AN ADAPTIVE 3-D PUSHOVER PROCEDURE FOR DETERMINING THE CAPACITIY OF EXISTING IRREGULAR REINFORCED CONCRETE (RC) BUILDINGS

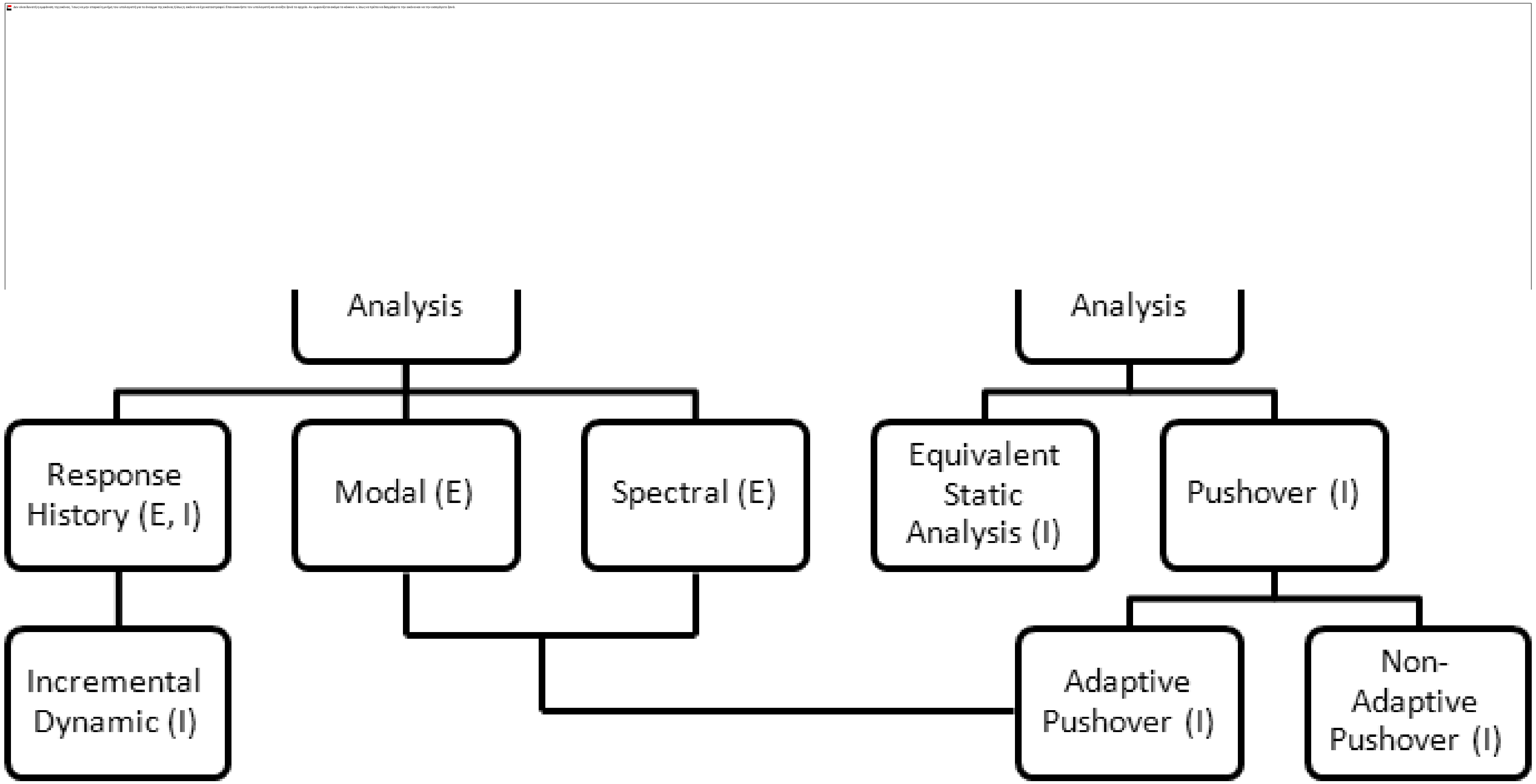
RES. ASST. DR. REŞAT A. OYGUÇ
PROF. DR. HASAN BODUROĞLU

FEBRUARY 2012

OUTLOOK

- Structural Analysis Methods and the main differences between them
- Deficiencies of conventional methods and need of an adaptive procedures
- Story shear adaptive pushover procedure (SSAP)
- Properties of Seismic Performance Assessment and Rehabilitation of Existing Buildings (SPEAR)
- Nonlinear adaptive structural analysis program (NASAP) and the adaptive analyse of SPEAR
- Results

ANALYSIS METHODS



ANALYSIS METHODS

Properties	Static Analysis	Dynamic Analysis
Detailed Models		
Stiffness representation		
Mass representation		
Damping representation		
Additional operators		
Input motion		
Target displacement		
Action distribution fixed		
Short analysis time		

COEFFICIENT METHOD

$$T_e = T_i \sqrt{\frac{K_i}{K_e}}$$

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\Pi^2} g$$

C_0 relates spectral displacement of an equivalent SDOF system to the roof displacement of the building

C_1 correlates the maximum inelastic displacements to linear elastic displacements.

C_2 represents the pinched hysteretic shape

C_3 is a factor that takes care about the P-Δ effects

COEFFICIENT METHOD

Values for Modification Factor C_0

	Shear Buildings		Other Buildings
Story No.	Triangular Load	Uniform Load	Any Load
1	1	1	1
2	1.2	1.15	1.2
3	1.2	1.2	1.3
5	1.3	1.2	1.4
10	1.3	1.2	1.5

C_1 is the modification factor that correlates the maximum inelastic displacements to linear elastic displacements. It is taken as 1 when T_e effective fundamental period is greater than or equal to T_s characteristic period of response spectrum.

COEFFICIENT METHOD

Values for Modification Factor C_2

	T ≤ 0.1 second		T ≥ Ts	
Performance Level	Frame-1	Frame-2	Frame-1	Frame-2
I. Occupancy	1	1	1	1
Life Safety	1.3	1	1.1	1
Collapse Prevention	1.5	1	1.2	1

C_3 is a factor that takes care about the P-Δ effects. For buildings with positive post yield stiffness it can be taken as 1.0. For buildings with negative post yield stiffness, C_3 should be calculated with the given formulation in FEMA 356 document.

DEFICIENCIES OF CONVENTIONAL METHODS

- Conventional pushover analyses investigate structural capacity and earthquake demand separately.
- only the lateral load pattern and lateral deformations of the structure is investigated.
- does not account for the higher mode effects
- Torsional effects are induced after the analysis by combining the pushover results or by amplifying the results.
- it is clear that conventional pushover analysis lacks of the dynamic quantities.

ADAPTIVE METHODS

- The gravity loads are applied in a single step.
- With its current initial stiffness the structure has been subjected to **an eigenvalue analysis** and the modal properties are determined.
- Modal participation factor should be calculated
- **Modal story forces at each floor level for the N modes should be determined**
- Static pushover analysis is performed
- Each modal quantity is combined using the SRSS rule
- **These values are added to the previous step of the analysis.**

STORY SHEAR BASED ADAPTIVE PUSHOVER

The story shear based adaptive pushover procedure (SSAP) has been proposed by Shakeri et al. in 2010.

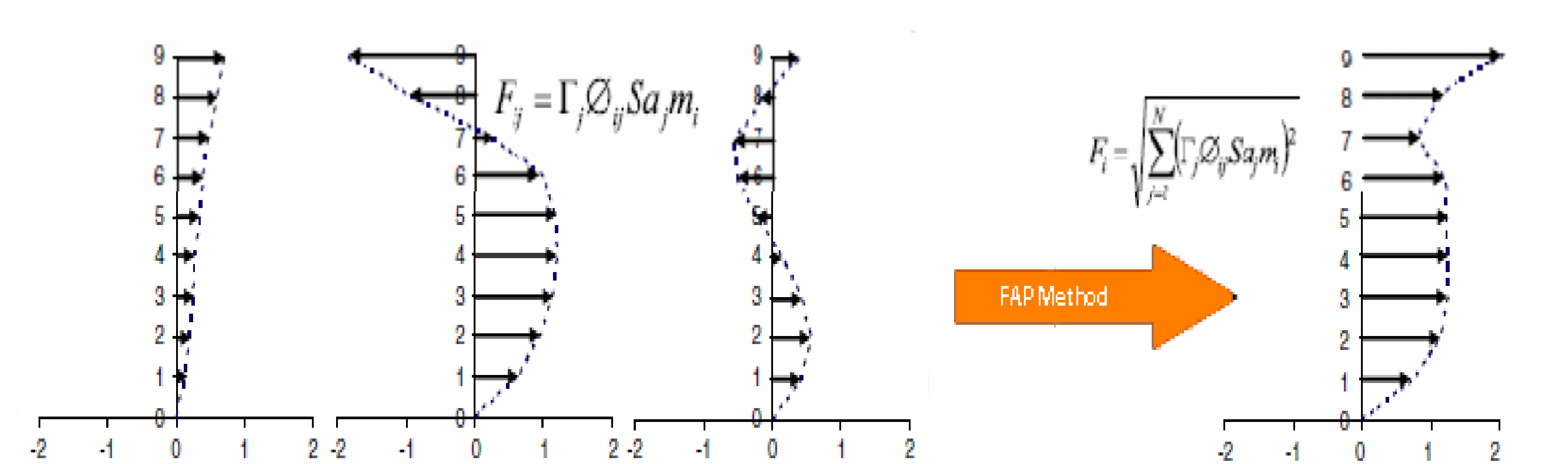
The newly procedure considers the story shear effects instead of the base shears and uses this lateral load pattern during the analysis.

- based on the modal story shear profile the load pattern is updated at each analysis step.
- by using the previous load pattern, the mode shape is derived
- the last step is converting the capacity curve of multi degree of freedom system (MDOF) to an equivalent single degree of freedom system (SDOF).

STORY SHEAR BASED ADAPTIVE PUSHOVER

- consider the higher mode effects
- can take care about the progressive changes in the modal properties, stiffness degradation and the frequency content of a design or particular response spectra.
- the SRSS rule always leads to a positive value for all the story levels in the incremental load pattern.

