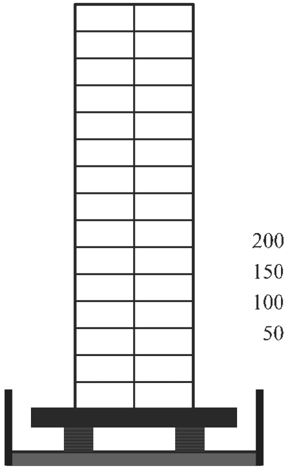
アクティブ制御を併用した
超高層免震建物の風応答予測

○ 佐藤大樹　　東京工業大学
陳　錦華　　東京工科大学

一般財団法人 大成学術財団 第3 回 研究成果発表会

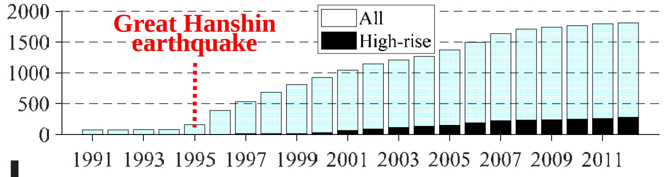
Introduction

Recently, use of **PBI** in **high-rise** buildings increases *)



Passive base-isolated (**PBI**) buildings

- minimize damages of superstructures
- resume operation

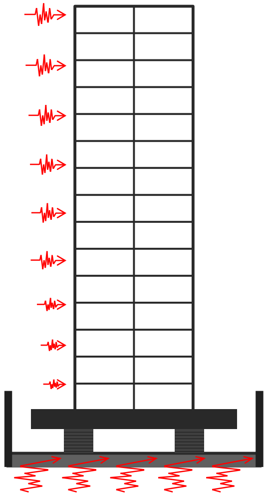


Recent trends of PBI building in Japan *)

*) : Yuji T., Nobuo F., Jun T., Masafumi M., development and analysis of database for base-isolated buildings in japan, 2011

Introduction

Recently, use of **PBI** in **high-rise** buildings increases *)



Issues:

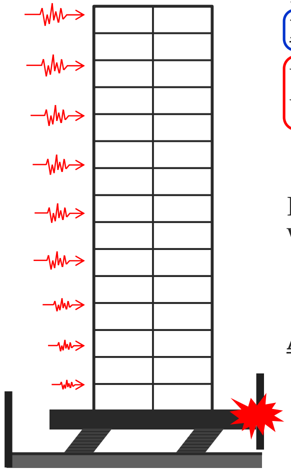
PBI layer is relatively **soft**

Wind load contains **mean component** (along-wind)
Wind load acts **directly on the superstructure**

*) : Yuji T., Nobuo F., Jun T., Masafumi M., development and analysis of database for base-isolated buildings in japan, 2011

Introduction

Recently, use of **PBI** in **high-rise** buildings increases *)



Issues:

PBI layer is relatively **soft**

Wind load contains **mean component** (along-wind)
Wind load acts **directly on the superstructure**

↓

It is difficult to suppress **displacement** response within the allowable range

↓

Active structural control (ASC) strategy

- Control system designed by trial-and-error approach
- Much guess and simulations are required

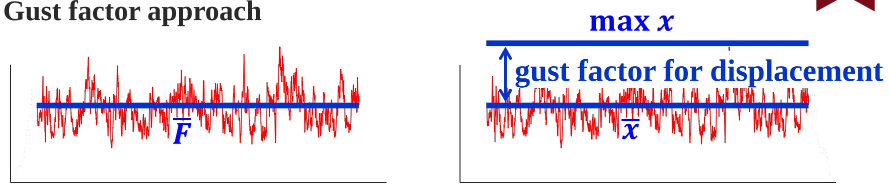
↓

Design method for PBI buildings with ASC

*) : Yuji T., Nobuo F., Jun T., Masafumi M., development and analysis of database for base-isolated buildings in japan, 2011

Introduction

Gust factor approach



Story wind force (along-wind direction)

