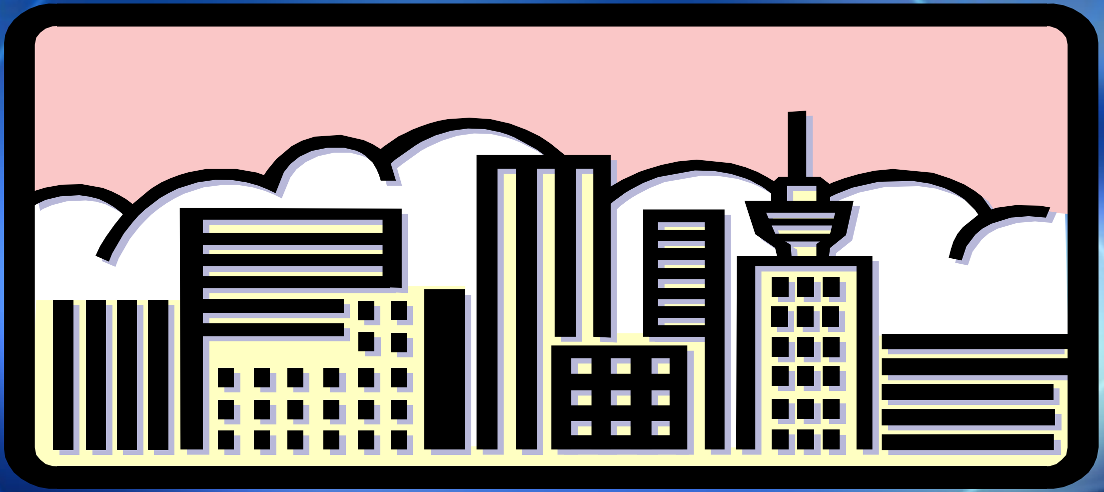
Behavior, Modeling and Design of Shear Wall-Frame Systems



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The Basic Issues

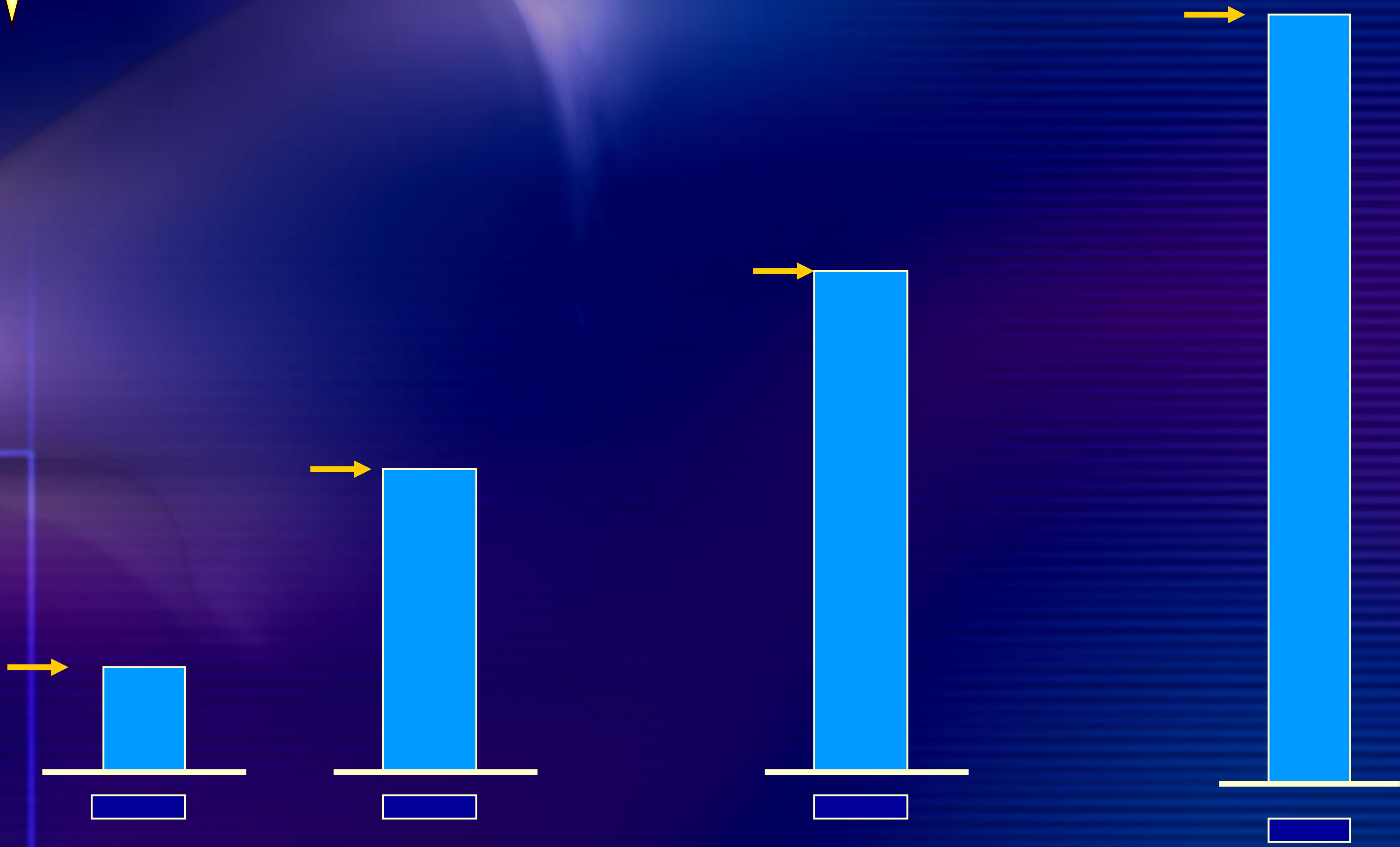
- **Modeling and analysis issues**
  - Transfer of loads to shear walls
  - Modeling of shear walls in 2D
  - Modeling of shear Walls in 3D
  - Interaction of shear-walls with frames

- **Design and detaining issues**
  - Determination of rebars for flexure
  - Determination of rebars for shear
  - Detailing of rebars near openings and corners
  - Design and detailing of connection between various commonest of cellular shear walls

Shear Wall – Common Misconceptions

- Due to misleading name "Shear Wall"
- The dominant mode of failure is shear
- Strength is controlled by shear
- Designed is governed primarily by shear
- Force distribution can be based on relative stiffness

Shear Wall or Column

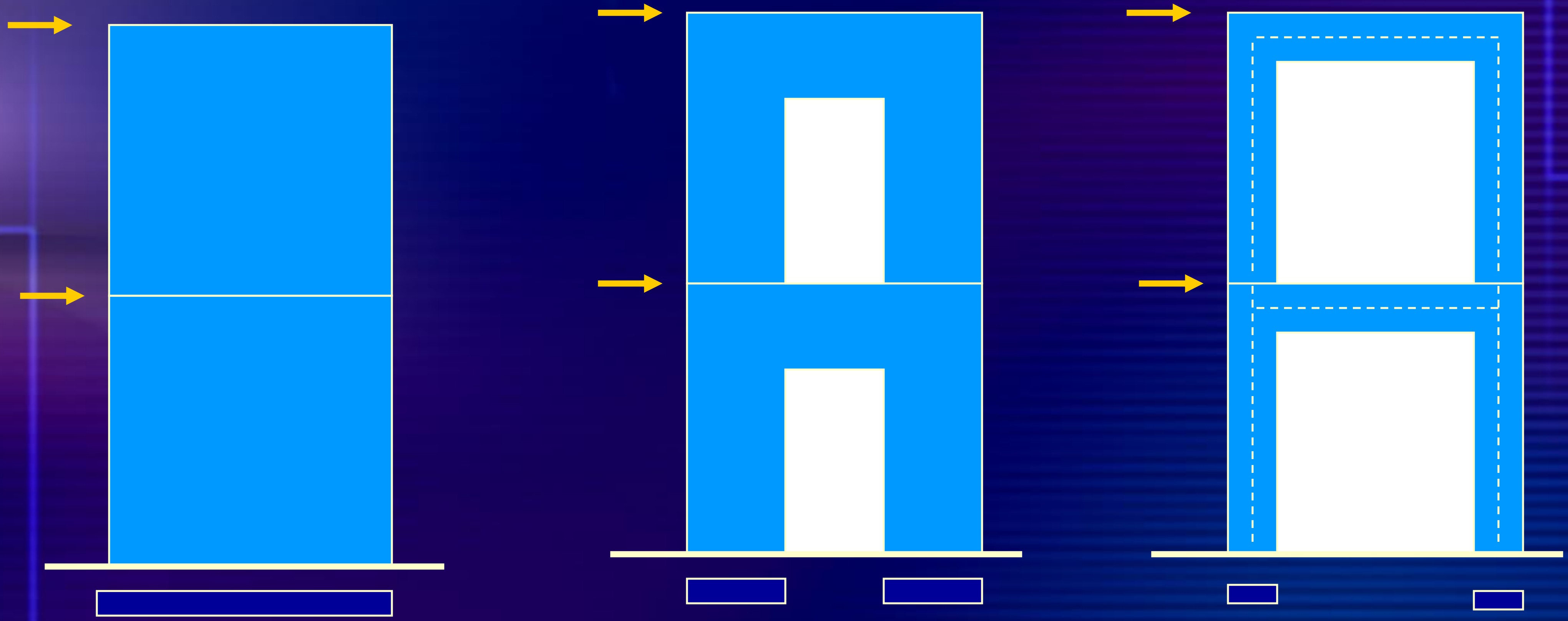


Shear Wall or Frame

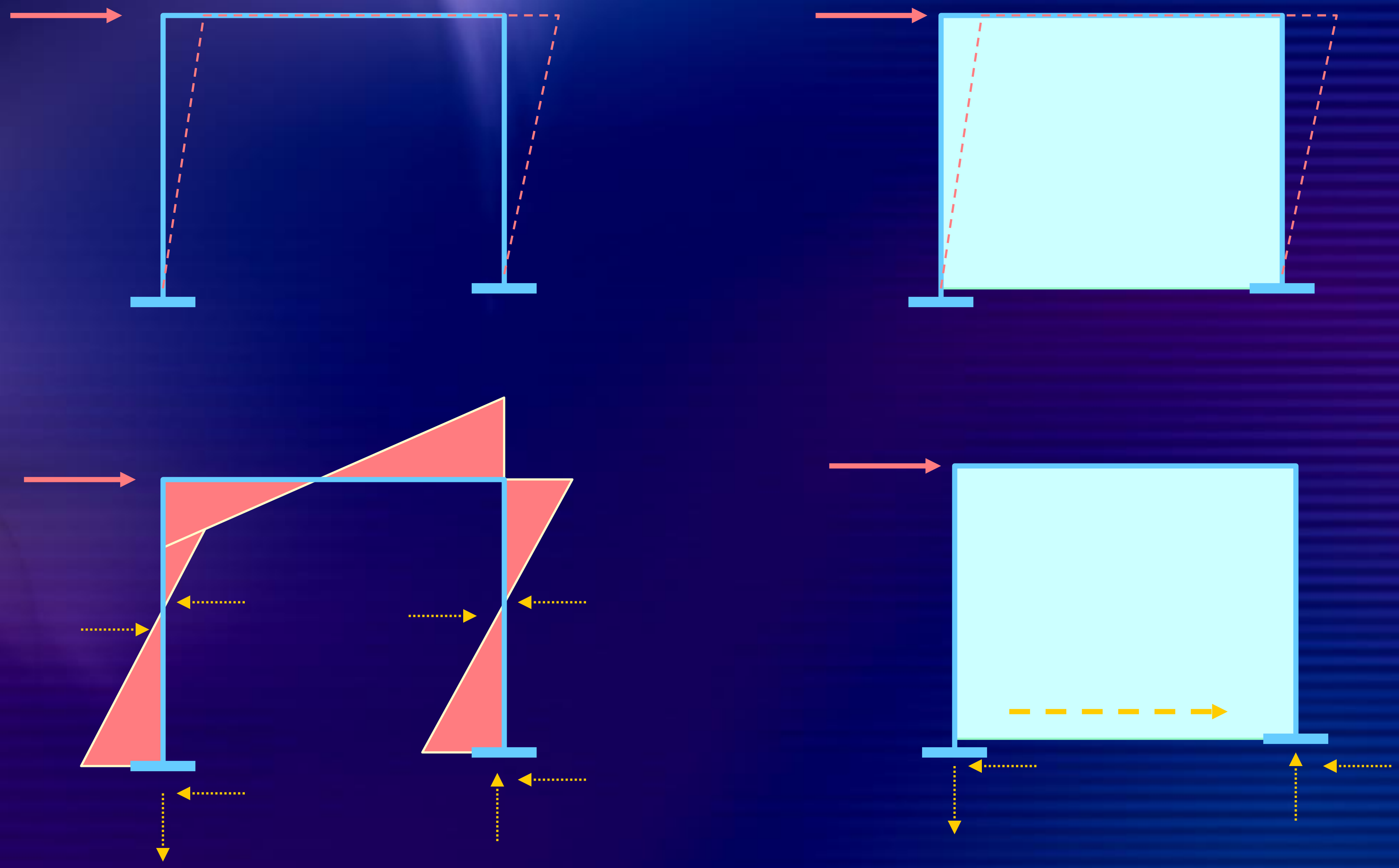
Shear Wall

Shear Wall or Frame ?