STORY SHEAR BASED ADAPTIVE PUSHOVER



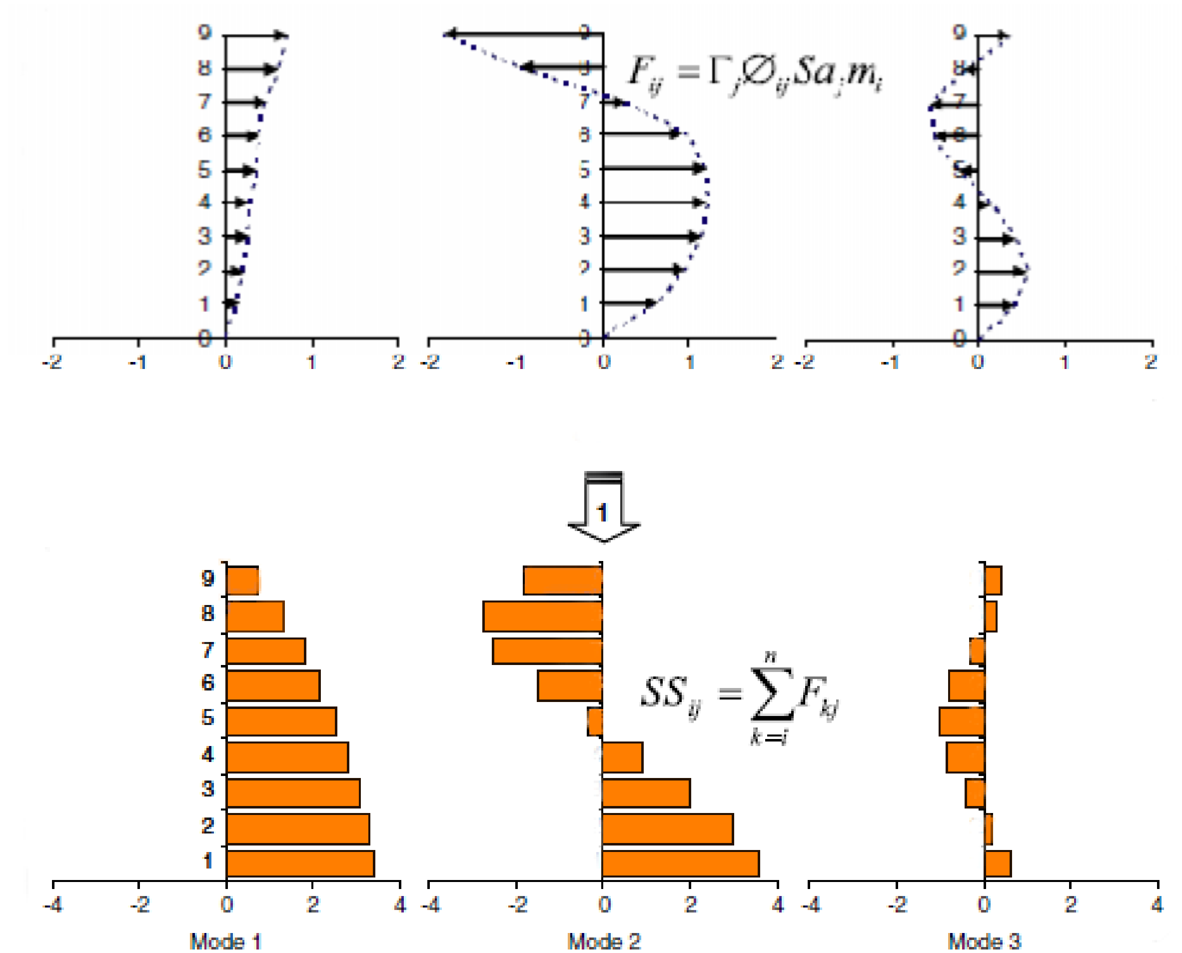
STORY SHEAR BASED ADAPTIVE PUSHOVER

$$F_{ij} = \Gamma_j \emptyset_{ij} m_i Sa_j$$

$$SS_{ij=} \sum_{k=i}^{n} F_{kj}$$

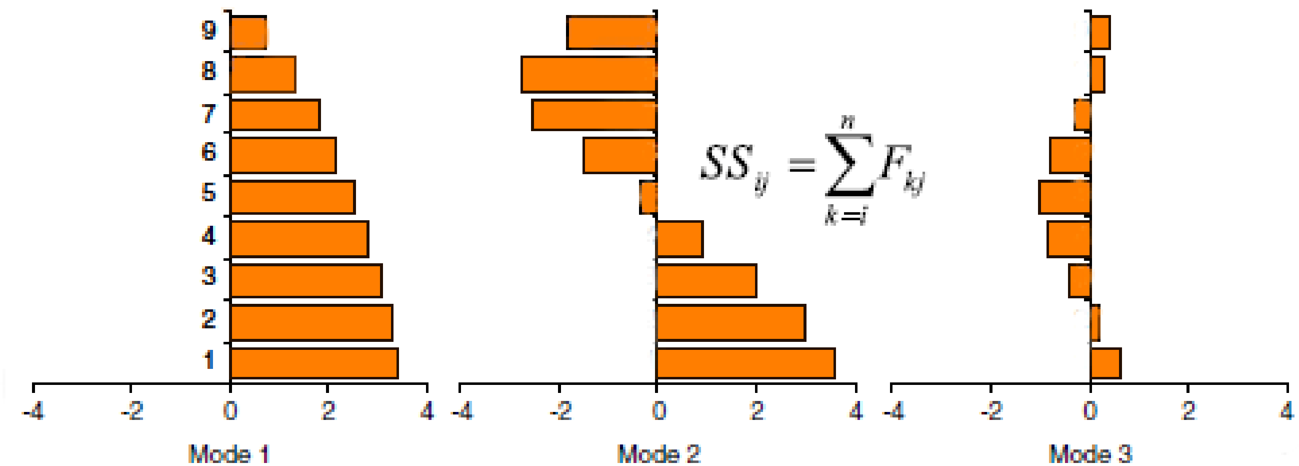
Here, i is the story number, j is the mode number, $\emptyset_{ij}$ is the ith component of the jth mode shape, m_i is the mass of the ith story, Γ_j is the modal participation factor for the jth mode, S_{aj} is the spectral acceleration corresponding to the jth mode, SS_{ij} is the story shear in level i associated with mode j.

STORY SHEAR BASED ADAPTIVE PUSHOVER



STORY SHEAR BASED ADAPTIVE PUSHOVER

$$SS_i = \sqrt{\sum_{j=1}^{m} SS_{ij}^2}$$



$$SS_{ij} = \sum_{k=i}^{n} F_{kj}$$

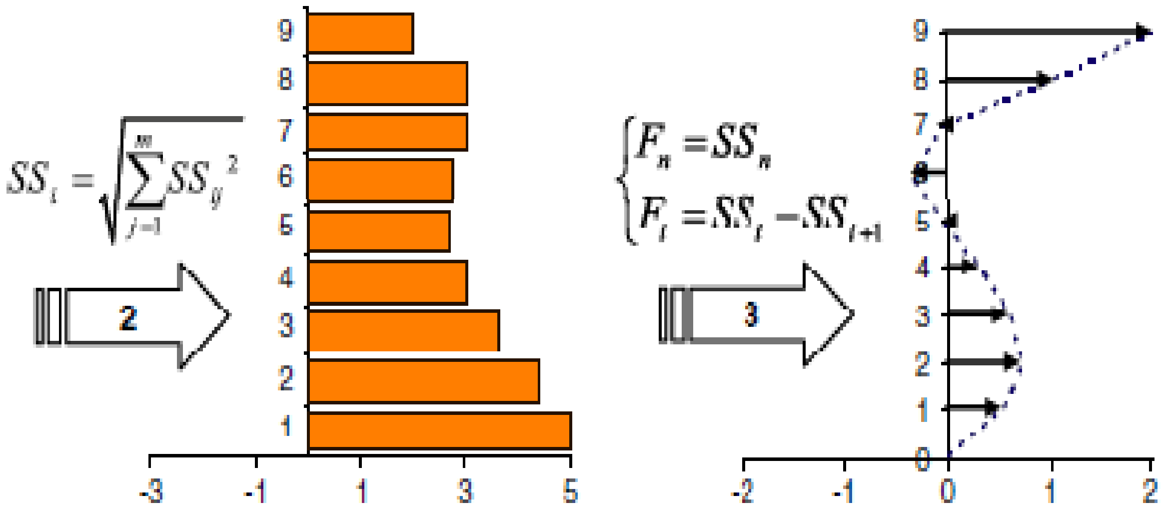
STORY SHEAR BASED ADAPTIVE PUSHOVER

The last step is the evaluation of the load pattern for the pushover analysis. The required story forces are calculated by subtracting the combined modal shear of consecutive stories using the following equations.

$$F_i = SS_i - SS_{i+1} \quad i = 1,2,\dots,(n-1)$$

$$F_n = SS_n \quad i = n$$

STORY SHEAR BASED ADAPTIVE PUSHOVER



STORY SHEAR BASED ADAPTIVE PUSHOVER

The lateral load pattern is normalized with respect to its total value by;

$$\bar{F}_i = \frac{F_i}{\sum F_i}$$

$$\Delta F_i = \Delta V_b x \bar{F}_i$$

Here; ΔV_b is the incremental base shear, ΔF_i is the i^{th} component of the incremental applied load at each step.

FLOWCHART OF SSAP

Create a nonlinear structural model

↓

Determine ω_j and $\emptyset_j$

↓

$$F_{ij} = \Gamma_j \emptyset_{ij} m_i Sa_i$$

↓

$$SS_{ij} = \sum_{k=i}^{n} F_{kj}$$

↓

$$SS_i = \sqrt{\sum_{j=1}^{m} SS_{ij}^2}$$

↓

$$F_i = SS_i - SS_{i+1} \quad i = 1,2,\dots,(n-1)$$

$$F_n = SS_n \quad i = n$$

$$\bar{F}_i = \frac{F_i}{\sum F_i} \Delta F_i$$

↓

$$\Delta F_i = \Delta V_b x \bar{F}_i$$

↓

$$\{\emptyset\}^k = [m]^{-1} x \{f\}^k$$

↓

Obtain force-displacement and capacity curves.

↓

obtain seismic demands

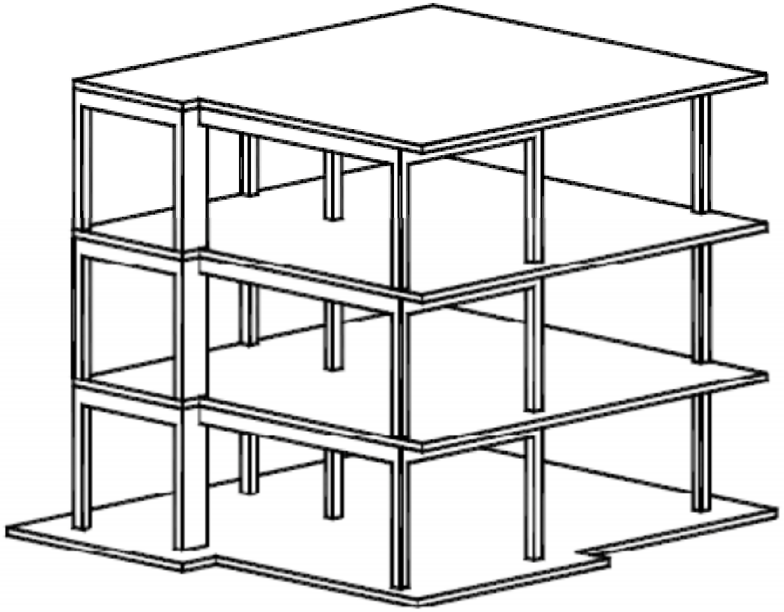
PERFORMANCE EVALUATION OF EXISTING IRREGULAR 3 D BUILDINGS

- **The aforementioned story shear based adaptive pushover procedure** has been extended for existing reinforced concrete buildings (RC) to include the irregularity effects.
- **Seismic Performance Assessment and Rehabilitation of Existing Buildings (SPEAR)** building has been investigated through a newly written computer code.
- **Nonlinear adaptive structural analysis program (NASAP)** bases on 3-D modeling of the structural systems. It is developed for to implement the SSAP procedure with a difference of involving the torsional components to the 3-D pushover analysis of existing RC structures.

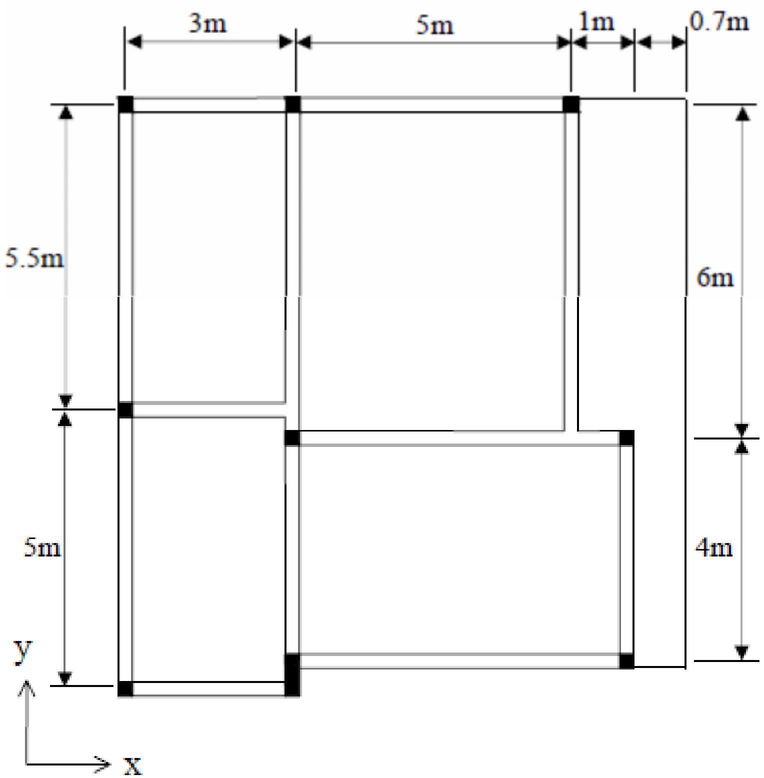
EXISTING IRREGULAR SPEAR BUILDING

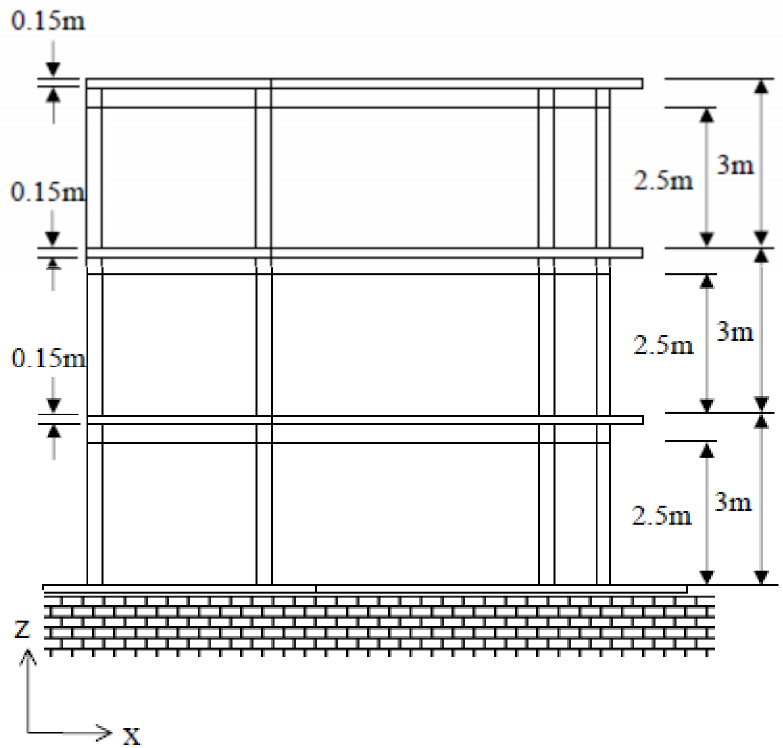
- The SPEAR structure was designed by Fardis in 2002.
- It is a representative of an 3 story existing reinforced concrete (RC) building constructed in Greece, without code provisions for earthquake resistance.
- It has been designed using the design code criteria in Greece between 1954 and 1995, with the knowledge and materials of early 70's for only gravity loads.
- Beams are stronger than the columns
- Transverse reinforcement in columns for shear and confinement are minimal, especially in the plastic hinge zones.