Displacement response

mean displacement

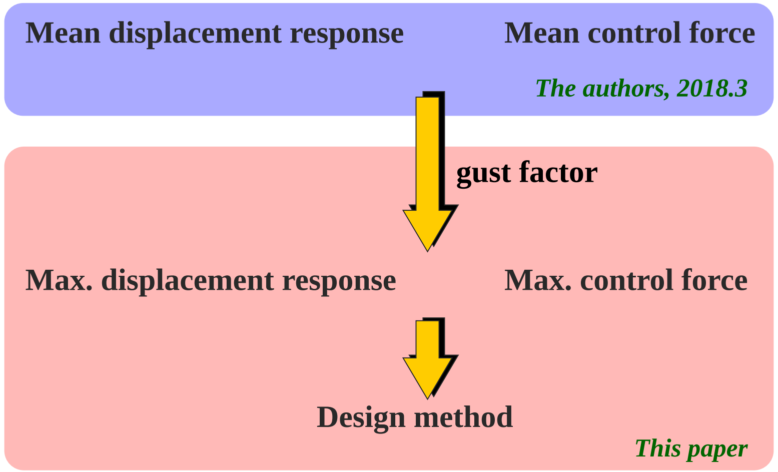
$$= \frac{\text{mean wind force} \quad - \quad \text{mean control force}}{\text{stiffness}}$$

gust factor **gust factor**

maximum displacement maximum control force

Objective of this study

PBI buildings with ASC



Mean displacement response **Mean control force**

The authors, 2018.3

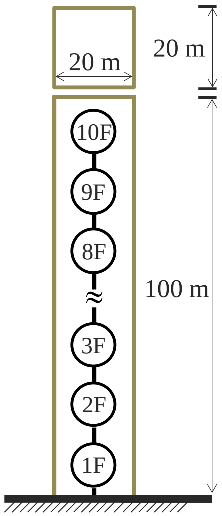
gust factor

Max. displacement response **Max. control force**

Design method

This paper

Model of buildings



aspect ratio **5**

superstructure

height: 100m

aspect ratio: 5

10 DOF

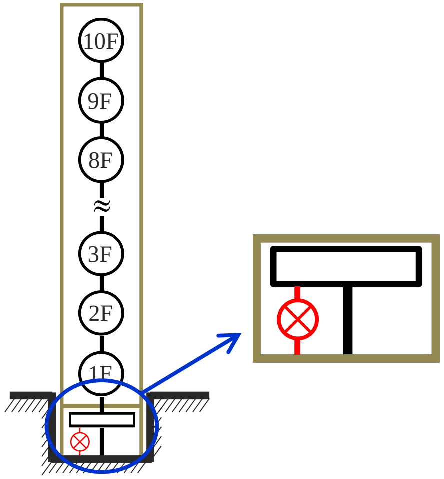
shear building model

1st natural period: 2 s

1st damping ratio: 0.02

PBI layer

Model of buildings



superstructure

height: 100m

aspect ratio: 5

10 DOF

shear building model

1st natural period: 2 s

1st damping ratio: 0.02

PBI layer

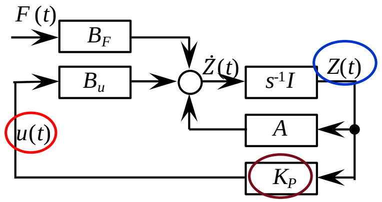
isolated period: 3, 4 and 5 s

damping ratio: 0.05

ASC device installed

Control system

Feedback control



$u(t)$ control force

$Z(t)$ state vector $\longleftarrow \begin{bmatrix} X(t) \\ \dot{X}(t) \end{bmatrix}$

K_P feedback gain

$\boldsymbol{K_{PD}}$ displacement feedback gain

$\boldsymbol{K_{PV}}$ velocity feedback gain

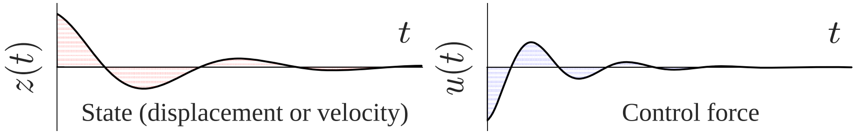
control law:
$$
\begin{aligned}
u(t) &= K_P Z(t) \\
&= [K_{PD} \quad K_{PV}] \begin{bmatrix} X(t) \\ \dot{X}(t) \end{bmatrix} \\
&= K_{PD} X(t) + K_{PV} \dot{X}(t)
\end{aligned}
$$

