An Approach for Estimating Seismic Force Modification Factor of Hybrid Building Systems

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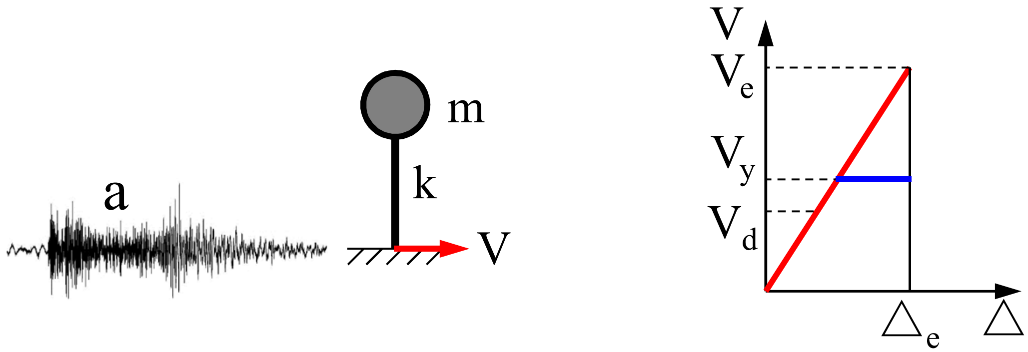
1. Introduction

- **Equivalent Static Force Procedure**



$$V_e = S(T_a)$$

$$V_y = V_e / R_d$$

$$V_d = V_y / R_o$$

(a) *Earthquake excitation to single-mass system*

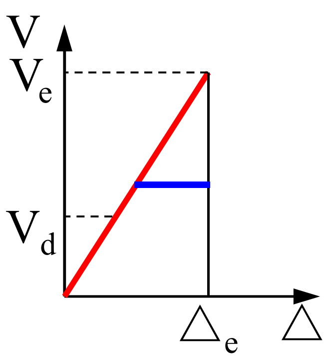
(b) *Seismic force*

Fig. 1. *Seismic force estimation*

- **Seismic force modification factors**

1. Introduction

- **Design base shear of building in Eurocode 8**



$$V_d = \frac{V_e}{q}$$

$$q = \frac{PGA_{u,eff}}{PGA_{code}}$$ PGA-based method

$$q = \frac{V_e}{V_{\max,nl}}$$ Shear-based method

where, V_e – elastic force obtained from spectra with probability of exceedance of 10% in 50 years (475 years return);

q – behaviour factor;

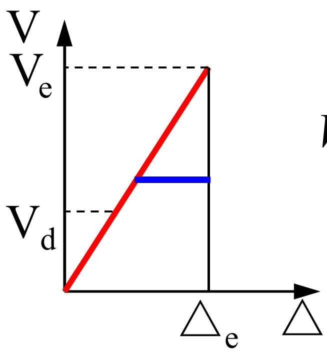
$PGA_{u,eff}$ – PGA of the earthquake record that causes near collapse state of the non-linear structural model;

PGA_{code} – design PGA for the location;

$V_{max,nl}$ – base shear obtained from the non-linear analysis of the building model for any particular earthquake record.

1. Introduction

- **Design base shear of building in IBC and ASCE 7**



$$V_d = \frac{S_{DS} I_e W}{R}$$

FEMA P695

FEMA P795

potential variations in
(a) structural configuration of buildings,
(b) ground motions, and
(c) quality of the available test results.

where, S_{DS} – design spectral response acceleration parameter with probability of exceedance of 2% in 50 years (2,475 years return) in the short period range;

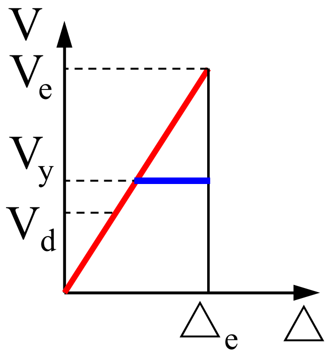
R – response modification factor;

I_e – importance factor;

W – effective seismic weight.

