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DESIGN FOR ISOLATED BUILDING CONSIDERING STIFFNESS DISTRIBUTION FOR INHOMOGENEOUS MASS

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Isolated Building　Energy Based Design　Stiffness Correction
Shear Coefficient　Mass Distribution

1. Introduction

Due to the Tohoku Earthquake in 2011, there has been increasing cases of adopting seismic isolation structures to buildings. Fu and Sato *et al.*[1] proposed a design method (energy balance method) for isolated buildings which obtained the appropriate range of superstructure period to satisfy the criteria. However, this method did not confirm whether the stiffness distribution can be applied to inhomogeneous mass model (IHM model). Therefore, this report introduces a design example for IHM model considering superstructure stiffness distribution based on the design flow (Fig. 1) by Chen and Sato *et al.*[2].

2. Design Flow

In Fig. 1 showing design flow, the superstructure period T_u and stiffness distribution k_u are initially obtained (S0 to S8) by using energy balance method. Then, by shear coefficient amplification method (S9), k_u can be corrected in S11 by using the design value of deformation R_p (S10).

3. Target Model and Input

The target model shown in Fig. 2 consists of an isolation layer with mass M_0 = 1.7×M_1, and a 4-mass-point superstructure model with top-most story mass M_4=M_1/10 (IHM model), where M1 is the 1st story mass. Each superstructure story height is 7.5 m.

the isolation layer (Story 0) is composed of (i) an isolator (linear stiffness k_f) and (ii) a hysteresis damper (initial stiffness k_s). Initial stiffness-proportional damping ratio of superstructure h_u = 2%.

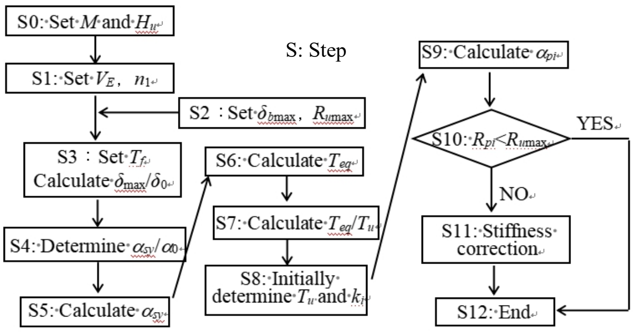
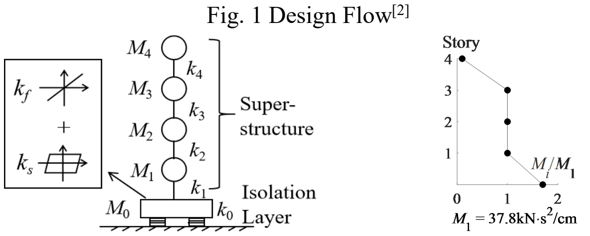


Fig. 1 Design Flow[2]



(a) Mass Point model　(b) Mass Normalization

Fig. 2 Target Model

The Hachinohe (1968) EW component (ART-HACHI) is used as input ground motion. From time-history analysis using ART-HACHI, the equivalent hysterisis loop of input motion n_1 = 6.8 and the equivalent velocity of input energy V_E = 191 cm/s were obtained.

4. Design Example

The design example adopting the design flow (Fig. 1) using the IHM model (Fig. 2) and ART-HACHI is introduced in this chapter.

Step 0: Total Mass and Height of Superstructure

Total mass M = 181.44 kN·s²/cm (i.e., superstructure + isolation layer); superstructure mass M_u = 117.18 kN·s²/cm; superstructure height H_u = 30 m (Fig. 3).

Step 1: Input Motion

Using the input earthquake motion as ARTHACHI, V_E = 191 cm/s, n_1 = 6.8 as Chapter 3.

Step 2: Design Criteria

Assuming the criteria deformation of isolation layer δ_{bmax} = 40 cm, equivalent deformation of superstructure δ_{ueq} = 5 cm, equivalent superstructure height H_{ueq} = 1/2×H_u = 15 m (Fig. 3). The deformation angle of superstructure R_{umax} = δ_{ueq}/H_{ueq} = 1/300 is known.