Control system design

control law: $u(t) = \boldsymbol{K_P} Z(t)$

LQR Method

$$J = \int_0^\infty \left(\underbrace{Z^{\mathrm{T}}(t) Q Z(t)}_{\text{Aera} \times \boldsymbol{Q} \times \text{Aera}} + \underbrace{u^{\mathrm{T}}(t) R u(t)}_{\text{Aera} \times \boldsymbol{R} \times \text{Aera}} \right) \mathrm{d}t$$



weight matrix

$Q = 10^{\boxed{\alpha}} \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}$ and $R = 1$

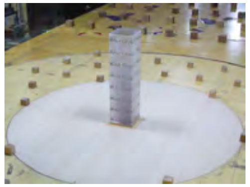
$$\begin{tikzcd} u & \boldsymbol{K_P} \arrow[l] & Q, R \arrow[l] & \boldsymbol{\alpha} \arrow[l] \arrow[lll, bend left, dashed] \end{tikzcd}$$

Along-wind force

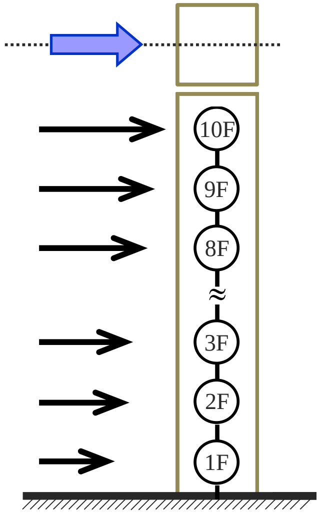
Along-wind force is calculated by wind tunnel experiment *)

Information of design wind load	
location (expectation)	Tokyo
flat terrain category	III
wind direction	0°
return period	500-years
top wind speed	63.8 m/s
story	10F

A5 building model



A4 building model



Mean control force

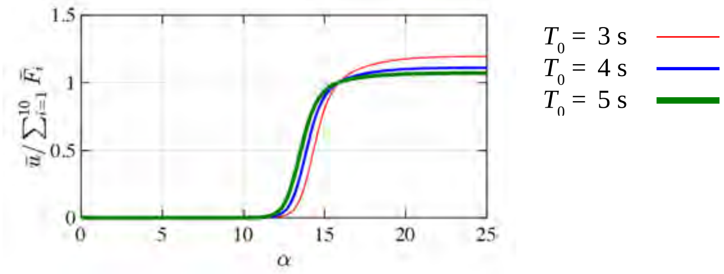
$$\bar{u} = K_P \bar{Z} = K_P \begin{bmatrix} \boxed{\bar{X}} \\ 0_{11\times1} \end{bmatrix}$$

$$\boxed{\bar{X} = K^{-1} \begin{bmatrix} \bar{u} \\ \bar{F}_1 \\ \vdots \\ \bar{F}_{10} \end{bmatrix}}$$

$$\bar{u} = \underset{\uparrow \atop \boldsymbol{\alpha}}{\boxed{K_P}} \begin{bmatrix} \overset{\boldsymbol{T_0} \atop \downarrow}{\boxed{K}}{}^{-1} \begin{bmatrix} \bar{u} \\ \bar{F}_1 \\ \vdots \\ \bar{F}_{10} \end{bmatrix} \\ 0_{11\times1} \end{bmatrix}$$

Eq.(1)

accuracy verification

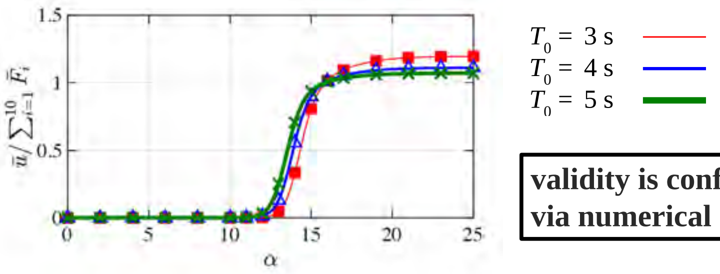


Mean control force

$$\bar{u} = K_P \bar{Z} = K_P \begin{bmatrix} \boxed{\bar{X}} \\ 0_{11\times1} \end{bmatrix} \qquad \boxed{\bar{X} = K^{-1}\begin{bmatrix} \bar{u} \\ \bar{F}_1 \\ \vdots \\ \bar{F}_{10} \end{bmatrix}} \quad \Rightarrow \quad \bar{u} = \underset{\alpha}{\boxed{K_P}} \begin{bmatrix} \overset{T_0}{\boxed{K}}{}^{-1} \begin{bmatrix} \bar{u} \\ \bar{F}_1 \\ \vdots \\ \bar{F}_{10} \end{bmatrix} \\ 0_{11\times1} \end{bmatrix}$$

