Optimization of Seismic Response in Tall Buildings Using Structural Dampers

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Outline / Agenda :

- Introduction
- Methodology
- Case Studies
- Comparison: BEM (PLPAK) vs FEM (ETABS)
- Comparison between MR Dampers and Static Dampers

• Introduction

- Seismic design of high-rise buildings remains challenging
- International design codes lack explicit rules for:
    - Required number of dampers
    - Optimal damper distribution along building height
- Damper design is commonly based on:
    - Trial-and-error procedures
- This research proposes a **model-independent framework** for damper integration
- Material-based (static) dampers are incorporated by:
    - Modifying global stiffness and damping matrices
- An optimization approach based on:
    - Influence matrices
    - Integer linear programming

      is used to determine the **optimal number and location of dampers**
- Targeted performance objectives:
    - Reduction in displacement
    - Reduction in inter-story drift
    - Reduction in floor acceleration

Energy Dissipation Systems (Vibration Control Systems)

Static Damper

Passive Energy Dissipation Devices

- Viscous Damper
- Viscoelastic Damper
- Metallic Yield Damper
- Friction Damper

$$F(t) = k_{\text{tot}}\, x(t) + c_{\text{tot}}\, v(t) + m\ddot{x}(t)$$

Viscous Damper

•Relies on the viscosity of a fluid passing through an orifice.
•Provides **damping only** .(erutcurts eht ot ssenffits lanoitidda on)

C

Viscoelastic Damper

•Contains a material with both **elastic and viscous**.seitreporp
•Provides **damping + some additional stiffness**.

C & K

Metallic Yield Damper

- Dissipates energy through the **plastic deformation of metals** (steel plates or braces).
- Provides **both stiffness and damping**.

C & K

Friction Damper

- Relies on **friction between metallic surfaces**.
- Provides **mainly damping**, and sometimes **additional stiffness** depending on the design.

C & K

- # Methodology

Objective:

Develop a user-friendly tool inside PLPAK (BEM) to incorporate static dampers by modifying the global system matrices

Direct modification of:

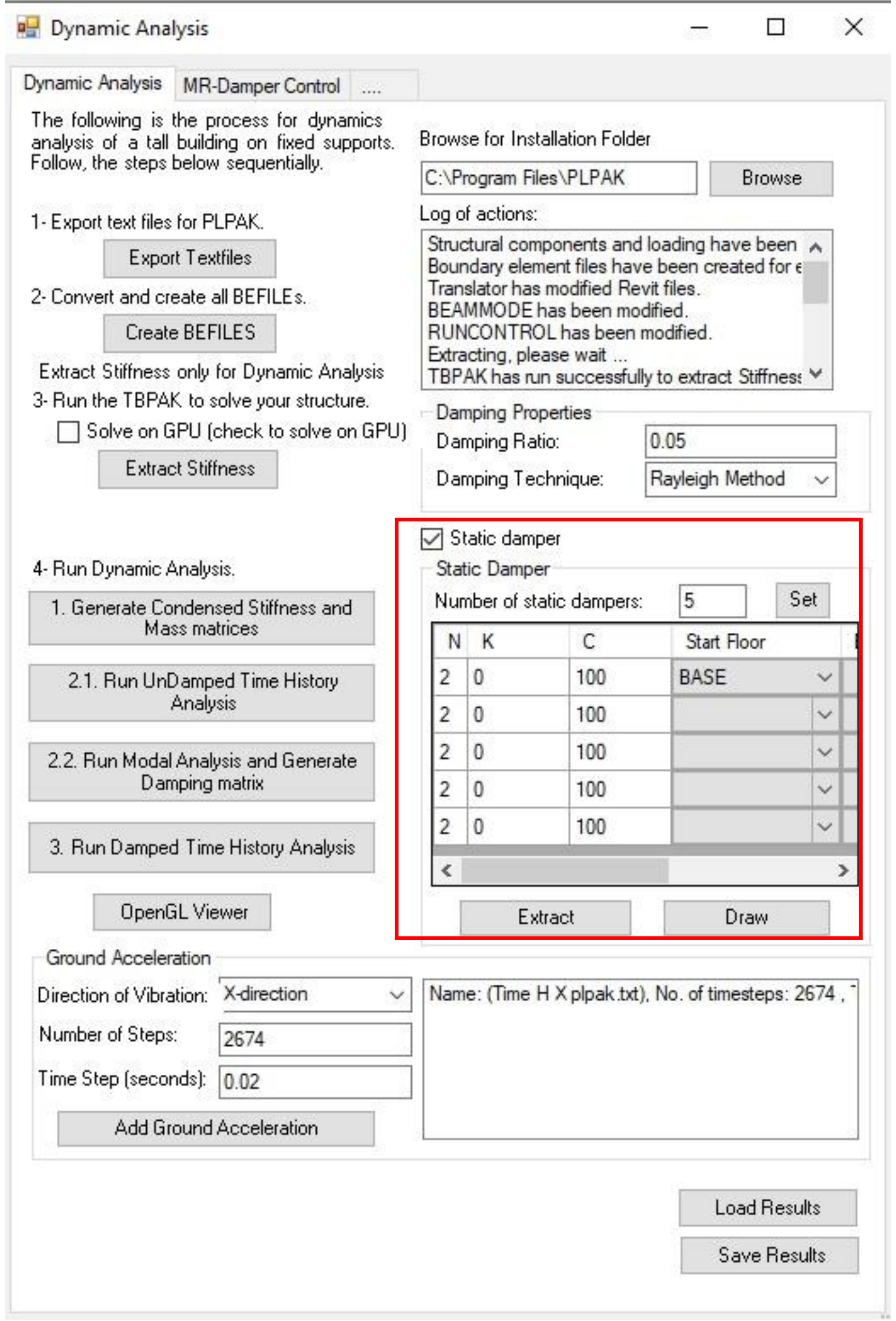
✓ Global stiffness matrix [K]
✓ Global damping matrix [C]

Features of the Tool:

✓ Control over the **number of dampers**.
✓ Define **orientation** (horizontal / vertical).
✓ Select **specific floors** for damper installation.
✓ Real-time **3D visualization** of dampers in the structural model.

Validation:

✓ Comparative analysis with **ETABS (FEM)**.


Dynamic Analysis
Dynamic Analysis
MR-Damper Control
....
The following is the process for dynamics analysis of a tall building on fixed supports. Follow, the steps below sequentially.
1- Export text files for PLPAK.
Export Textfiles
2- Convert and create all BEFILEs.
Create BEFILES
Extract Stiffness only for Dynamic Analysis
3- Run the TBPAK to solve your structure.
Solve on GPU (check to solve on GPU)
Extract Stiffness
4- Run Dynamic Analysis.
1. Generate Condensed Stiffness and Mass matrices
2.1. Run UnDamped Time History Analysis
2.2. Run Modal Analysis and Generate Damping matrix
3. Run Damped Time History Analysis
OpenGL Viewer
Browse for Installation Folder
C:\Program Files\PLPAK
Browse
Log of actions:
Structural components and loading have been
Boundary element files have been created for e
Translator has modified Revit files.
BEAMMODE has been modified.
RUNCONTROL has been modified.
Extracting, please wait ...
TBPAK has run successfully to extract Stiffnes
Damping Properties
Damping Ratio:
0.05
Damping Technique:
Rayleigh Method
Static damper
Static Damper
Number of static dampers:
5
Set
N
K
C
Start Floor
2
0
100
BASE
Extract
Draw
Ground Acceleration
Direction of Vibration:
X-direction
Number of Steps:
2674
Time Step (seconds):
0.02
Add Ground Acceleration
Name: (Time H X plpak.txt), No. of timesteps: 2674 ,
Load Results
Save Results


Static damper
Static Damper
Number of static dampers:
5
Set
Start Floor
End Floor
Direction
01
02
Y
Extract
Draw