1. Introduction

- **Design base shear of building in NBCC**



$$V_d = \frac{S(T_a) M_v I_e W}{R_d R_o}$$

$$R_d = \begin{cases} \sqrt{2\mu - 1} & 0.1s \le T_a \le 0.5s \\ \mu & T_a > 0.5s \end{cases}$$

$$R_o = R_{size} R_{\phi} R_{yield} R_{sh} R_{mech}$$

where, $S(T_a)$ – design spectral acceleration with probability of exceedance of 2% in 50 years (2,475 years return) at selected period;

M_v – higher mode effect factor;

R_d – ductility-related force modification factor;

R_o – over-strength related force modification factor;

μ – ductility ratio.

1. Introduction

- Only the modification factor of single systems is provided by codes.
- Modification factors of hybrid-systems?

□ To use the lowest one(s) → Too conservative

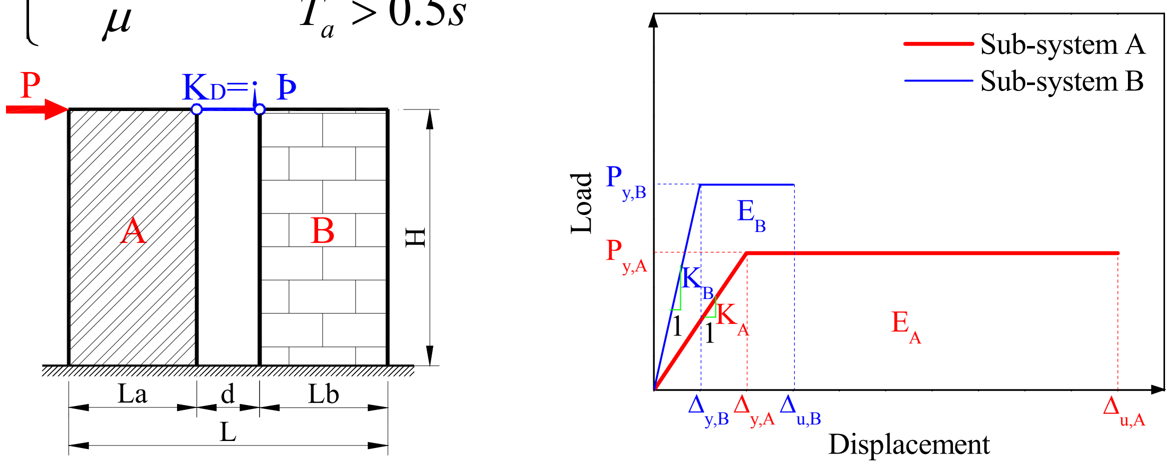
□ To performing non-linear time history analysis → Time consuming

➢ **Objective** of this study – to develop an approach for estimating the ductility-related force modification factor, R_d, for hybrid systems

2. Proposed Method for Estimating R_d of Hybrid Systems

- **2.1 Theoretical Derivation of System μ**

$$R_d = \begin{cases} \sqrt{2\mu - 1} & 0.1s \le T_a \le 0.5s \\ \mu & T_a > 0.5s \end{cases}$$



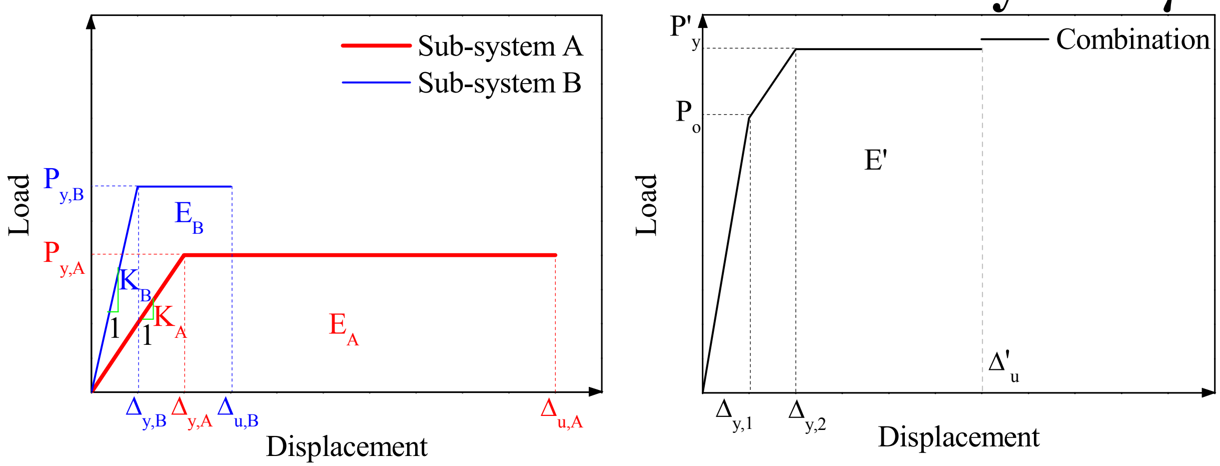
***(a)** Hybrid system* ***(b)** EEEP curves of the two sub-systems*

