TMD example of a high-rise building (20-story model)

1. Building Model

- 20 story steel building (lumped mass model with shear spring)
- Story height 3.2 m
- Building height $H = 3.2$ m × 20 = 64 m
- Natural period $T = 0.02\ H = 1.28$ sec
- Plan size X direction: 20 m, Y-direction: 28 m
- Story weight Assuming the unit weight 12 kN/m², W_i = 6720 kN
- Story mass $M_i = \frac{W_i}{g} = \frac{6720\ kN}{9.806\times10^3\ mm/s^2} = 0.6853\ {kN.s^2}/{mm}$
- Building mass $M_s = \frac{W_s}{g} = \frac{134.4\times10^3\ kN}{9.806\times10^3\ mm/s^2} = 13.71\ {kN.s^2}/{mm}$
- Story stiffness From the Appendix

$$k_i = \frac{1}{2}[n(n+1) - i(i-1)]m_i\omega^2 \qquad i = 1\ to\ n$$

- Story damping Assuming the proportional damping to the stiffness

$$c_i = 2h\omega\frac{k_i}{\omega^2} = \frac{2h}{\omega}k_i = \alpha\,k_i\ , \qquad \alpha = \frac{2h}{\omega}$$

where h is the damping factor (=0.02)

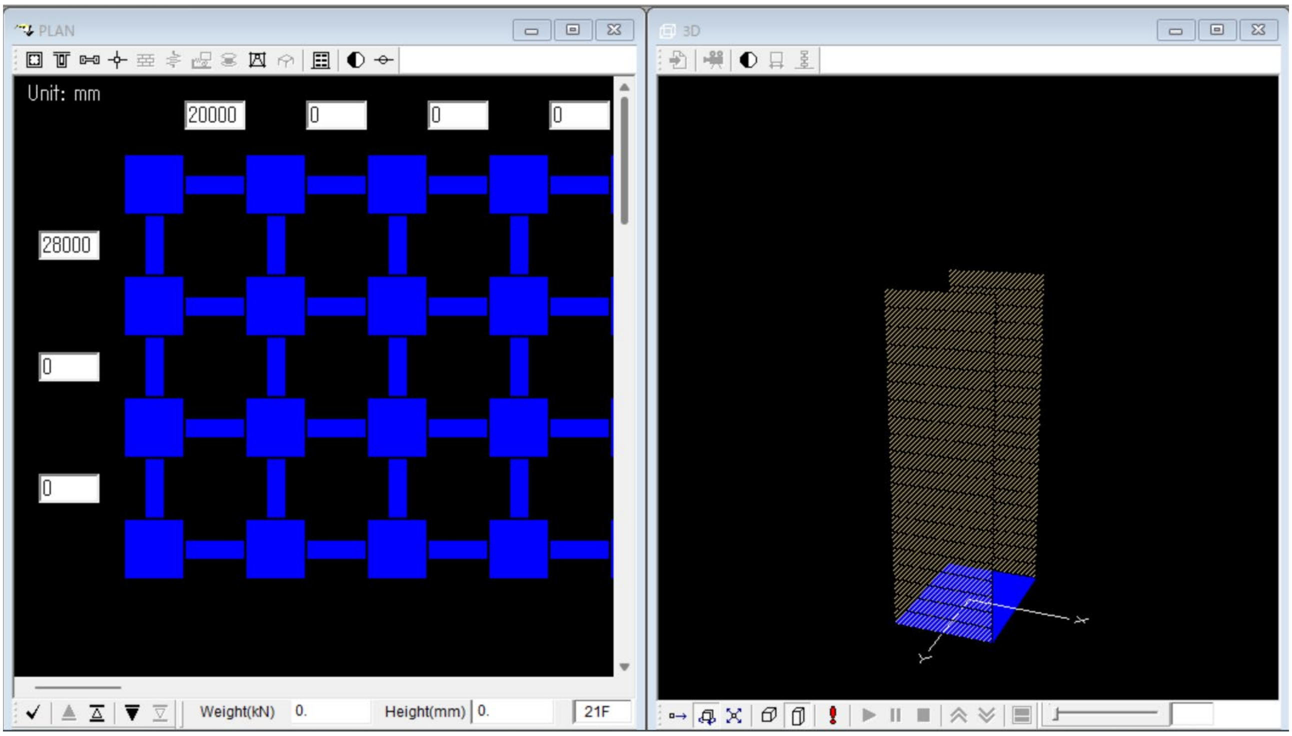


Figure 1 Analysis model of the building (20-story model without TMD.stera)

Table 1 Properties of Building

Story	Height (mm)	Weight (kN)	K (kN/mm)	C ($kN.s/mm$)
1	3200	6720	3467.7	28.3
2	3200	6720	3451.1	28.1
3	3200	6720	3418.1	27.9
4	3200	6720	3368.6	27.4
5	3200	6720	3302.5	26.9
6	3200	6720	3220.0	26.2
7	3200	6720	3120.9	25.4
8	3200	6720	3005.3	24.5
9	3200	6720	2873.2	23.4
10	3200	6720	2724.6	22.2
11	3200	6720	2559.5	20.9
12	3200	6720	2377.8	19.4
13	3200	6720	2179.7	17.8
14	3200	6720	1965.0	16.0
15	3200	6720	1733.8	14.1
16	3200	6720	1486.1	12.1
17	3200	6720	1221.9	10.0
18	3200	6720	941.2	7.7
19	3200	6720	644.0	5.2
20	3200	6720	330.3	2.7

2. Design of TMD

Assuming the mass ratio $\mu = 0.03$

Weight of TMD $W_d = W_s \times \mu = 134.4 \times 10^3\ kN \times 0.03 = 4032\ kN$