		6			5			4			3			2			1		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	1	2.33E+02	8.48E-09	-1.16E-03	-2.48E+02	-8.01E-09	1.17E-03	2.20E+01	-3.15E-10	5.52E-05	-4.73E+00	3.26E-10	-8.86E-05	1.06E+00	-3.34E-10	3.40E-05	-2.12E-01	-6.48E-11	-1.39E-05
	2	8.48E-09	3.27E+01	3.73E-08	-7.86E-09	-4.83E+01	-3.43E-08	-3.99E-10	2.20E+01	-2.01E-09	3.23E-10	-4.73E+00	1.43E-09	-3.60E-10	1.06E+00	-1.64E-09	-8.47E-11	-2.12E-01	-3.97E-10
6	3	-1.16E-03	3.73E-08	9.65E+02	1.17E-03	-3.41E-08	-1.52E+03	5.56E-05	-2.11E-09	7.41E+02	-8.86E-05	1.43E-09	-1.66E+02	3.41E-05	-1.66E-09	3.73E+01	-1.38E-05	-4.18E-10	-8.81E+00
	4	-2.48E+02	-7.86E-09	1.17E-03	5.15E+02	1.21E-08	-1.88E-03	-2.89E+02	-3.08E-09	4.94E-04	3.07E+01	-2.00E-09	3.46E-04	-6.69E+00	1.11E-09	-1.81E-04	1.51E+00	-3.60E-10	6.86E-05
	5	-8.01E-09	-4.83E+01	-3.41E-08	1.21E-08	1.15E+02	5.03E-08	-3.03E-09	-8.87E+01	-1.08E-08	-1.98E-09	3.07E+01	-9.64E-09	1.14E-09	-6.69E+00	5.21E-09	-3.32E-10	1.51E+00	-1.59E-09
5	6	1.17E-03	-3.43E-08	-1.52E+03	-1.88E-03	5.03E-08	3.64E+03	4.94E-04	-1.08E-08	-2.92E+03	3.45E-04	-9.62E-09	1.06E+03	-1.81E-04	5.25E-09	-2.37E+02	6.84E-05	-1.56E-09	5.59E+01
	7	2.20E+01	-3.99E-10	5.56E-05	-2.89E+02	-3.03E-09	4.94E-04	5.37E+02	6.53E-09	-1.05E-03	-2.94E+02	-1.44E-09	2.32E-04	3.19E+01	-2.56E-09	4.24E-04	-7.23E+00	1.30E-09	-2.21E-04
	8	-3.15E-10	2.20E+01	-2.11E-09	-3.08E-09	-8.87E+01	-1.08E-08	6.53E-09	1.37E+02	2.44E-08	-1.45E-09	-9.36E+01	-3.25E-09	-2.57E-09	3.19E+01	-1.24E-08	1.29E-09	-7.23E+00	6.03E-09
4	9	5.52E-05	-2.01E-09	7.41E+02	4.94E-04	-1.08E-08	-2.92E+03	-1.05E-03	2.44E-08	4.45E+03	2.32E-04	-3.26E-09	-3.10E+03	4.24E-04	-1.24E-08	1.10E+03	-2.21E-04	6.02E-09	-2.59E+02
	10	-4.73E+00	3.23E-10	-8.86E-05	3.07E+01	-1.98E-09	3.45E-04	-2.94E+02	-1.45E-09	2.32E-04	5.38E+02	6.06E-09	-9.73E-04	-2.94E+02	-1.19E-09	1.93E-04	3.34E+01	-2.96E-09	4.92E-04
	11	3.26E-10	-4.73E+00	1.43E-09	-2.00E-09	3.07E+01	-9.62E-09	-1.44E-09	-9.36E+01	-3.26E-09	6.06E-09	1.38E+02	2.21E-08	-1.19E-09	-9.42E+01	-2.06E-09	-2.96E-09	3.34E+01	-1.42E-08
3	12	-8.86E-05	1.43E-09	-1.66E+02	3.46E-04	-9.64E-09	1.06E+03	2.32E-04	-3.25E-09	-3.10E+03	-9.73E-04	2.21E-08	4.49E+03	1.93E-04	-2.06E-09	-3.12E+03	4.92E-04	-1.42E-08	1.15E+03
	13	1.06E+00	-3.60E-10	3.41E-05	-6.69E+00	1.14E-09	-1.81E-04	3.19E+01	-2.57E-09	4.24E-04	-2.94E+02	-1.19E-09	1.93E-04	5.40E+02	5.64E-09	-9.05E-04	-3.01E+02	-1.07E-10	1.02E-05
	14	-3.34E-10	1.06E+00	-1.66E-09	1.11E-09	-6.69E+00	5.25E-09	-2.56E-09	3.19E+01	-1.24E-08	-1.19E-09	-9.42E+01	-2.06E-09	5.64E-09	1.40E+02	2.02E-08	-1.08E-10	-1.01E+02	2.97E-09
2	15	3.40E-05	-1.64E-09	3.73E+01	-1.81E-04	5.21E-09	-2.37E+02	4.24E-04	-1.24E-08	1.10E+03	1.93E-04	-2.06E-09	-3.12E+03	-9.05E-04	2.02E-08	4.55E+03	1.02E-05	2.97E-09	-3.36E+03
	16	-2.12E-01	-8.47E-11	-1.38E-05	1.51E+00	-3.32E-10	6.84E-05	-7.23E+00	1.29E-09	-2.21E-04	3.34E+01	-2.96E-09	4.92E-04	-3.01E+02	-1.08E-10	1.02E-05	3.70E+02	3.49E-09	-5.48E-04
	17	-6.48E-11	-2.12E-01	-4.18E-10	-3.60E-10	1.51E+00	-1.56E-09	1.30E-09	-7.23E+00	6.02E-09	-2.96E-09	3.34E+01	-1.42E-08	-1.07E-10	-1.01E+02	2.97E-09	3.49E-09	1.70E+02	9.77E-09
1	18	-1.39E-05	-3.97E-10	-8.81E+00	6.86E-05	-1.59E-09	5.59E+01	-2.21E-04	6.03E-09	-2.59E+02	4.92E-04	-1.42E-08	1.15E+03	1.02E-05	2.97E-09	-3.36E+03	-5.48E-04	9.77E-09	5.59E+03

$$\begin{array}{cc} & \begin{array}{ccc} u_{start} & & u_{end} \end{array} \\ C_{Add} = & \begin{bmatrix} C_{Damper} & \cdots & -C_{Damper} \\ \vdots & \ddots & \vdots \\ -C_{Damper} & \cdots & C_{Damper} \end{bmatrix} \begin{array}{c} u_{start} \\ \\ u_{end} \end{array} \end{array}$$

$$K_{Add} = \begin{bmatrix} k_{Damper} & \cdots & -k_{Damper} \\ \vdots & \ddots & \vdots \\ -k_{Damper} & \cdots & k_{Damper} \end{bmatrix} \begin{array}{c} u_{start} \\ \\ u_{end} \end{array}$$

Add this matrix between two degrees of freedom that are linked by damper in overall matrix to structure.

Proposed Optimization Technique

The method aims to determine the optimal number of dampers on each floor to achieve a target structural response, particularly minimizing the displacement of the top floor under dynamic loading. The contribution of each damper to the floor displacements is quantified using an influence matrix. This matrix is generated by calculating the change in displacement resulting from adding a single damper at each floor, effectively capturing the effect of individual dampers on the overall structural response. These influence values are then used within the optimization model, which seeks to minimize the absolute difference between the actual top-floor displacement and the target displacement, while simultaneously minimizing the total number of dampers.

- New Response Calculation (Linear Model):

The new response R_k^{new} for any response type R at any floor k is a linear function of the initial response and the effect of the dampers ($I^R \times X$):

$$R_k^{new} = R_k^{actual} - \sum_{j=1}^{n} I_{kj}^{R} . x_j$$

$$\begin{pmatrix} R_1^{new} \\ R_2^{new} \\ \vdots \\ R_n^{new} \end{pmatrix} = \begin{pmatrix} R_1^{actual} \\ R_2^{actual} \\ \vdots \\ R_n^{actual} \end{pmatrix} - \begin{pmatrix} I_{11}^R & I_{12}^R & \cdots & I_{1n}^R \\ I_{21}^R & I_{22}^R & & I_{2n}^R \\ \vdots & & \ddots & \vdots \\ I_{n1}^R & I_{n2}^R & \cdots & I_{nn}^R \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

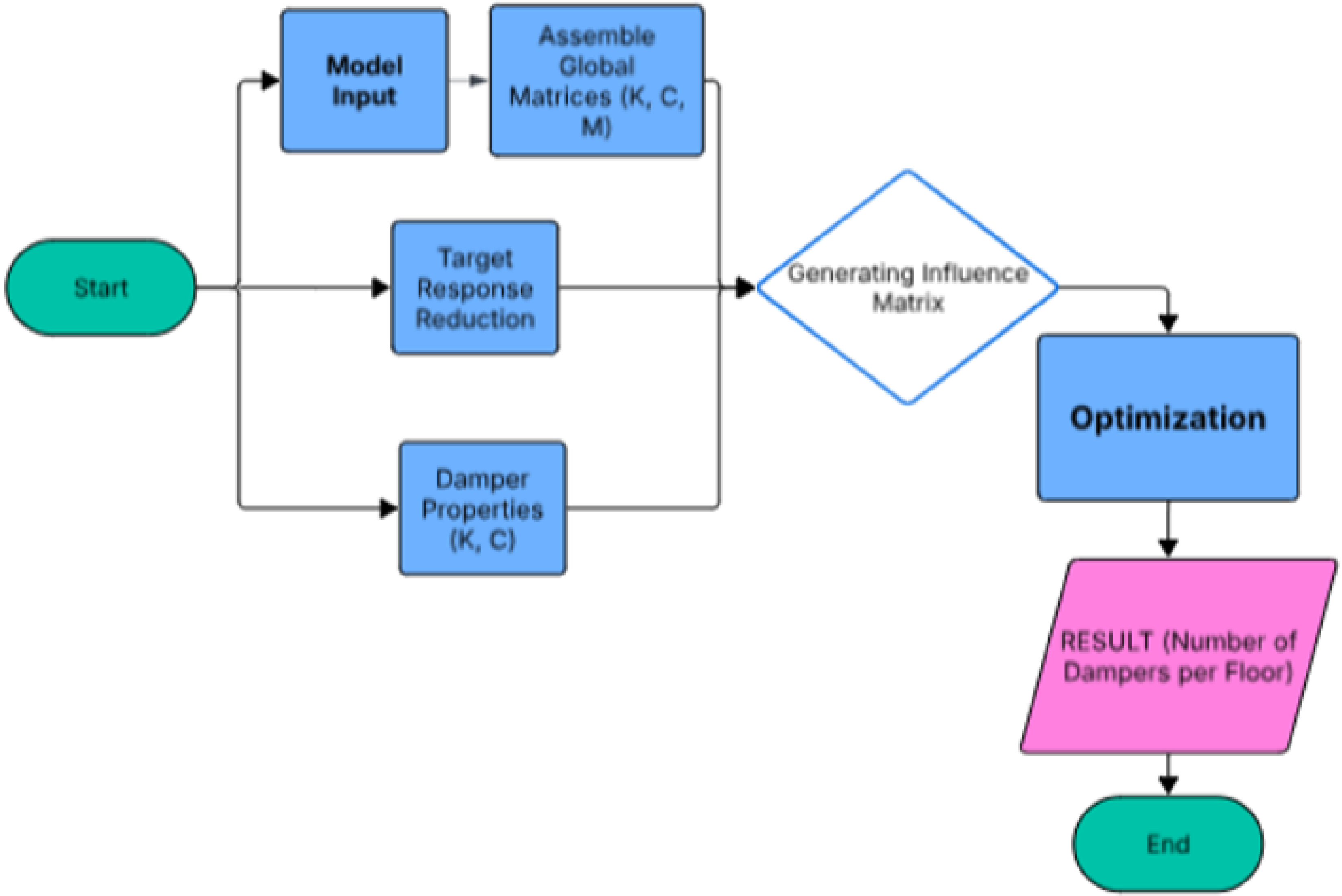
- Defining the Maximum (R_{new}^{max}):

$$\text{Constraint:} \quad R_{new}^{max} \geq R_k^{actual} - \sum_{j=1}^{n} I_{kj}^{R} . x_j \quad \rightarrow k = 1,2, \dots, n \text{ for } R \in \{U, D, A\}$$