SPEAR BUILDING



SPEAR BUILDING

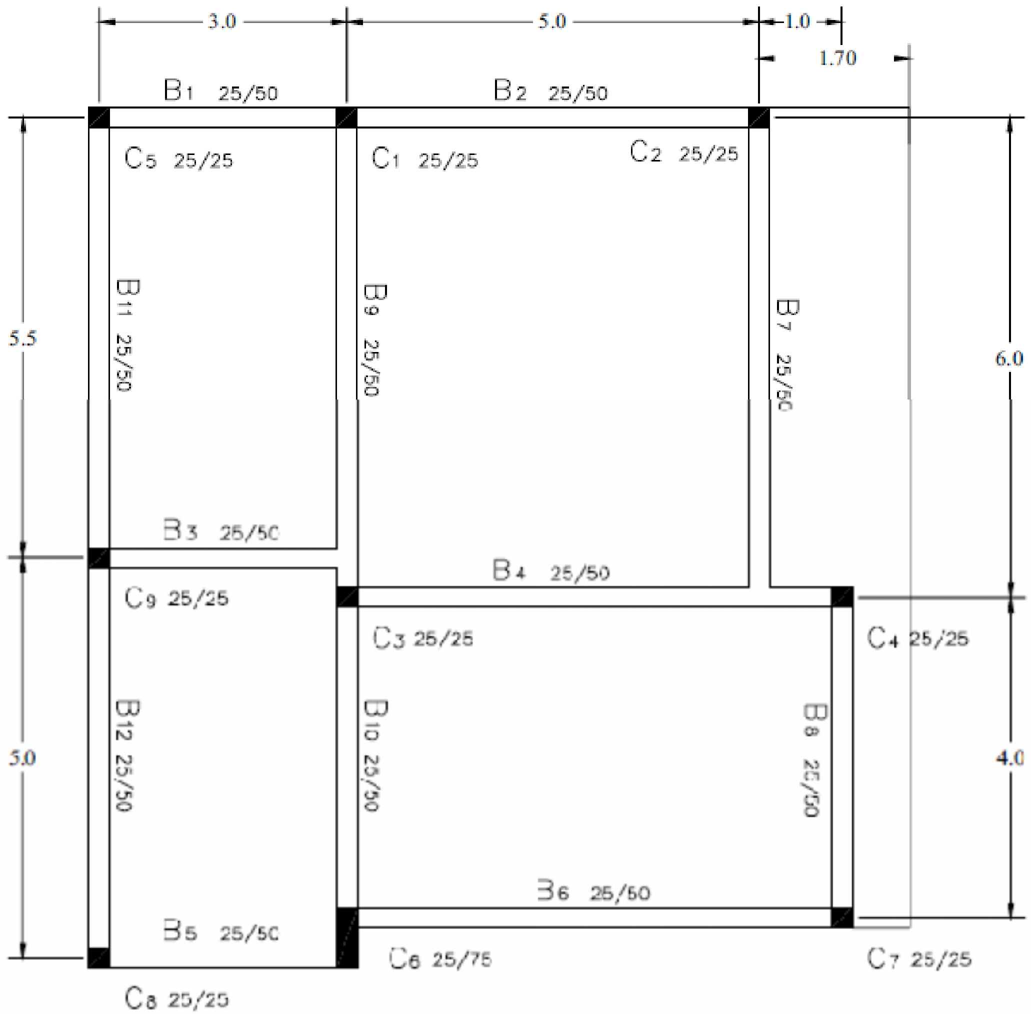




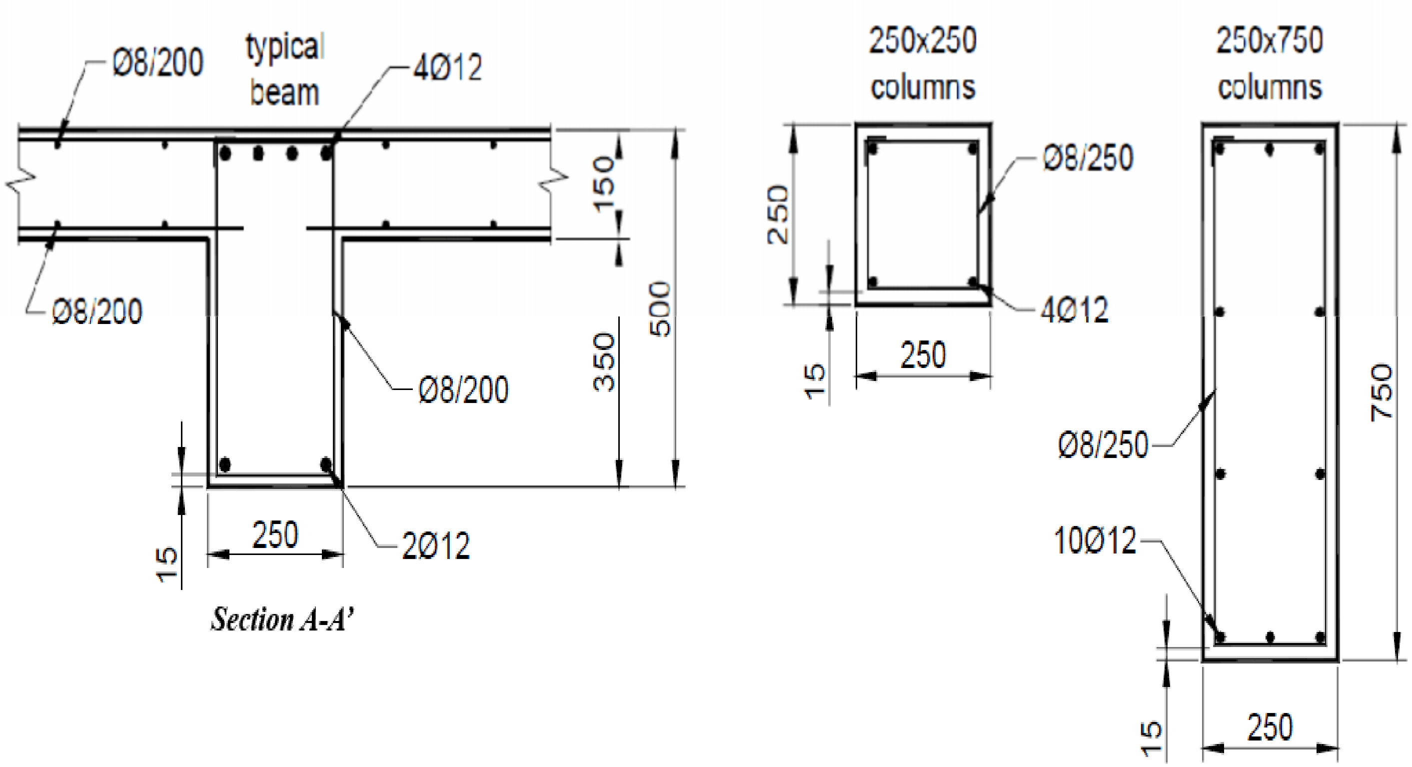
SPEAR BUILDING

- The story height is 3 m, with 2.5 m clear height of columns between the beams.
- The specified design strength of concrete is f_c=25 MPa, and the design yield strength of reinforcement is f_y=320 MPa.
- Design gravity loads on slabs are 0.5 kN/m^2 for dead and 2 kN/m^2 for live loads.
- Slab thickness is 150 mm and total beam depth is 500 mm.
- The slab is reinforced with 8 mm bars at 200 mm intervals.

SPEAR BUILDING



SECTIONS



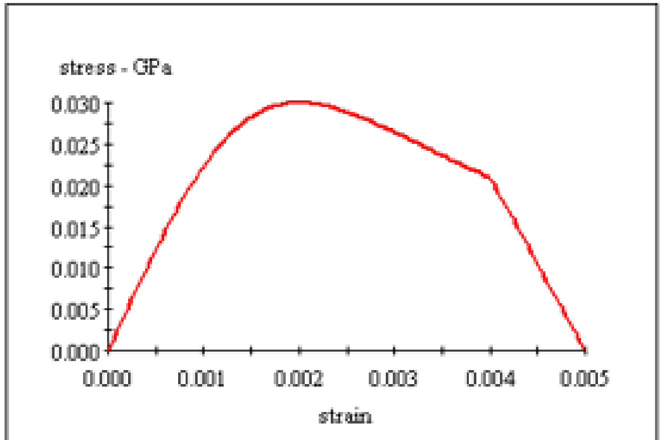
Ø8/200
typical beam
4Ø12
150
500
Ø8/200
Ø8/200
350
15
250
2Ø12
Section A-A'
250x250 columns
Ø8/250
250
4Ø12
15
250
250x750 columns
750
Ø8/250
10Ø12
15
250

DESIGN PROPERTIES OF SPEAR BUILDING

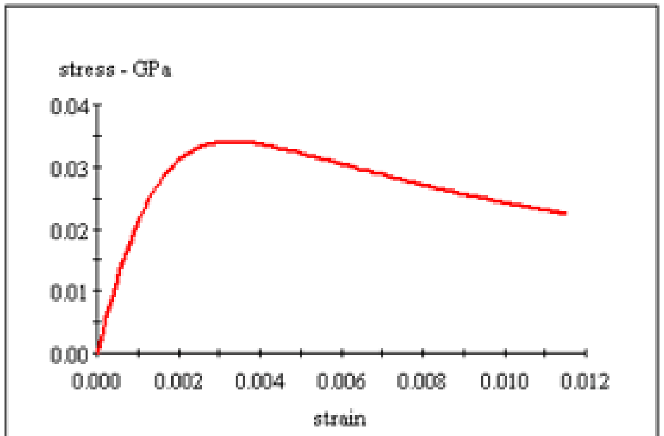
cover concrete thickness is assumed to be 15 mm for all members. Slabs are omitted and their contribution to beam stiffness and strength is reflected by effective width of the T-section.

Cross sections of the building has been modeled using XTRACT. As known Xtract is a cross sectional analysis program for structural components. It is capable of determining the inertial moment, moment curvature and interaction of structural components.

