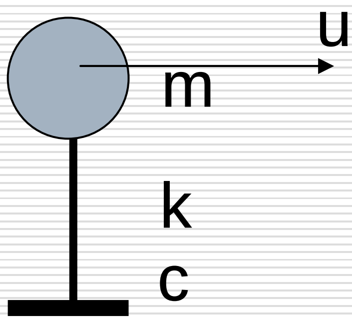
Friction force



Energy dissipation per cycle due to a constant friction force is

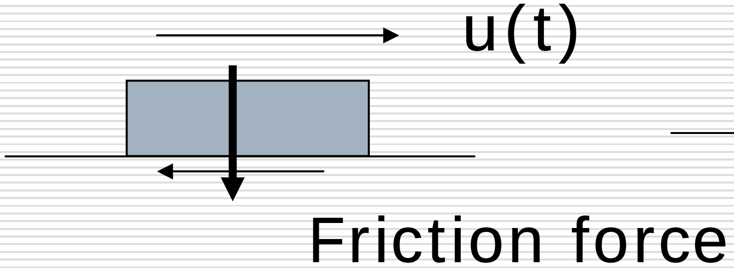
$$W_f = 4F_f u$$

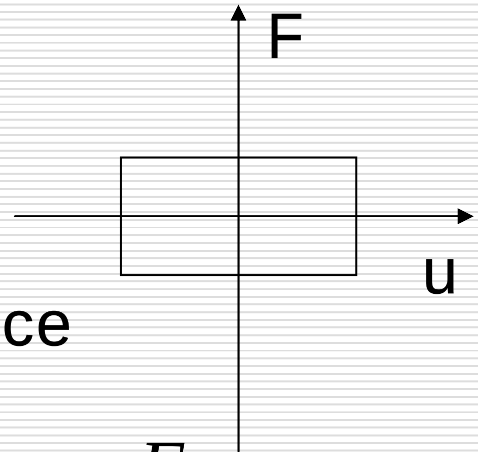
If we consider a SDOF system with a viscous damper, the energy dissipation of a damper per cycle is



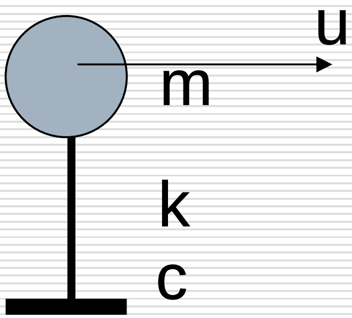
$$W_d = c\omega A^2 \pi$$

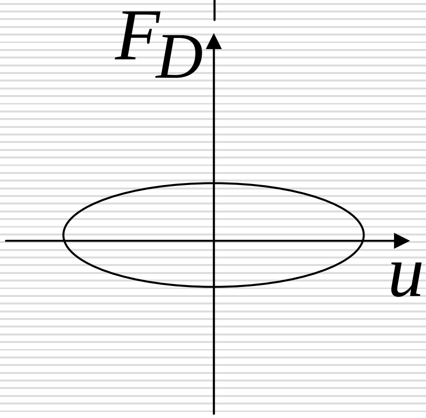
3) Equivalent damping coefficient (contd.)





$$W_f = 4F_f u$$





$$W_d = c\omega A^2 \pi$$

By equating $W_f = W_d$

$$c_{eq} = \frac{W_f}{\pi\omega A^2}$$

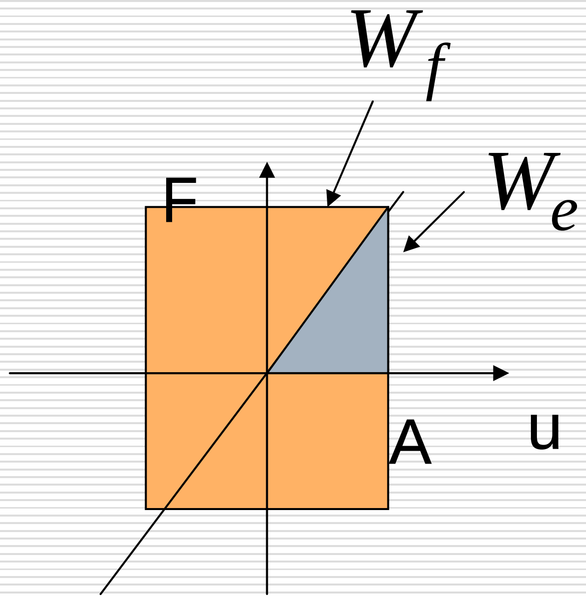
3) Equivalent damping coefficient (contd.)

Equivalent damping ratio h_{eq} for c_{eq} is

$$h_{eq} = \frac{c_{eq}}{c_{cr}} = \frac{\dfrac{W_f}{\pi\omega A^2}}{2\sqrt{mk}} = \frac{1}{2\pi}\frac{W_f}{kA^2}$$