***Fig. 2.** Hybrid structural system*

EEEP – Equivalent Energy Elastic-Plastic, ASTM E 2126.

2. Proposed Method for Estimating R_d of Hybrid Systems

- ## 2.1 Theoretical Derivation of System μ



***(a)** EEEP curves of the two sub-systems* ***(b)** Combination curve of hybrid system*

***Fig. 3.** EEEP curves of hybrid structural system*

$$K = K_A + K_B$$

$$P_o = \frac{\Delta_{y,B}}{\Delta_{y,A}} P_{y,A} + P_{y,B}$$

$$P_y' = P_{y,A} + P_{y,B}$$

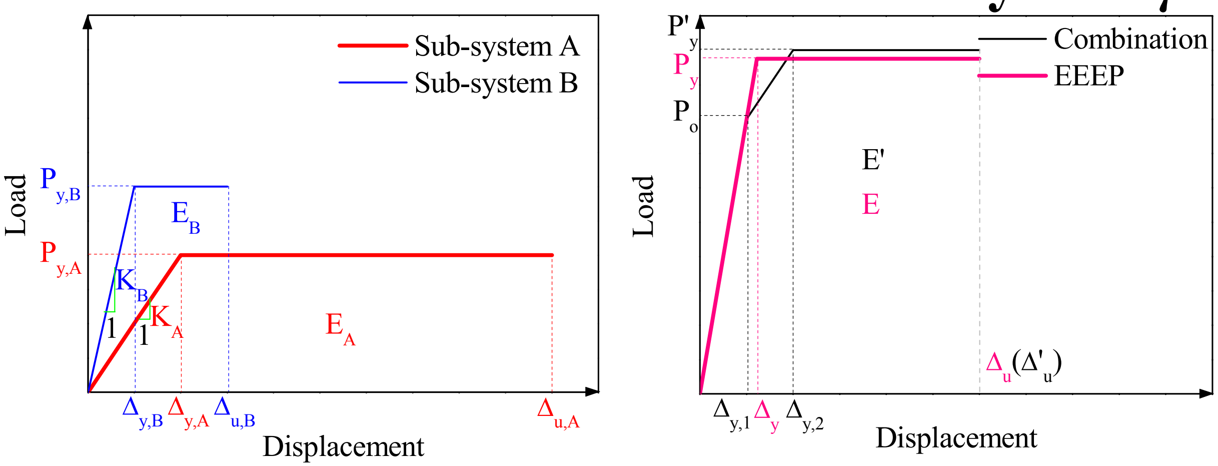
$$\because \quad E' = E_A + E_B$$

$$\therefore \quad \Delta_u' = \alpha_{F,A}\Delta_{u,A} + \alpha_{F,B}\Delta_{u,B}$$