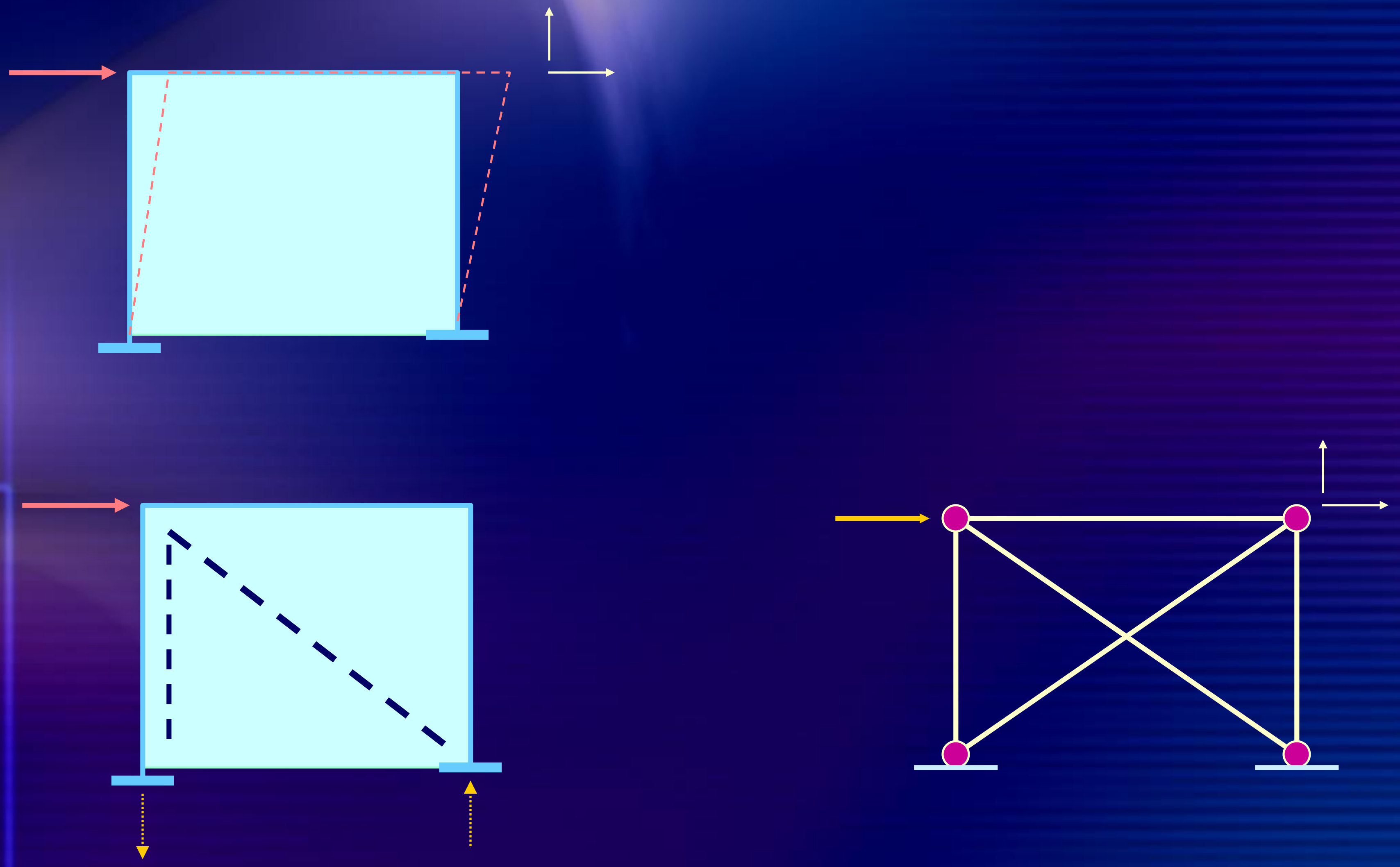
Frame



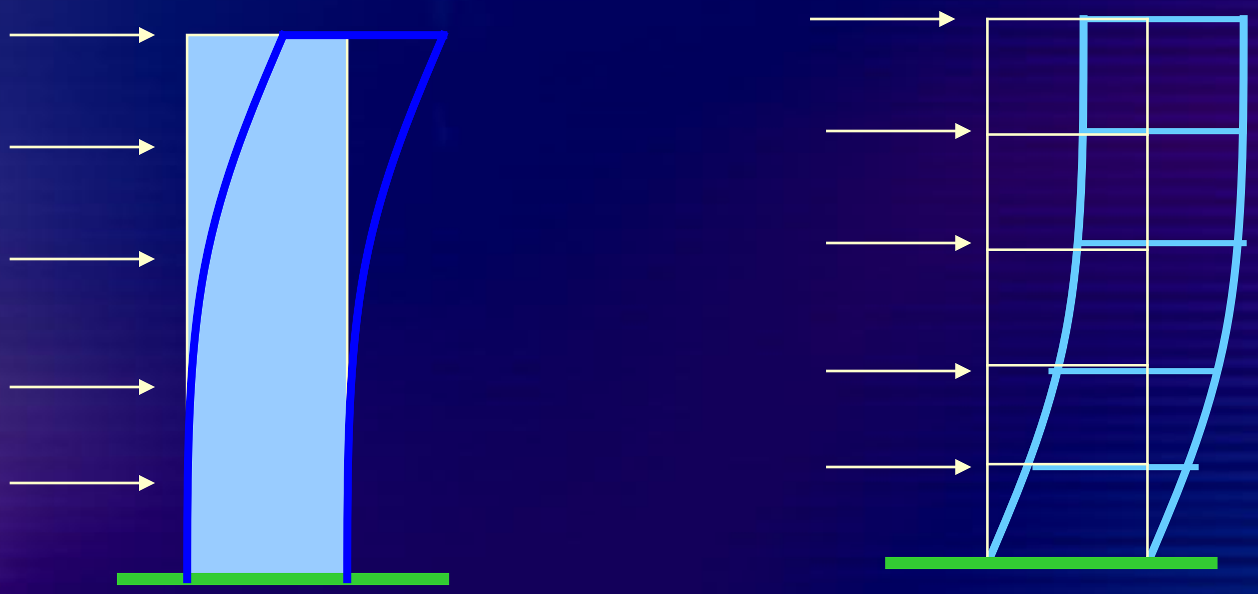
Shear Wall and Frame Behavior



Shear Wall and Truss Behavior



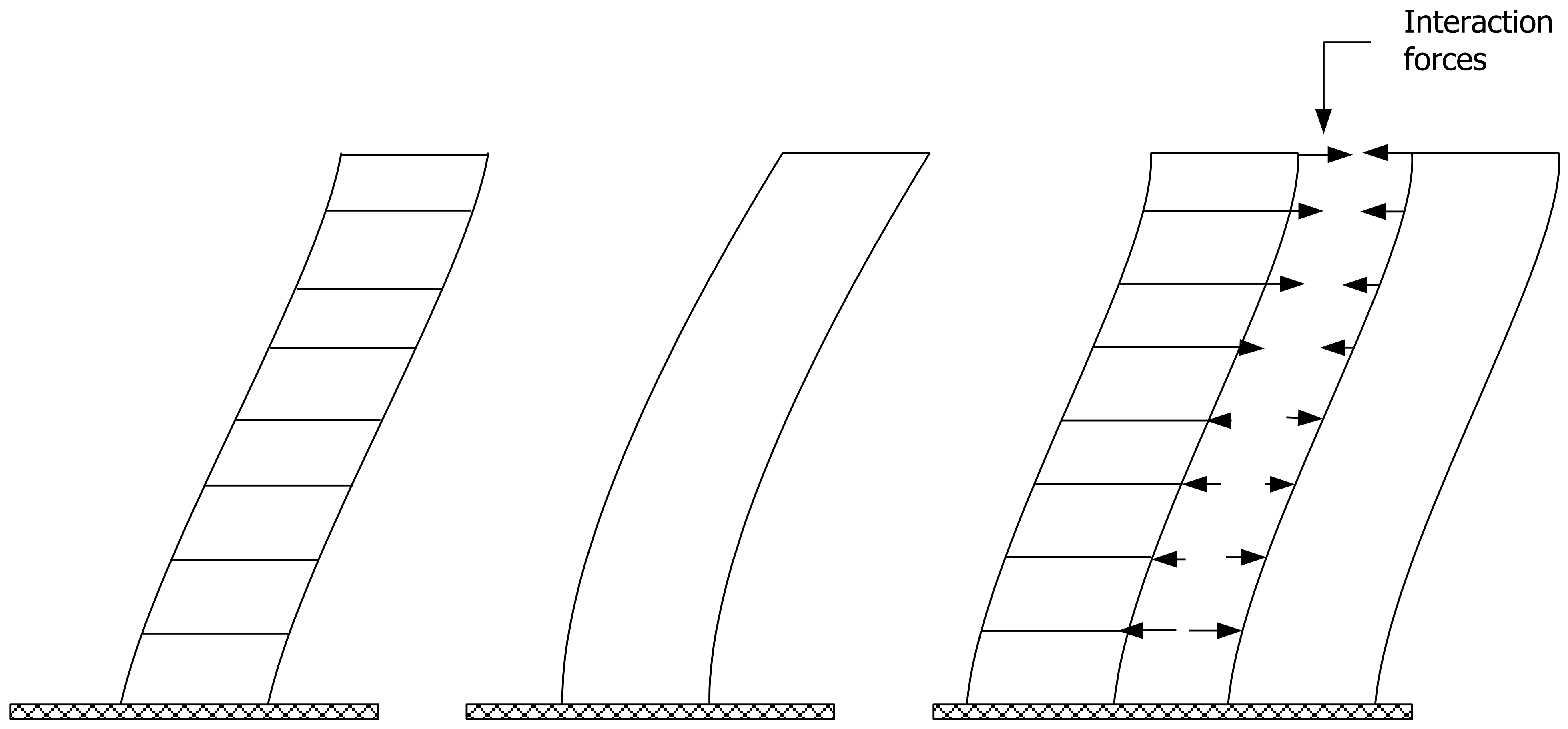
Shear Wall and Frame



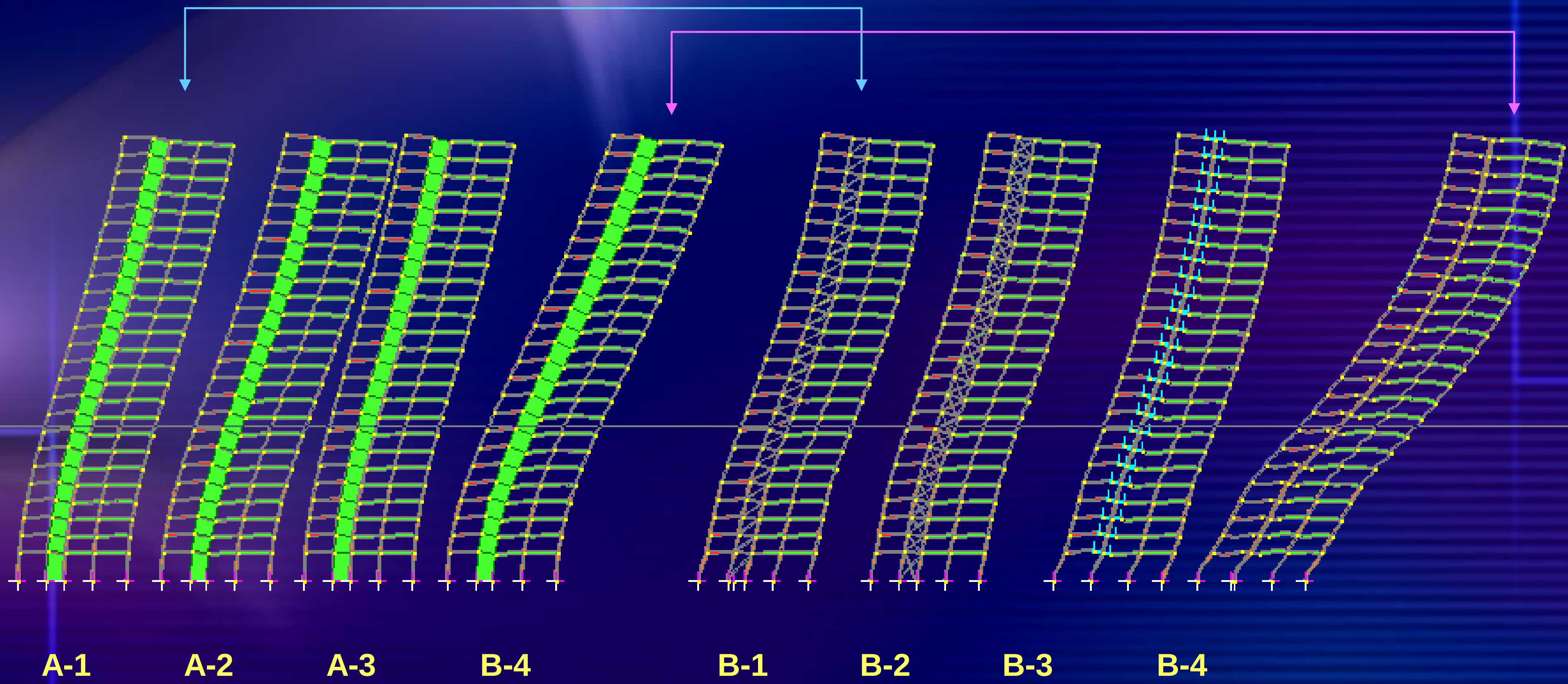
Shear Wall Behavior

Frame Behavior

Shear Wall and Frame Interaction



Frame and Frame-Shear Wall



Shear Wall and Frame Interaction

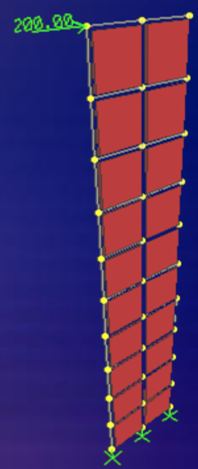
- **Frames Deform**
  - Predominantly in a shear mode
  - Source of lateral resistance is the rigidity of beam-column/slab joints