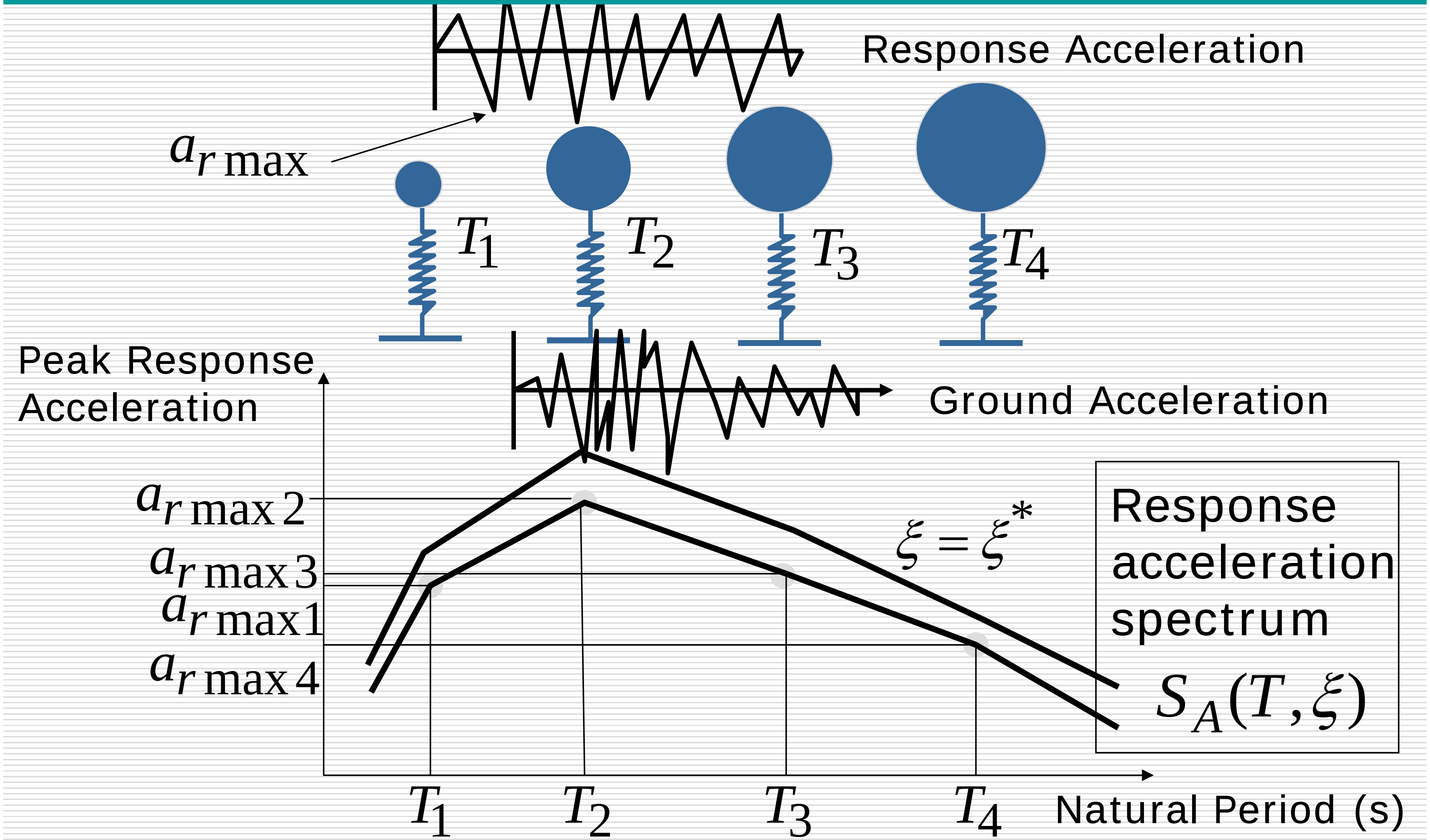
Substituting $W_e = \dfrac{1}{2}kA^2$

$$h_{eq} = \frac{1}{4\pi}\frac{W_f}{W_e}$$



3.6 Approximately how much response reduction can we have by increasing damping?

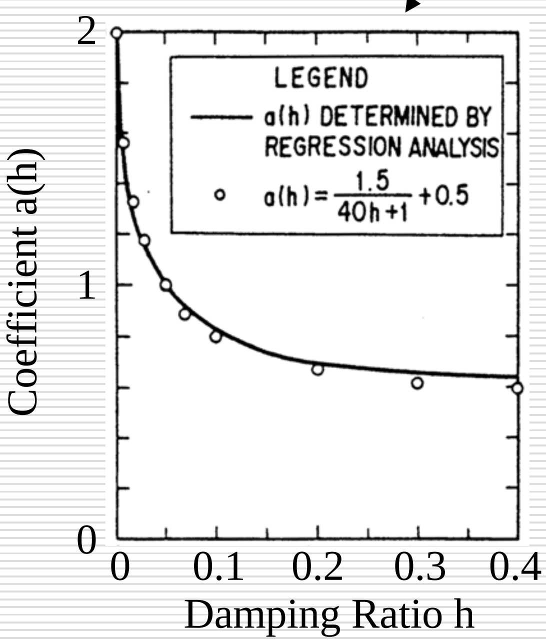
1)Definition of Response Acceleration

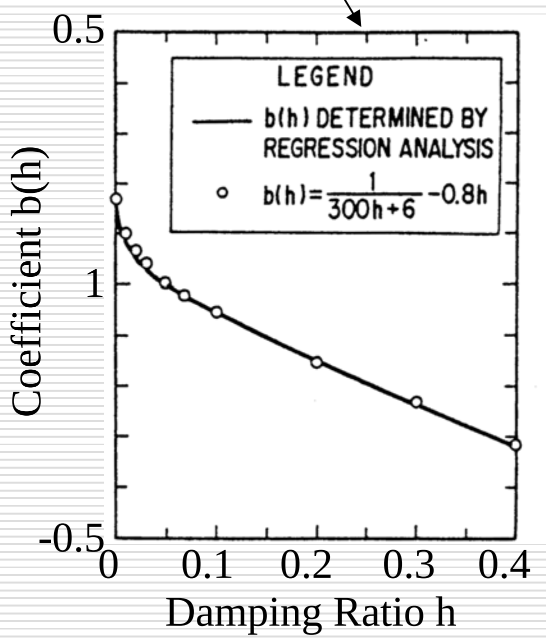


2) How much reduction of response acceleration S_A can we have by increasing damping ratio?

$$c_D(T,\xi) = \frac{S_A(T,\xi)}{S_A(T,0.05)}$$

$$c_D(T,\xi) = \left(\frac{1.5}{40\xi+1}+0.5\right) \times \left(\frac{S_A(T,0.05)}{a_{\max}}\right)^{\left(\frac{1}{300\xi+6}-0.8\xi\right)}$$





2) How much reduction of response acceleration S_A can we have by increasing damping ratio? (contd.)