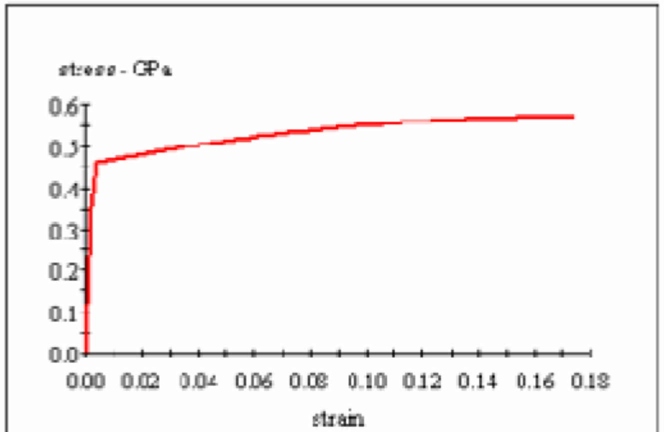
DESIGN PROPERTIES OF SPEAR BUILDING



Stress Strain Model Unconfined Concrete



Stress-Strain Model Confined Concrete

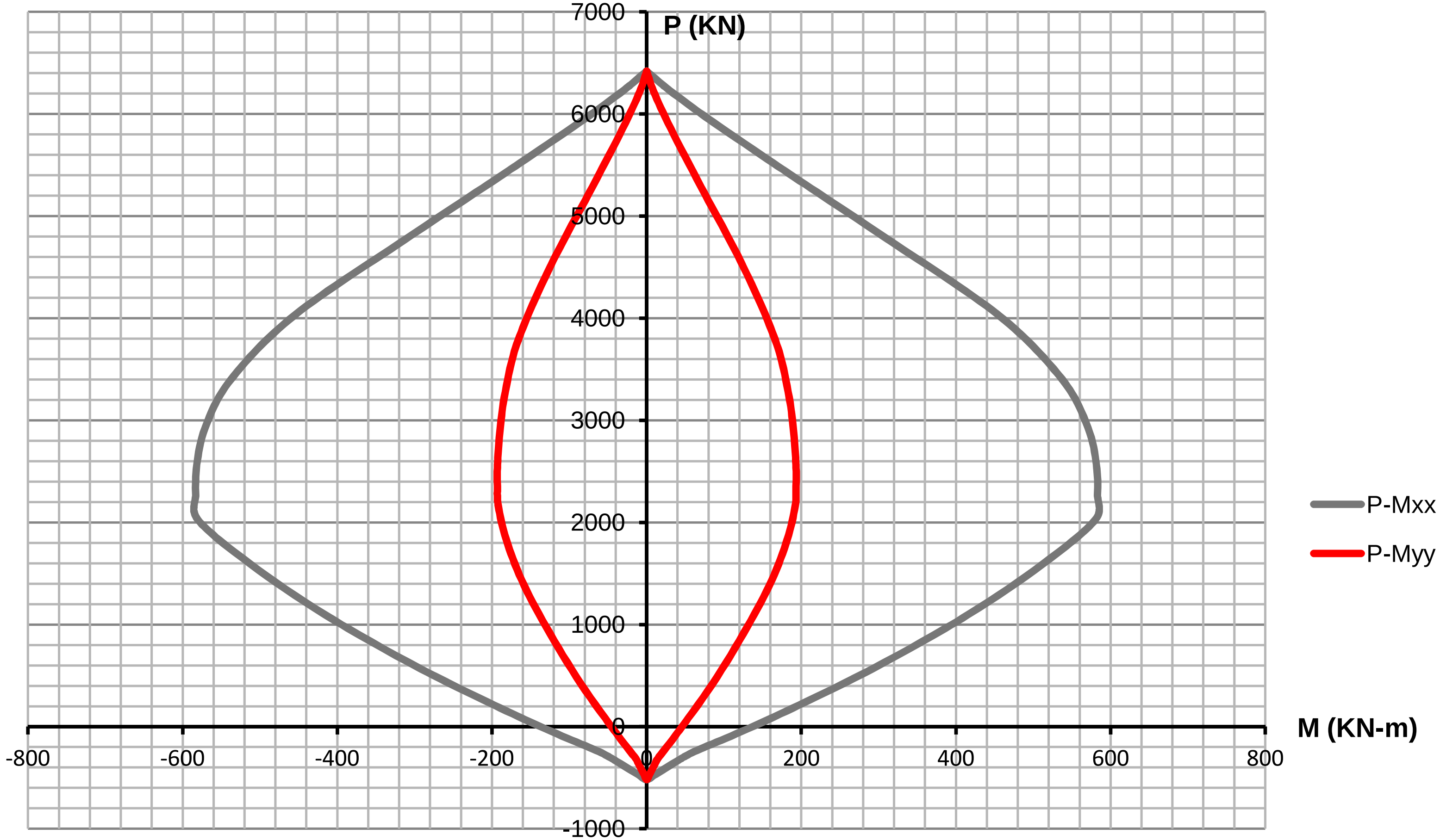


Stress Strain Model Steel

DESIGN PROPERTIES OF SPEAR BUILDING

	Centre of Mass (m)	Mass (KNs^2/m)	Modulus of Inertia [$KNm^2/(m/s^2)$]
FLOOR 1&2	X = 4.53	66.57	1249
	Y = 5.29		
ROOF	X = 4.57	64.43	1170
	Y = 5.33		

DESIGN PROPERTIES OF SPEAR BUILDING



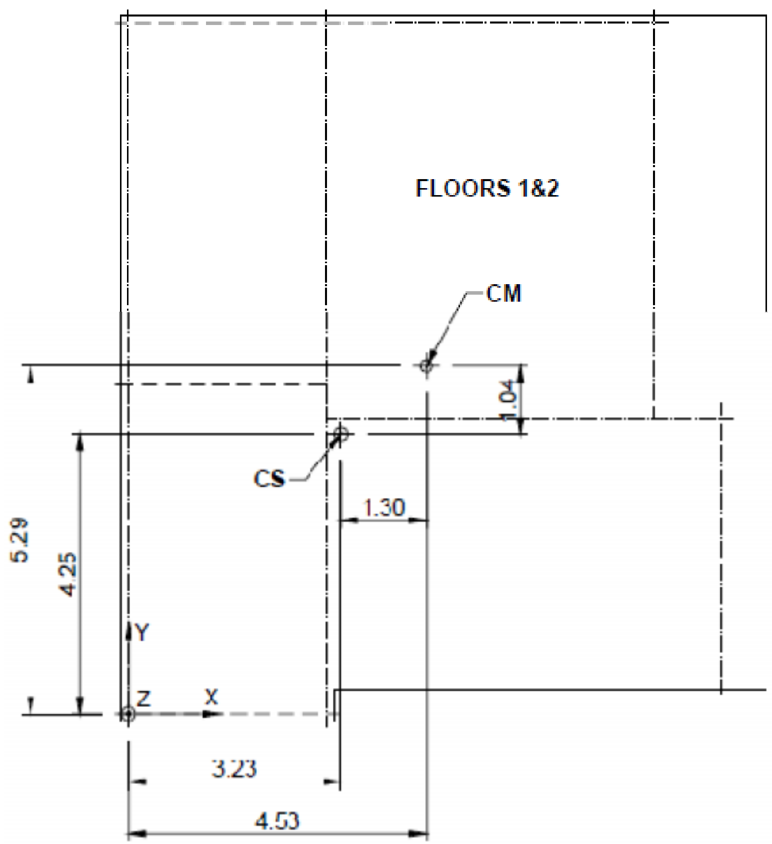
P-M interaction for C6 column in both directions

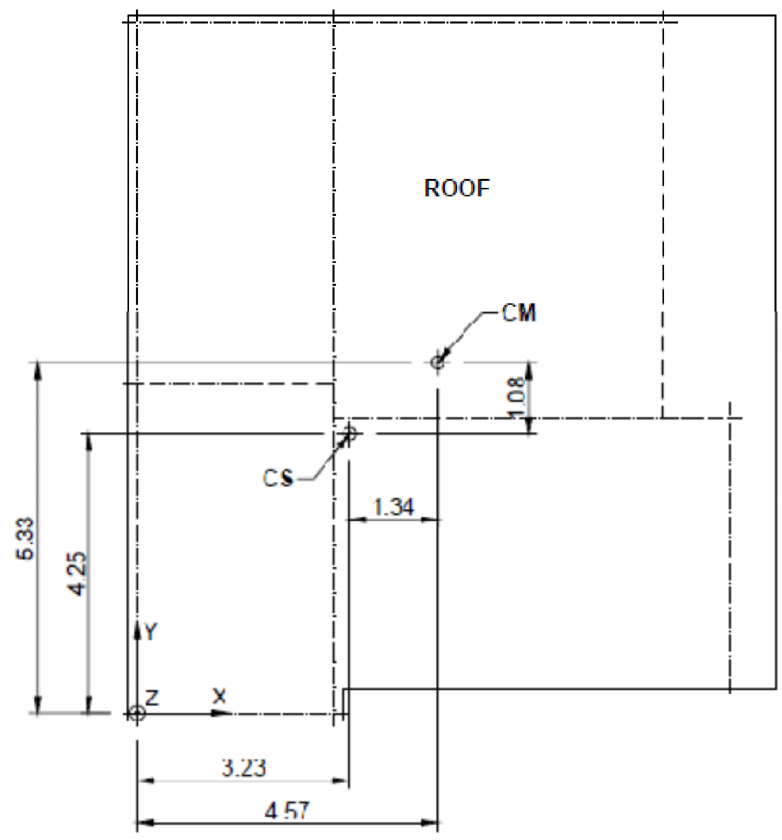
DESIGN PROPERTIES OF SPEAR BUILDING

Centre of stiffness and center of mass values are calculated according to EC8. Torsional parameters of SPEAR building was calculated by Fajfar et al before. e_{0x} and e_{0y} are the eccentricities measured for the X and Y direction respectively. r_x and r_y are torsional radius and l_s is the radius of rotation of a floor in plan.

	e_{0x} (m)	e_{0y} (m)	r_x (m)	r_y (m)	l_s (m)	0.3 r_x	0.3 r_y
FLOOR 1&2	1.302	1.037	1.44	2.57	4.38	0.43	0.77
ROOF	1.338	1.081	1.44	2.57	4.32	0.43	0.77

DESIGN PROPERTIES OF SPEAR BUILDING





DESIGN PROPERTIES OF SPEAR BUILDING

According to EC8 a structural system should satisfy the following equations to be assumed as a regular one.

$$e_{0x} \leq 0.3r_x;\ e_{0y} \leq 0.3r_y$$

$$r_x \geq l_s;\ r_y \geq l_s$$

It is obvious that the SPEAR structure can be classified as irregular in plan according to EC8. Especially in y-direction torsional eccentricities are larger.

EARTHQUAKE RECORD

The input signal consisted of seven semi-artificial series obtained by the modification of the North-South (NS) and West-East (WE) components of Herceg Novi record of 1979 Montenegro earthquake.

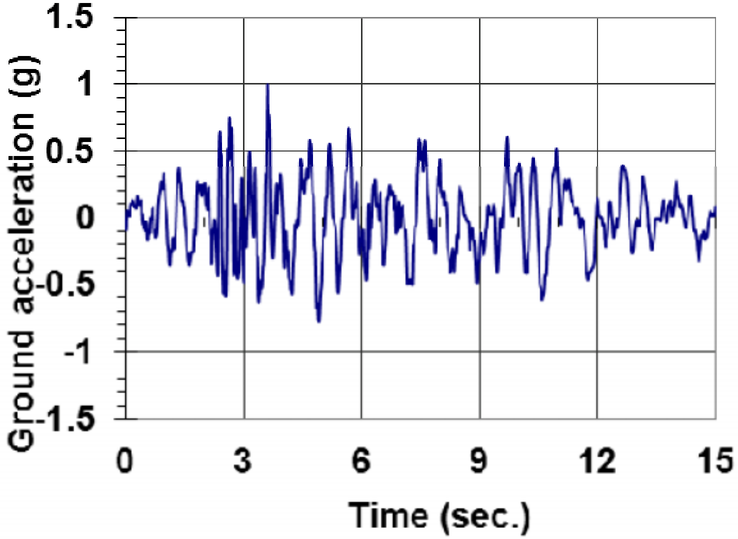
Each of them is consist of two orthogonal components (Longitudinal and Translational) of horizontal accelerations and modified from natural records to be compatible to the **EC8 Type 1 design spectrum, soil Type C and 5% damping**. The latter records were normalized to peak ground acceleration (PGA) of 1.0g on rock site, which means that PGA is 1.15g on soil type C.

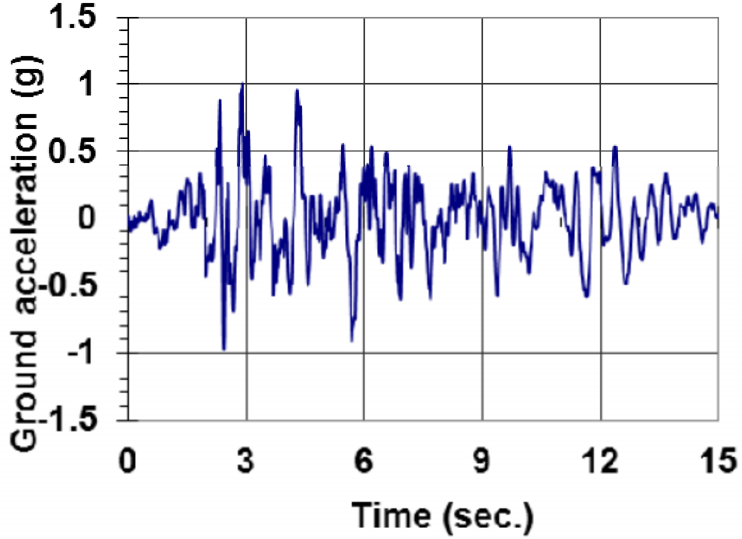
EARTHQUAKE RECORD

No	Earthquakes	Stations	Components	PGA (g)
1	Montenegro 1979	Ulcinj	L,T	1.15
2	Montenegro 1979	Herceg Novi	L,T	1.15
3	Friuli 1976	Tolmezzo	L,T	1.15
4	Imperial Valley 1940	El Centro Array 9	L,T	1.15
5	Kalamata 1986	Prefecture	L,T	1.15
6	Loma Prieta 1989	Capitola	L,T	1.15
7	Imperial Valley 1979	Bonds Corner	L,T	1.15

EARTHQUAKE RECORD

The signal is scaled to 1g, by a scale factor of 0.869 for both directions.