- Objective Function:

$$\text{Minimize:} \quad Z = W_1 . e + \quad W_2 . \sum_{i=1}^{n} x_i$$

Notation	Description	Type	Size/Dimension	Role in the Model
n	The total number of floors in the structure.	Constant	Scalar	Defines the size of vectors and matrices.
P	Required percentage reduction (e.g., 0.30 for 30%).	Constant	Scalar	Determines the value of R^{target}
x	Damper Design Vector (Decision Variables). Contains the number of dampers to be installed at each floor.	Integer Vector	n×1	The primary output (solution) of the optimization.
R_{actual}^{max}	Maximum Initial Response. The largest value found across all floors and all actual responses (U,D,A) before adding dampers.	Constant	Scalar	Used to calculate Rtarget.
R^{actual}	The actual initial response value (e.g., Ukactual, Dkactual, Akactual) at floor k before damper installation.	Vector	n×1	Serves as the baseline for the new response calculation.
R^{target}	Relative Target Value. The target response the optimization aims to achieve: $R_{target} = (1 - P) \times R_{actual}^{max}$	Vector	n×1	The reference point for the deviation variable e.
R_{new}^{max}	Auxiliary Maximum Response Variable. The largest calculated response value (max R_k^{new}) after he optimal dampers.	Variable	Scalar	Forced by constraints to equal the worst-case response, serving as the response metric in the objective.
I^R	Influence Coefficient Matrix for a specific response R∈{U,D,A}.	Matrix	n×n	Quantifies the linear effect of damper xj on response Rk.
e	Auxiliary Deviation Variable. Represents the absolute difference	Variable	Scalar	$R_{new}^{max} - R^{target}$
W1	Weight coefficient for minimizing deviation (e).	Constant	Scalar	Assigned a high value (e.g., 10000) to prioritize matching the target.
W2	Weight coefficient for minimizing total dampers (∑xi).	Constant	Scalar	Assigned a low value (e.g., 1) to prioritize cost reduction after meeting the target.


Model Input
Assemble Global Matrices (K, C, M)
Start
Target Response Reduction
Damper Properties (K, C)
Generating Influence Matrix
Optimization
RESULT (Number of Dampers per Floor)
End

Influence matrix

A1 | 0.000106

	A	B	C	D	E	F	G	H	I	J
1	1.06E-04	1.01E-04	-2.24E-05	1.17E-05	-1.22E-05	-7.85E-05	-0.00016	-0.00045	-0.00039	-0.00026
2	5.37E-05	4.12E-04	4.38E-04	5.23E-04	0.000541	0.000548	0.000462	0.00049	0.001133	0.001293
3	3.51E-05	2.43E-04	0.000538	0.000779	0.000986	0.001193	0.001265	0.001339	0.002432	0.002665
4	5.52E-05	2.02E-04	3.43E-04	8.39E-04	0.001177	0.001422	0.001547	0.001725	0.003015	0.004171
5	1.29E-04	3.10E-04	3.58E-04	6.97E-04	1.23E-03	1.48E-03	0.0016	0.001784	0.003133	0.004584
6	0.000129	0.000348	0.000321	0.000425	6.36E-04	1.11E-03	0.001348	0.001631	0.003051	0.004388
7	6.21E-05	0.000127	3.77E-05	0.000152	0.000308	0.000596	0.001039	0.001362	0.002652	0.003045
8	2.74E-05	0.000157	4.11E-05	9.05E-05	0.000213	0.000348	0.000441	0.000832	0.002009	0.00201
9	-8.57E-05	-8.11E-05	-0.00012	-7.12E-05	-1.32E-05	6.58E-05	0.000101	0.000242	0.001301	0.00179
10	-9.97E-05	-0.00015	-0.00031	-0.00036	-0.00031	-0.0002	-0.00011	9.61E-05	0.000748	0.001637
11										

Actual displacement

A1 | 0.00127493

	A	B	C	D	E	F	G	H	I	J
1	0.001275	0.003945	0.007188	0.010874	0.01446	0.017648	0.020247	0.022381	0.025168	0.027829
2										
3										
4										

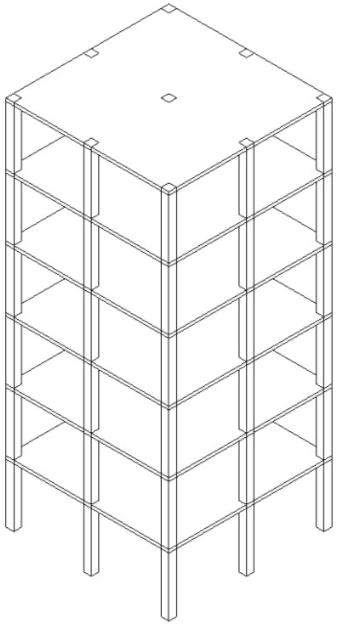
Target displacement

	A	B	C	D	E	F	G	H	I	J
1	0.000637	0.001973	0.003594	0.005437	0.00723	0.008824	0.010124	0.01119	0.012584	0.013915
2										
3										

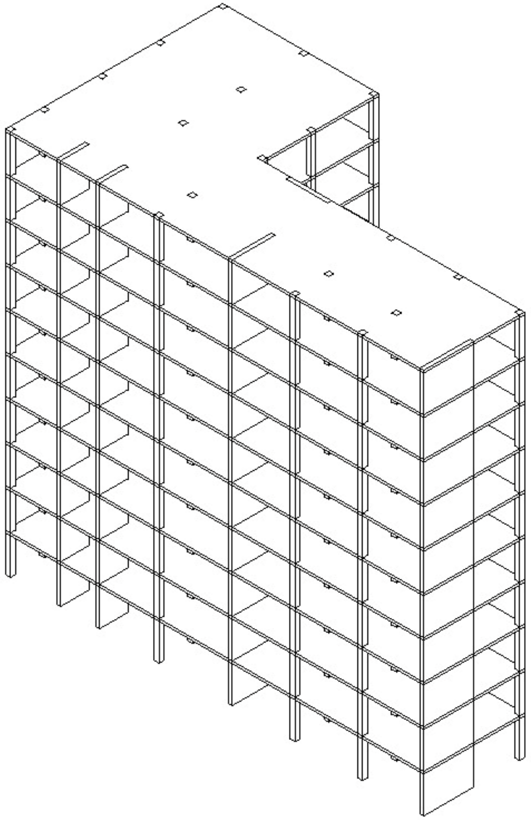
```
Result - Optimal solution found

Objective value:                4.25600000
Enumerated nodes:               76
Total iterations:               808
Time (CPU seconds):             0.05
Time (Wallclock seconds):       0.05

Option for printingOptions changed from normal to all
Total time (CPU seconds):       0.05   (Wallclock seconds):       0.05

Optimal dampers distribution:
Floor 1: 0 dampers
Floor 2: 0 dampers
Floor 3: 2 dampers
Floor 4: 1 dampers
Floor 5: 0 dampers
Floor 6: 1 dampers
Floor 7: 0 dampers
Floor 8: 0 dampers
Floor 9: 0 dampers
Floor 10: 0 dampers

Total dampers = 4
Displacement at last floor: 0.01394030
Target for last floor: 0.01391470
```

- ## Case Studies

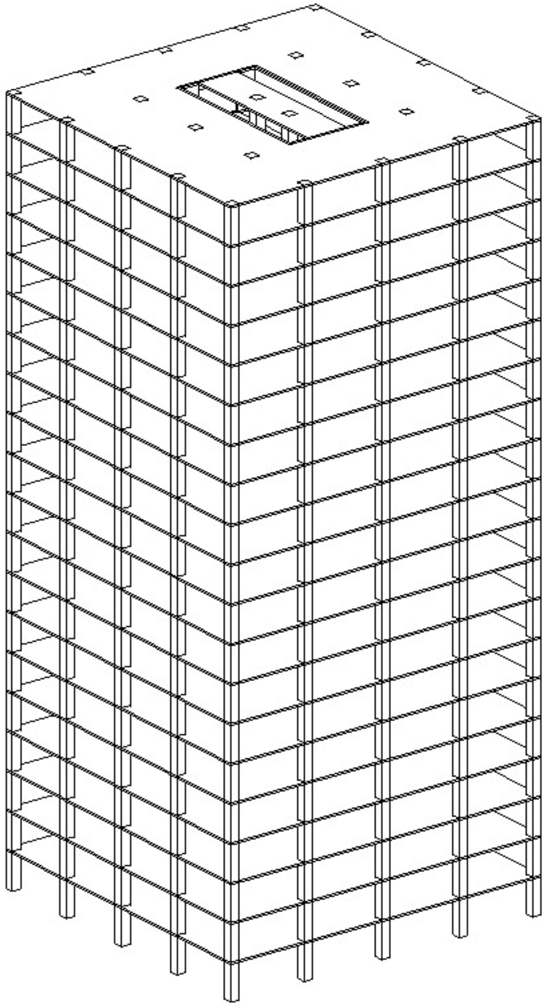
BEM (PLPAK)