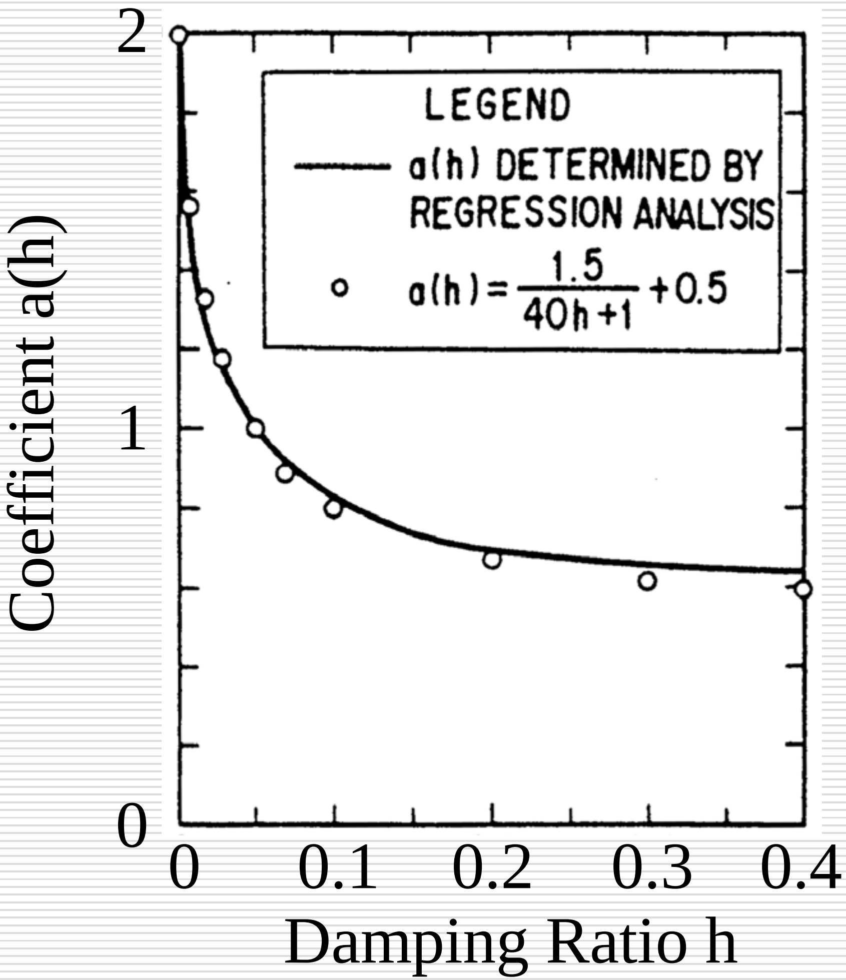
$$c_D(h) = \frac{1.5}{40h+1} + 0.5$$

$$c_D(0) = \frac{1.5}{1} + 0.5 = 2$$

$$c_D(0.05) = \frac{1.5}{2+1} + 0.5 = 1$$

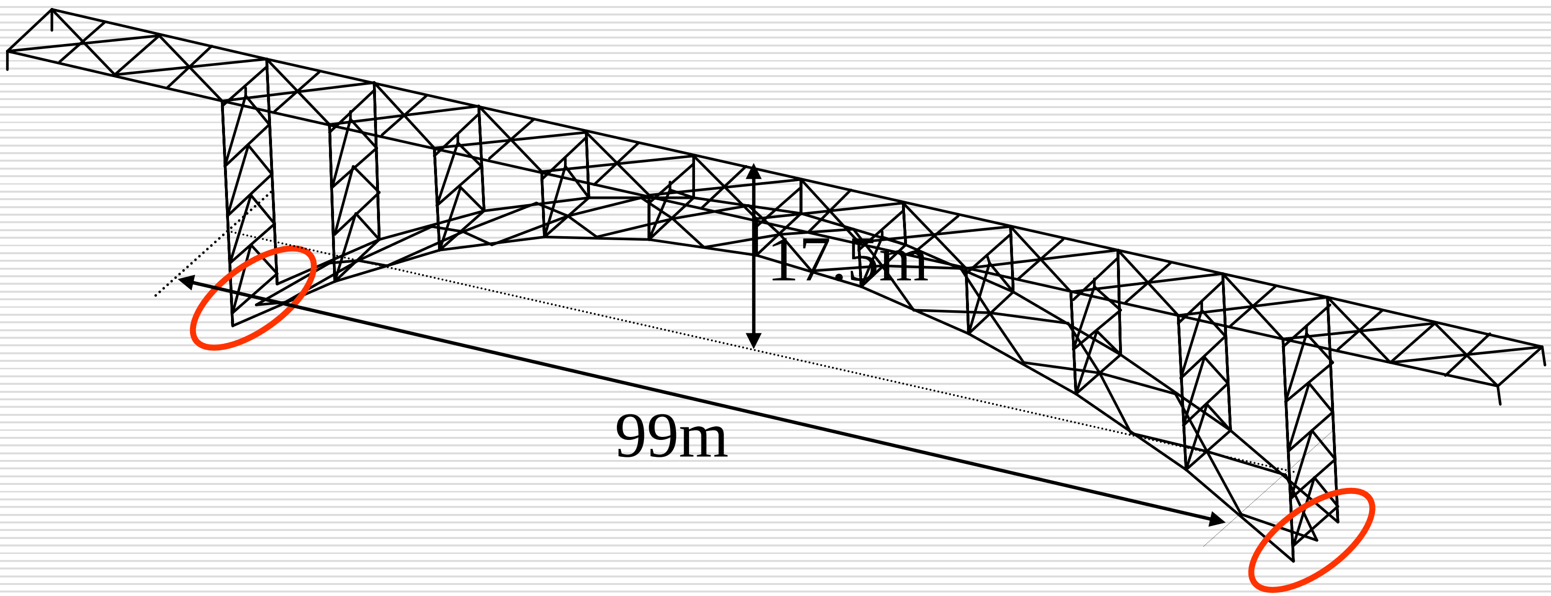
$$c_D(0.1) = \frac{1.5}{5} + 0.5 = 0.8$$