$$\alpha_{F,i} = P_{y,i} \Big/ \sum_{i=A}^{B} P_{y,i}$$

2. Proposed Method for Estimating R_d of Hybrid Systems

- ## 2.1 Theoretical Derivation of System μ



***(a)** EEEP curves of the two sub-systems*

***(b)** Combination curve of hybrid system*

***Fig. 3.** EEEP curves of hybrid structural system*

$$\mu = \frac{\sum_{i=A}^{B}\left(\alpha_{F,i}\Delta_{u,i}\right)}{\sum_{i=A}^{B}\left(\alpha_{F,i}\Delta_{u,i}\right) - \sqrt{\left(\sum_{i=A}^{B}\left(\alpha_{F,i}\Delta_{u,i}\right)\right)^2 - 2\sum_{i=A}^{B}\left(\alpha_{K,i}\frac{\Delta_{u,i}^2}{\mu_i}\right) + \sum_{i=A}^{B}\left(\alpha_{K,i}\frac{\Delta_{u,i}^2}{\mu_i^2}\right)}}$$

$\because \quad \Delta_u = \Delta_u' \ \ \& \ \ E = E'$

$\therefore$

$$\Delta_y = \Delta_u - \sqrt{\Delta_u^2 - 2\sum_{i=A}^{B}\left(\alpha_{K,i}\frac{\Delta_{u,i}^2}{\mu_i}\right) + \sum_{i=A}^{B}\left(\alpha_{K,i}\frac{\Delta_{u,i}^2}{\mu_i^2}\right)}$$

$$P_y = \left(K_A + K_B\right)\Delta_y$$

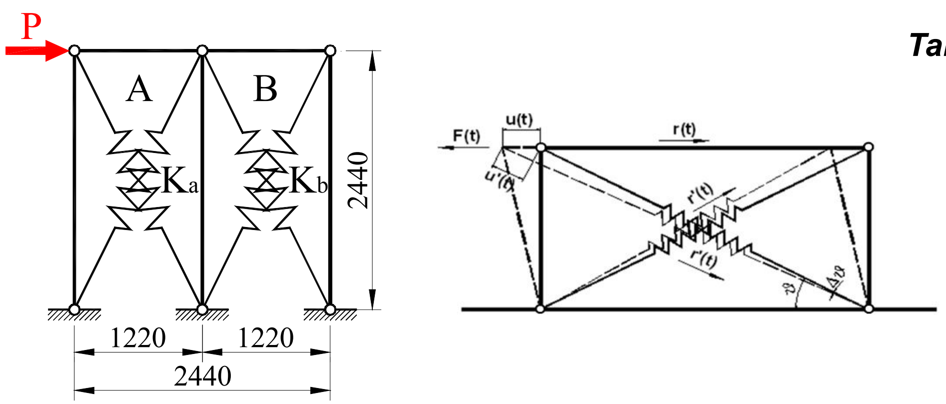
Then

$$u = f\left(\alpha_{K,i}, \alpha_{F,i}, \mu_i, \Delta_{\mu,i}\right)$$

$$\alpha_{F,i} = P_{y,i} \Big/ \sum_{i=A}^{B} P_{y,i} \qquad \alpha_{K,i} = K_i \Big/ \sum_{i=A}^{B} K_i$$

2.2 Numerical Simulation of System μ

- ## 2.2.1 Finite Element Analysis Model



(a) *FEA model* ***(b)*** *Macro-element model*

Fig. 4. *FEA model of hybrid system*

Table 1. *Structural performance of sub-systems*

No.	HD	LD_I	LD_II	LD_III
K (kN/mm)	0.65	0.86	0.65	0.36
P_y (kN)	8.4	9.3	7.4	4.4
Δ_y (mm)	13.1	10.6	11.3	12.1
P_{max} (kN)	9.2	10.4	8.2	4.9
Δ_u (mm)	89.0	17.0	28.3	43.6
μ	6.7	1.6	2.5	3.6

- Two types (High / Low ductility) of sub-system with six combination cases of strength ratio (0.0, 0.2, …, 1.0) were analysed.