- **Shear Wall Deform**
  - Essentially in bending mode
  - Shear deformations are rarely significant
  - Only very low shear walls with H/W ratio <1 fail in shear
  - Behave mostly like a slender cantilever
  - Designed to resist the combined effect of axial, bending and shear

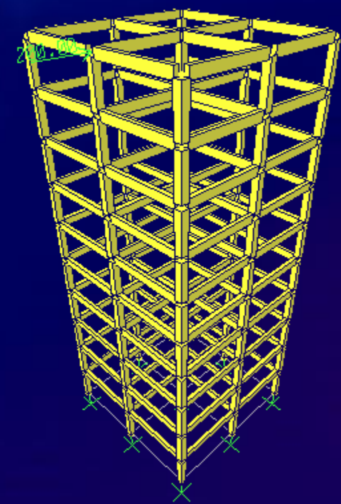
The Basic Behavior of Shear Walls, Frames and Shear Wall-Frames

Case Studies: Shear Wall–Frame Interaction

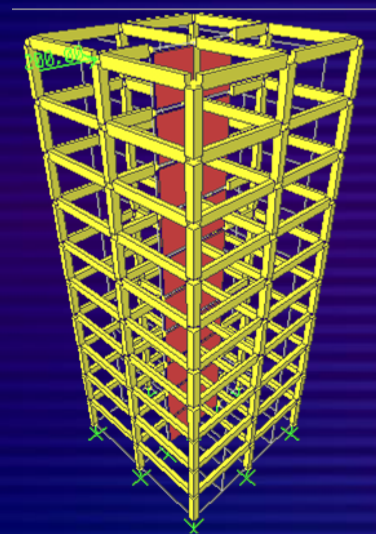
For each 10, 20 and 30 story buildings



Only Shear Wall
(Total 3 Cases)



Only Frame
(Total 3 Cases)

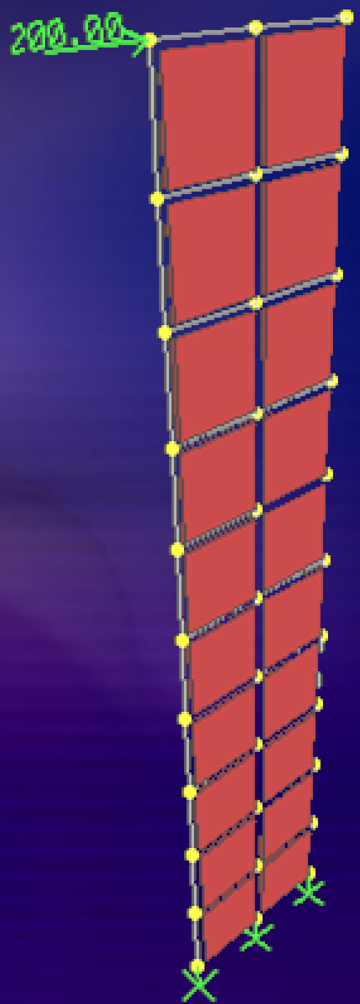


Only Shear + Frame
(Total 3 Cases)