$$c_D(\infty) = 0.5$$



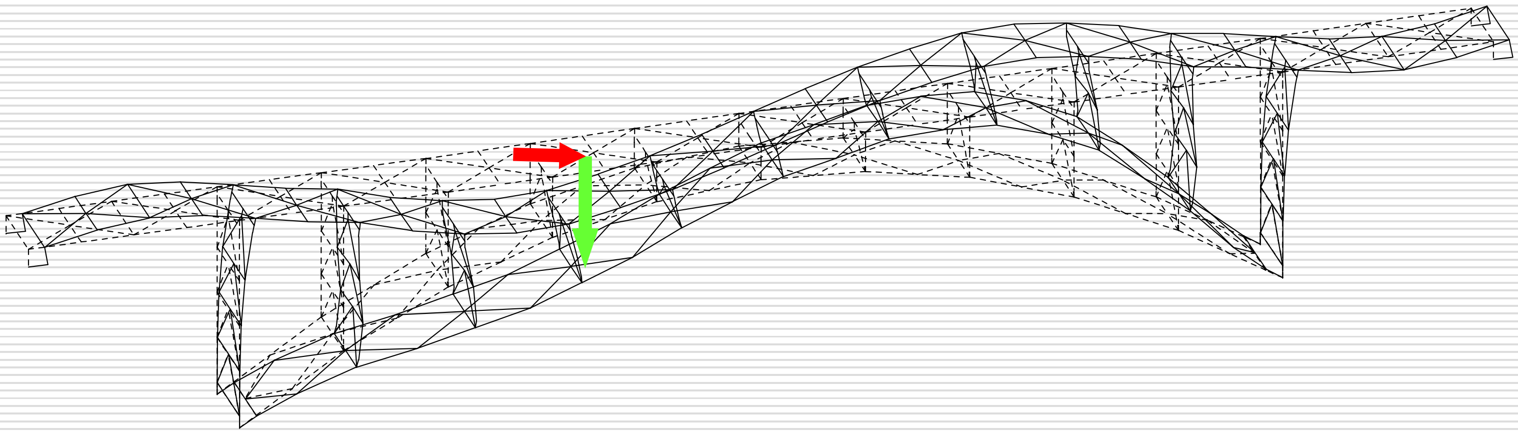
3.7 How effective is the response control by unbond brace dampers for a steel arch bridge?

1) Target bridge



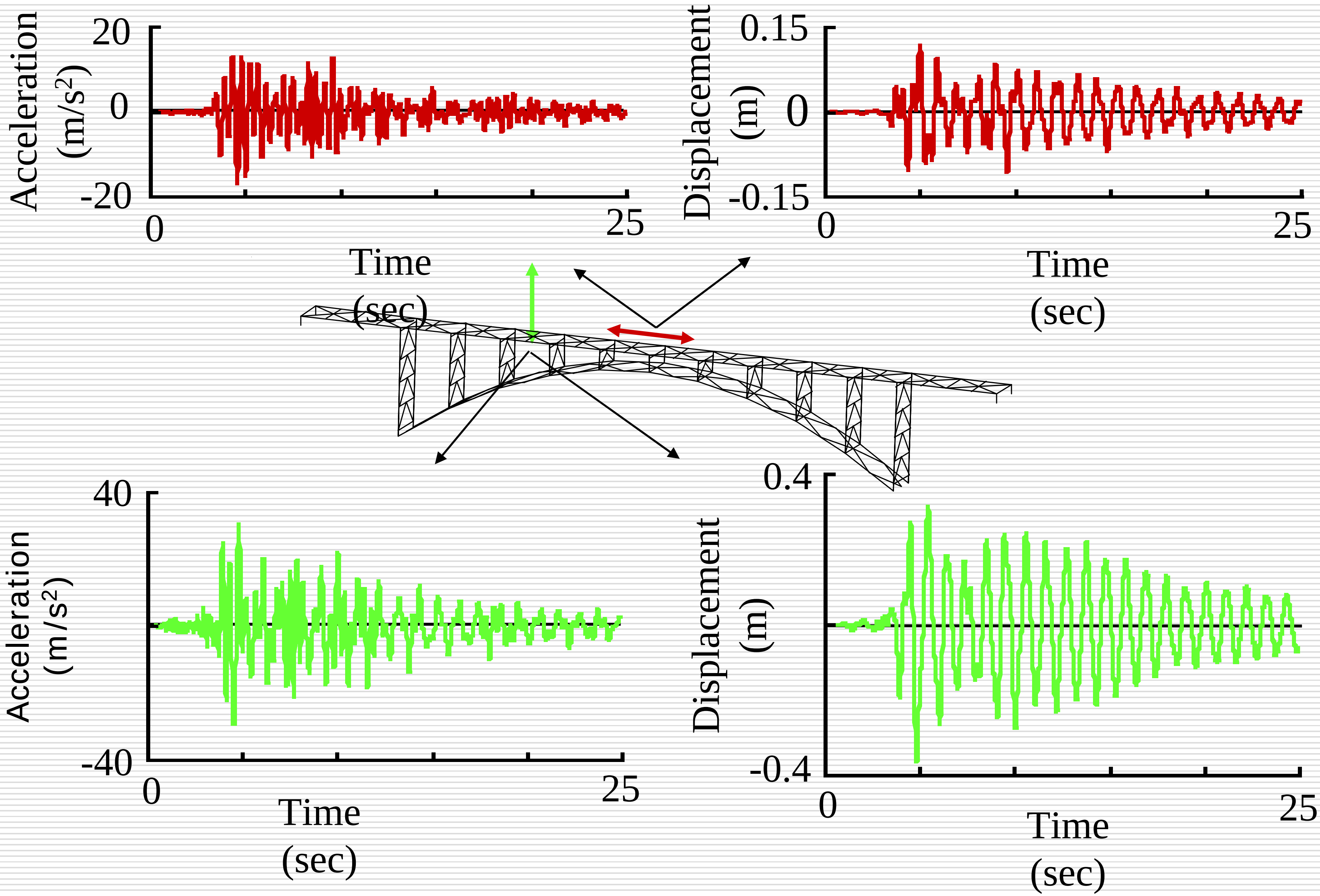
福田、川島、渡辺、構造工学論文集、Vol. 51A、2005

(2) Peculiar Response of Arch Bridges due to Coupling of Longitudinal and Vertical Modes