Mass of TMD $m_d = \frac{W_d}{g} = 0.4112\ kN.s^2/mm$

Optimum frequency ratio $\frac{\omega_\mathrm{d}}{\omega_\mathrm{s}} = \frac{1}{1+\mu} = \frac{1}{1.03} = 0.97$

Circular frequency of TMD $\omega_\mathrm{d} = 0.97 \times \omega_\mathrm{s} = 0.97 \times \frac{2\pi}{T_s} = 0.97 \times \frac{2\pi}{1.28} = 4.766$

Natural period of TMD $T_\mathrm{d} = \frac{1.28}{0.97} = 1.318$ sec

Stiffness of TMD $K_d = m_d {\omega_\mathrm{d}}^2 = 0.4112 \times 4{,}76^2 = 9.34\ kN/mm$

Optimum damping factor $h_{opt} = \sqrt{\frac{3\mu}{8(1+\mu)^3}} = 0.101$

Damping coefficient of TMD $C_d = \frac{2h_{opt}}{\omega_\mathrm{d}} K_d = 0.398\ kN.s/mm$

Story height of TMD 6 m

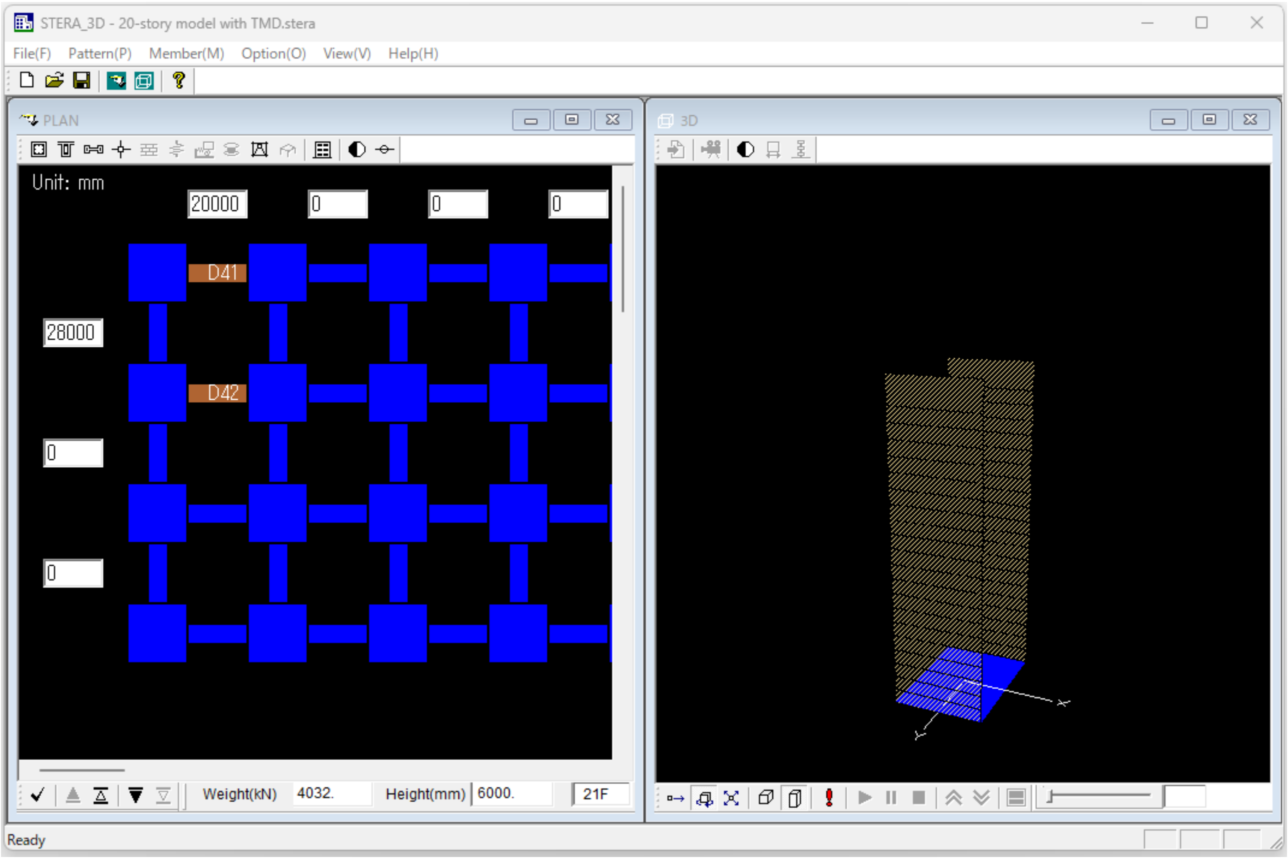


Figure 2　Analysis model of the building with TMD（20-story model with TMD.stera）

Table 2　Properties of TMD

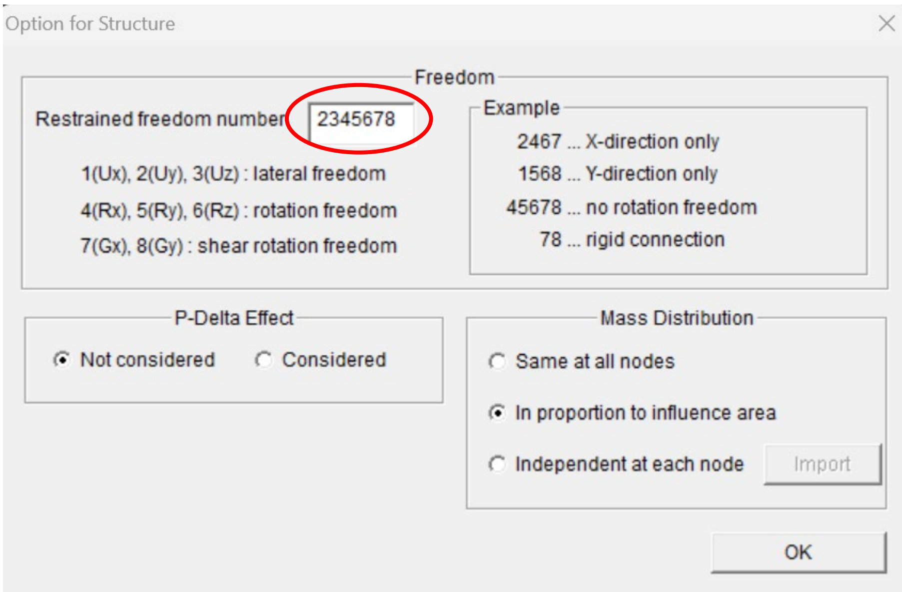
Story	Height (mm)	Weight (kN)	K (kN/mm)	C ($kN.s/mm$)
1	6000	4032	9.34	0.398

3. Input procedures of STERA_3D

Step 1. Restrained freedom number

Option > Structure

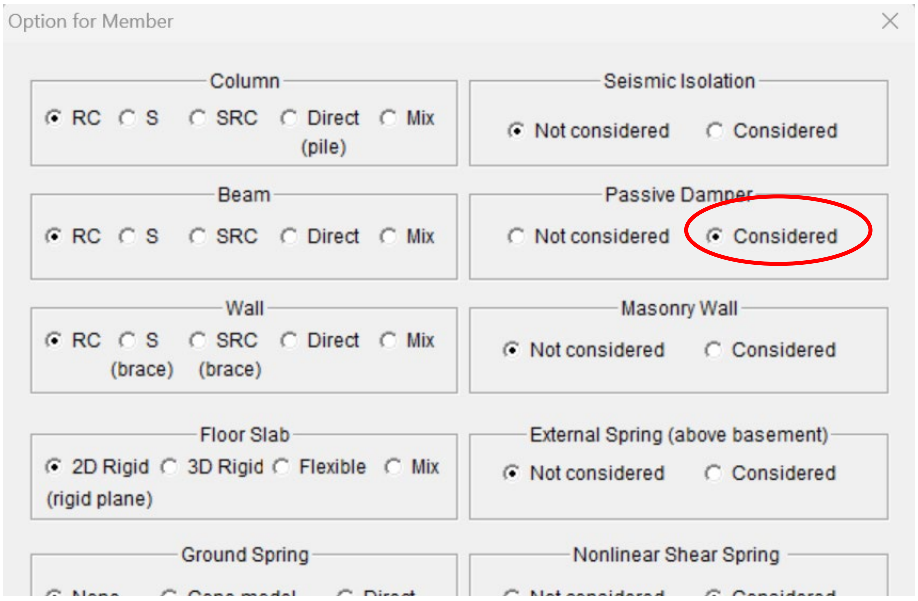
Since the direction of freedom is only X-direction (1), set "Restrained freedom number" to be 2345678.



Step 2. Passive damper

Option > Member

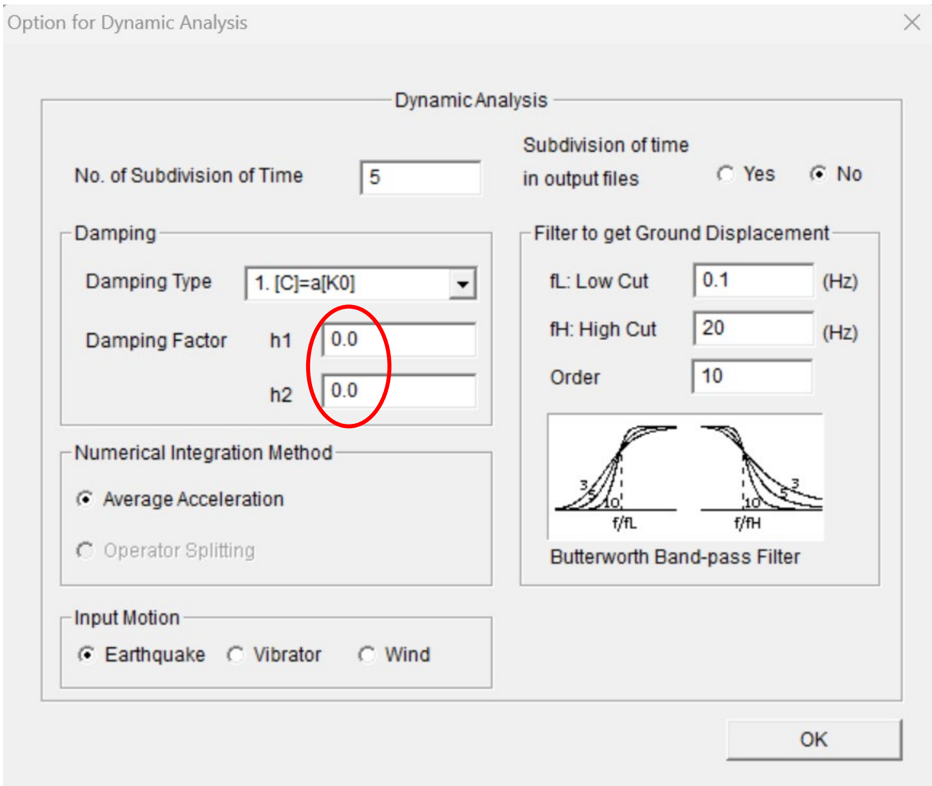
Since the passive damper is used for the lateral spring, set "Passive Damper" to be Considered.