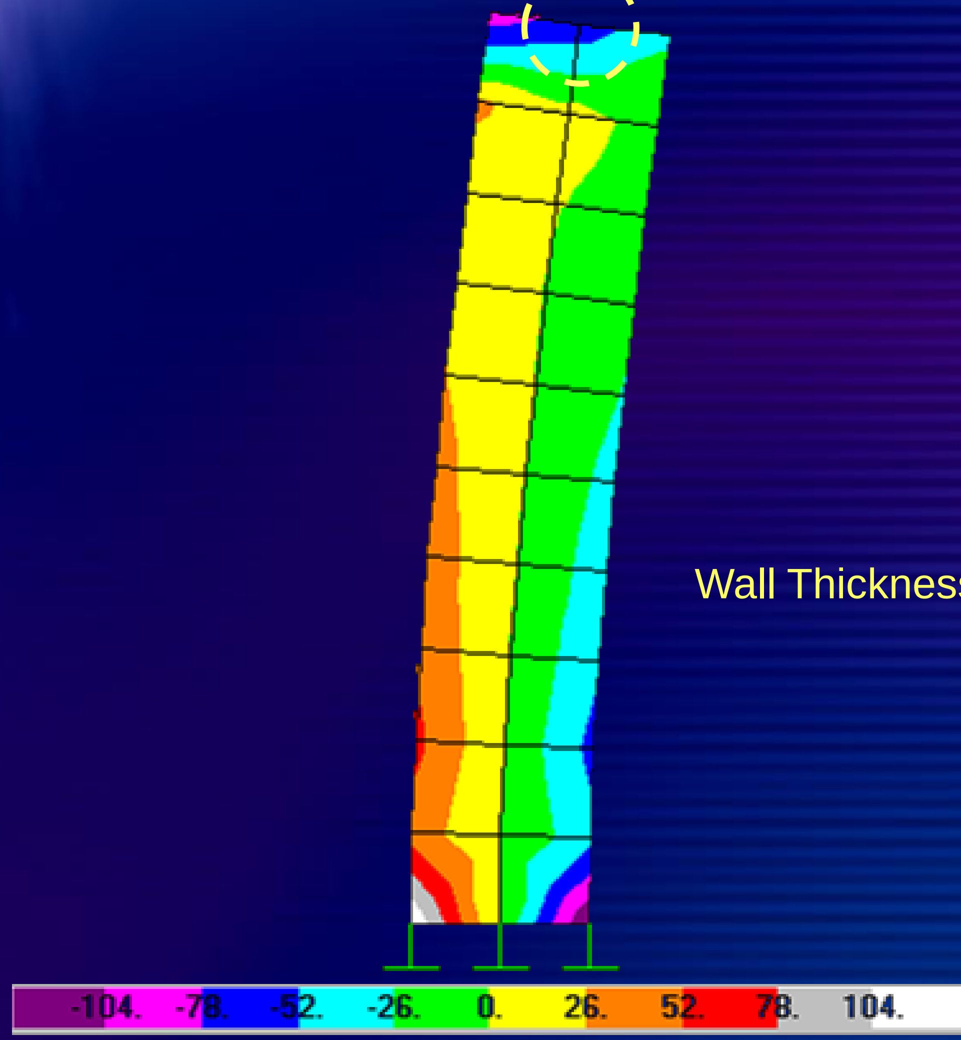
Total 3x3 = 9 Cases

Case 1: Shear Wall–Frame Interaction

10 Story Wall



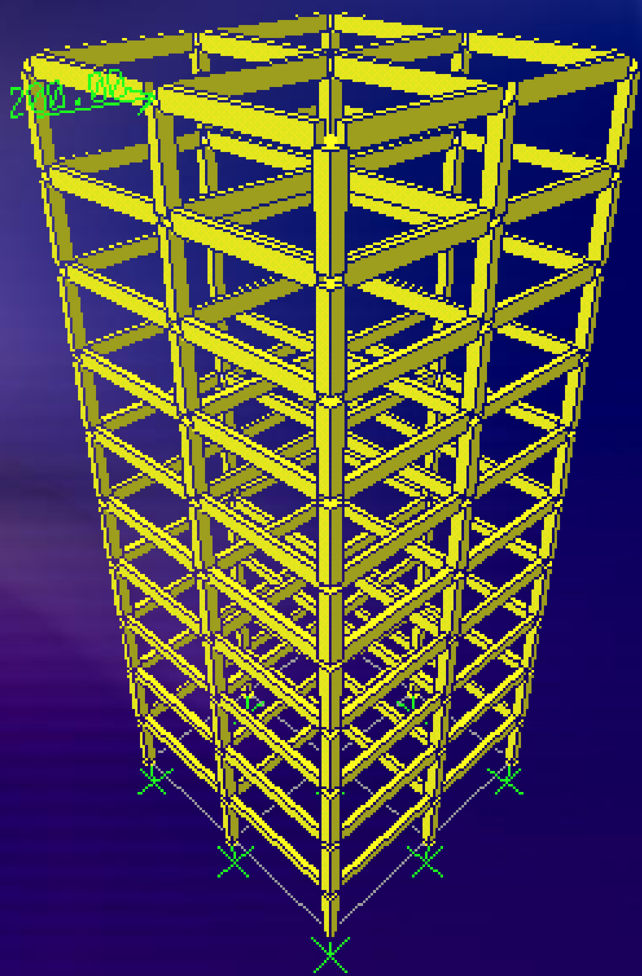
$\Delta = 26.73$ cm

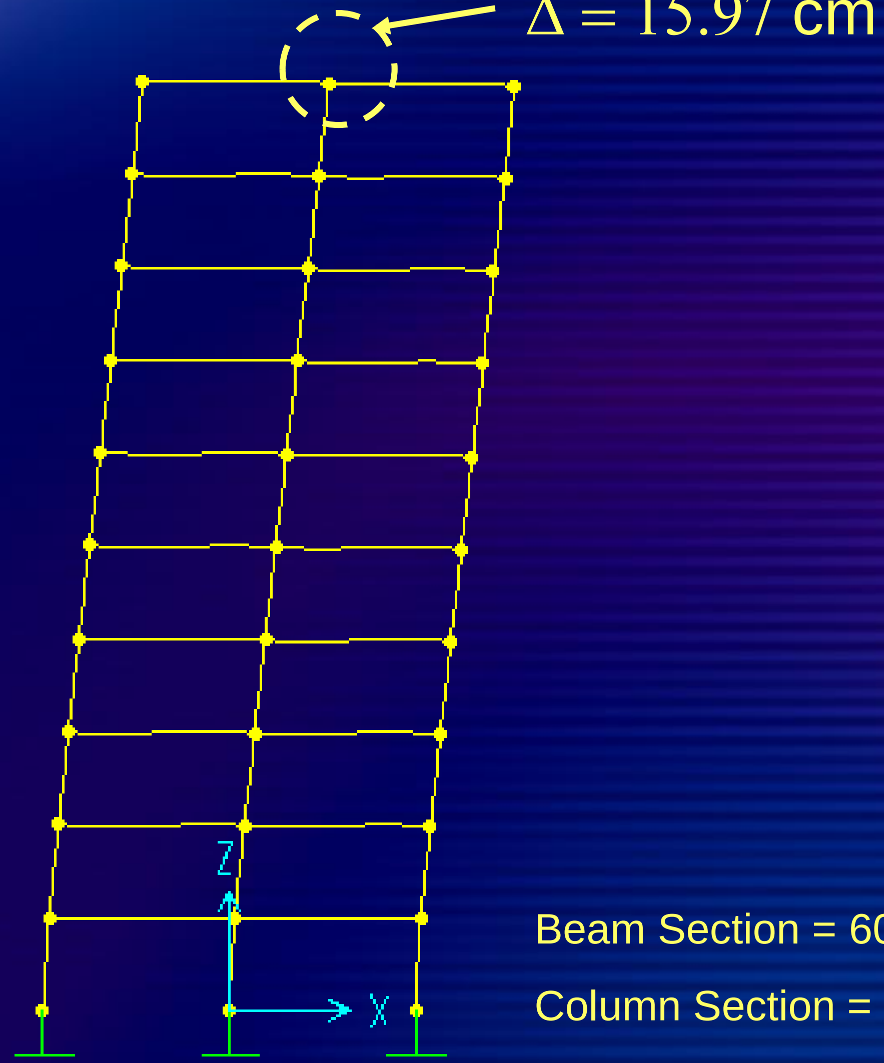


Wall Thickness = 15 cm

Case 2: Shear Wall–Frame Interaction

10 Story Frame



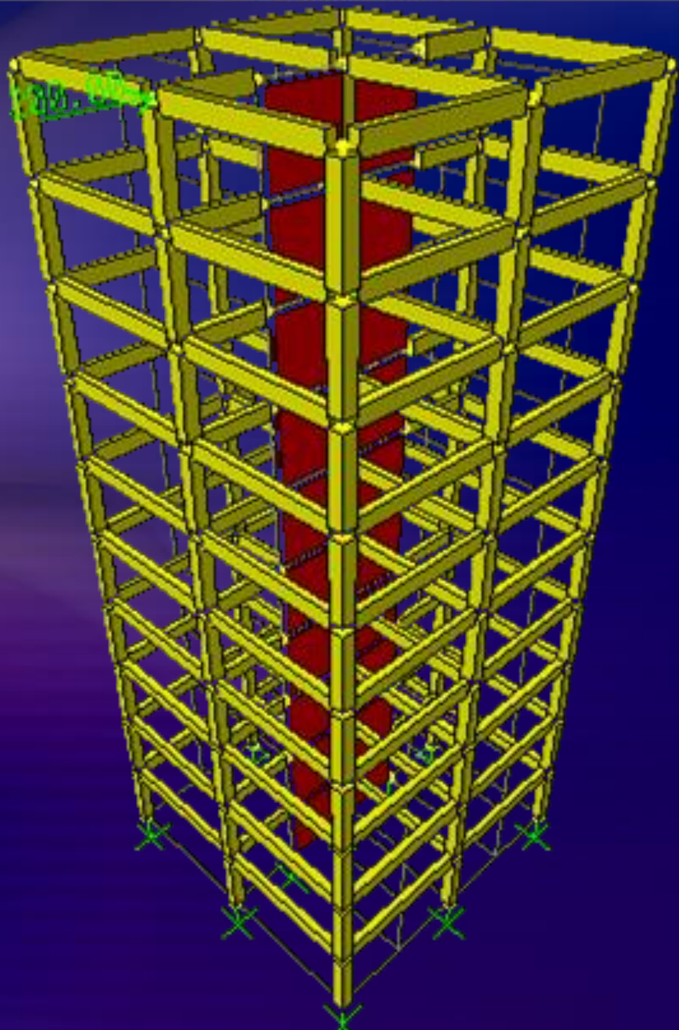


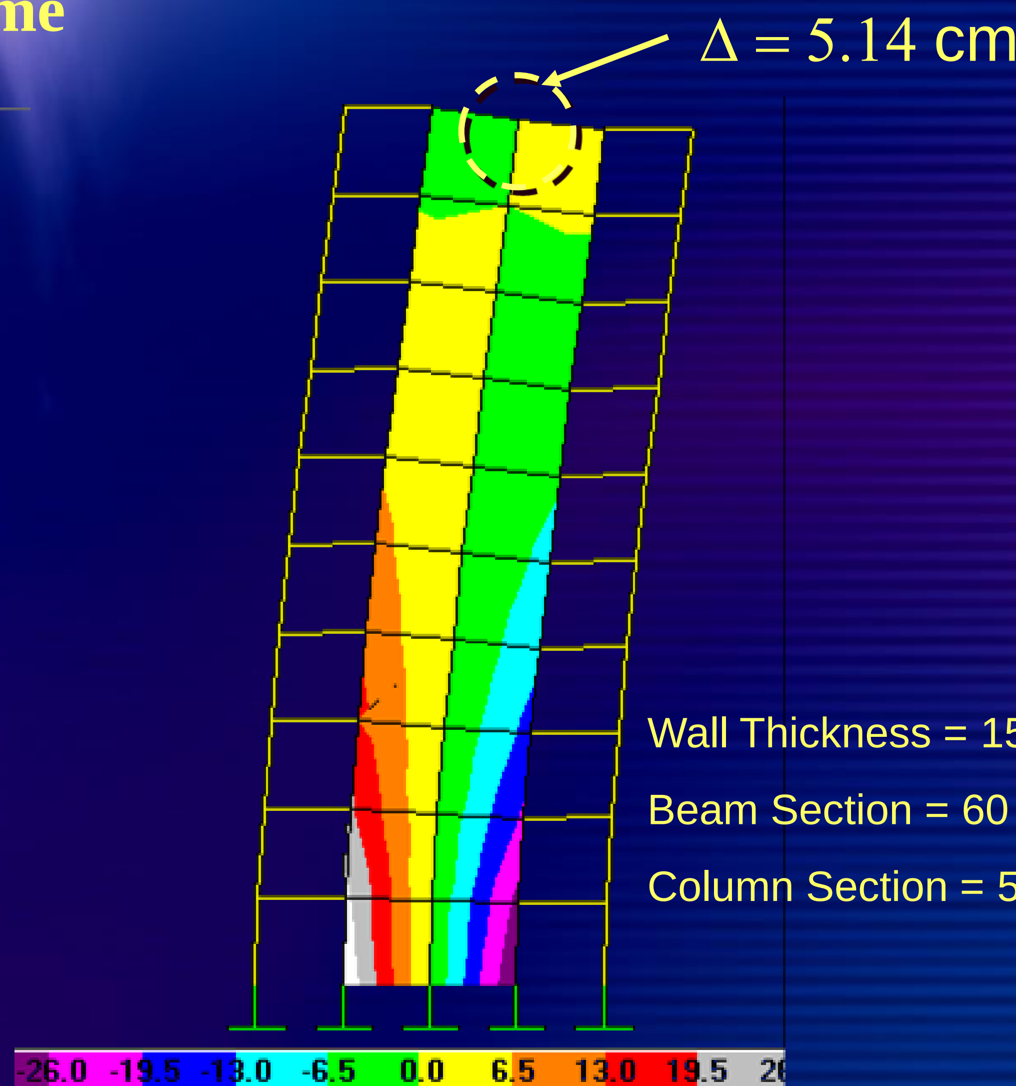
Beam Section = 60 cm x 30 cm

Column Section = 50 cm x 50 cm

Case 3: Shear Wall–Frame Interaction

10 Story Wall and Frame





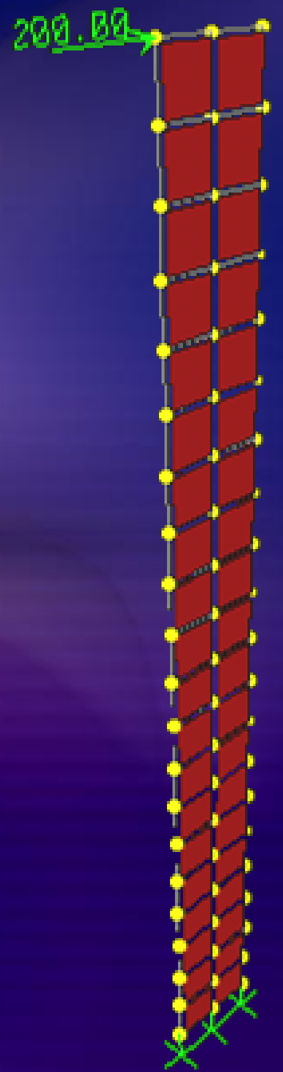
Wall Thickness = 15 cm

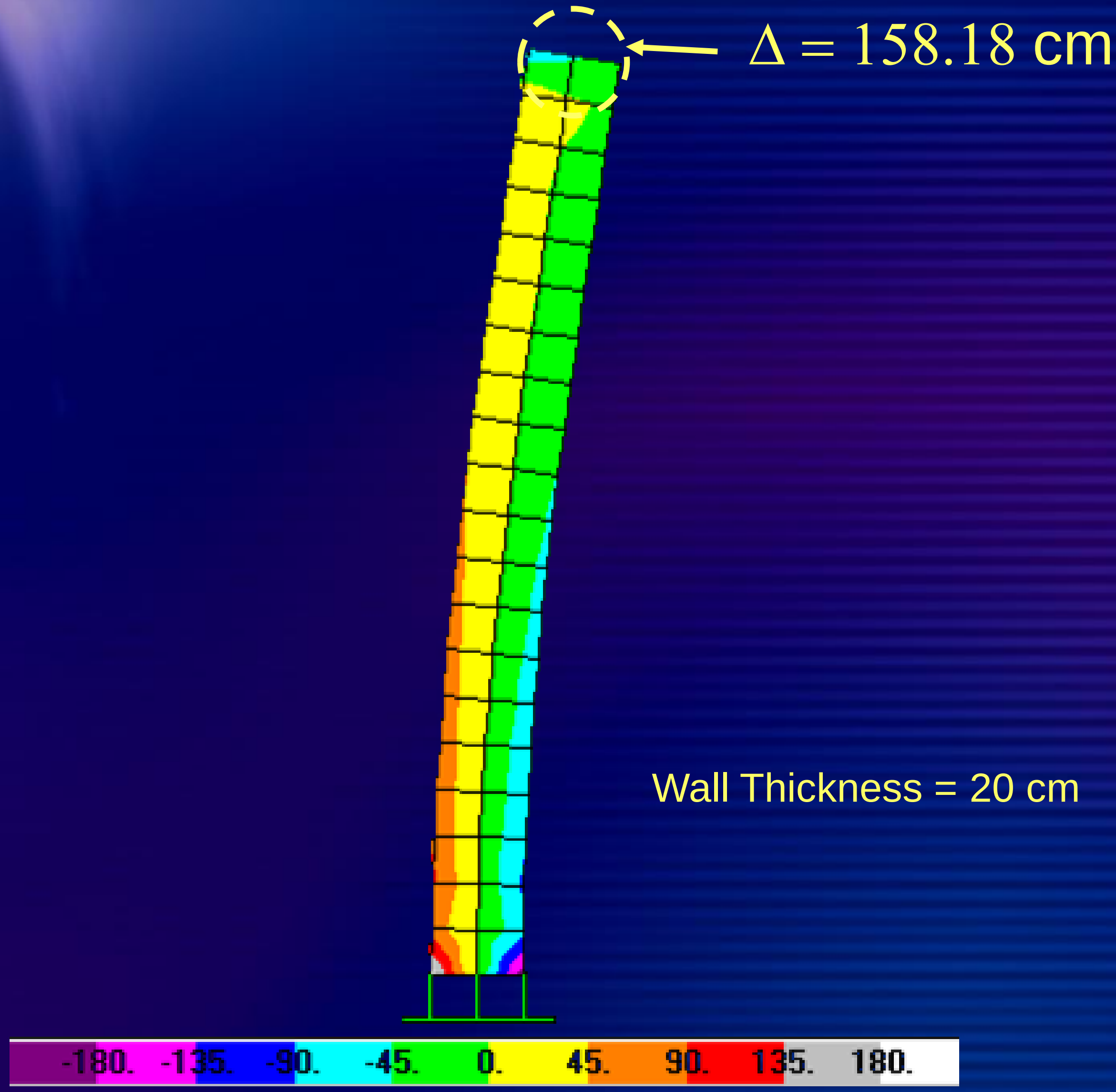
Beam Section = 60 cm x 30 cm

Column Section = 50 cm x 50 cm