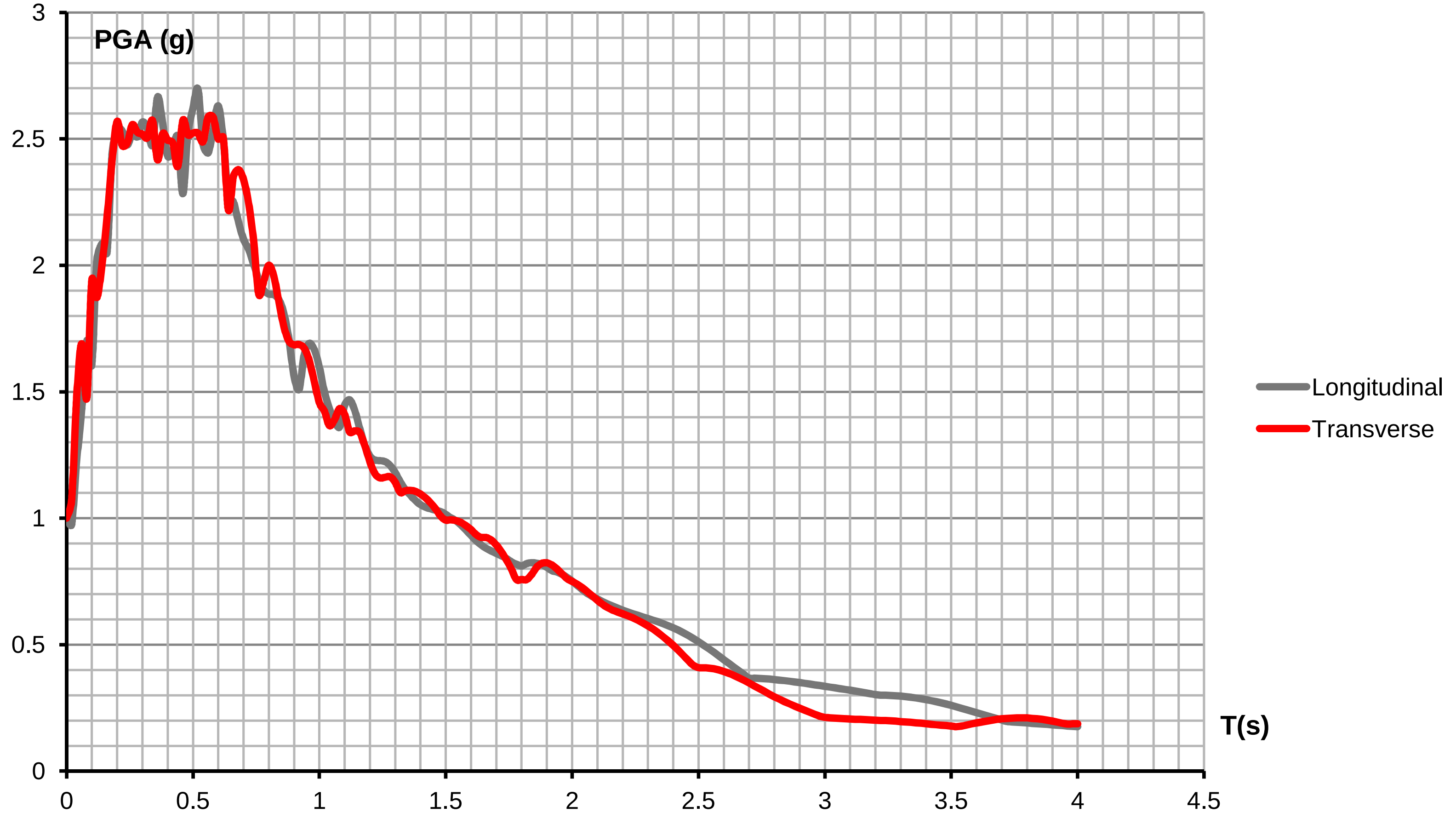


EARTHQUAKE RECORD

The response spectrum, which is needed for adaptive pushover analysis, is determined by FFT analysis of the earthquake signal. Longitudinal and transverse response spectrums are fitted to EC8.

The scaling of the records and the FFT analyses are conducted with Seismosignal, OASYS and PRISM computer codes. All of the products are capable of determining the elastic and inelastic response spectrum with a great accuracy. In the theoretic study that is conducted within the scope of this thesis, PRISM is chosen to be FFT converter.

EARTHQUAKE RECORD

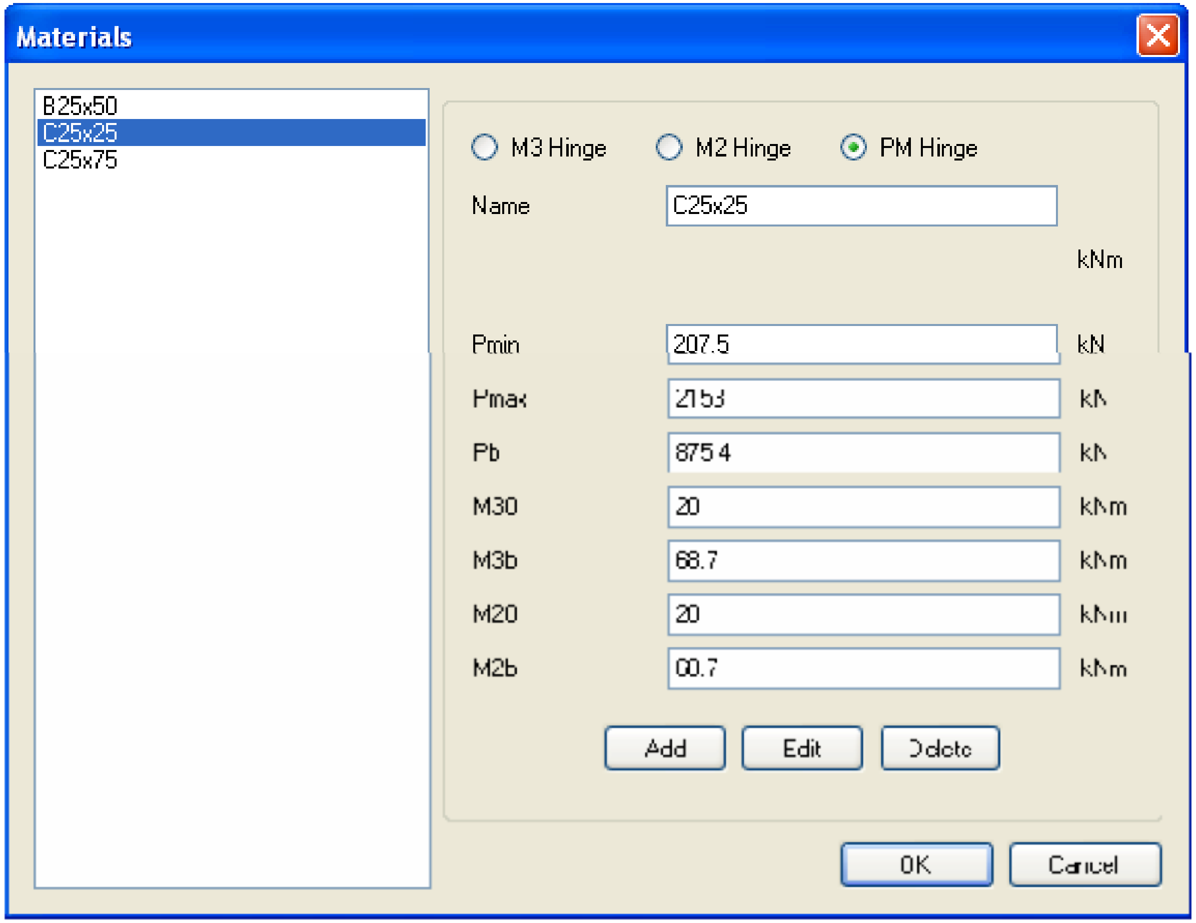


ADAPTIVE ANALYSIS

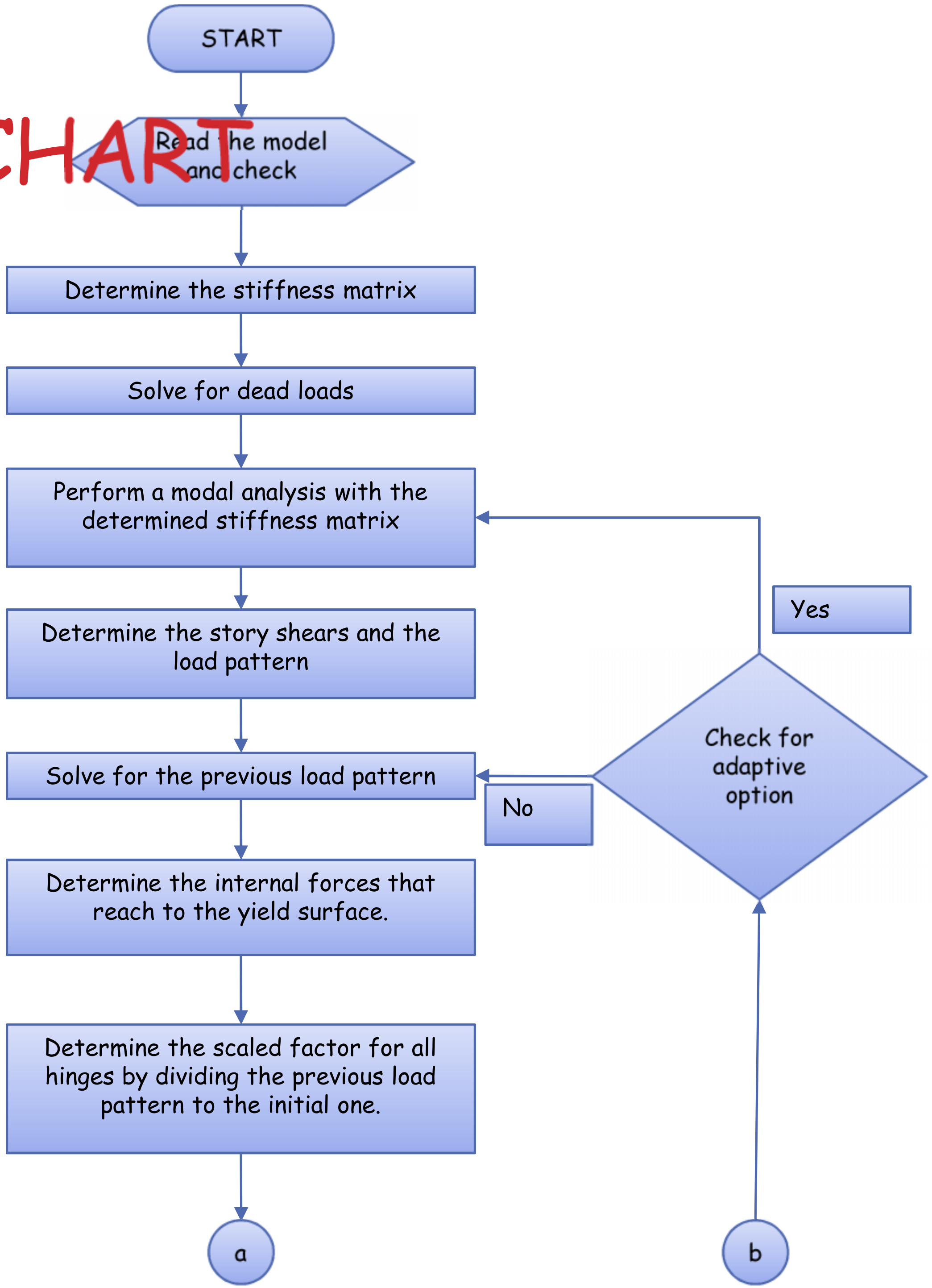
The 3-D software package used in the present work is called as "NASAP" coded by Özçıtak and Oyguç in 2010. This is a tool for finite element analysis of structural elements, meaning "Nonlinear Adaptive Structural Analysis Program".

Irregular SPEAR building has been analyzed with NASAP, and the capacity of the structure is determined using the aforementioned adaptive pushover procedure. The drift profile of the structure is also plotted for comparison. **PERFORM 3-D (CSI)** is chosen to test the accuracy of NASAP. Nonlinear time history analysis are evaluated with PERFORM 3-D (CSI). The drift profiles of the dynamic analysis are compared with the NASAP results.