Step 3. Damping factor

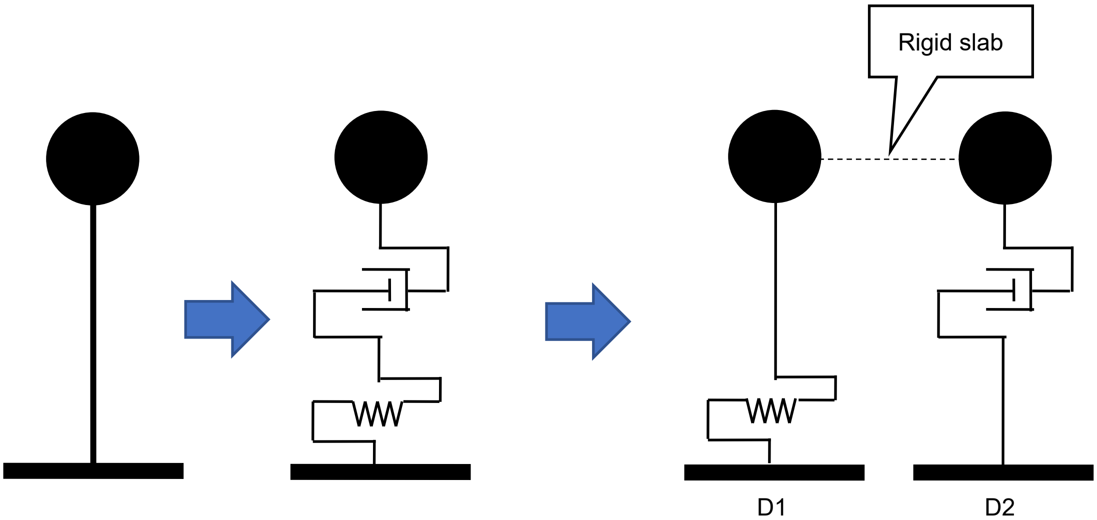
Option > Analysis > Dynamic

Since the damping property is given for each individual element, the viscous damping factors, h1 and h2, are set to be zero.



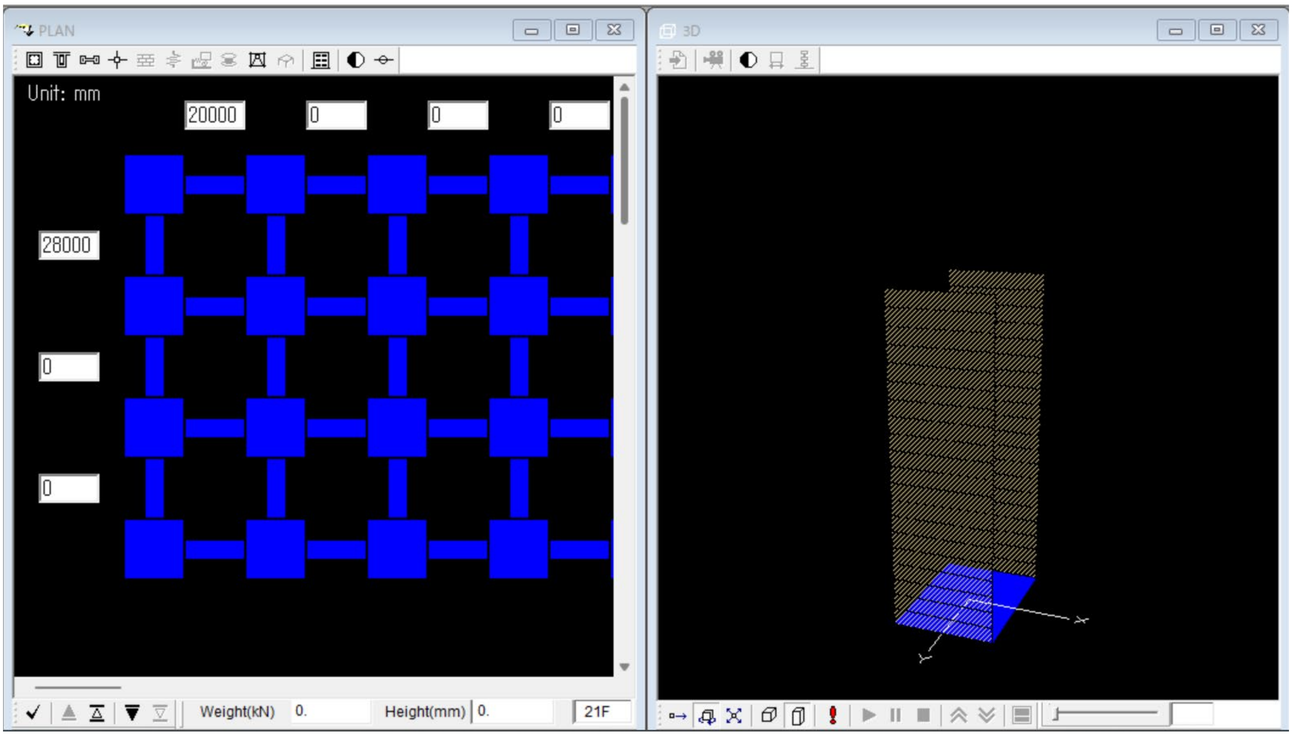
Step 4. Member setting (Main Building)

One story consists of two passive dampers (D1 and D2) with D1 as a spring member and D2 as a damping member.