Case 4: Shear Wall–Frame Interaction

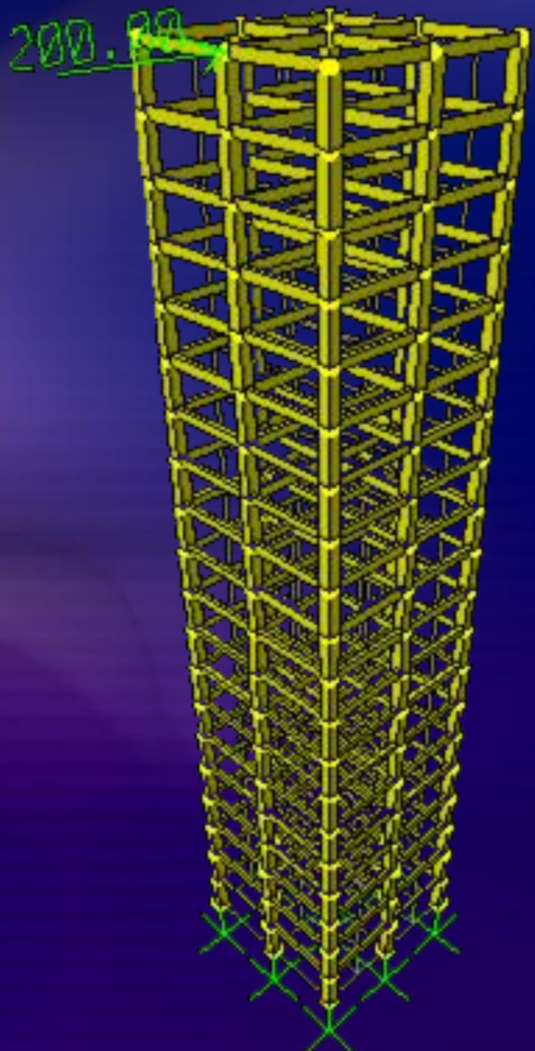
20 Story Wall



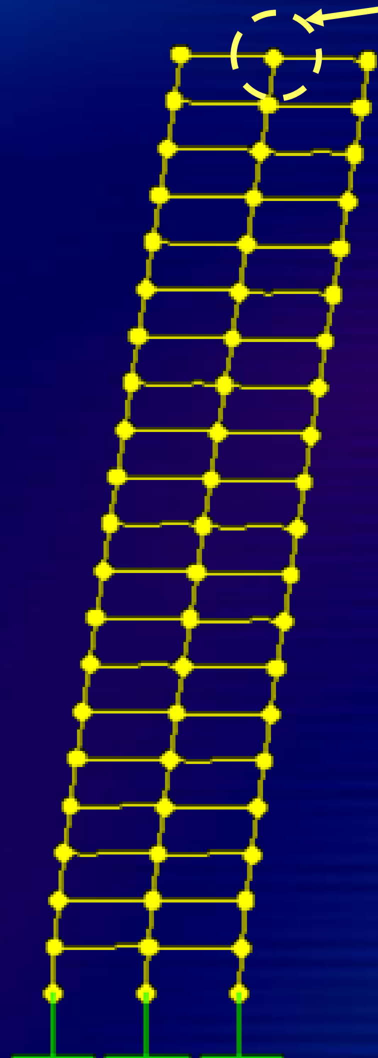


Case 5: Shear Wall–Frame Interaction

20 Story Frame



$\Delta = 27.35$ cm

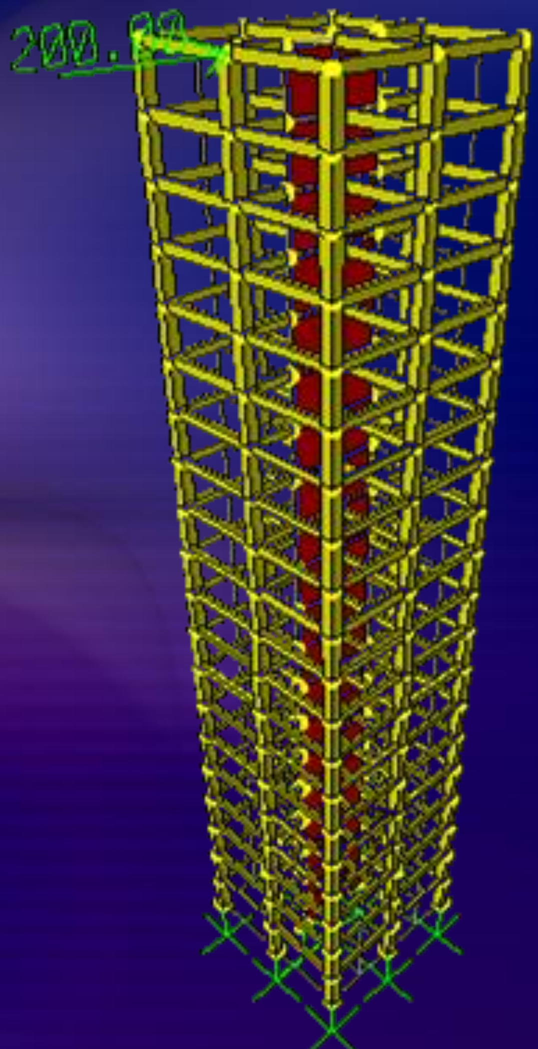


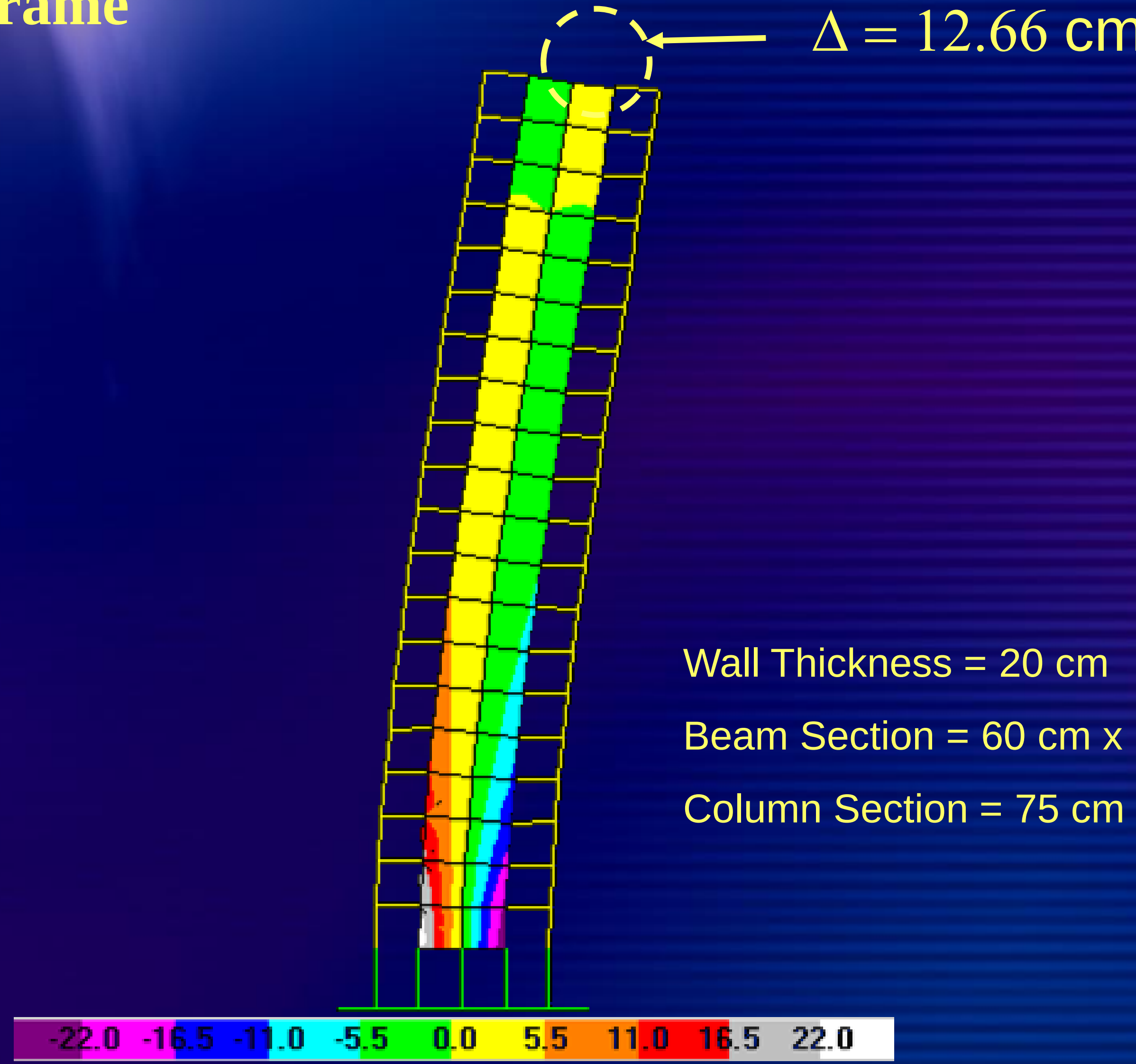
Beam Section = 60 cm x 30 cm

Column Section = 75 cm x 75 cm

Case 6: Shear Wall–Frame Interaction

20 Story Wall and Frame



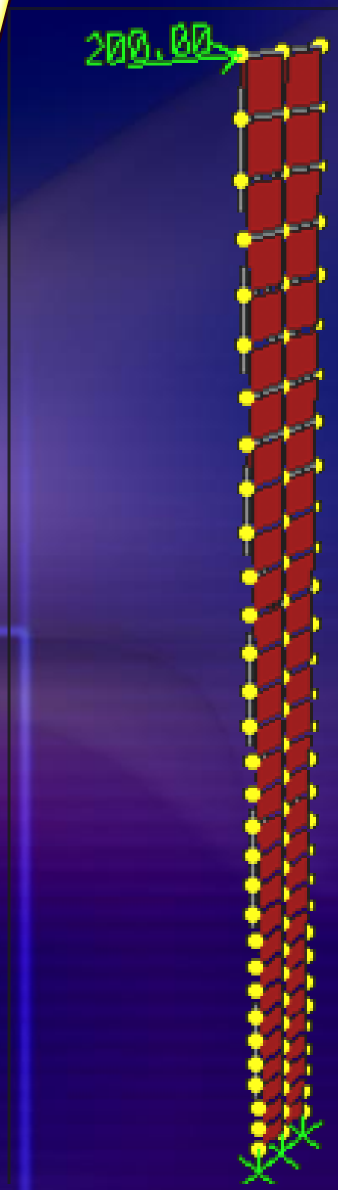


Wall Thickness = 20 cm

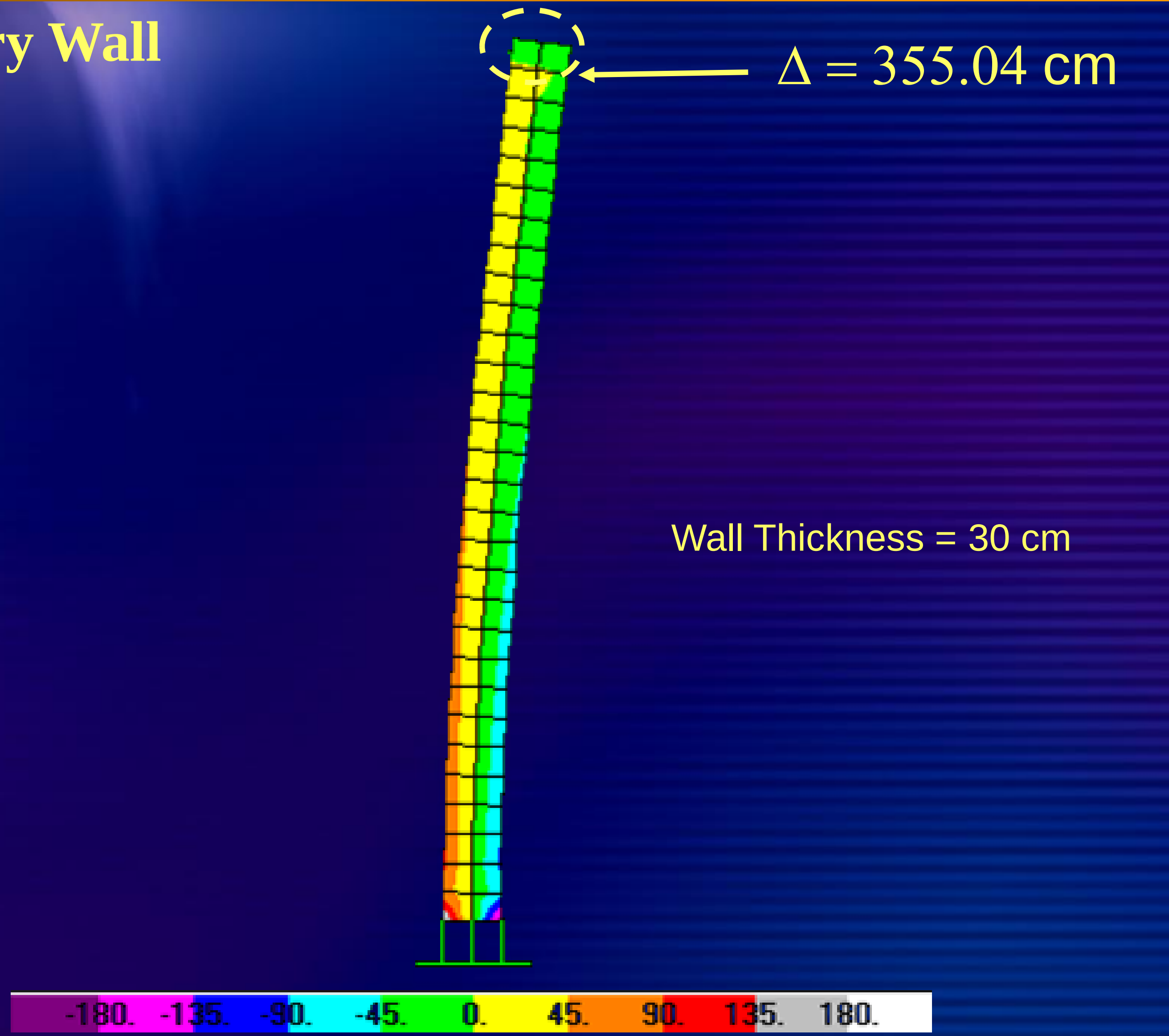
Beam Section = 60 cm x 30 cm

Column Section = 75 cm x 75 cm

Case 7: Shear Wall–Frame Interaction



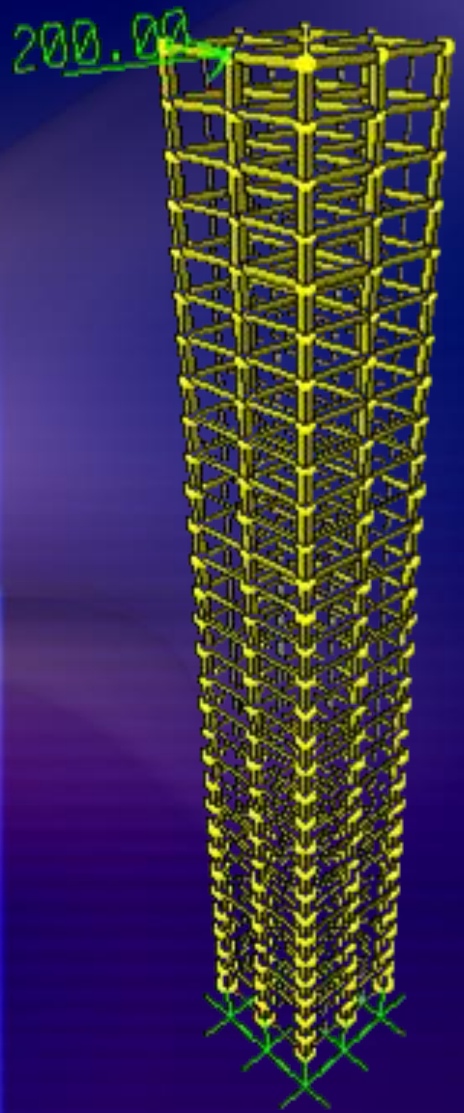
30 Story Wall