Step 3: Isolator Period and Max. Deformation Ratio

Assuming isolator period T_f = 4 s, max. deformation of isolation layer without damping δ_0 and max. deformation ratio δ_{bmax}/δ_0 are calculated as:

$$\delta_0 = \frac{T_f \times V_E}{2\pi} = \frac{4\times 191}{2\pi} = 121.59\ \text{cm},\quad \frac{\delta_{b\max}}{\delta_0} = \frac{40}{121.59} = 0.33 \qquad (1),(2)$$

STEP 4: Yield Shear Coefficient Ratio of Hysteresis Damper

Fig. 4 shows the relation between total shear coefficient ratio of isolation layer α_1/α_0, shear coefficient ratio of isolator α_f/α_0 (Eq. (3)) and yield shear coefficient ratio of hysteresis damper α_{sy}/α_0, when n_1 = 6.8. Note: the shear coefficient of isolation layer without damper α_0 will be shown next step. Accordingly, α_{sy}/α_0 = 0.05[3].

$$\frac{\delta_{b\max}}{\delta_0} = \frac{\alpha_f}{\alpha_0} = -4n_1\frac{\alpha_{sy}}{\alpha_0} + \sqrt{\left(4n_1\frac{\alpha_{sy}}{\alpha_0}\right)^2 + 1} \qquad (3)$$

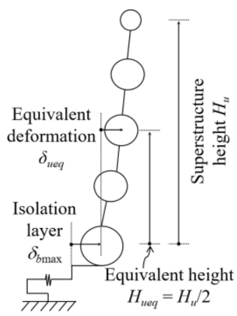


Fig. 3 δ_{ueq} and H_{ueq}

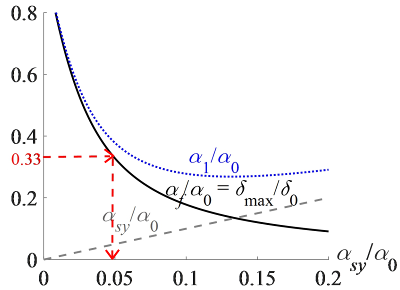


Fig. 4 Prediction Curve (n_1 = 6.8)

STEP 5: Yield Shear Coefficient of Hysteresis Damper

Eq. (4) gives α_0, and correspondingly, the yield shear coefficient of hysteresis damper $\alpha_{sy} = (\alpha_{sy}/\alpha_0)\times\alpha_0 = 0.015$ is obtained.

$$\alpha_0 = \frac{2\pi \cdot V_E}{T_f \cdot g} = \frac{2\pi \times 191}{4\times 980} = 0.306 \tag{4}$$

STEP 6: Equivalent Period

For the case of $T_f = 4$ s (Step 3), isolator stiffness k_f is obtained by Eq. (5). Moreover, assuming yield deformation of hysteresis damper $\delta_{sy} = 3$ cm, the initial damper stiffness k_s is obtained by Eq. (6):

$$k_f = \frac{4\pi^2 M}{T_f^2} = \frac{4\pi^2 \times 181.44}{4^2} = 448 \text{ kN/cm} \tag{5}$$

$$k_s = \frac{\alpha_{sy} Mg}{\delta_{sy}} = \frac{0.015\times 181.44\times 980}{3} = 904 \text{ kN/cm} \tag{6}$$

Equivalent stiffness of isolation layer k_{beq} and equivalent period T_{eq} are calculated as:

$$k_{beq} = k_f + k_s \frac{\delta_{sy}}{\delta_{b\max}} = 448 + 904\times\frac{3}{40} = 516 \text{ kN/cm} \tag{7}$$

$$T_{eq} = 2\pi\sqrt{M/k_{beq}} = 2\pi\sqrt{181.44/516} = 3.7 \text{ s} \tag{8}$$

STEP 7: Equivalent Period Ratio

Equivalent period ratio $T_{eq}/T_u = (\delta_{b\max}/\delta_{ueq})^{0.5} = (40/5)^{0.5} = 2.83$.