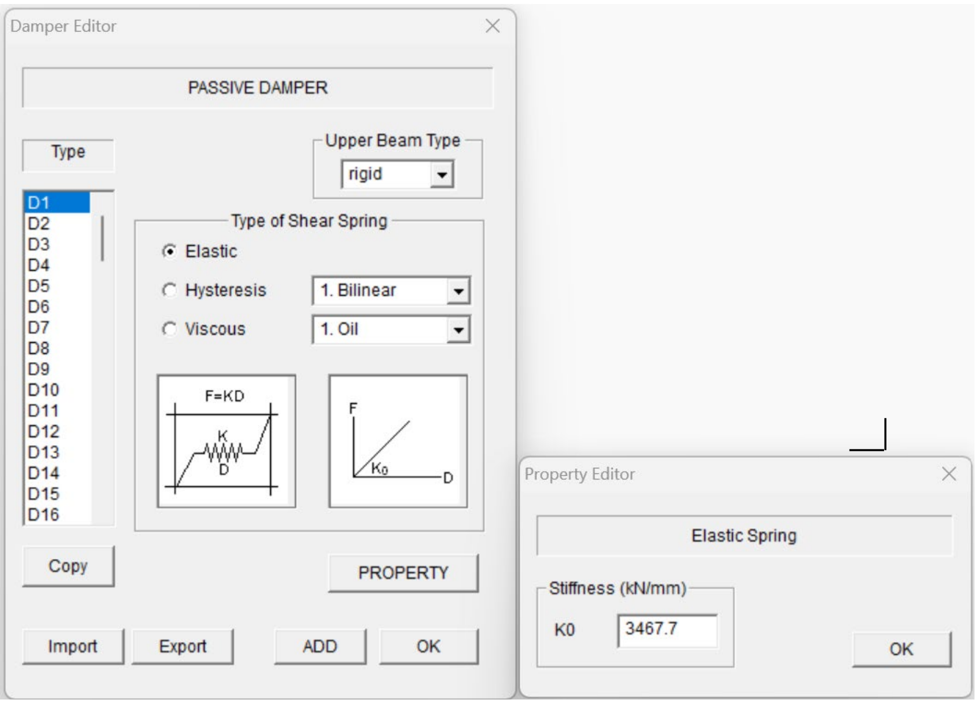
X-span 20000 mm, Y-span 28000mm, Story Weight 6720 kN, Story Height 3200 mm

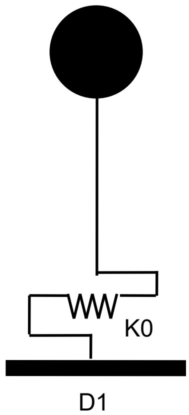
Continue to create up to 20th floor (D1～D40)



Passive dampers　D1, D3, …, D39 

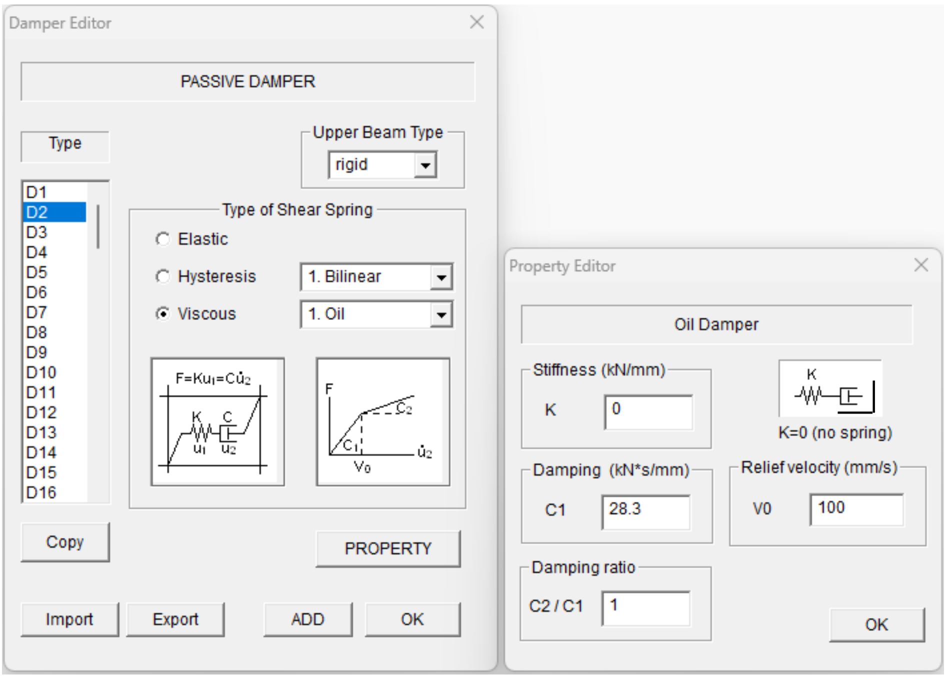
Select type of shear spring to be “Elastic”, and input the stiffness K0 in “`PROPERTY” window.

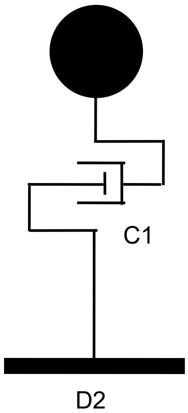




Passive dampers D2, D4, …, D40

Select type of shear spring to be “Viscous” and input the damping coefficient C1 in “PROPERTY” window. Other parameters, stiffness K =0, Damping ratio(C2/C1) =1, Relief velocity V0 = 100 mm/s.