Building 1: 6-story

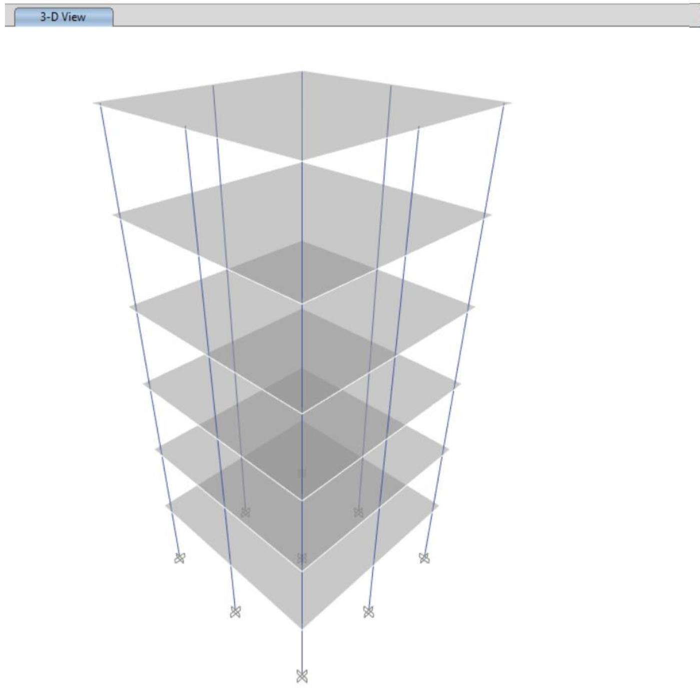


Building 2: 10-story

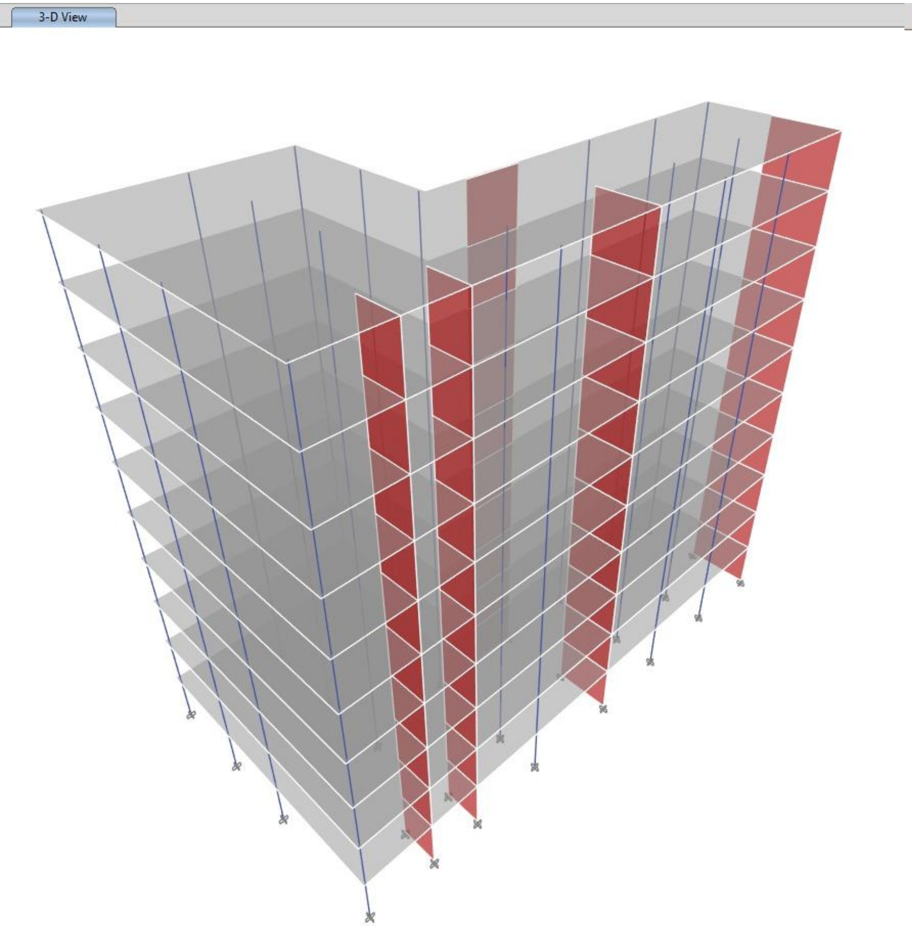


Building 3: 20-story

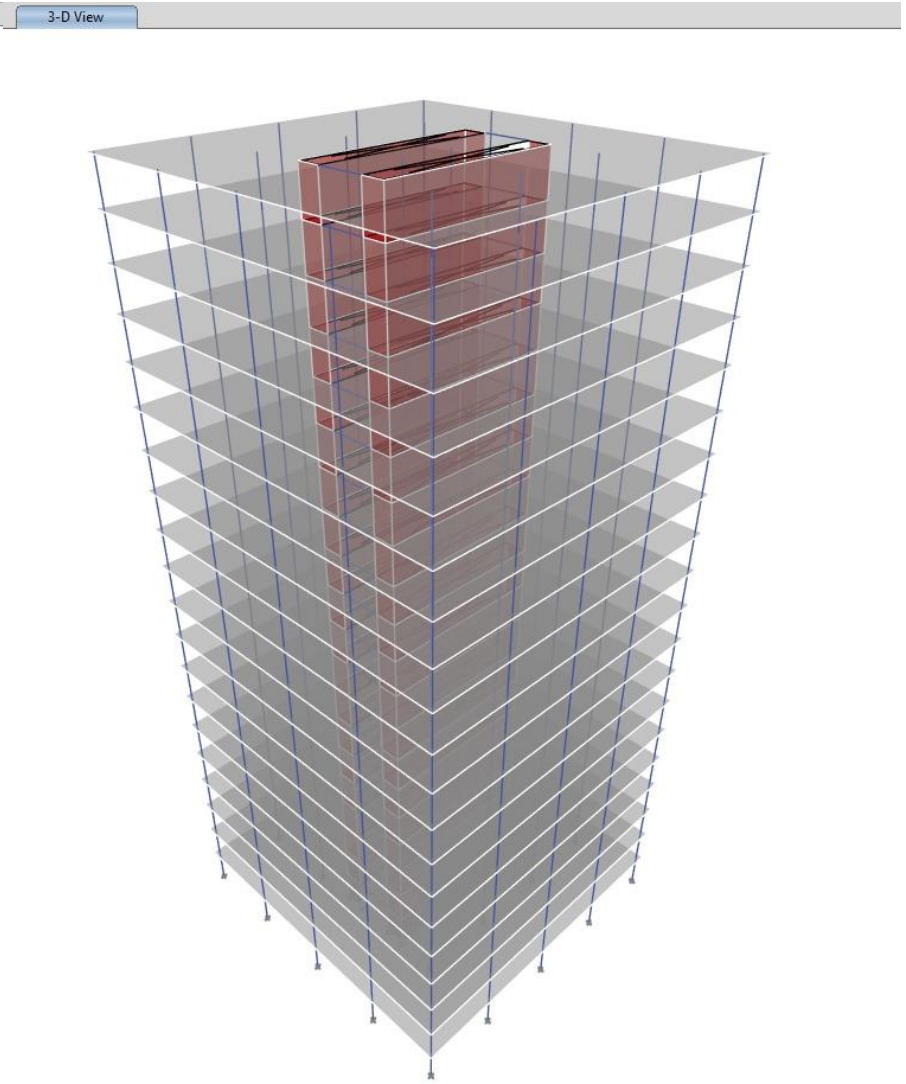
FEM (ETABS)



Building 1: 6-story



Building 2: 10-story



Building 3: 20-story

- ## Comparison: BEM (PLPAK) vs FEM (ETABS)