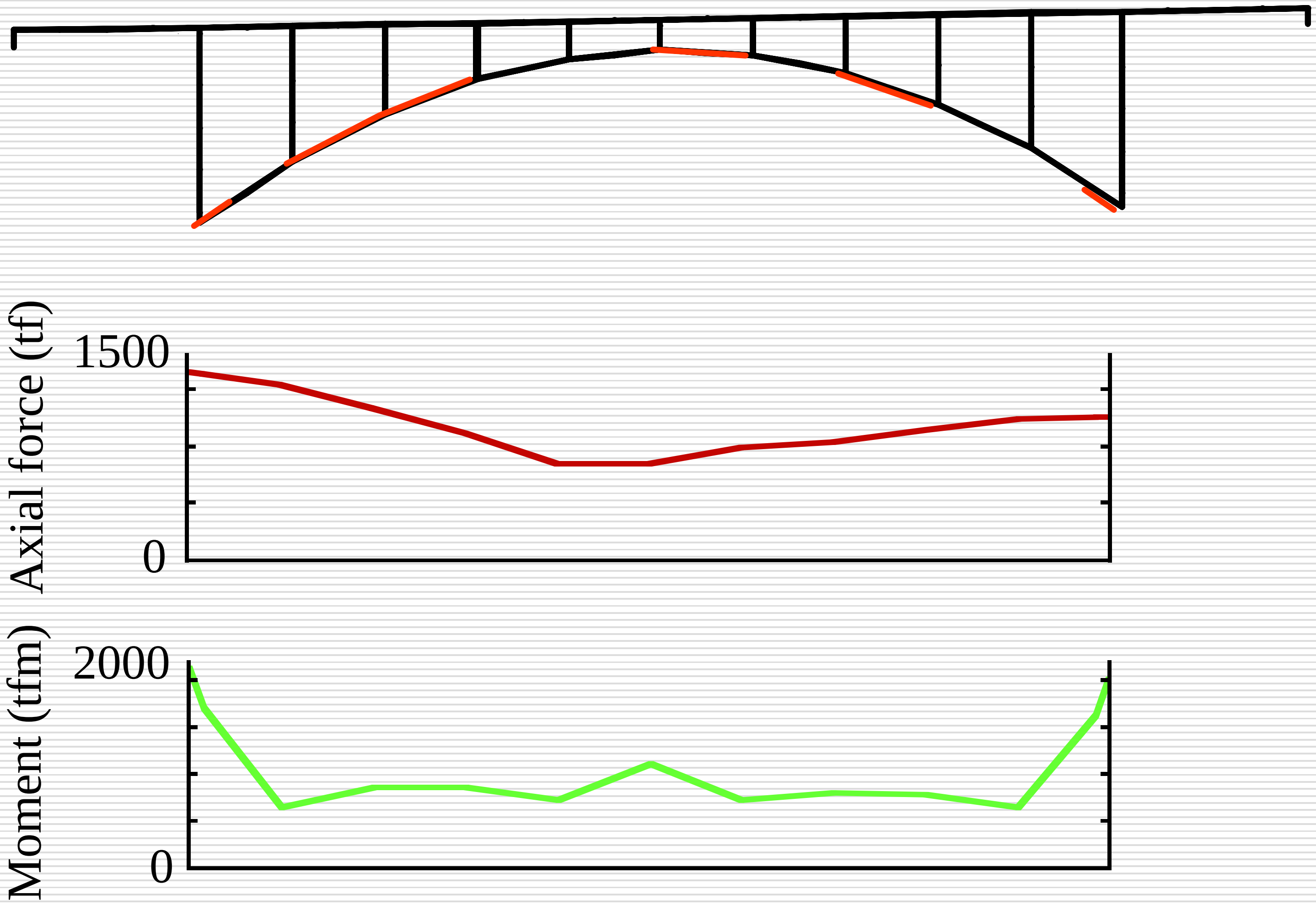


Fundamental Natural Period T=1.1 sec

3) Seismic Response of As-Built Bridge under JMA Kobe Ground Acceleration, 1995 Kobe EQ



4) Arch Members which undergo Inelastic Deformation



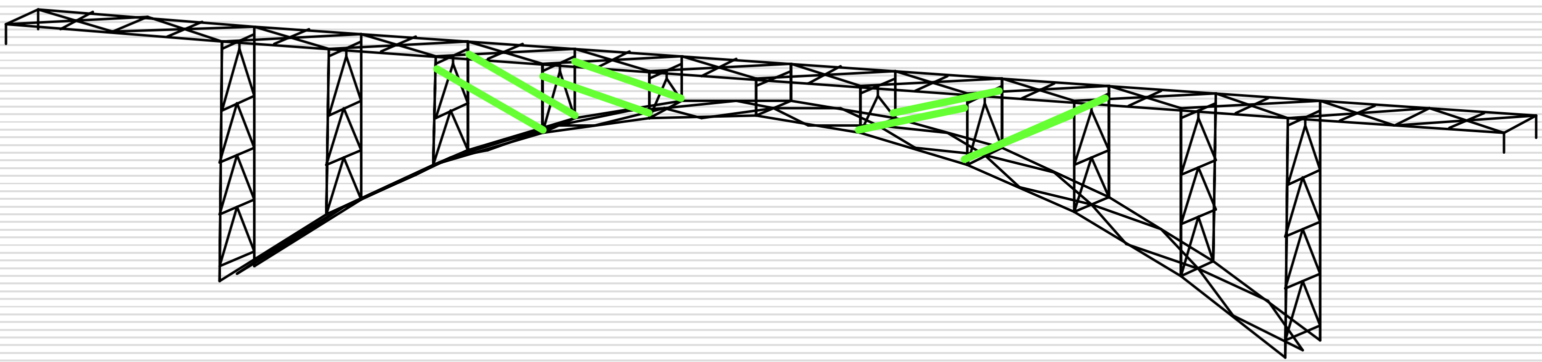
5) Where should Damper Braces be Installed?