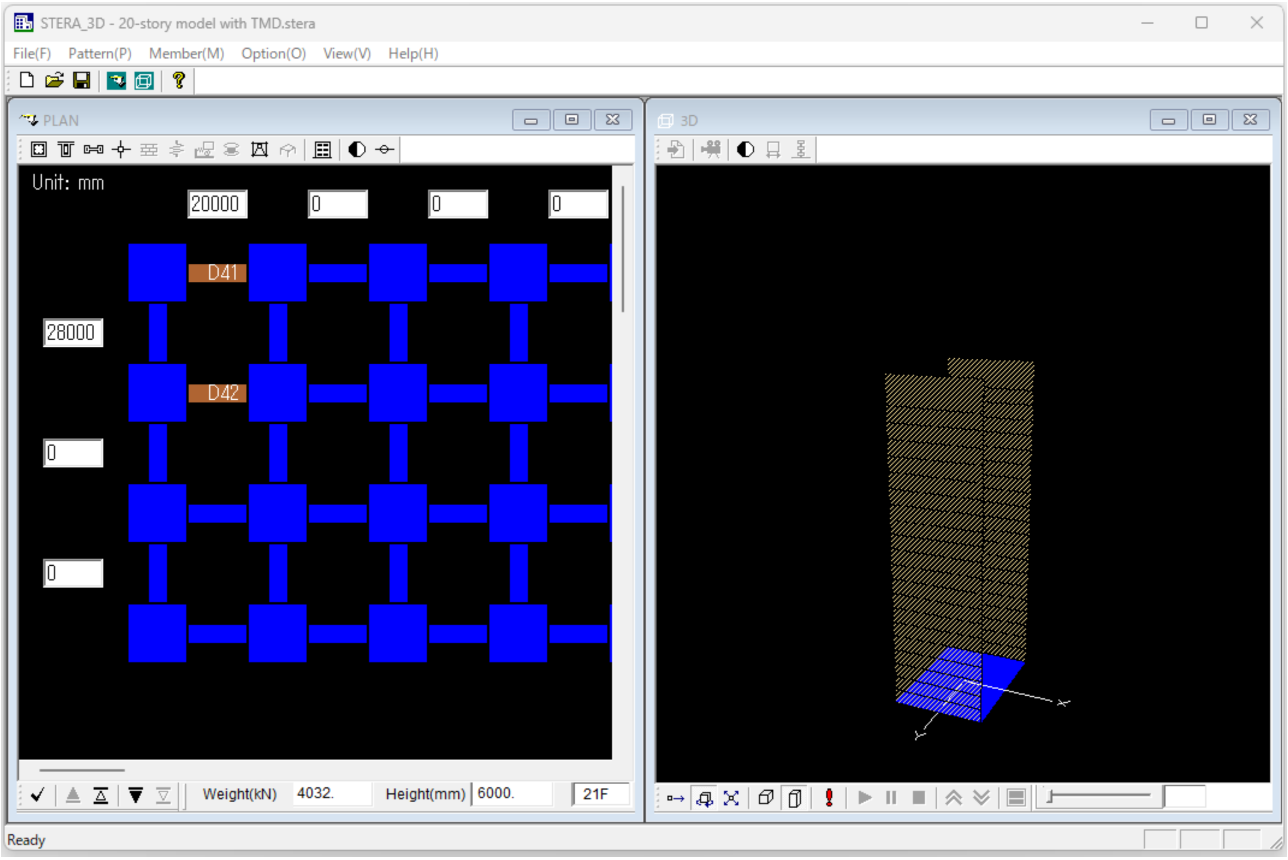




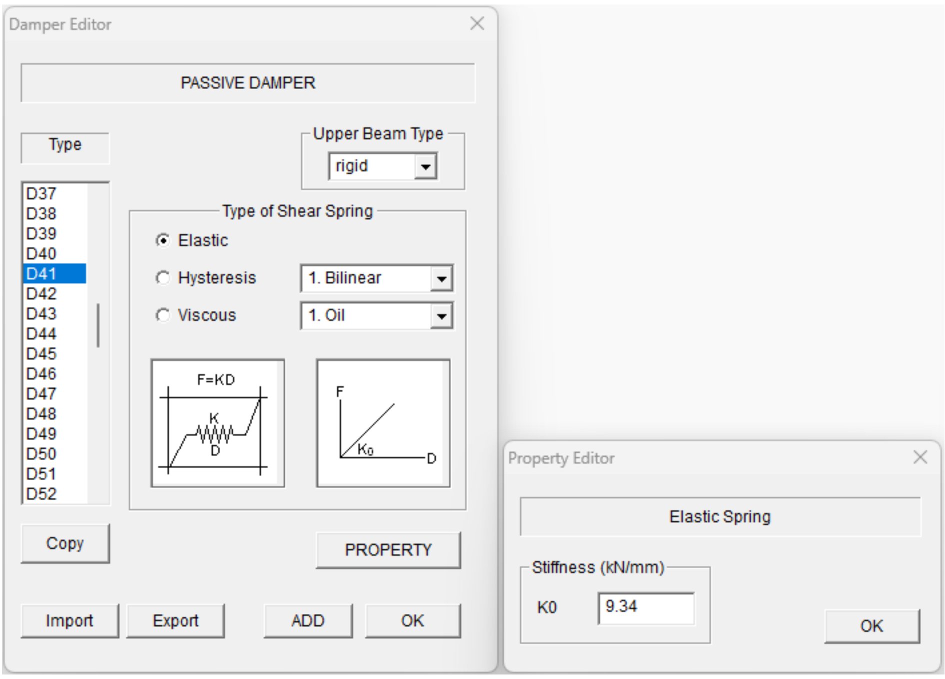
Save the input data in the file “20-story model without TMD.stera”.

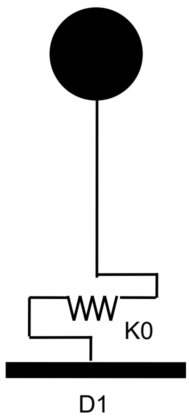
Step 5. Member setting (TMD)

Create a TMD model for one floor above the main building (21st floor) with D41 as a spring member and D42 as a damping member.
Assume that the weight of the floor is 4032 kN and the height of the floor is 6000 mm.