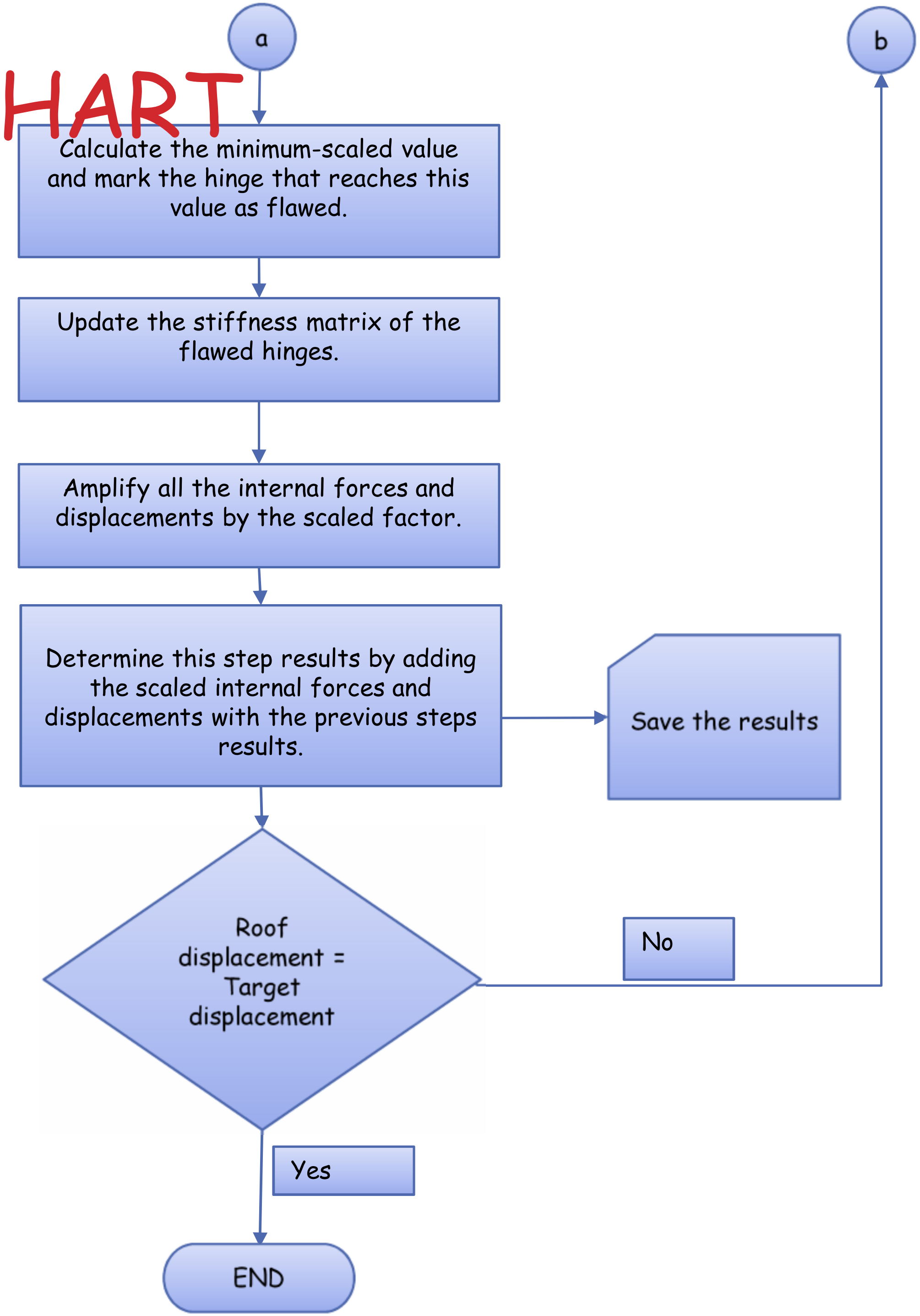
NASAP


Materials
B25x50
C25x25
C25x75
M3 Hinge
M2 Hinge
PM Hinge
Name
C25x25
kNm
Pmin
207.5
kN
Pb
M30
20
M3b
68.7
M20
20
M2b
kNm
Add
Edit
OK

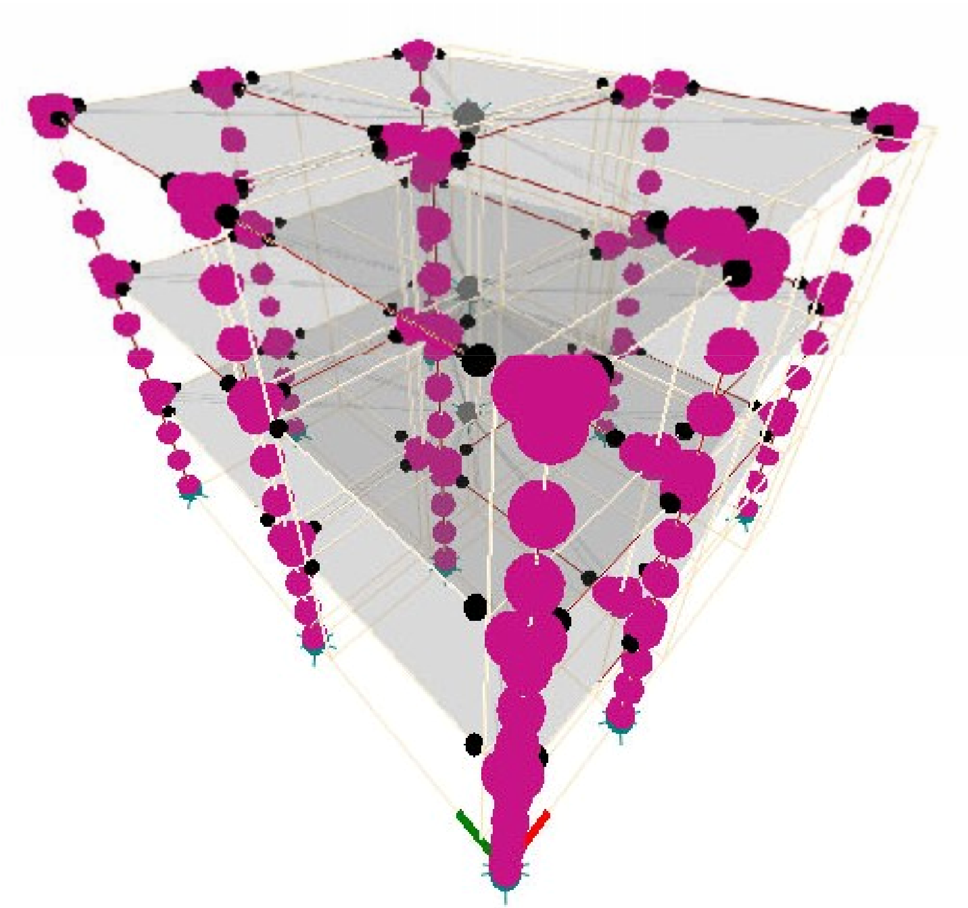
FLOWCHART


START
Read the model and check
Determine the stiffness matrix
Solve for dead loads
Perform a modal analysis with the determined stiffness matrix
Determine the story shears and the load pattern
Solve for the previous load pattern
Determine the internal forces that reach to the yield surface.
Determine the scaled factor for all hinges by dividing the previous load pattern to the initial one.
a
Yes
Check for adaptive option
No
b

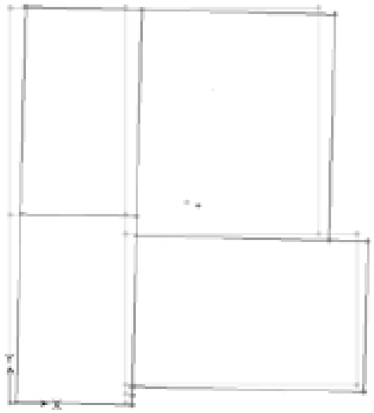
FLOWCHART


a
b
Calculate the minimum-scaled value and mark the hinge that reaches this value as flawed.
Update the stiffness matrix of the flawed hinges.
Amplify all the internal forces and displacements by the scaled factor.
Determine this step results by adding the scaled internal forces and displacements with the previous steps results.
Save the results
Roof displacement = Target displacement
No
Yes
END

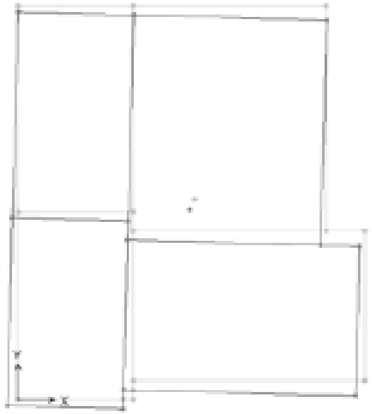
NASAP MODEL



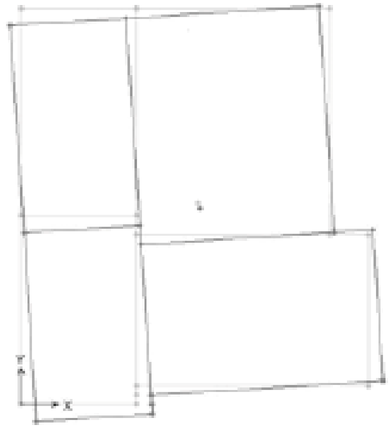
PERIODS



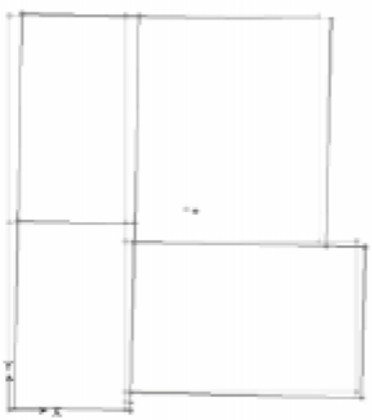
1st mode
T=0.614 s.



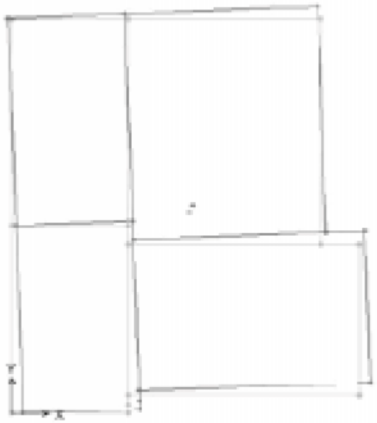
2nd mode
T=0.546 s.



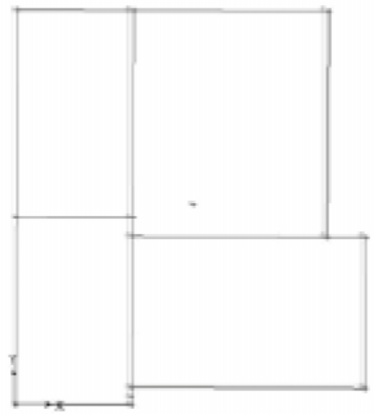
3rd mode
T=0.441 s.



4th mode
T=0.211 s.

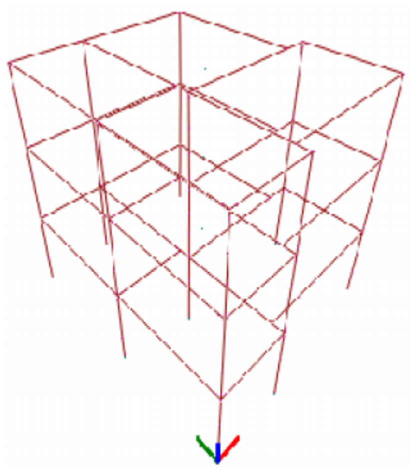


5th mode
T=0.176 s.

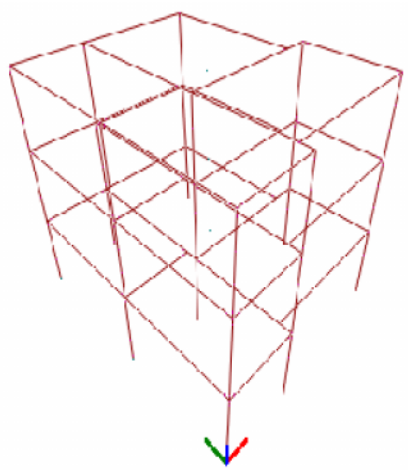


6th mode
T=0.142 s.