Eq.(1)

accuracy verification



validity is confirmed via numerical simulations

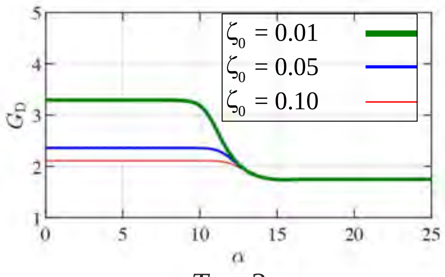
Gust factor for displacement

$$G_D = 1 + \boxed{g_D}\frac{C_g{}'}{C_g}\sqrt{1 + \phi_D^2 R_D}$$

natural period for the 1st mode (**with ASC**)

damping ratio for the 1st mode (**with ASC**)

accuracy verification



T_0 = 3 s

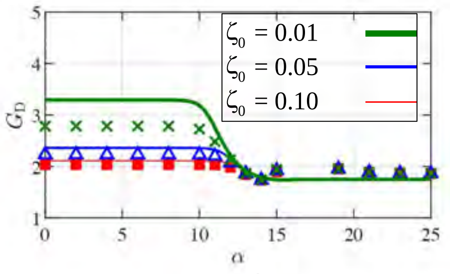
Gust factor for displacement

$$G_D = 1 + \boxed{g_D}\frac{C_g{}'}{C_g}\sqrt{1 + \phi_D^2 R_D}$$

natural period for the 1st mode (**with ASC**)

damping ratio for the 1st mode (**with ASC**)

accuracy verification



T_0 = 3 s

- Validity is confirmed via numerical simulations

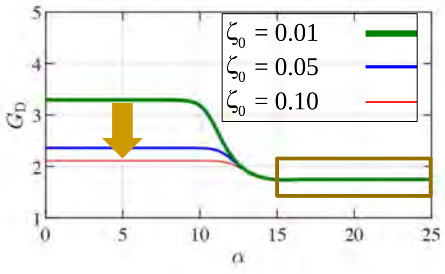
Gust factor for displacement

$$G_D = 1 + \boxed{g_D}\frac{C_g{}'}{C_g}\sqrt{1 + \phi_D^2 R_D}$$

natural period for the 1st mode (**with ASC**)

damping ratio for the 1st mode (**with ASC**)

accuracy verification



T_0 = 3 s

- Validity is confirmed via numerical simulations
- $G_D\downarrow$ as $\zeta_0\uparrow$ if $\alpha < 10$
- G_D is same for different ζ_0 if $\alpha > 15$

Gust factor for control force

$$G_u = \frac{\max\{|u|\}}{\bar{u}}$$

$$\boxed{u(t) = K_{PD}X(t) + K_{PV}\dot{X}\,(t)}$$

$$\approx \frac{K_{PD}\max\{X\} + K_{PV}\max\{\dot{X}\}}{K_{PD}\bar{X} + K_{PV}\boxed{\bar{\dot{X}}} \approx 0}$$

$$\boxed{\max\{\dot{X}\} \approx (\max\{X\} - \bar{X})\omega_1}$$

$$\approx \frac{K_{PD}\max\{X\} + K_{PV}\max\{\dot{X}\}}{K_{PD}\bar{X}}$$

$$\approx \frac{K_{PD}\max\{X\}}{K_{PD}\bar{X}} + \frac{K_{PV}(\max\{X\} - \bar{X})\omega_1}{K_{PD}\bar{X}}$$