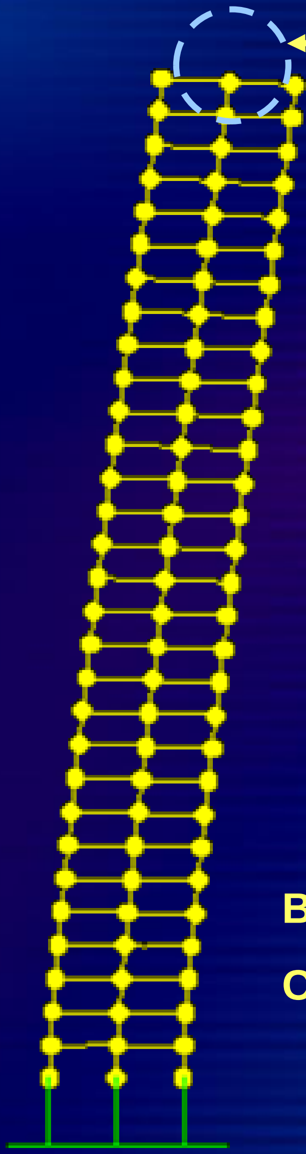


Wall Thickness = 30 cm

Case 8: Shear Wall–Frame Interaction

30 Story Frame





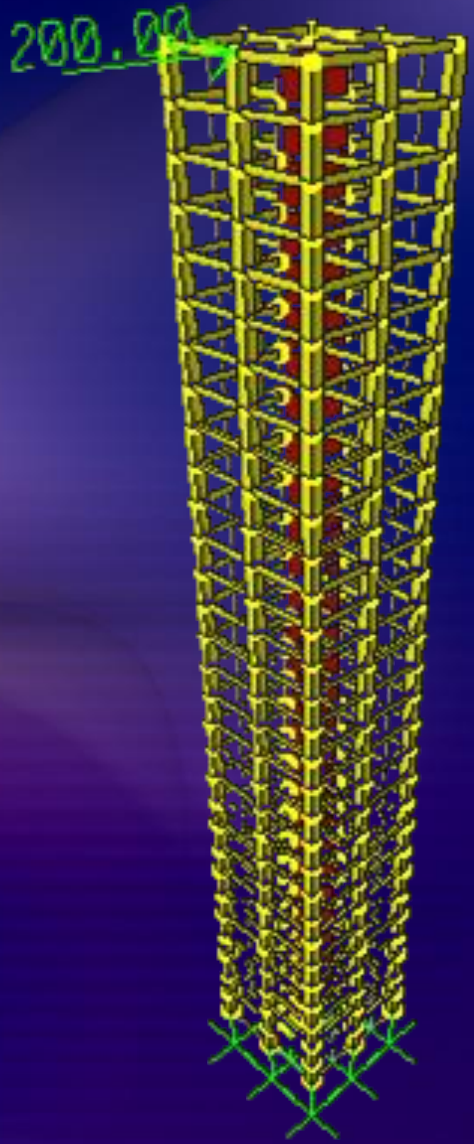
$\Delta = 40.79$ cm

Beam Section = 60 cm x 30 cm

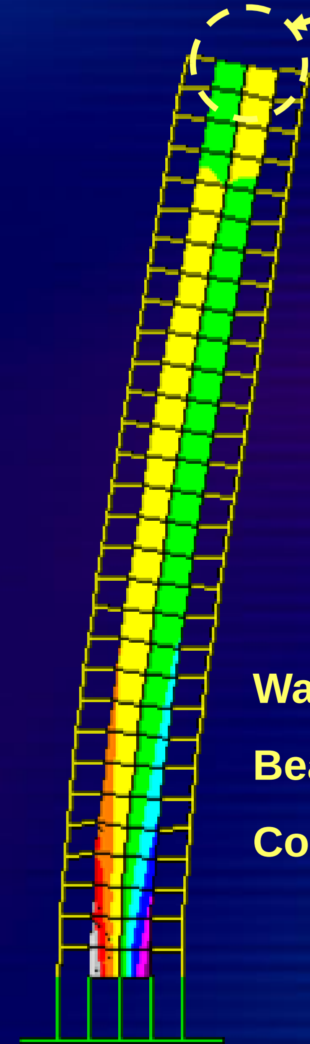
Column Section = 100 cm x 100 cm

Case 9: Shear Wall–Frame Interaction

30 Story Wall and Frame



Δ = 20.87 cm

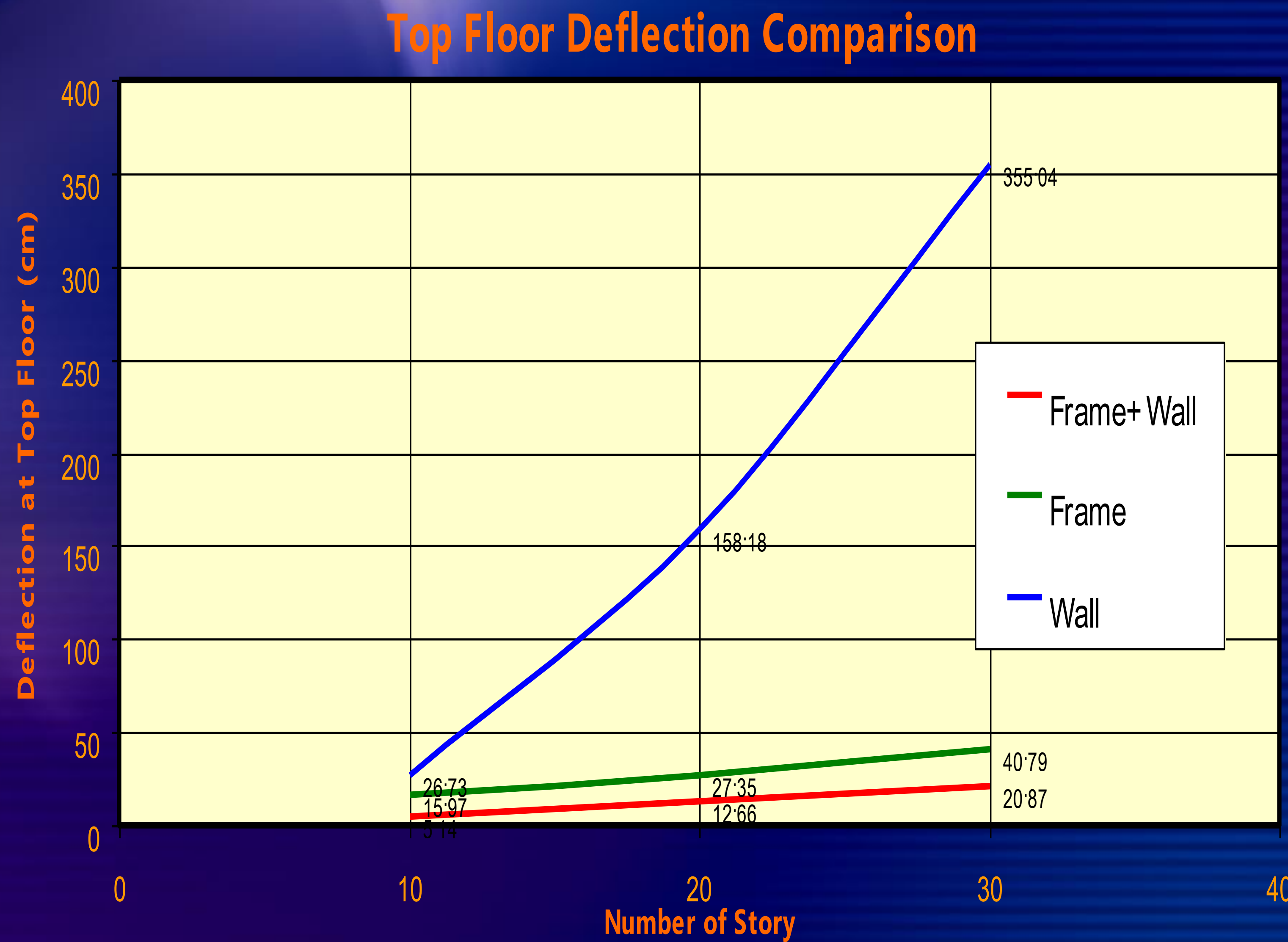


Wall Thickness = 30 cm

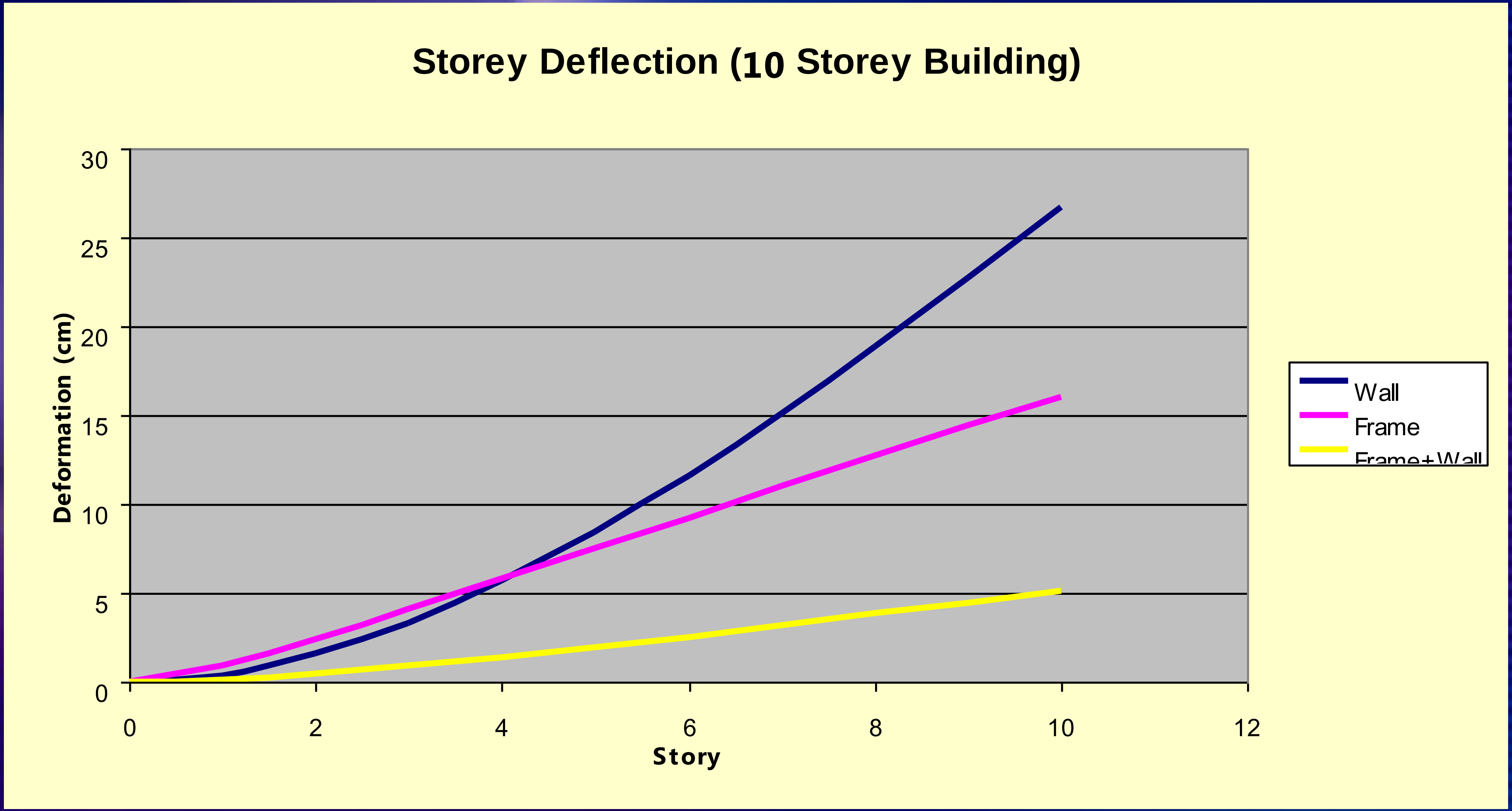
Beam Section = 60 cm x 30 cm

Column Section = 100 cm x 100 cm

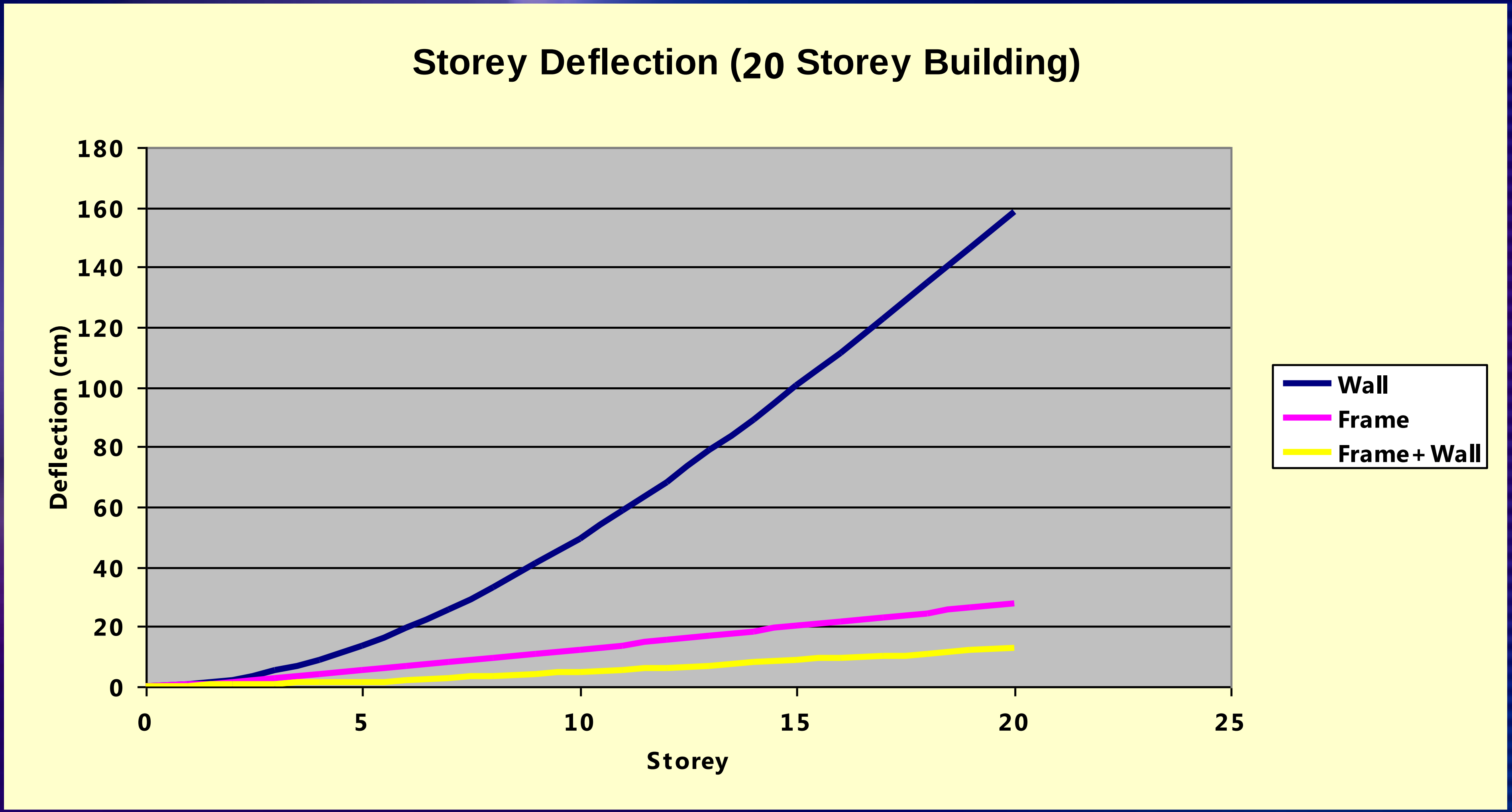
Shear Wall–Frame Interaction



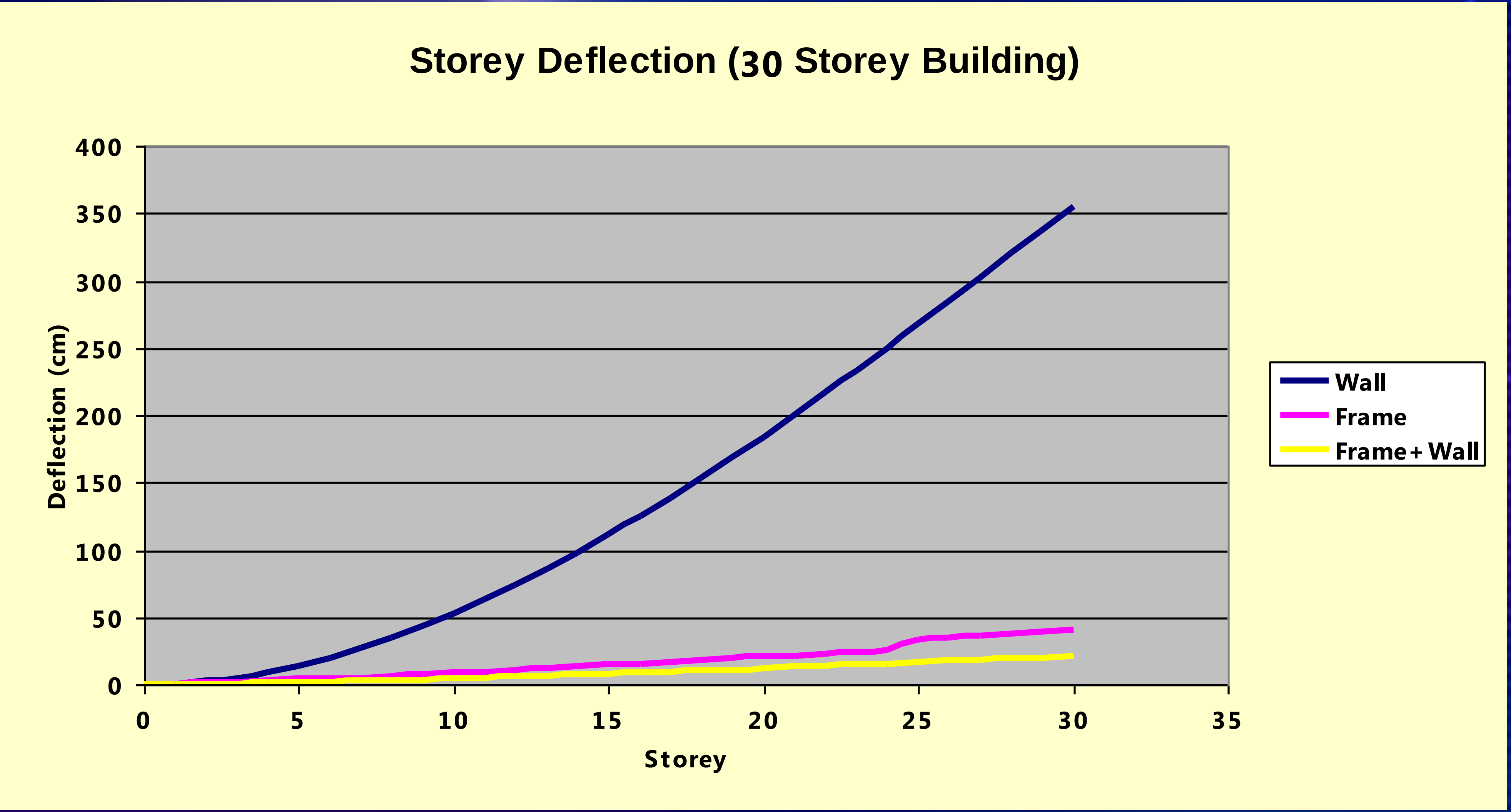
Shear Wall–Frame Interaction