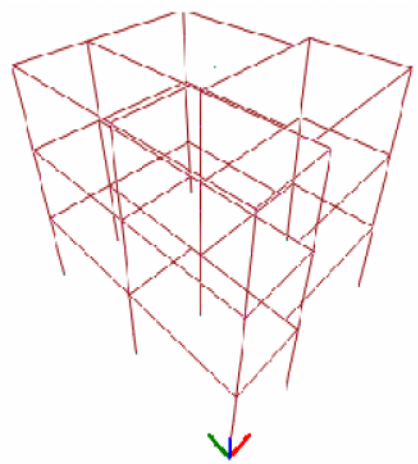
MODAL SHAPES



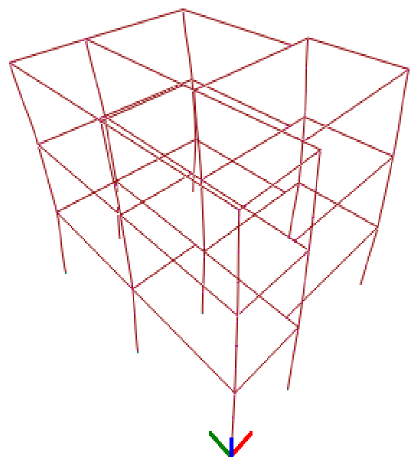
MODE-1



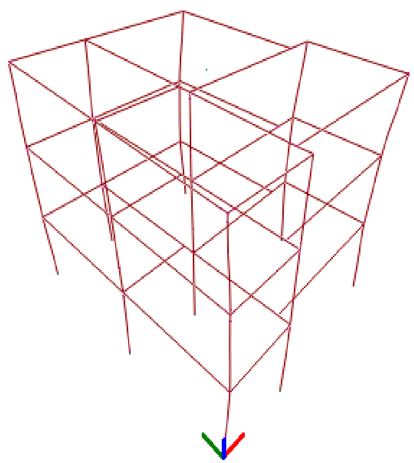
MODE-2



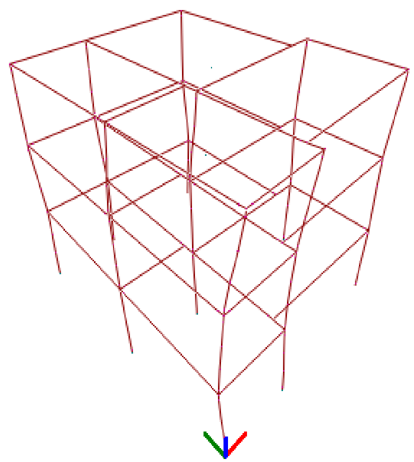
MODE-3



MODE-4



MODE-5



MODE-6

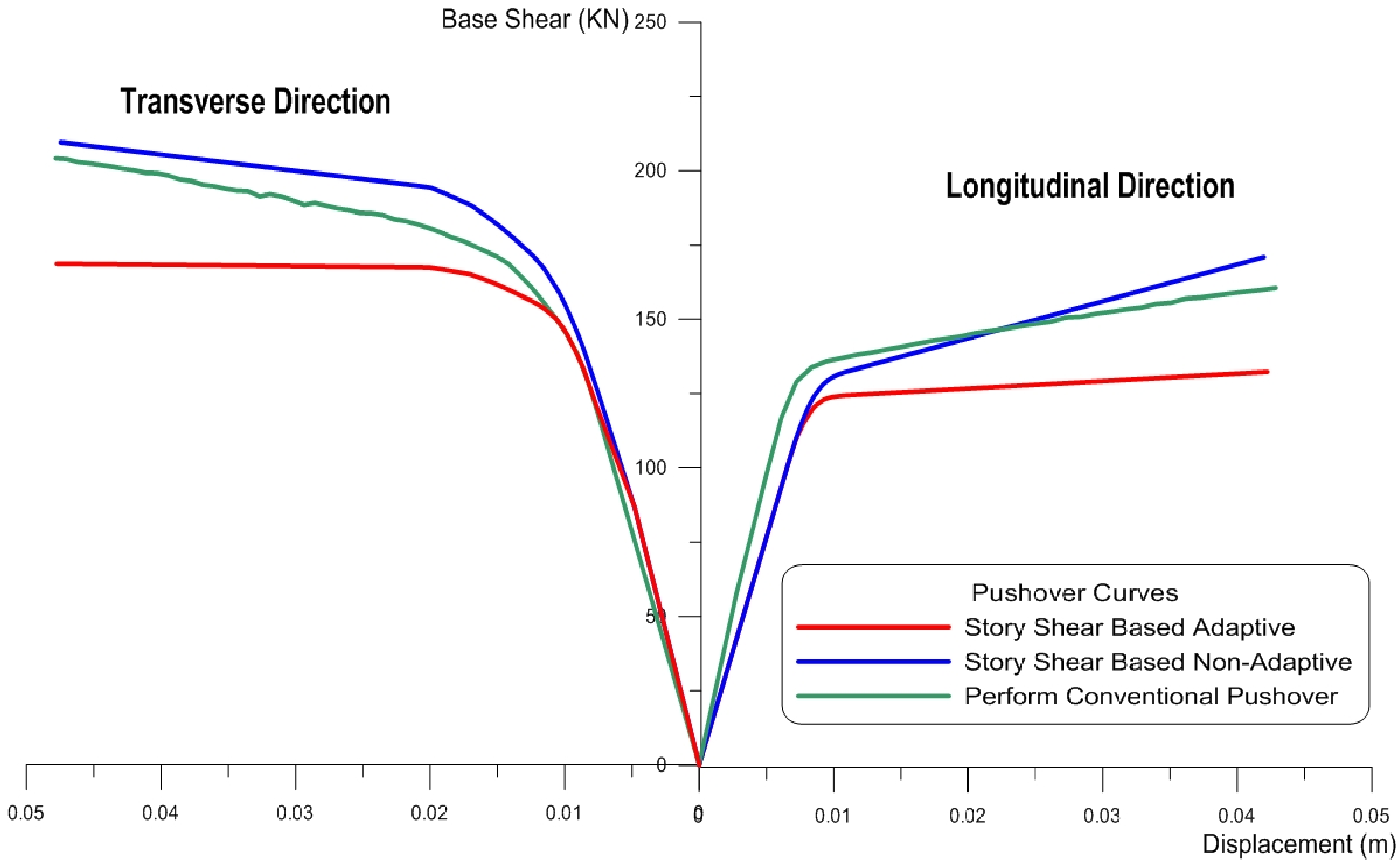
PARTICIPATION FACTORS RESULTS

Mode	X Direction	Y Direction	Around Z Direction
1	12.02	-3.14	-20.52
2	4.76	11.07	21.50
3	2.71	-5.56	52.46
4	3.83	-0.86	-6.38
5	1.55	3.52	10.36
6	-0.21	3.02	-14.94

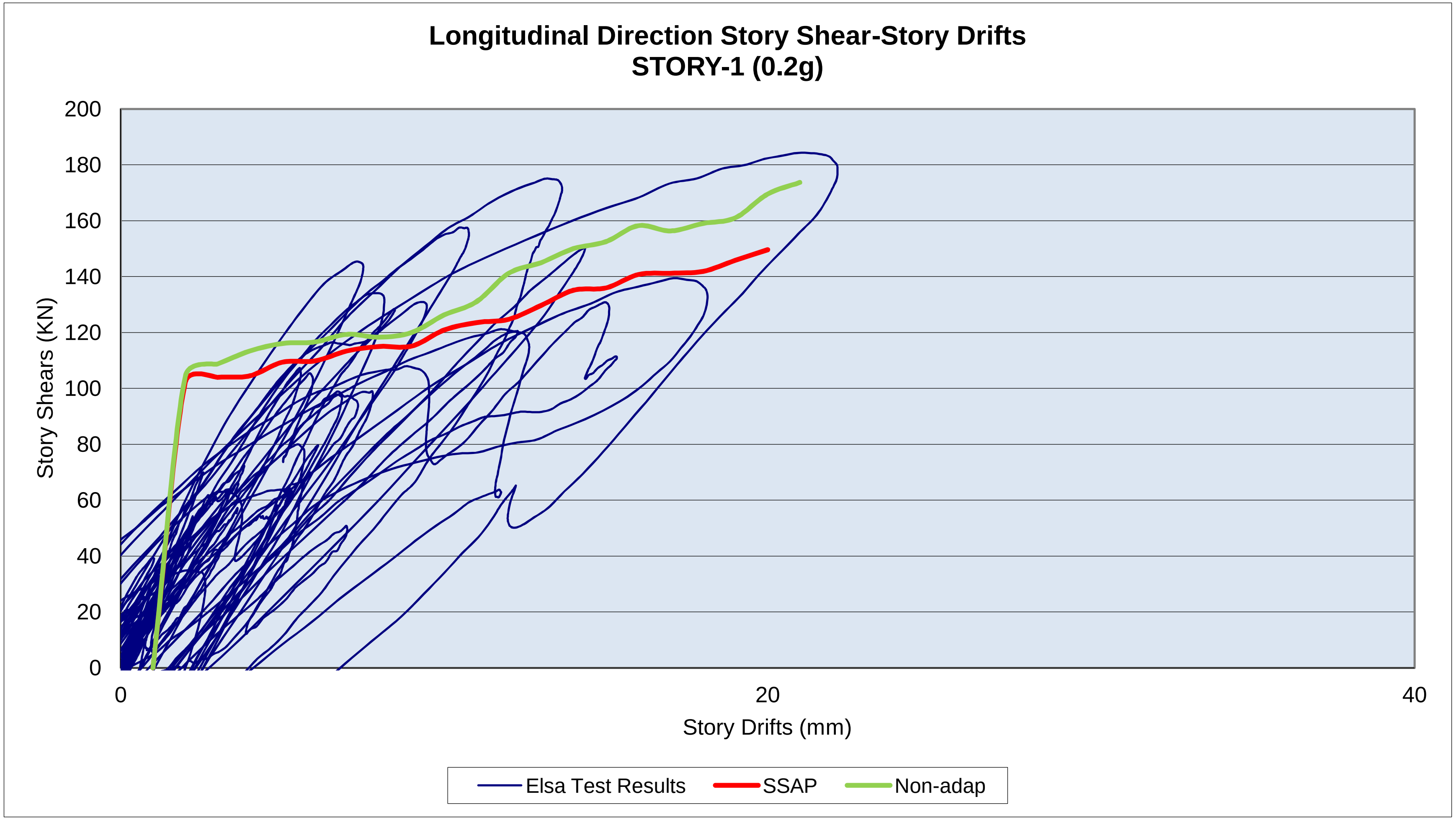
MASS RATIOS

Mode	Period (s)	Long. M. Ratio	Trans. M. Ratio	Torsional M. Ratio
1	0.614	0.74	0.051	0.104
2	0.546	0.116	0.629	0.114
3	0.441	0.038	0.158	0.677
4	0.211	0.075	0.004	0.01
5	0.176	0.012	0.064	0.026
6	0.142	0	0.047	0.055