2.2 Numerical Simulation of System μ

- **2.2.2 Ductility Ratio of Hybrid Systems**

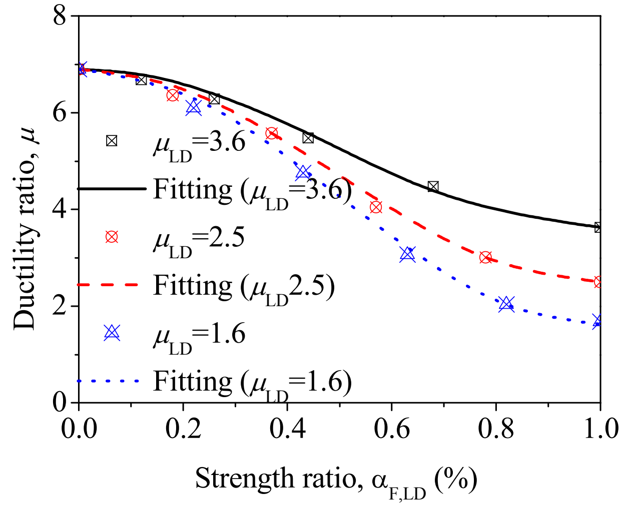


Fig. 5. *System μ of hybrid structural systems with different strength ratios*

$$\mu = \mu_{LD} \sin^2\left(\alpha_{F,LD}\frac{\pi}{2}\right) + \mu_{HD} \cos^2\left(\alpha_{F,LD}\frac{\pi}{2}\right)$$

2.3 System R_d of Hybrid Buildings

- **Relationship between μ and R_d**

$$R_d = \begin{cases} \sqrt{2\mu - 1} & 0.1s \le T_a \le 0.5s \\ \mu & T_a > 0.5s \end{cases}$$

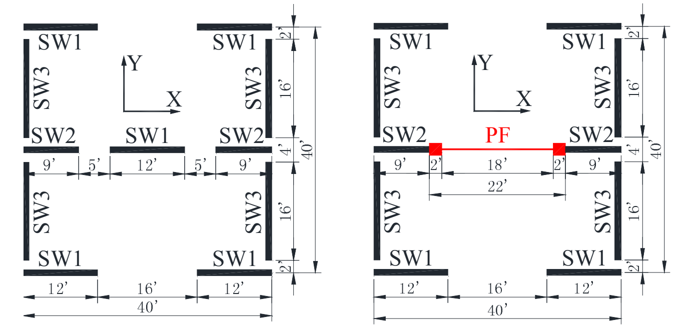
- **System R_d of hybrid buildings**

$$R_d = \sqrt{R_{d,LD}^2 \sin^2\left(\alpha_{F,LD}\frac{\pi}{2}\right) + R_{d,HD}^2 \cos^2\left(\alpha_{F,LD}\frac{\pi}{2}\right)}$$

4. Response of Hybrid Building Systems

- ## 4.1 Structural Design

Two four-storey LWFBs were designed and analysed



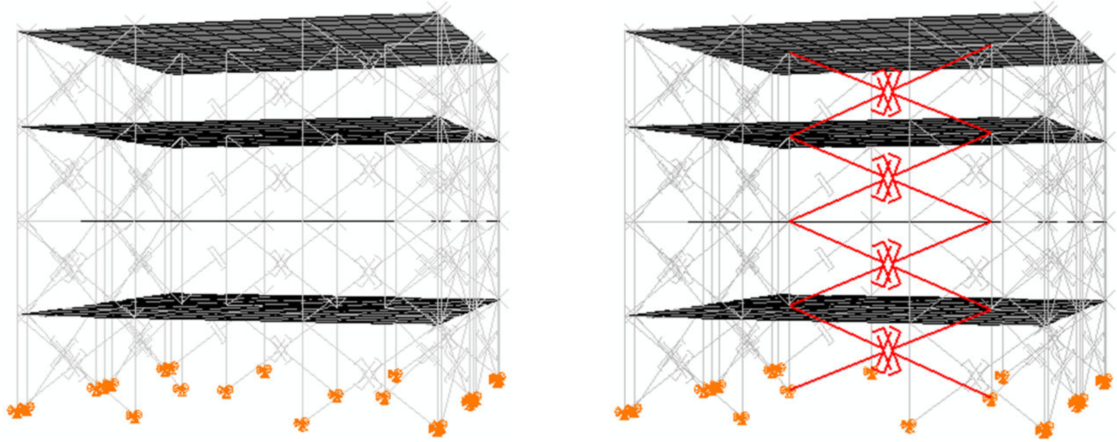
(a) *Reference building* ***(b)*** *Hybrid building*