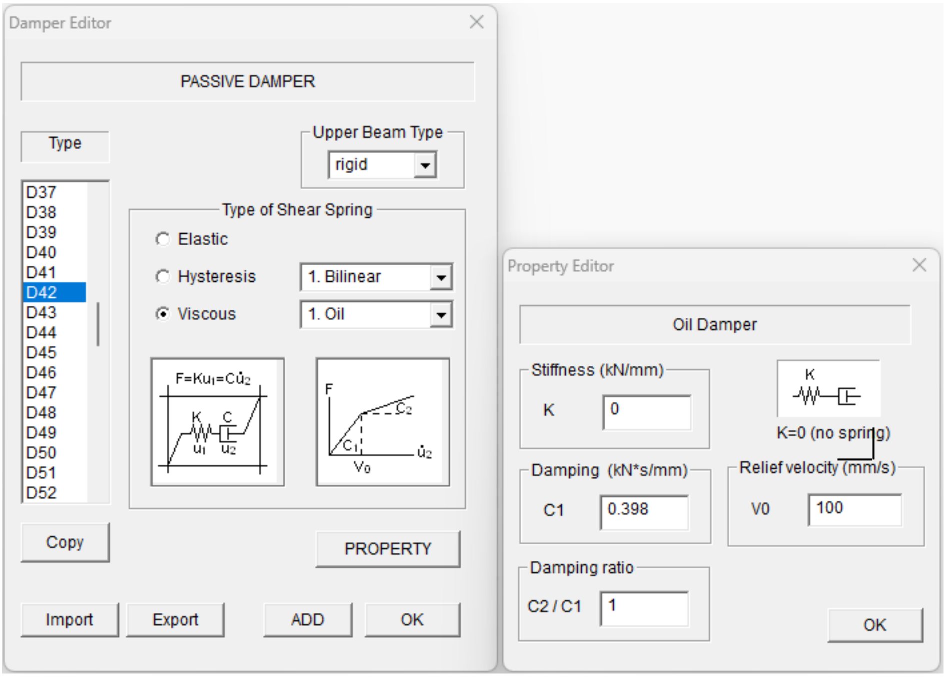
Passive damper D41 
Select type of shear spring to be “Elastic”, and input the stiffness K0 in “`PROPERTY” window.

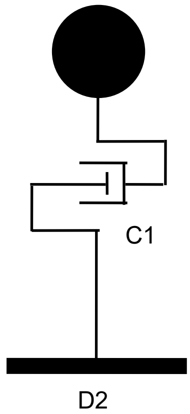




Passive damper D42 

Select type of shear spring to be “Viscous” and input the damping coefficient C1 in “PROPERTY” window. Other parameters, stiffness K =0, Damping ratio(C2/C1) =1, Relief velocity V0 = 100 mm/s.