Criteria for deciding where damper braces should be installed

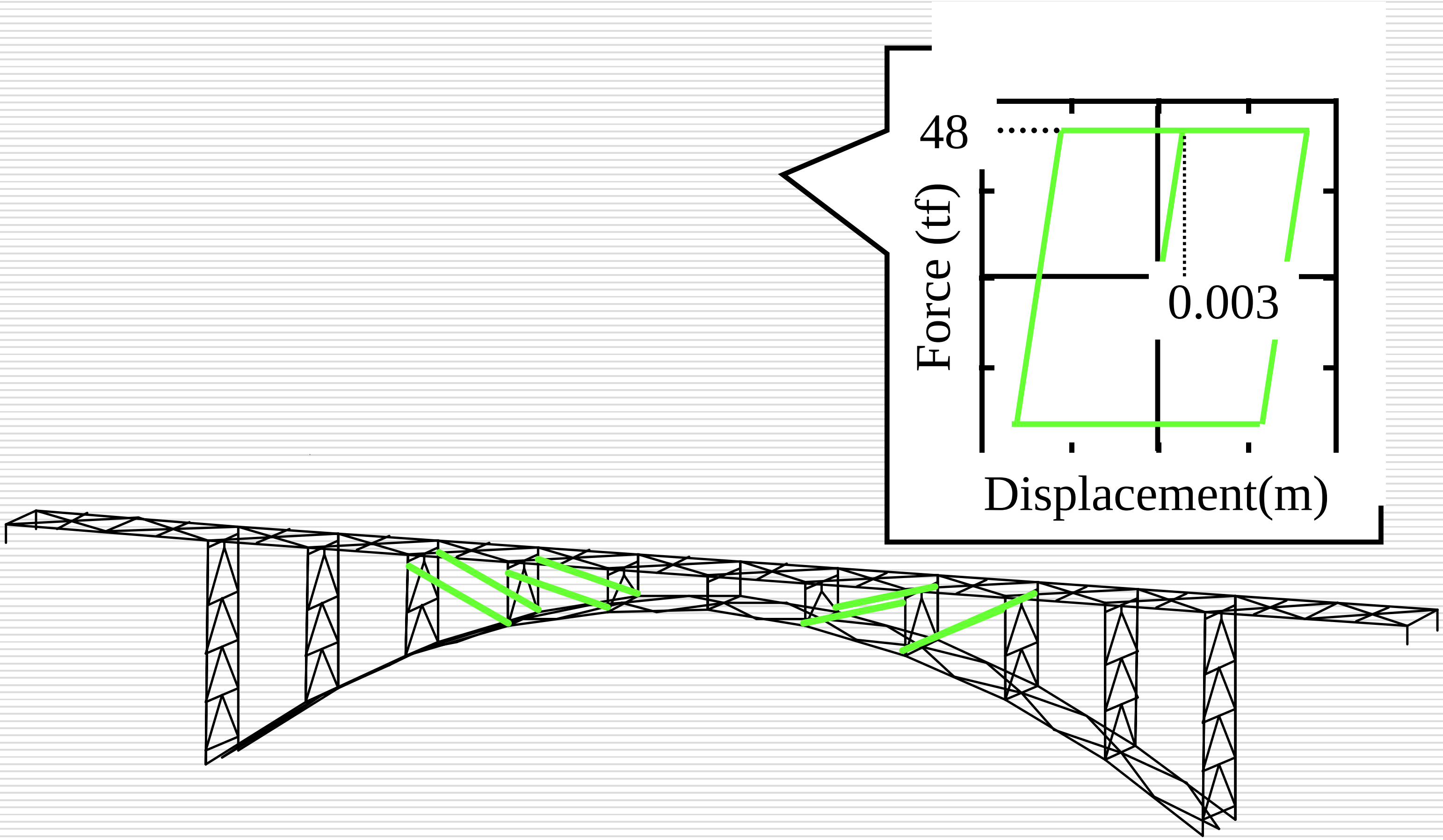
$\varepsilon > \varepsilon_a = 1/100$ Axial strain between 2 nodes