Shear Wall–Frame Interaction



Shear Wall–Frame Interaction



Δ = Force / Stiffness $\longrightarrow$ Stiffness = Force / Δ

For the cases considered here (30 story example):

$$\text{Stiffness}_{\text{Frame}} = 200 / 40.79 = 04.90 \rightarrow$$ Force=200 Deflection = 40.79

$$\text{Stiffness}_{\text{Wall}} = 200 / 355.04 = 00.56$$

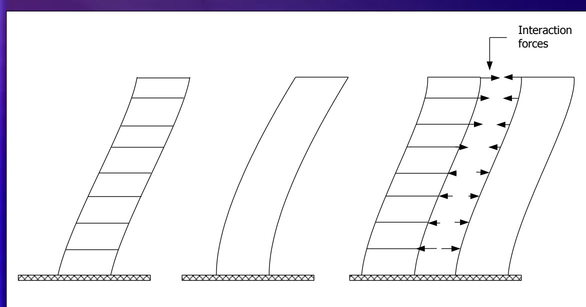
$$\text{Stiffness}_{\text{Frame + Wall}} = 200 / 12.66 = 15.79$$

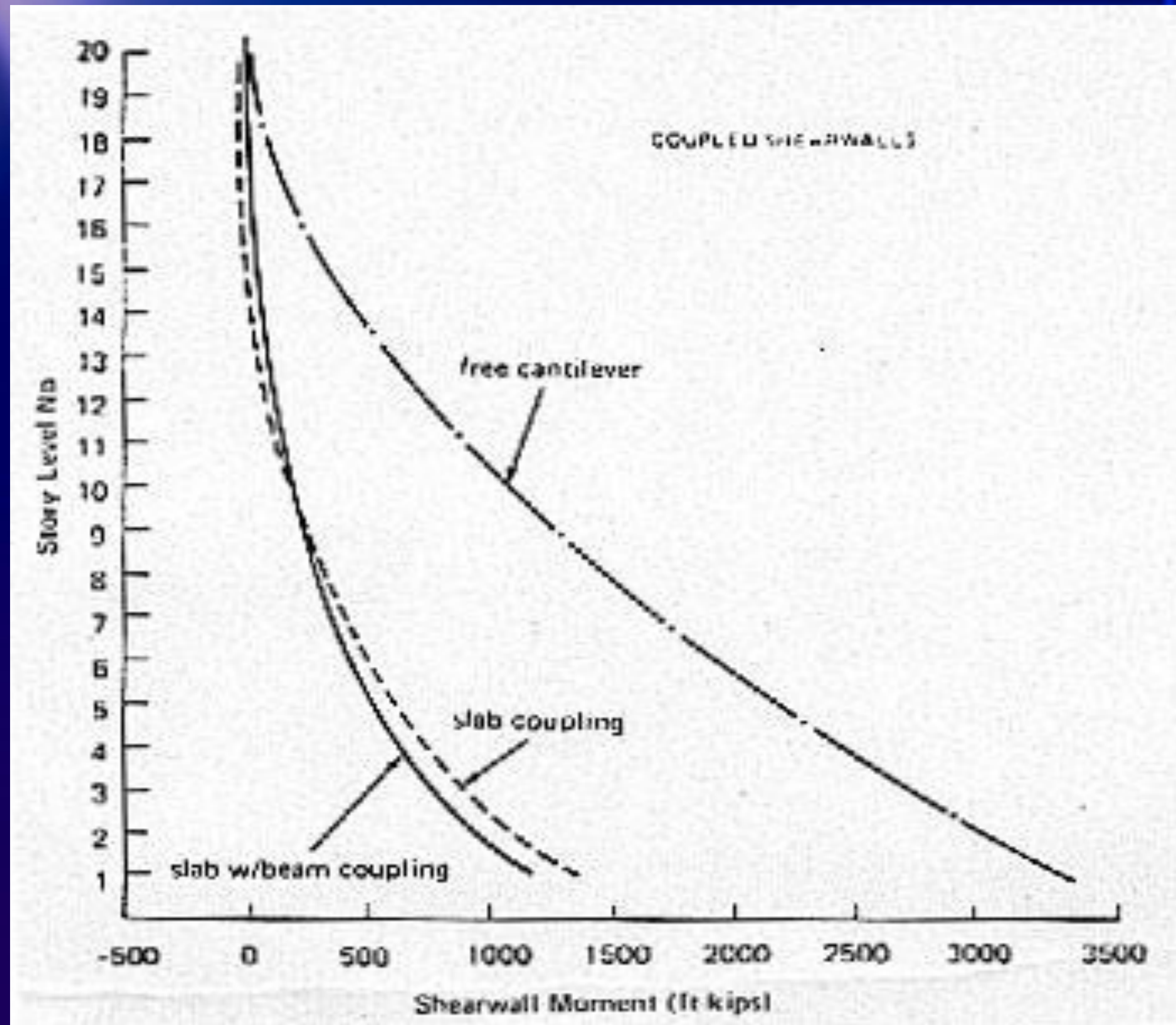
$$\text{Stiffness}_{\text{Frame}} + \text{Stiffness}_{\text{Wall}} = 4.90 + 0.56 = 5.46$$

$$\text{Stiffness}_{\text{Frame}} + \text{Stiffness}_{\text{Wall}} \neq \text{Stiffness}_{\text{Frame + Wall}}$$