Building 1: 6-story

Dimension of slab = 10.5*10.5 m

Dimension of column = 500*500 mm

Thickness of slab = 200 mm

Spacing between column = 5 m

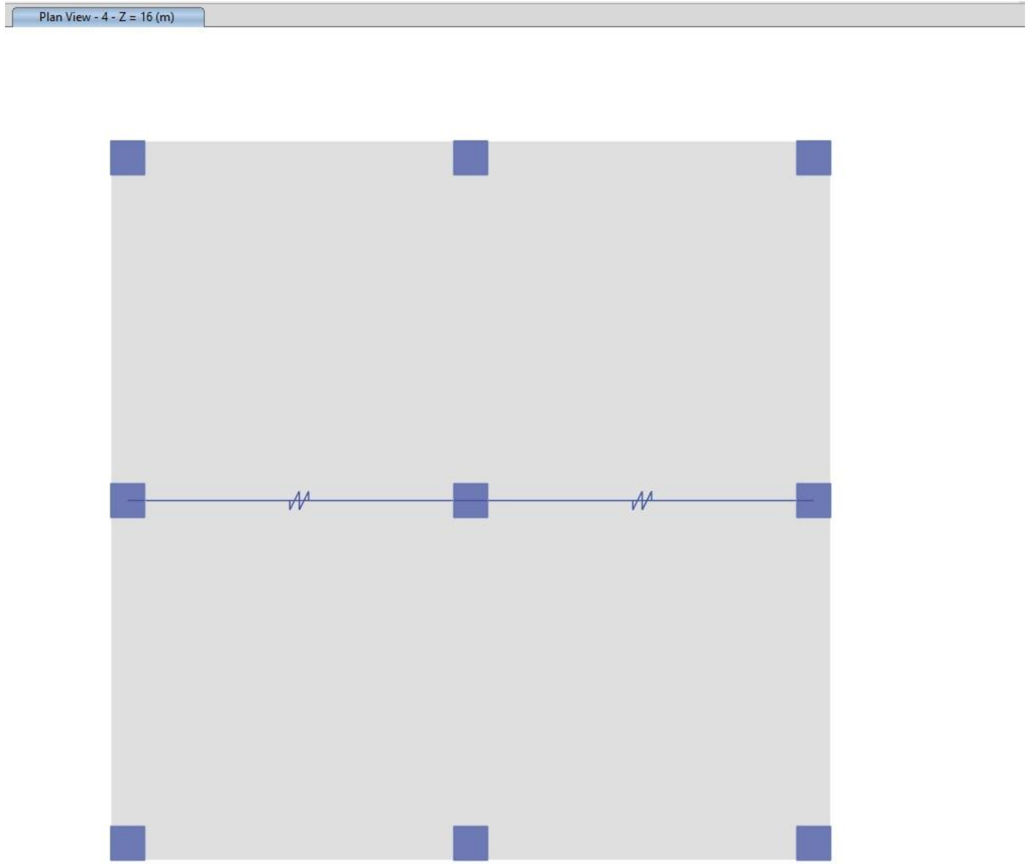
Story height = 4

Number of stories = 6

Damping ratio = 0.05

Rigid Diaphragm

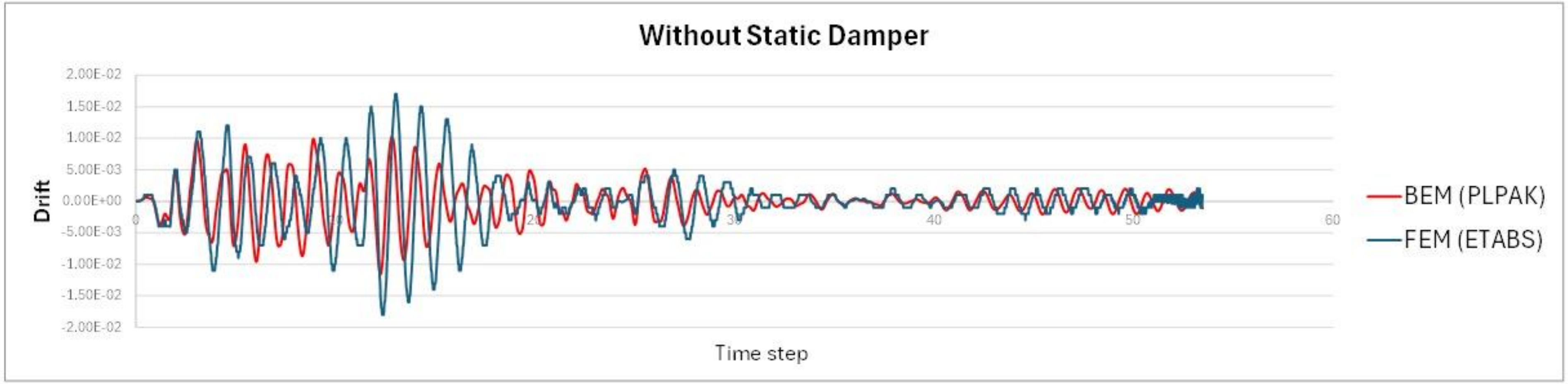
Static Damper: C = 1000 KN. s/m , K=0 KN/m , N=2



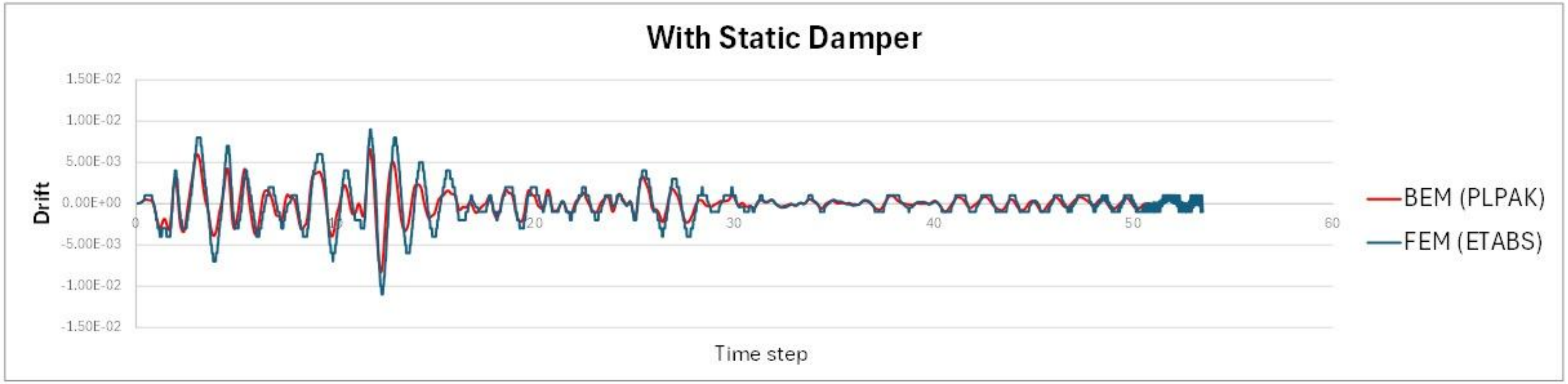
Time History:

EL CENTRO EARTHQUAKE MAY 18, 1940
NORTH-SOUTH COMPONENT

Max drift FEM = 0.018 mm
Max drift BEM =0.012 mm



Max drift FEM = 0.011 mm
Max drift BEM = 0.008 mm



$$\text{Reduction in ETABS} = \frac{18 - 11}{18} \times 100 = 38\%$$

$$\text{Reduction in PLPAK} = \frac{12 - 8}{12} \times 100 = 34\%$$

Building 2: 10-story

Dimension of column = 500*500 mm

Thickness of wall = 400 mm

Thickness of slab = 250 mm (Shell thick)