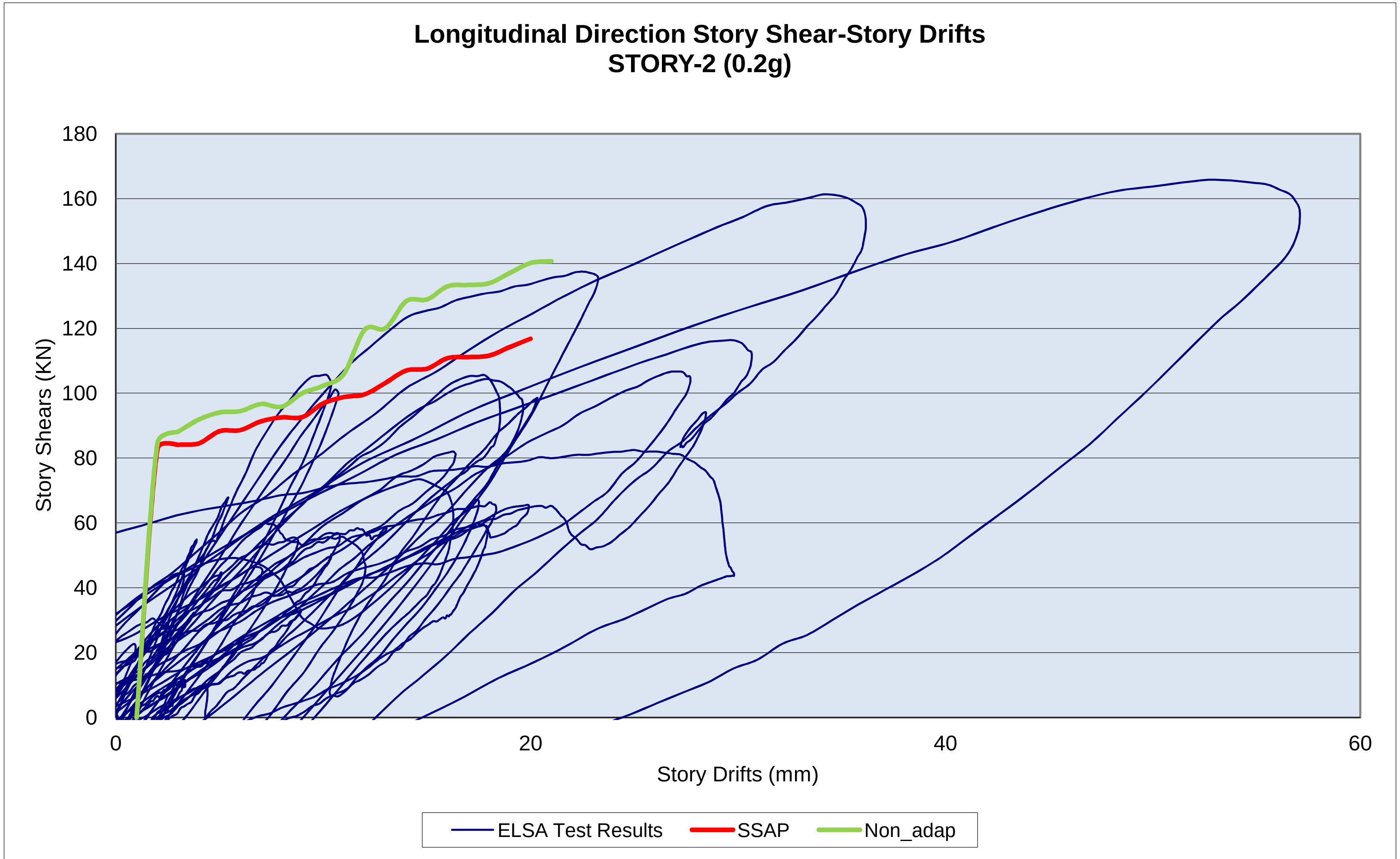
PUSHOVER COMPARISION



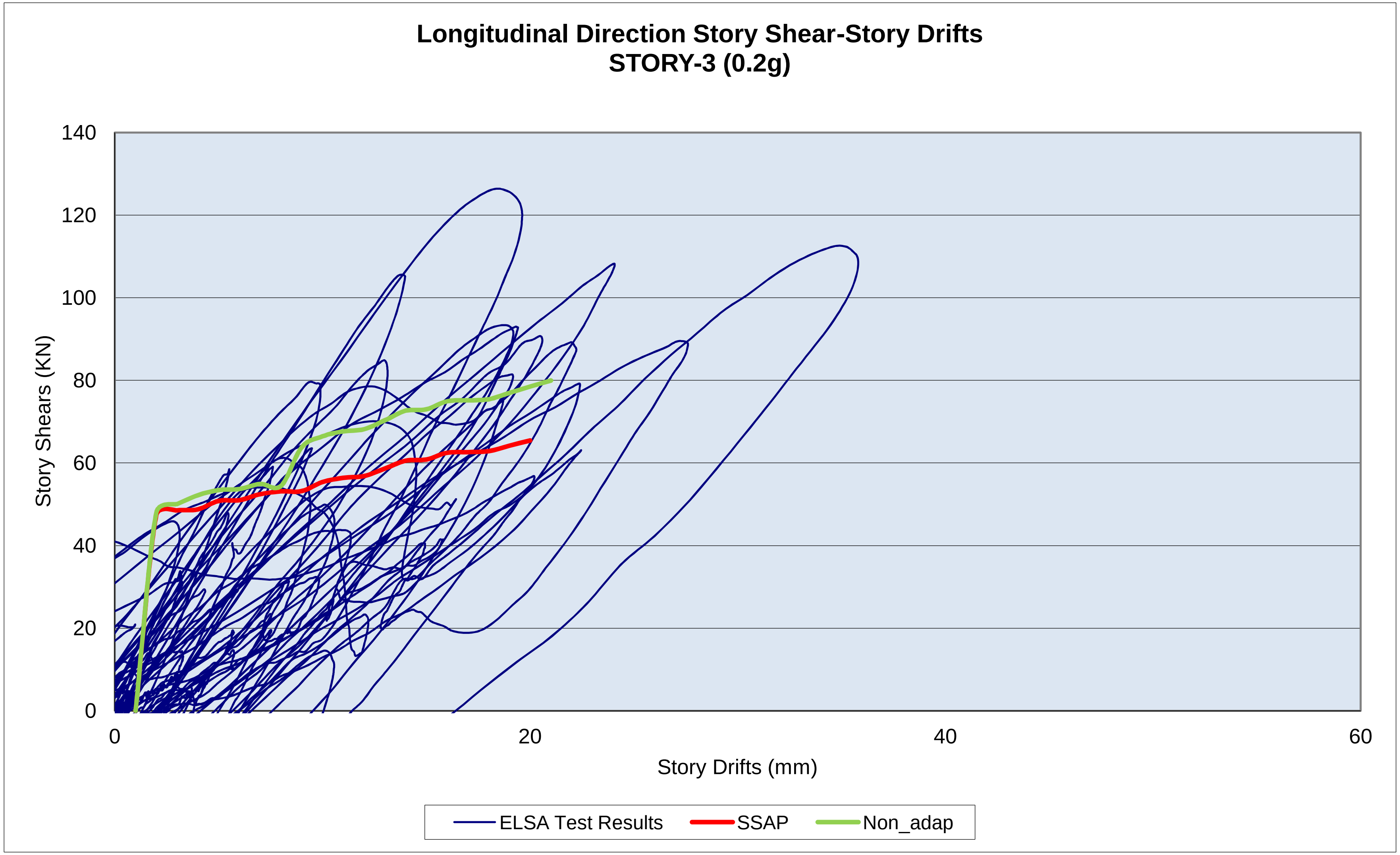
COMPARISION WITH ELSA



COMPARISION WITH ELSA

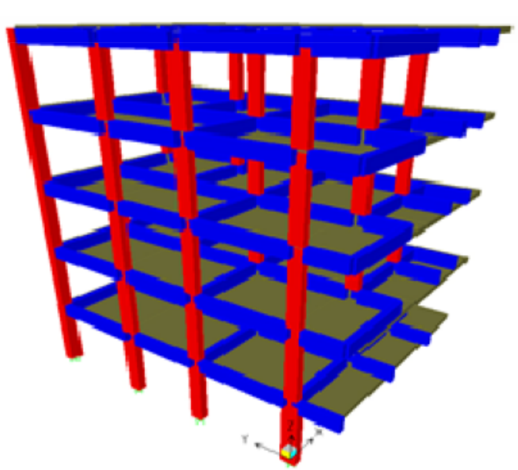


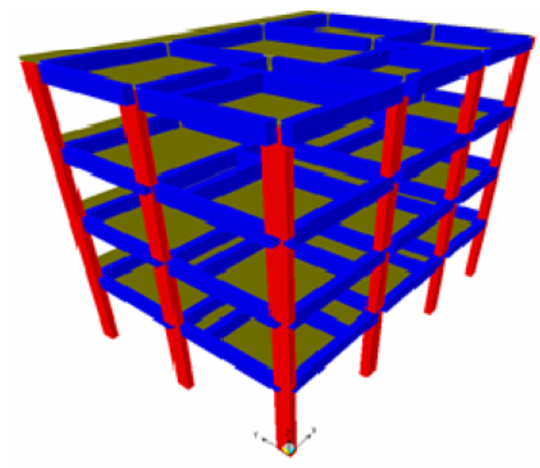
COMPARISION WITH ELSA



ZEYTINBURNU PILOT REGION

Two of the buildings are selected from the database of Istanbul Earthquake Master Plan 2003 project with in a concept of Zeytinburnu Pilot Region and named as Z1 and Z2.

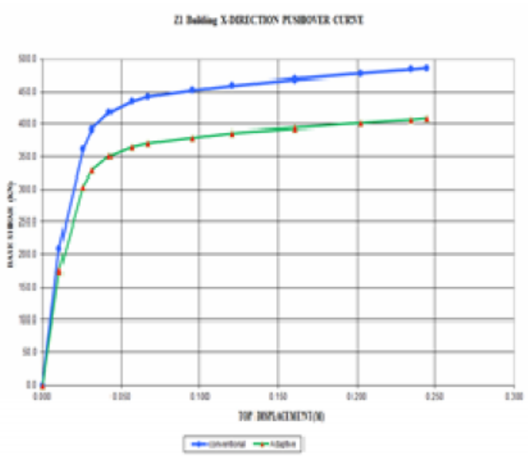


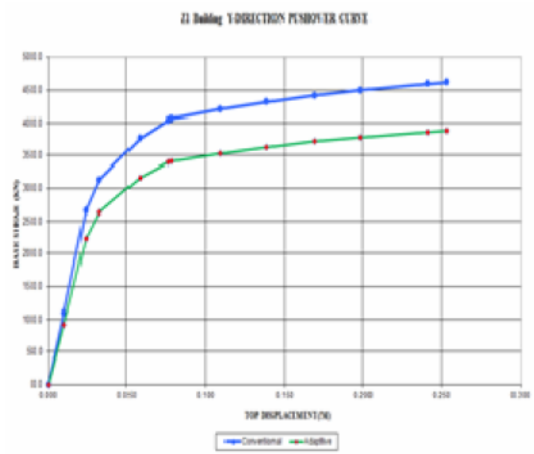


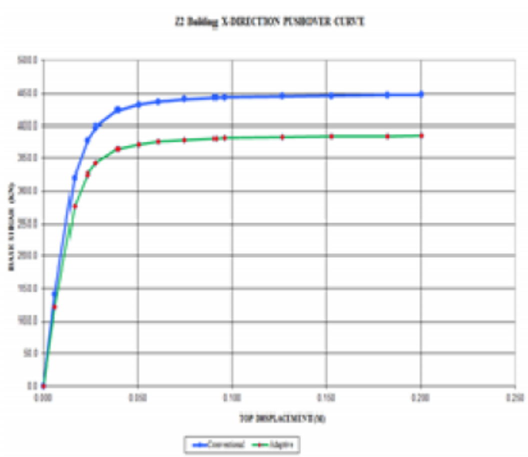
Z1 AND Z2 BUILDINGS

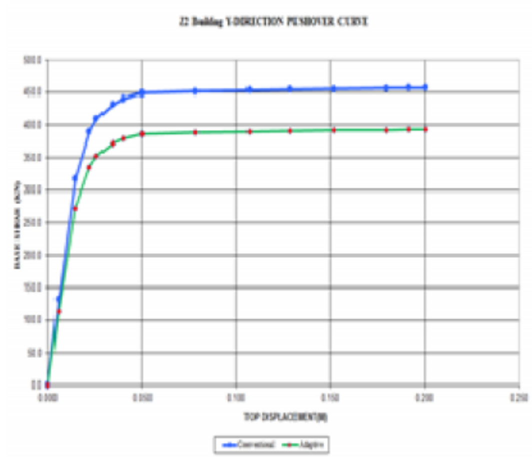
Building	Story Number	Mass (KNs²/m)	Modal Participation Factors		Period (sec)	Modal Mass Factors	
			X	Y		X	Y
Z1	1	109.27	20.33	20.13	0.99	81.44	79.90
	2	106.75	-7.46	-7.54	0.32	10.96	11.22
	3	109.38	4.71	5.06	0.19	4.37	5.06
	4	109.41	-3.36	-3.64	0.14	2.22	2.61
	5	70.98	2.23	2.46	0.12	0.98	1.20
Z2	1	116.07	20.87	20.80	0.75	91.30	90.65
	2	117.86	5.82	-5.99	0.23	7.11	7.53
	3	118.90	2.53	2.69	0.13	1.34	1.52
	4	124.45	-1.05	-1.15	0.09	0.23	0.27

3-DIMENSIONAL MODELS OF Z1 AND Z2 BUILDINGS









CONCLUSIONS

- ✓ The aforementioned story shear based adaptive pushover procedure has been adapted to a 3-D irregular building, SPEAR <u>without considering the P-Δ effects</u>. The analysis results are calculated for both directions with adaptive and non-adaptive solutions. Seismic capacity was evaluated by inelastic dynamic analysis.
- ✓ The structure has torsional irregularities, with eccentricities higher in the transverse direction. Calculated base shear capacity is higher in the same direction due to the strong C6 (25x75cm) column. Displacement values are calculated to be higher in the weaker longitudinal direction.

CONCLUSIONS

- ✓ Dynamic response history analyses were performed by **Perform 3-D** for assessment of peak displacement demand, amount of torsion etc. The corresponding time history results of drifts were compared with the adaptive pushover results of NASAP.

APPLICATION OF THE WORK

The majority of the building stocks in Turkey are irregular. Structural designer should include torsional effects in the design or while strengthening an existing building. The aforementioned procedure might be suitable to apply while assessing the capacity of the newly formed or existing irregular structures since it is a 3-D procedure. It takes care of the irregularity effects. This procedure would be a more accurate way of determining the capacity of an irregular building.

RESULTS

- ✓ Adaptive procedures are more accurate than conventional ones
- ✓ Adaptive SSAP procedure is more accurate compared to non-adaptive ones.
- ✓ Ignoring the higher modes can result in highly inaccurate estimates of deformation.
- ✓ SRSS makes it impossible to investigate the sign changes and reversal effects of higher modes during the analysis.

RESULTS

- ✓ in a story shear based adaptive pushover analysis, the required story forces are calculated by subtracting the combined modal shear of consecutive stories.
- ✓ The previous studies indicated that the adaptive pushover in general does not provide major advantages over the conventional methodology due to the fact that, while combining the modal forces with SRSS or CQC, the sign changes are not included.
- ✓ The procedure is also utilized for performance analysis of three dimensional frames with vertically and plan – wise irregular buildings. It is calculated that, the conventional pushover analysis overestimates the results by **15-19 % approximately.**

THANK YOU