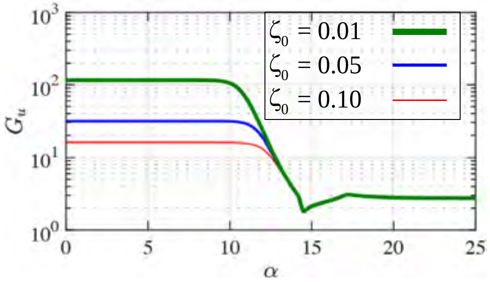
$$\approx \frac{K_{PD}\bar{X}G_D}{K_{PD}\bar{X}} + \frac{K_{PV}(\bar{X}G_D - \bar{X})\omega_1}{K_{PD}\bar{X}}$$

$$\approx G_D + \frac{K_{PV}\bar{X}}{K_{PD}\bar{X}}(G_D - 1)\omega_1$$

Gust factor for control force

$$G_u \approx G_D + \frac{K_{PV}\bar{X}}{K_{PD}\bar{X}}(G_D - 1)\omega_1$$

accuracy verification

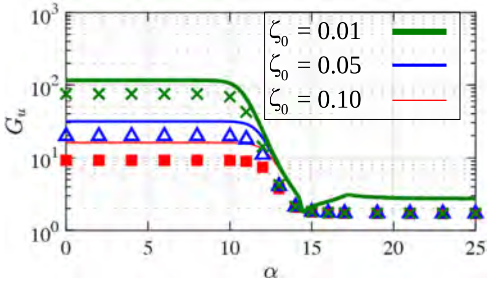


T_0 = 3 s

Gust factor for control force

$$G_u \approx G_D + \frac{K_{PV}\bar{X}}{K_{PD}\bar{X}}(G_D - 1)\omega_1$$

accuracy verification



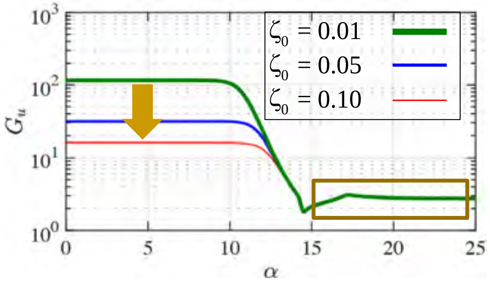
T_0 = 3 s

- Validity is confirmed via numerical simulations

Gust factor for control force

$$G_u \approx G_D + \frac{K_{PV}\bar{X}}{K_{PD}\bar{X}}(G_D - 1)\omega_1$$

accuracy verification



T_0 = 3 s

- Validity is confirmed via numerical simulations
- G_D↓as ζ_0↑if $\alpha < 10$
- G_D is same for different ζ_0 if $\alpha > 15$

Design method & example

Step 1. Specify: parameters of building, wind force

superstructure
PBI layer
return period

super struct.: **100 m, T_s = 2 s, ζ_s = 0.02**
PBI layer: **T_0 = 3 s, ζ_0 = 0.05** return period of **500 years**

Design method & example

Step 1. super struct.: **100 m, T_s = 2 s, ζ_s = 0.02**
PBI layer: **T_0 = 3 s, ζ_0 = 0.05** return period of **500 years**

Step 2. Determine the restrictions of max. response and control force

$x_{\max,\lim}$ = 40 cm, $u_{\max,\lim}$ = 10000 kN

Design method & example

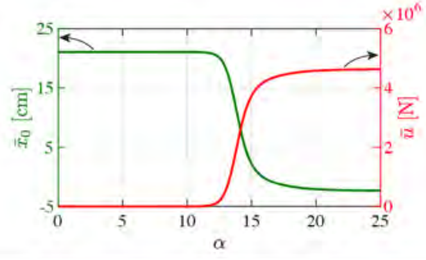
Step 1. super struct.: **100 m, T_s = 2 s, ζ_s = 0.02**
PBI layer: **T_0 = 3 s, ζ_0 = 0.05** return period of **500 years**

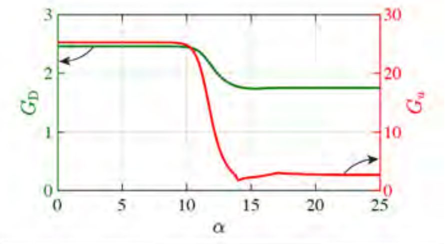
Step 2. **$x_{\max,\lim}$ = 40 cm, $u_{\max,\lim}$ = 10000 kN**