Story height = 4

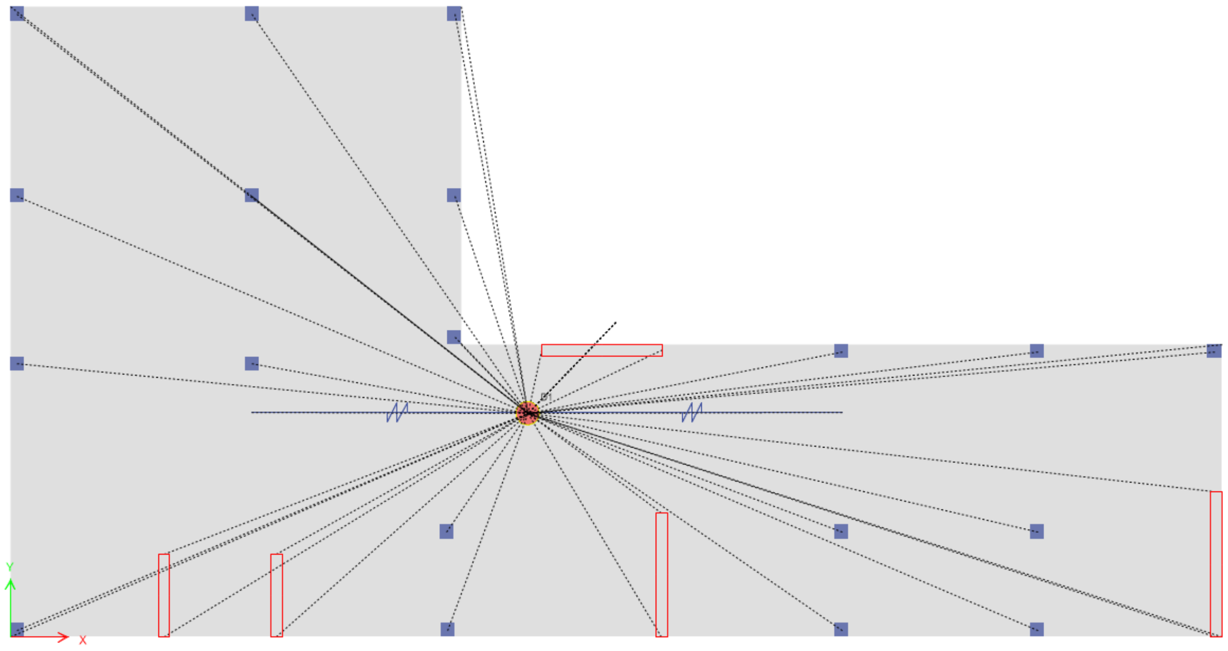
Number of stories = 10

Damping ratio = 0.05

Rigid Diaphragm

Static Damper: C = 50000 KN. s/m , K=10000 KN/m

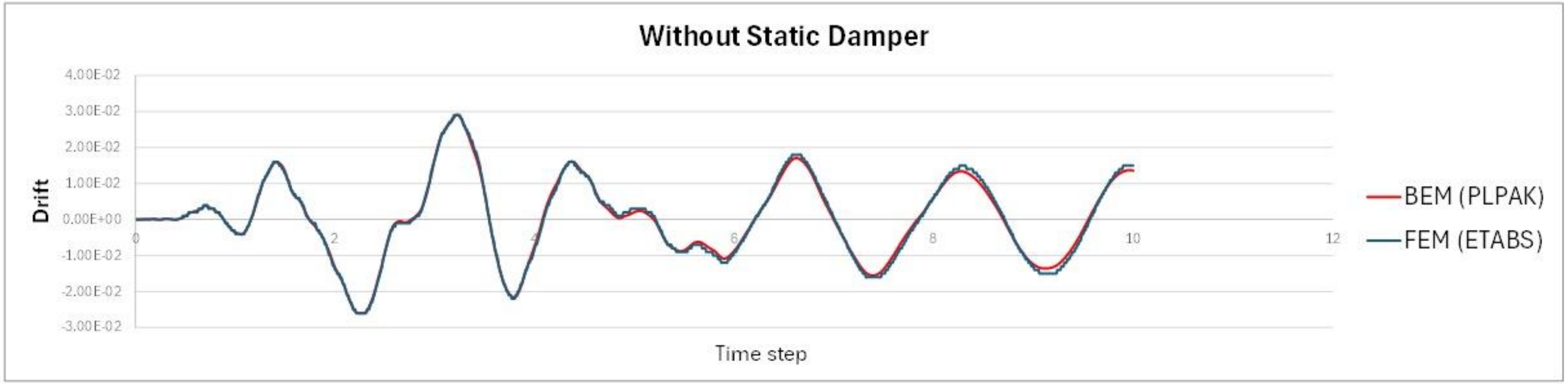
, N=2



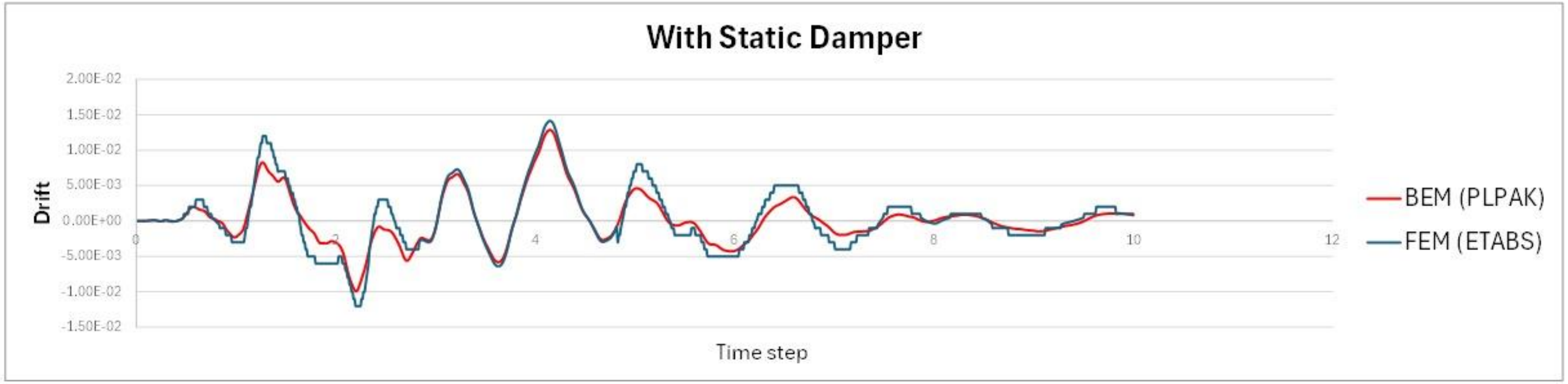
Time History:

1992 Cairo Earthquake

Max drift FEM = 0.0292 mm
Max drift BEM =0.029 mm



Max drift FEM = 0.014 mm
Max drift BEM =0.0136 mm



$$\text{Reduction in ETABS} = \frac{29.1 - 14.1}{29.1} \times 100 = 52\%$$

$$\text{Reduction in PLPAK} = \frac{29 - 13.6}{29} \times 100 = 54\%$$

Building 3: 20-story

Dimension of column = 1000*1000 mm

Thickness of wall = 300 mm

Thickness of slab = 200 mm

Story height = 4

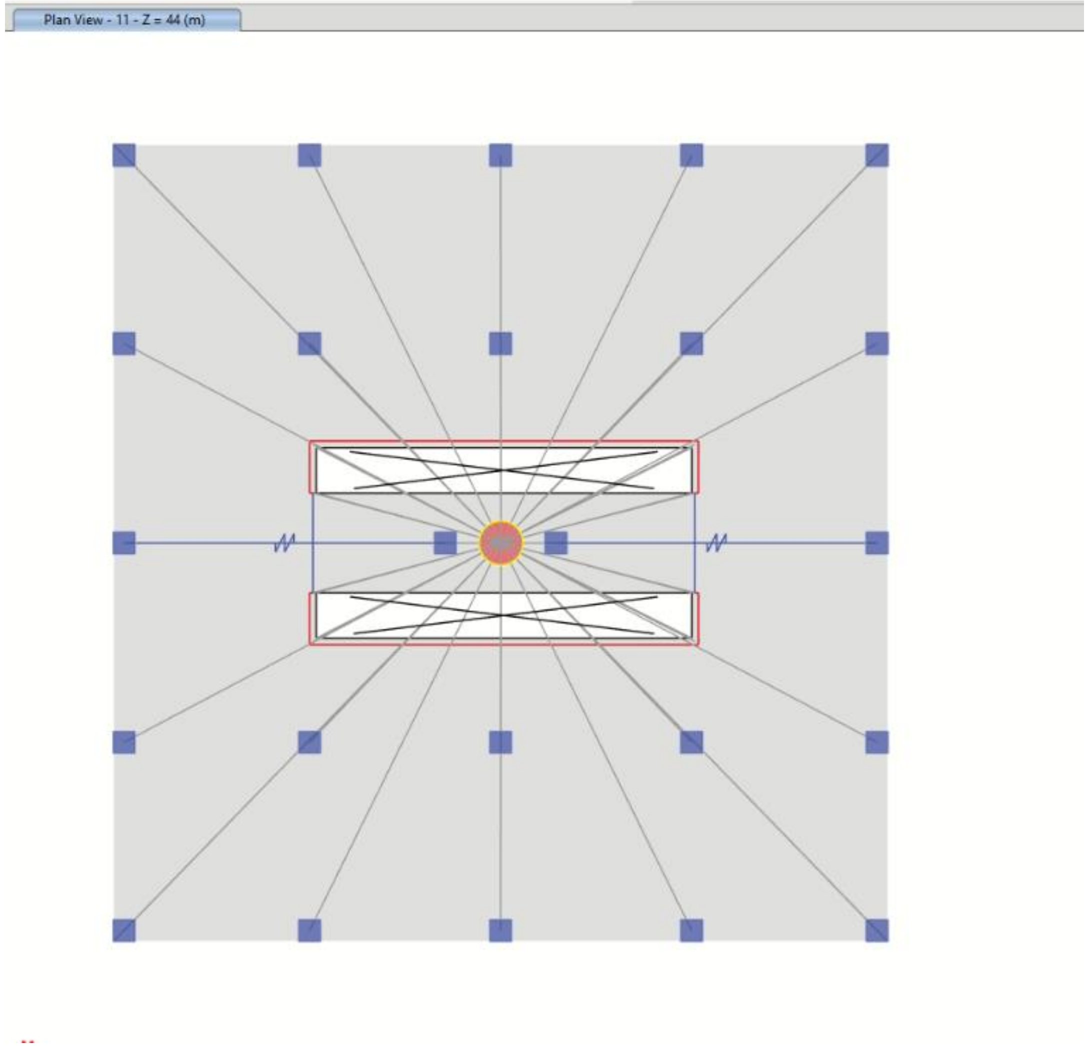
Number of stories = 20

Damping ratio = 0.05

Rigid Diaphragm

Static Damper: C = 50000 KN. s/m , K=25000 KN/m

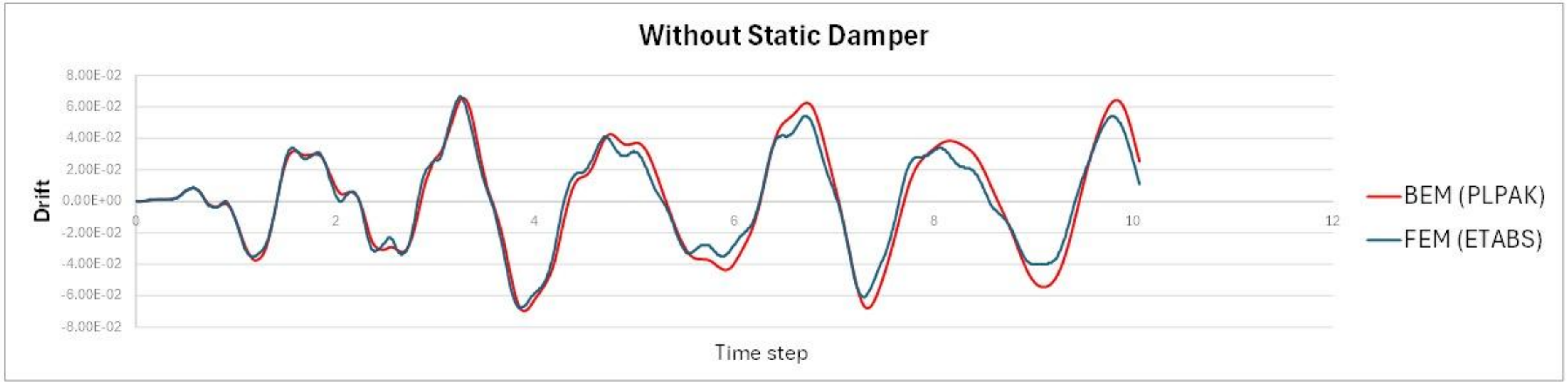
, N=2



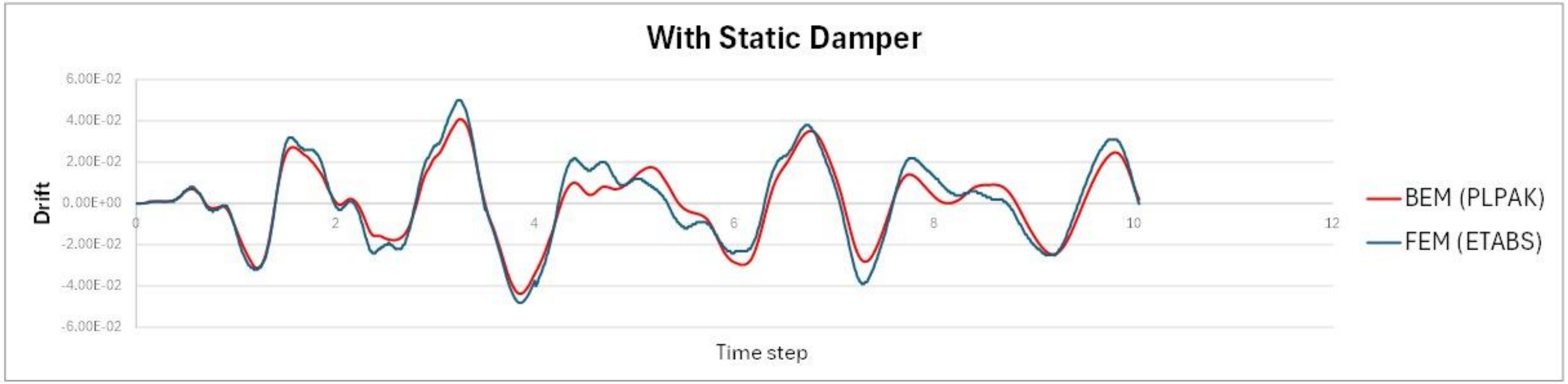
Time History:

Analyses using EGY spectrum matched time histories

Max drift FEM = 0.070 mm
Max drift BEM = 0.068 mm



Max drift FEM = 0.050 mm
Max drift BEM =0.045 mm

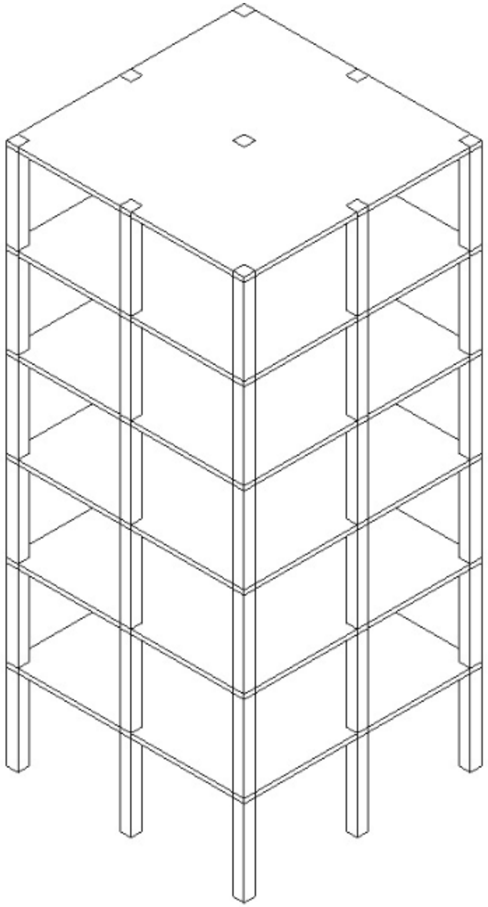


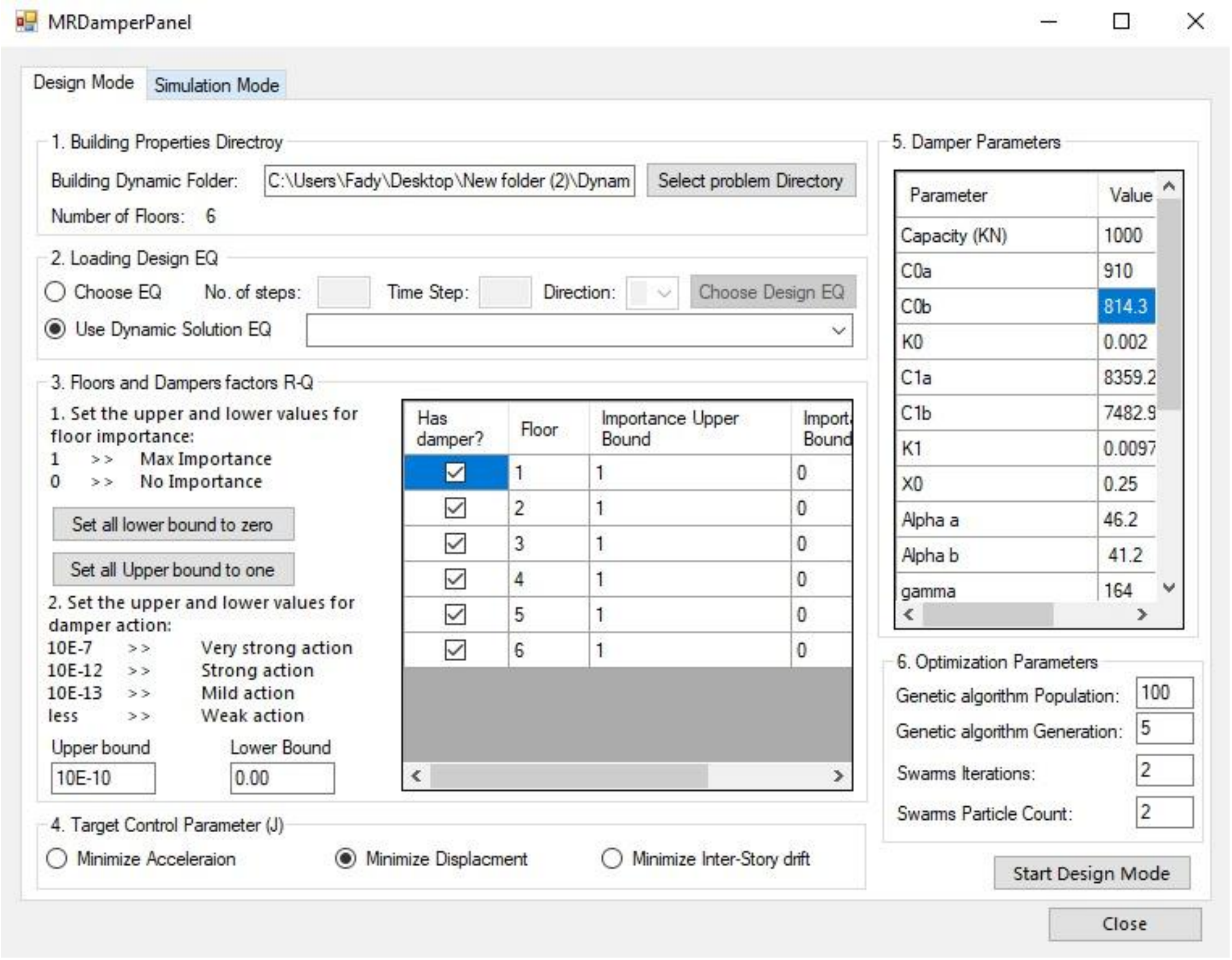
$$\text{Reduction in ETABS} = \frac{70 - 50}{70} \times 100 = 29\%$$