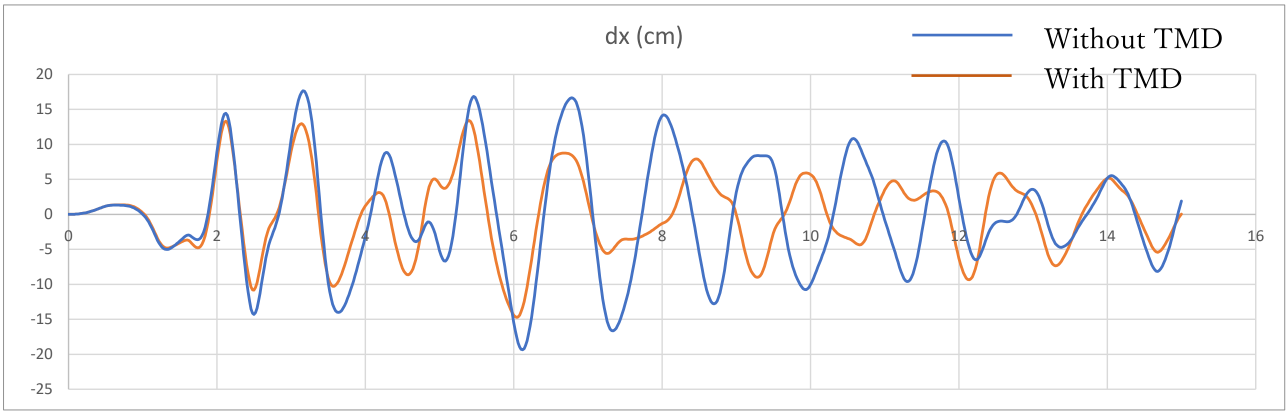


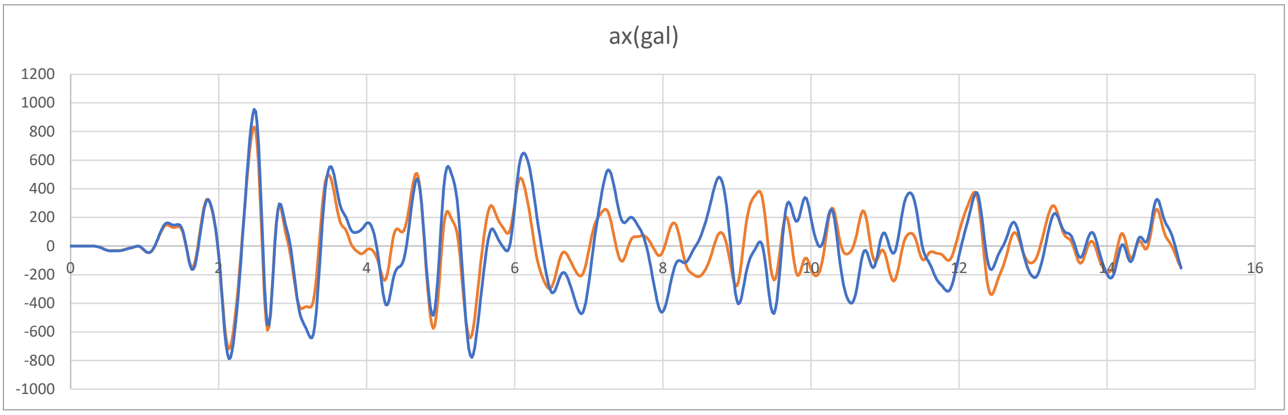


Save the input data in the file “20-story model with TMD.stera”.

Step 6. Comparison of responses between the buildings with and without TMD

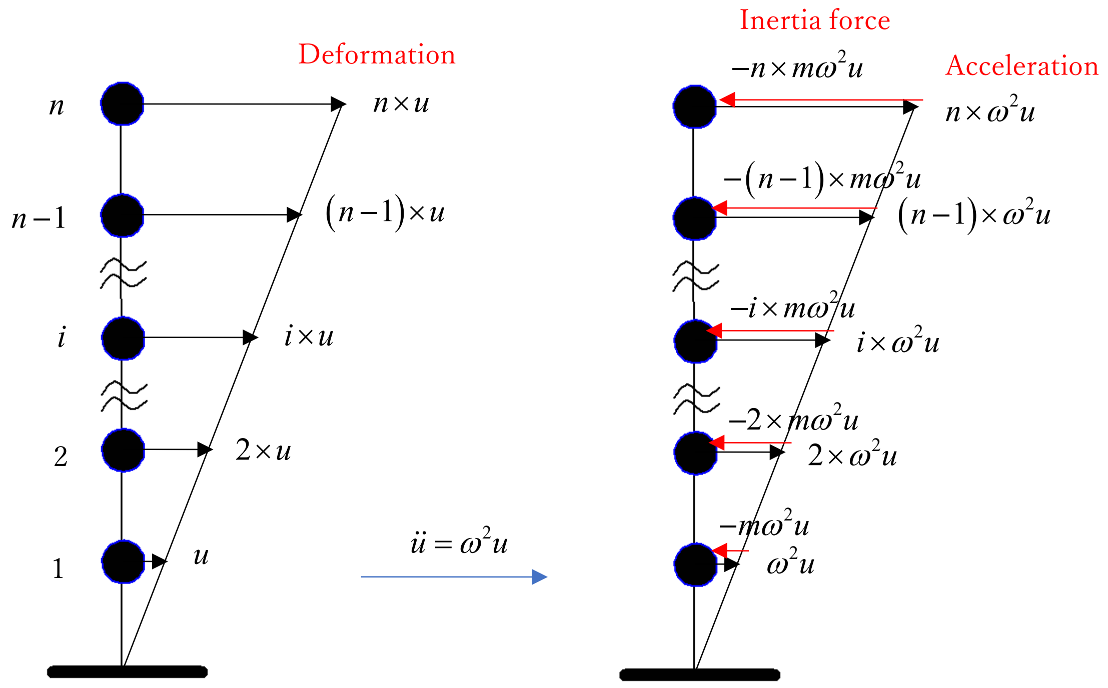
Displacement and acceleration responses at the 20th floor of the buildings with and without TMD under the El Centro 1940_NS earthquake wave are compared.

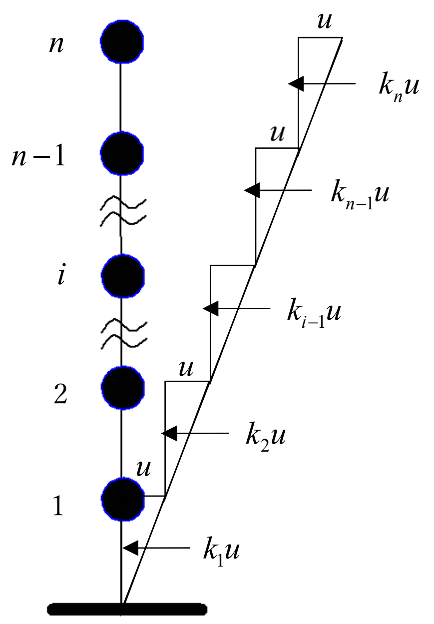


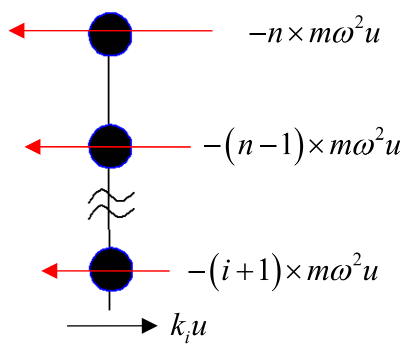


APPENDIX: Calculation of the story stiffness under an inverted triangle mode shape

Consider a building swaying with a first natural frequency ω and an inverted triangle natural vibration mode shape. The distributions of deformation, acceleration and inertia force (acceleration multiplied by the mass of each layer) are presented below.







Since the sum of the inertia forces above a layer is equal to the shear force of the story (story stiffness * story drift)

$$-\{n+(n-1)+\cdots+i\}\, m\omega^2 u + k_i u = 0$$

Therefore, the story stiffness is obtained as

$$k_i = \{n+(n-1)+\cdots+i\}\, m\omega^2 = \frac{1}{2}\{n(n+1)-i(i-1)\}\, m\omega^2$$