$\Delta u > \Delta u_a = 1/10m$ Relative displacement between 2 nodes

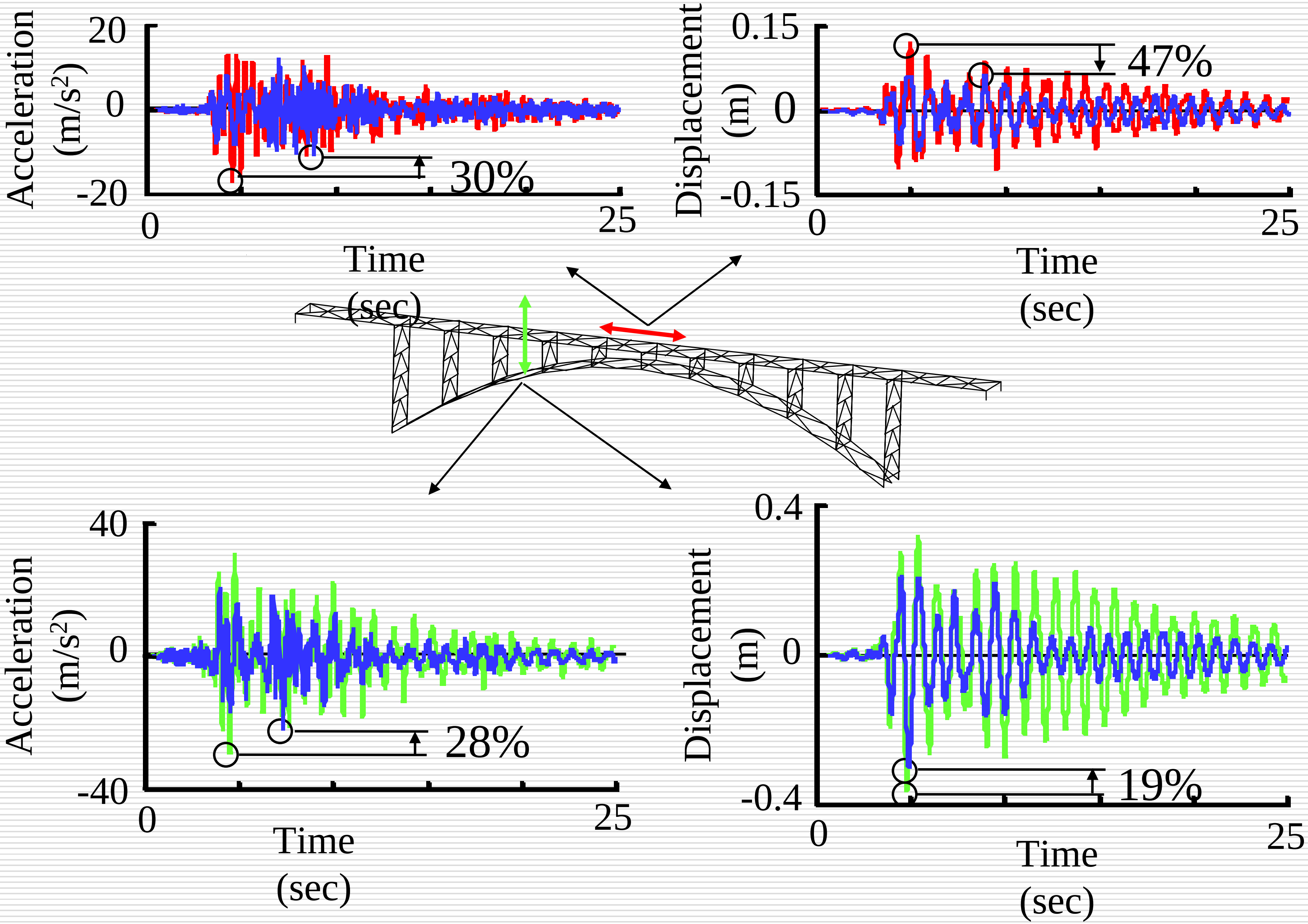
$l_D < 12m$ Length of member



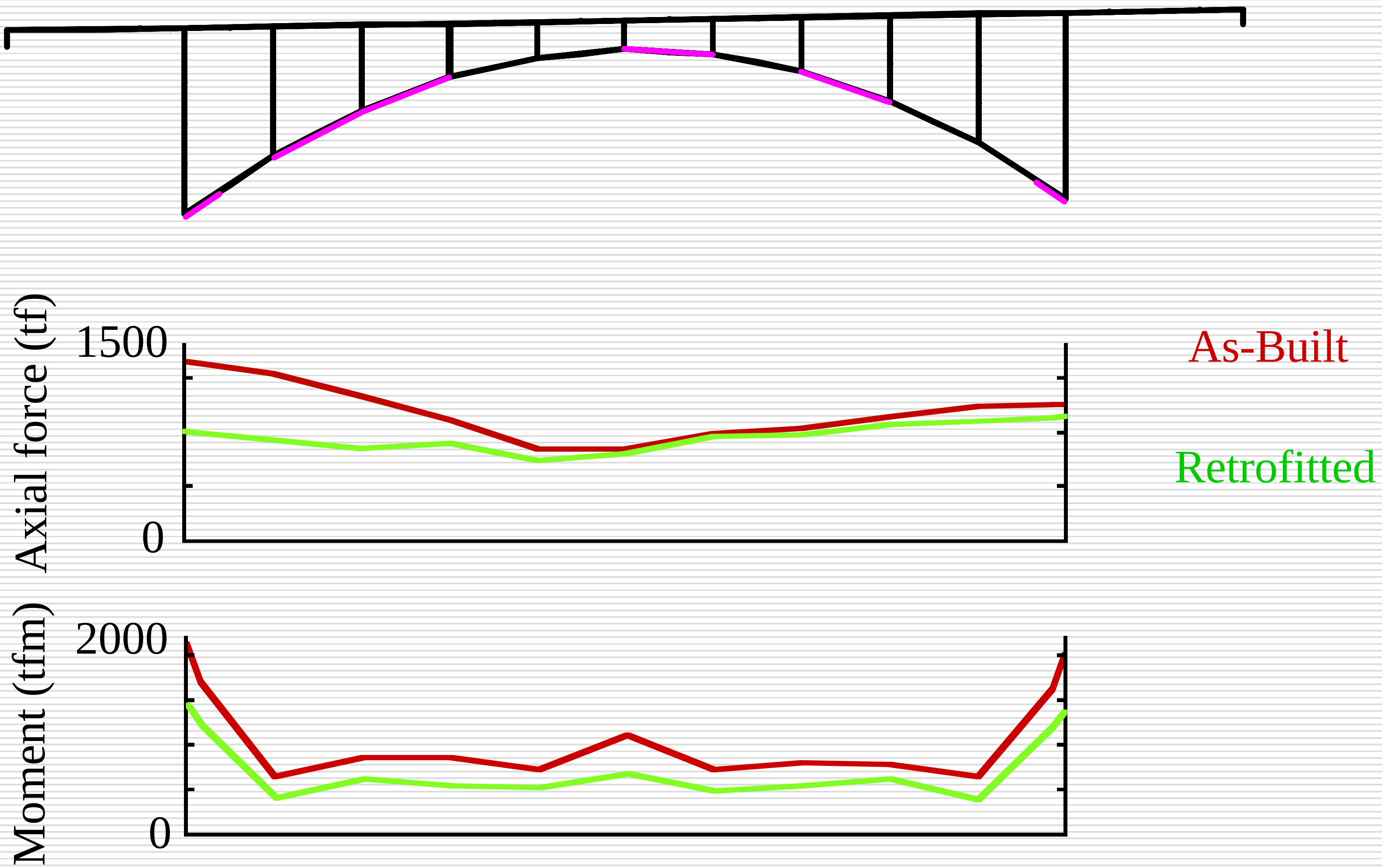
6) Analytical Idealization of Hysteretic Behavior of Unbond Brace Dampers