$$\text{Reduction in PLPAK} = \frac{68 - 45}{68} \times 100 = 34\%$$

- # Comparison between MR Dampers and Static Dampers

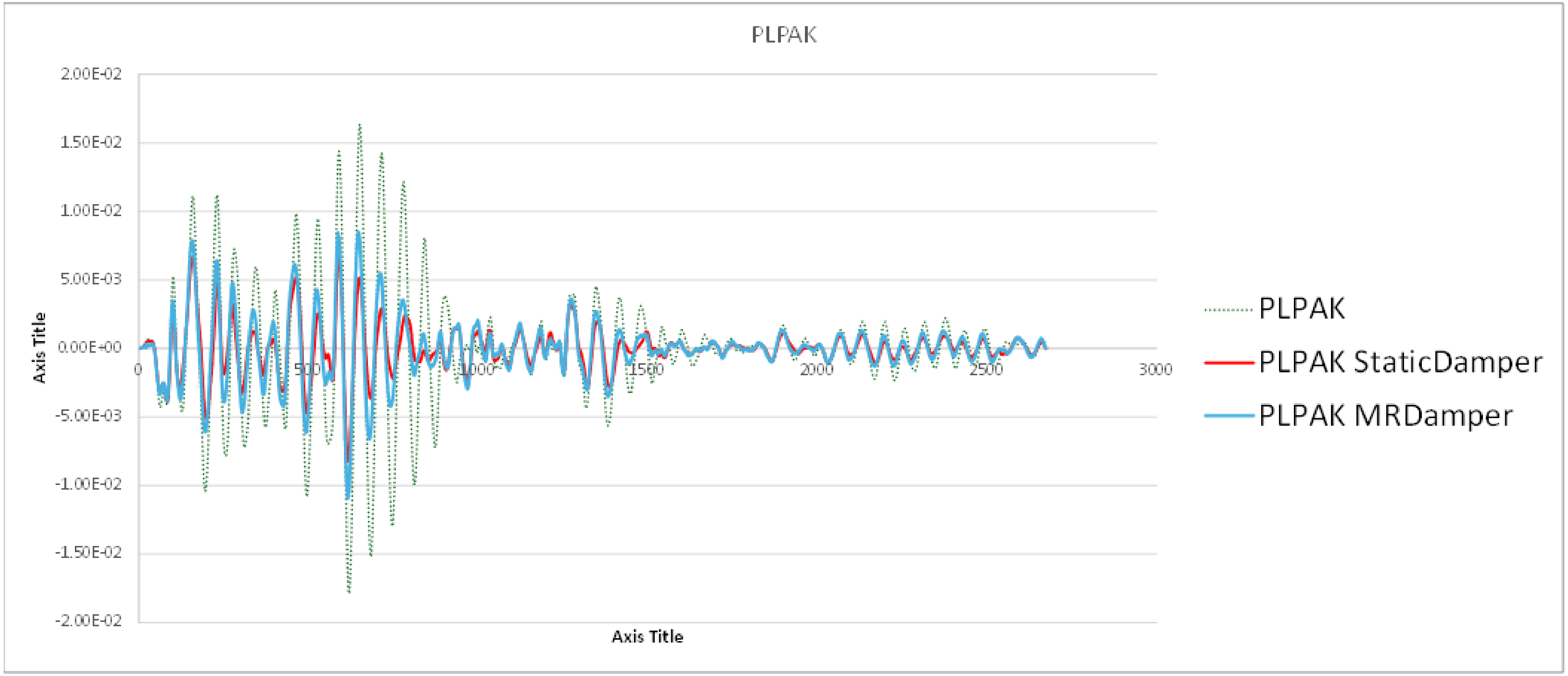
Building 1: 6-story





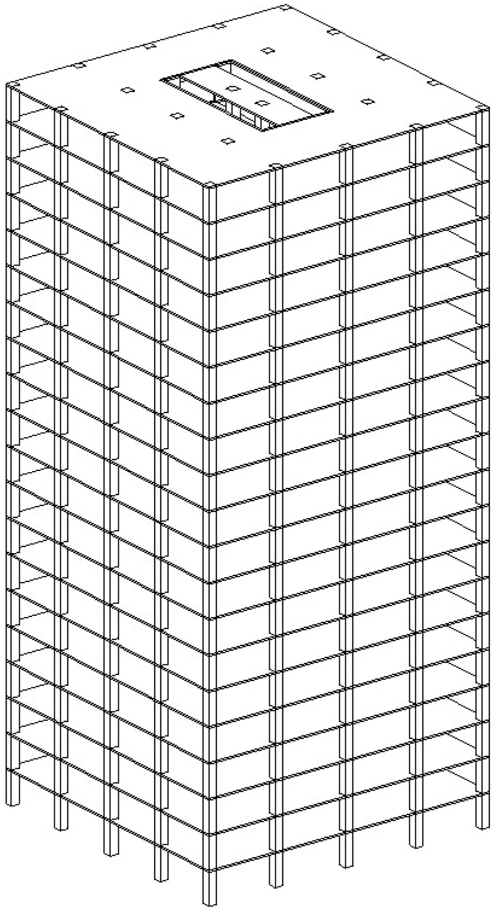
Static Damper: C = 1000 KN. s/m , K=0 KN/m , N=2

MR Damper: C = 1000 KN. s/m , N=1

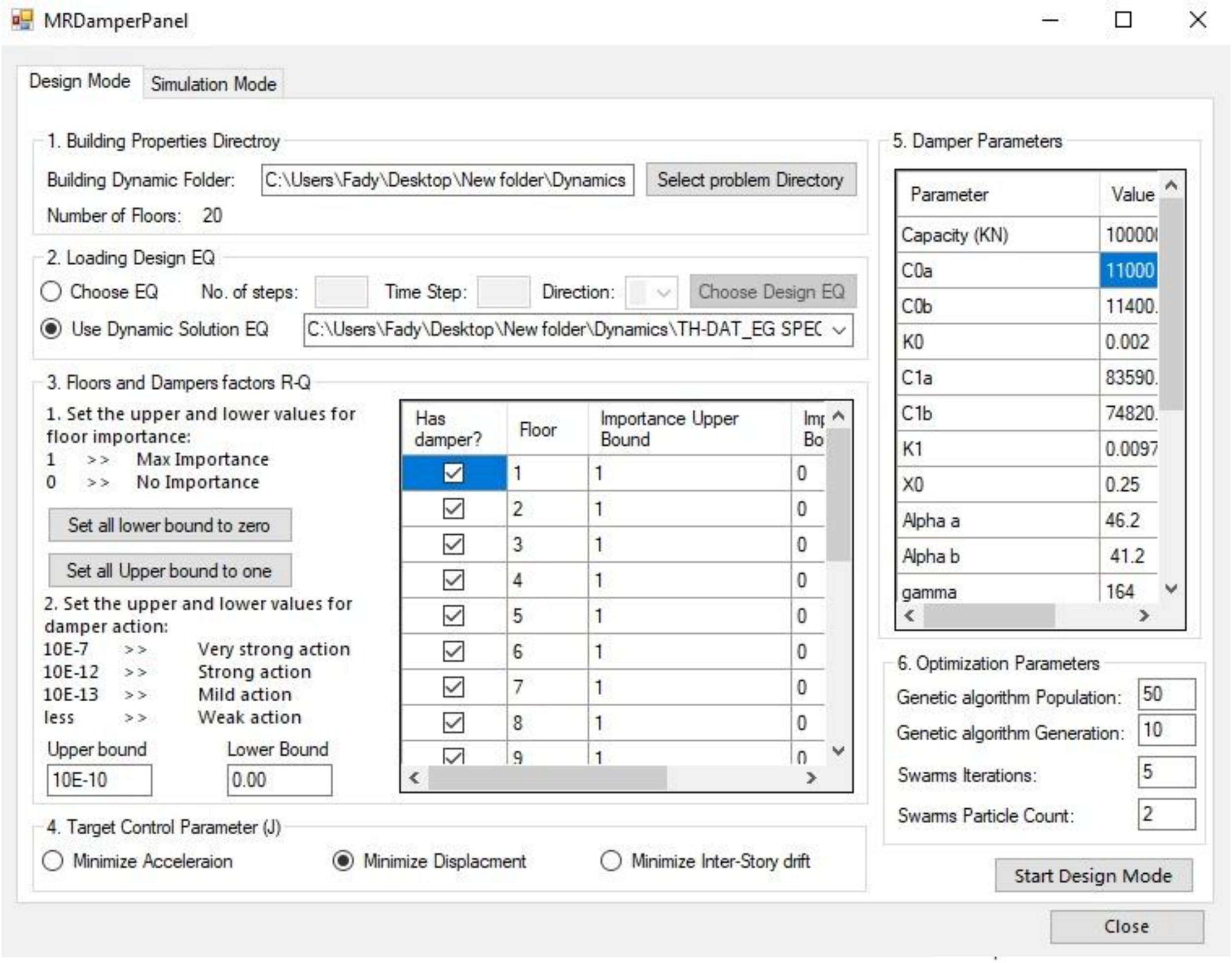


PLPAK
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
-5.00E-03
-1.00E-02
-1.50E-02
-2.00E-02
0
500
1000
1500
2000
2500
3000
Axis Title
Axis Title
PLPAK
PLPAK StaticDamper
PLPAK MRDamper

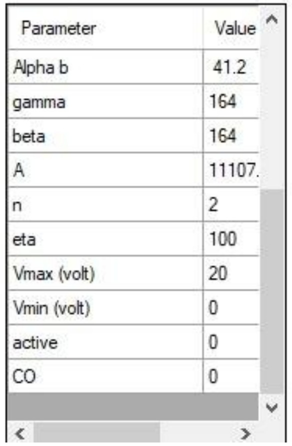
Building 3: 20-story

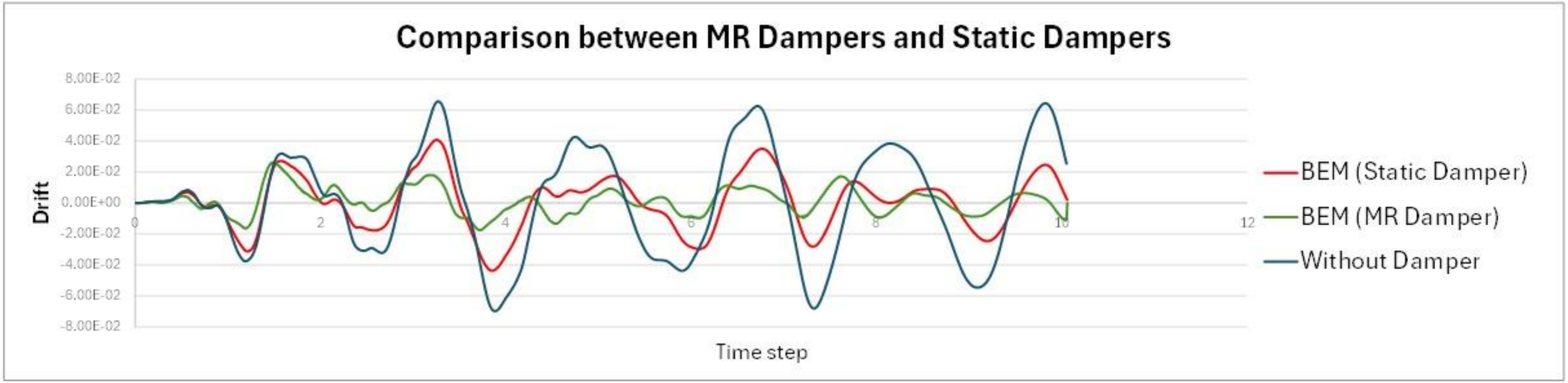


Static Damper: C = 50000 KN. s/m , K=25000 KN/m , N=2



MR Damper: C = 100000 KN. s/m , N=1





Max drift Without Damper = 0.068 mm
Max drift BEM (Static Damper) = 0.045 mm
Max drift BEM (MR Damper) =0.026 mm


thank
you