Step 3. Calculate the mean displacement and mean control force

Step 4. Calculate the gust factors

Step 5. Calculate the max. displacement and max. control force





Design method & example

Step 1. super struct.: **100 m, T_s = 2 s, ζ_s = 0.02**
PBI layer: **T_0 = 3 s, ζ_0 = 0.05** return period of **500 years**

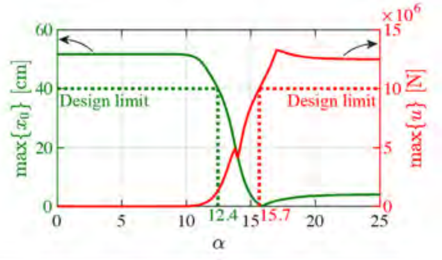
Step 2. **$x_{\max,\lim}$ = 40 cm, $u_{\max,\lim}$ = 10000 kN**

Step 3. Calculate the mean displacement and mean control force

Step 4. Calculate the gust factors

Step 5. Calculate the max. displacement and max. control force

Step 6. Select the weighting entry α



α = 13 for model 1

α = 15 for model 2

Design method & example

Step 1. super struct.: **100 m, $T_s = 2$ s, $\zeta_s = 0.02$**
PBI layer: **$T_0 = 3$ s, $\zeta_0 = 0.05$** return period of **500 years**

Step 2. **$x_{\max,\lim} = 40$ cm, $u_{\max,\lim} = 10000$ kN**

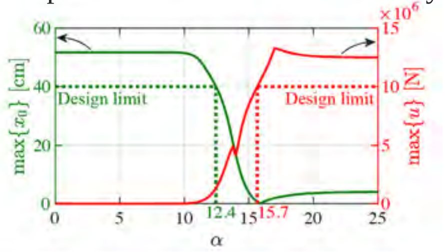
Step 3. Calculate the mean displacement and mean control force

Step 4. Calculate the gust factors

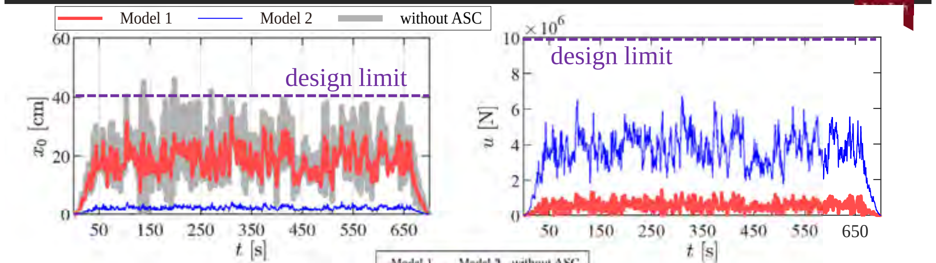
Step 5. Calculate the max. displacement and max. control force

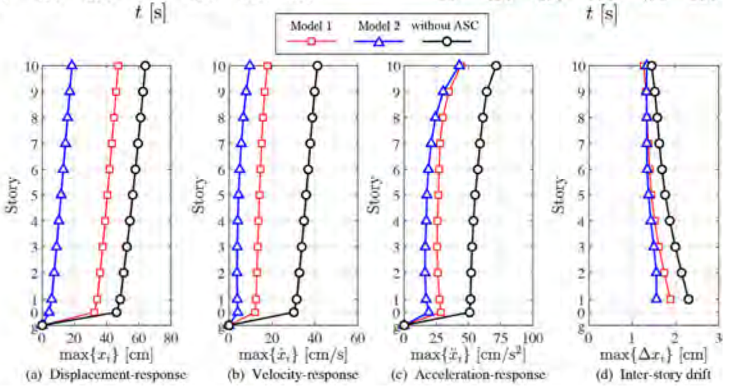
Step 6. **$\alpha = 13$ for model 1** **$\alpha = 15$ for model 2**

Step 7. Construction the control system



Design example: simulation results





Conclusion

This study developed:

1. **Gust factor approach** for PBI buildings with ASC
   - Estimation method for **mean control force and displacement**
   - **gust factor** for control force and displacement
   - Estimation method for **max. control force and displacement**

2. **Design method** for PBI buildings with ASC
   - **No trial-and-error approach**
   - **No numerical simulation**