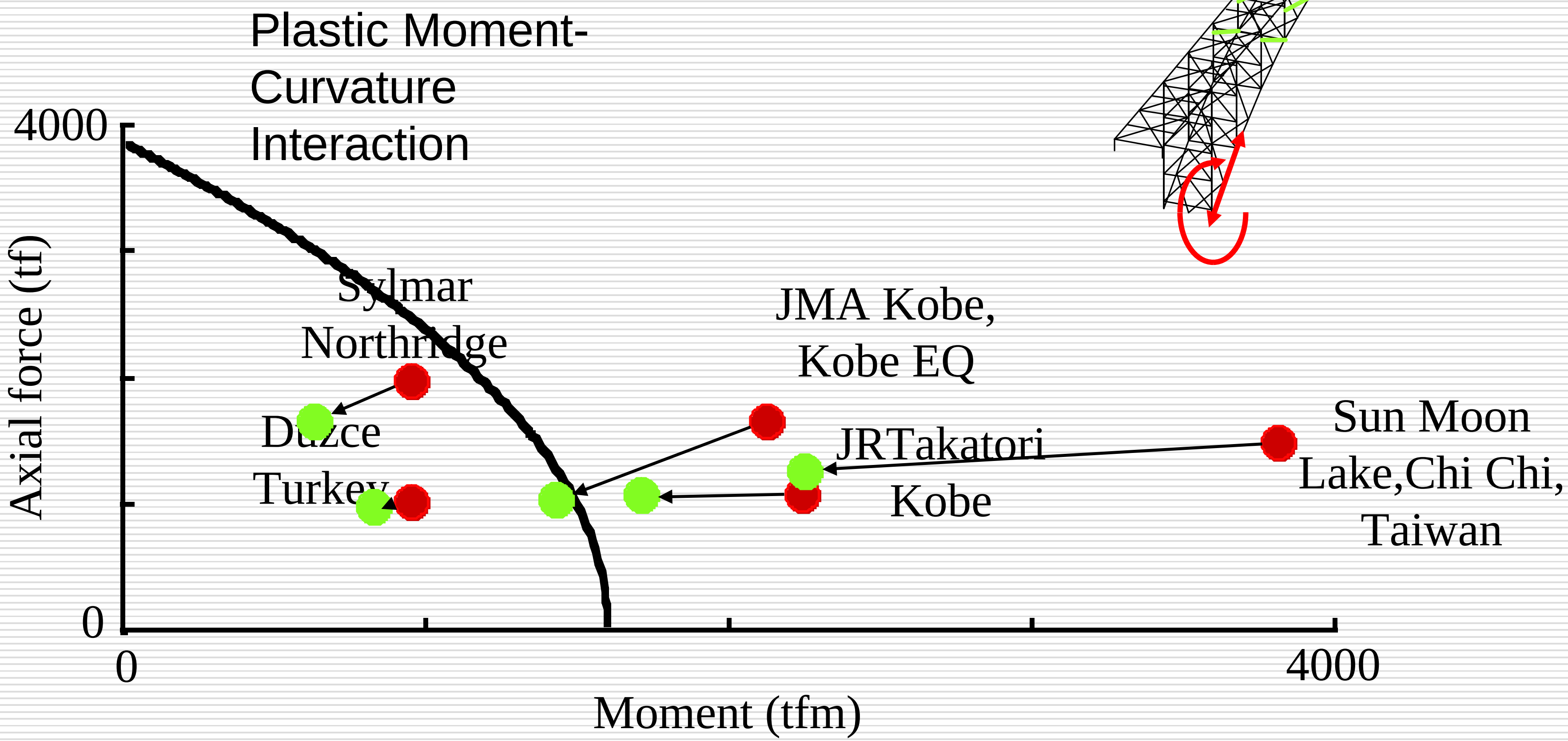
7) How effective are unbond brace dampers?

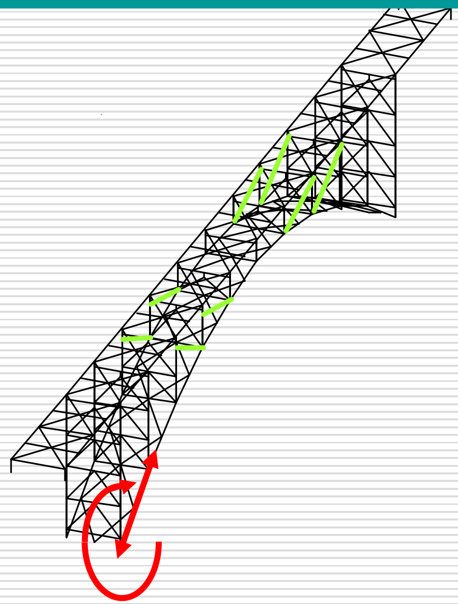


8) Effect of Seismic Retrofit by Damper Braces



9) Effect of Seismic Retrofit by Unbond Brace Dampers





10) Enhancement of Damping Ratio by Installing Unbond Brace Dampers