Fig. 6. *Layouts of buildings*

- Location: Vancouver, PGA=0.46g
- Site class: D (stiff soil)
- Seismic weight: 1.8kPa (floor) & 1.36kPa (roof)
- R factors: R_o=1.7 & R_d=3.57 (R) | 3.43 (H)
- T_a=0.75s

4.2 Numerical Simulation

Two 3-D FEA models of the LWFB was developed using ABAQUS



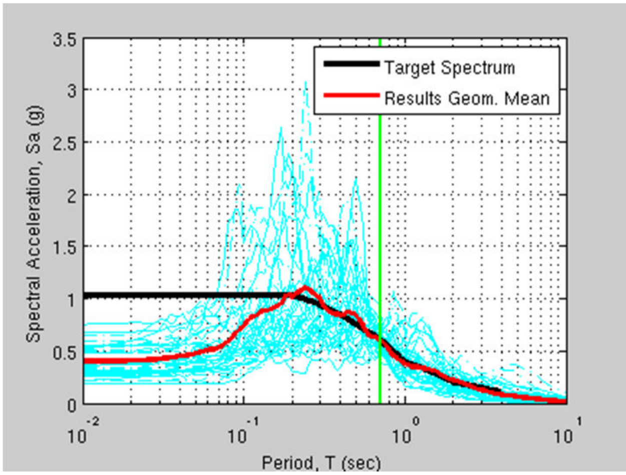
(a) Reference building *(b) Hybrid building*

Fig. 7. *FEA models*

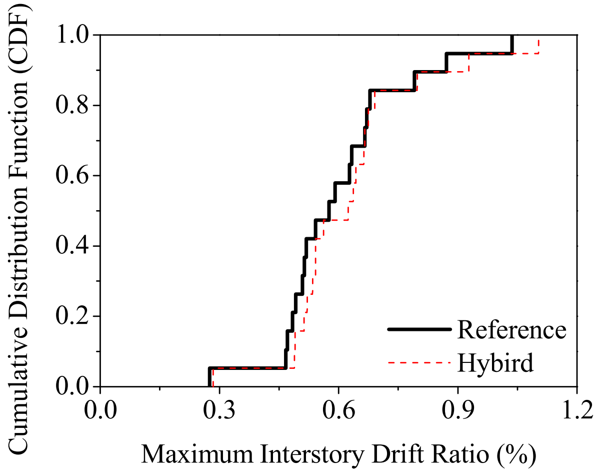
User-defined element – UEL, Truss element – T3D2, Connector element – CONN3D2, Shell element – S4R, Dashpot element – DASHPOTA, about “700 elements” in total.

4.3 Seismic Response

Nonlinear time history analysis using implicitly dynamic analysis method



(a) *Scaling earthquake records (0.70s)*



(b) *CDFs of maximum inter-storey drift ratio*

Fig. 8. *Nonlinear time history analysis*

- The seismic response of the hybrid building designed with the R_d estimated from the proposed approach is nearly the same as the reference building. Hence the approach for estimating the system R_d factor of hybrid system is appropriate.

5. Conclusions

- ✓ **An approach for estimating the ductility ratio, μ, and the ductility-related force modification factor, R_d, of hybrid buildings containing two types of LLRS is proposed.**
- ✓ **A reference and hybrid models were designed and analysed to verify the proposed approach for estimating the system R_d factor.**
- ✓ **The results show that the current NBCC approach for assigning R_d for hybrid building is conservative.**
- □ **For future investigation, a more comprehensive analysis on hybrid buildings incorporating varying types of LLRS's will be performed. This method still needs to be investigated further for applications that involve hybrid buildings incorporating other types of LLRS's. Similar method to estimate the system ductility ratio and R_d factor of multi-storey hybrid buildings will be investigated.**

THE END

"Thank you for your attentions!"

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