STEP 8: Superstructure Period and Stiffness Distribution

By T_{eq}/T_u in Step 7 and T_{eq} in Eq. (8), the superstructure period T_u is initially obtained as $T_u = T_{eq}/(T_{eq}/T_u) = 3.7/2.83 = 1.3$ s. Then, the superstructure stiffness k_u can be initially determined by linear mode shape as:

$$\begin{cases} k_{uN} = \dfrac{\omega_u^2 \times M_N \times \phi_N}{\phi_N - \phi_{N-1}} & (N=4) \\ k_{ui} = \dfrac{\omega_u^2 \times M_i \times \phi_i + k_{u,i+1}\times(\phi_{i+1}-\phi_i)}{\phi_i - \phi_{i-1}} & (i=2,3) \\ k_{u1} = \dfrac{\omega_u^2 \times M_1 \times \phi_1 + k_{u2}\times(\phi_2-\phi_1)}{\phi_1} & \end{cases} \tag{9}$$

Here, linear mode shape $\phi_i = i$ (where $i = 1$ to 4).

STEP 9: Shear Coefficient of Superstructure

Non-linear coefficient of isolation layer $NL = 0.12$ is calculated in Eq. (10)[4], and corresponding shear coefficient amplification factor a is obtained by Eq. (11)[5]. The shear coefficients at i-th story α_{pi} are obtained by trapezoidal distributioin of factor a. Accordingly, they are calculated by Eq. (12) and are indicated in Table 1.

$$NL = \frac{k_s\delta_{sy}(\delta_{b\max} - \delta_{sy})}{\delta_{b\max}(k_s\delta_{sy} + k_f\delta_{b\max})} = 0.12 \tag{10}$$

$$a = 1.66 + 2.58NL = 1.66 + 2.58\times 0.12 = 1.97 \tag{11}$$

$$\alpha_{pi} = \left[1 + \frac{i}{N}(a-1)\right]\times\frac{k_{beq}\cdot\delta_{b\max}}{M\cdot g} \quad (i = 0\sim 4) \tag{12}$$

STEP 10: Deformation Angle of Superstructure

The deformation angle of superstructure R_{pu} is calculated by Eq. (13). As Table 1 indicates, all the R_{pu} overpass the criteria 1/300.

$$R_{pui} = \frac{\alpha_{pi}\cdot\sum_{j=i}^{n} M_j \cdot g}{k_{ui}\cdot h_i} \quad (i = 1\sim 4) \tag{13}$$

STEP 11: Stiffness Correction Factor

The prediction value of deformation angle R_{pu} can be used to obtain the stiffness correction factor β_{ku} in Eq. (14) (Table 1). Note, for case $R_p \le R_{u\max}$, the factor $\beta_{ku} = 1.0$.

$$\beta_{kui} = \frac{R_{pui}}{R_{u\max}} \quad (\text{minimum value is } 1.0) \tag{14}$$

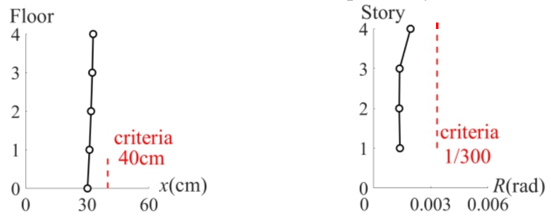
Multiplying β_{ku} to k_u (Eq. (9)), the correction stiffness distribution k_u' is obtained, indicated in Table 1.

Table 1 Design Values

Story	0	1	2	3	4
α_{pi}	0.180	0.223	0.267	0.311	0.354
R_{pu} (rad)		0.0060	0.0058	0.0056	0.0050
β_{ku}		1.81	1.74	1.69	1.49
k_u' (kN/cm)	1,352	10,256	8,308	5,065	525

5. Verification

According to the time-history results of $T_f = 4$ s, $\alpha_{sy} = 0.015$ model in Fg. 5, the displacements of isolation layer and the deformation angle of superstructure R are both in the safe side of criteria $\delta_{b\max} = 40$ cm and $R_{u\max} = 1/300$, respectively.



(a) Displacement (b) Deformation Angle

Fig. 5 Vertical Distribution (ARTHACHI)

6. Conclusion

In this paper, a new design method was introduced based on energy balance method by Fu *et al.*. By using shear coefficient amplification method, the stiffness distribution of superstructure was improved and could be considered for analysis of inhomogeneous modeling.

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