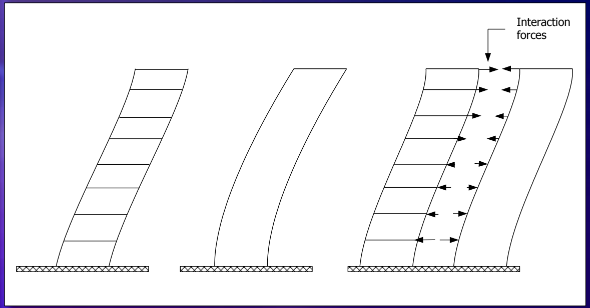
Change in Shear Wall Moments

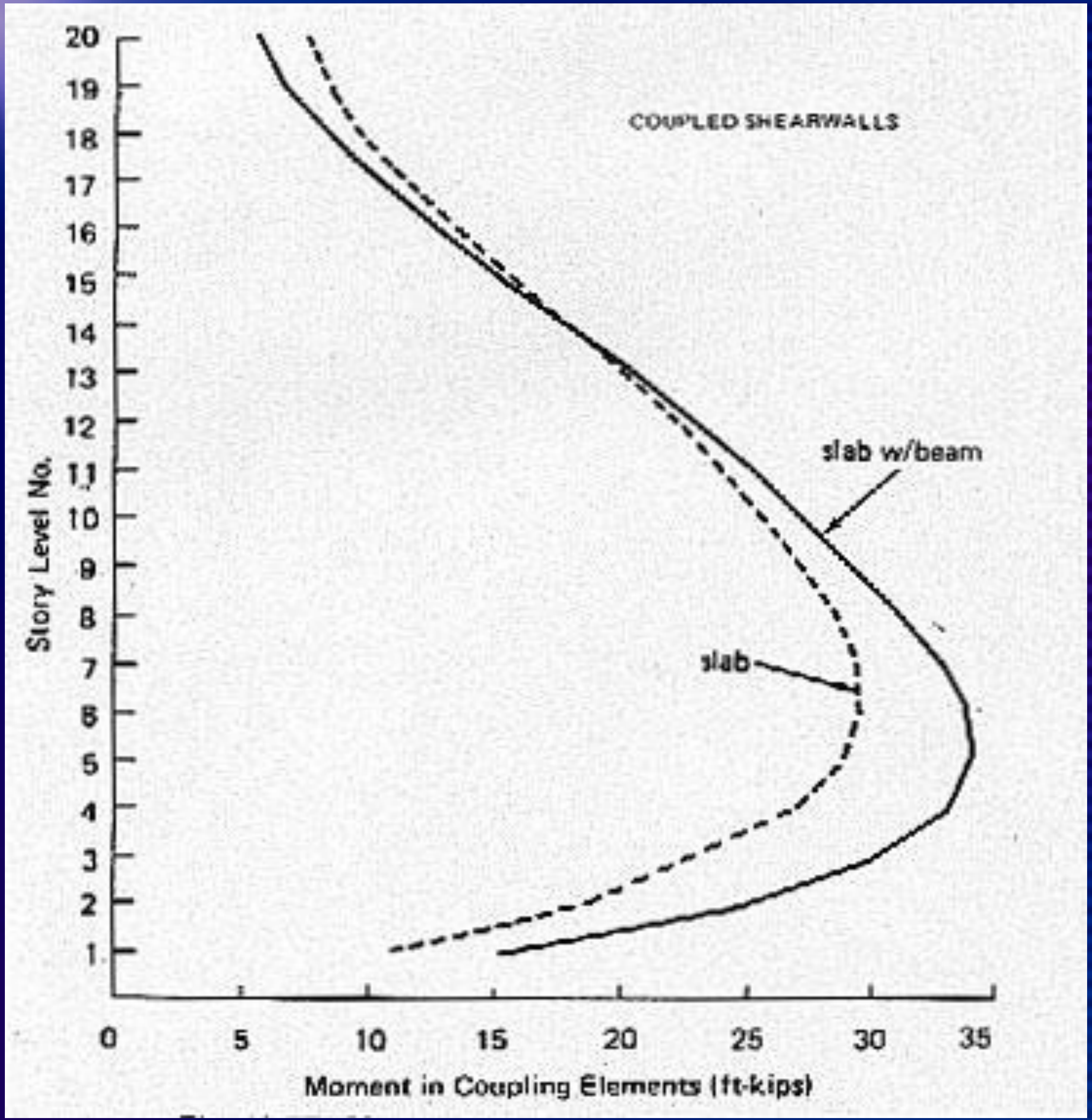
Shear Wall Moments
for the Coupled System



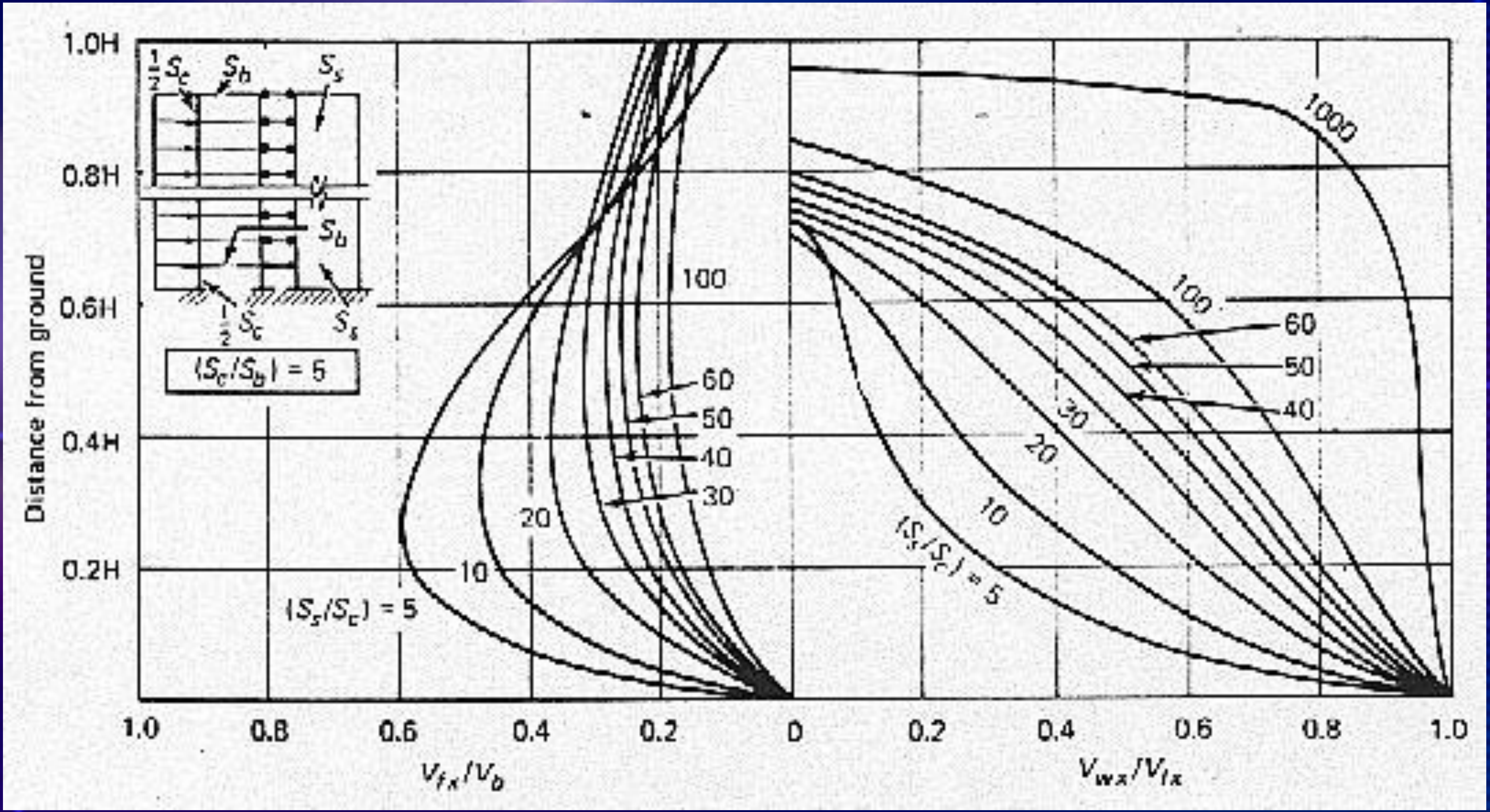


Coupling Element Moments

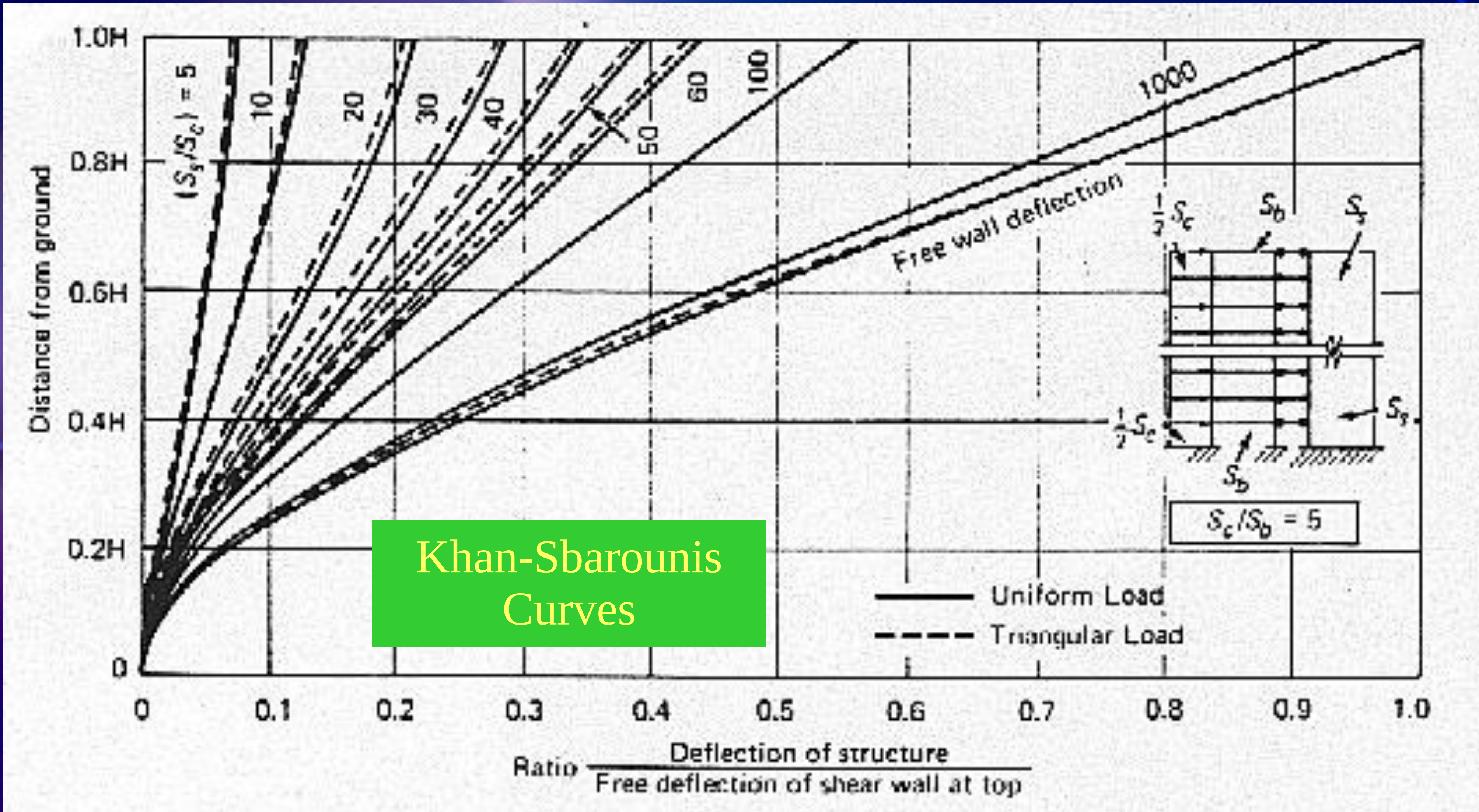




Shear Wall-Frame Load Distribution Curves

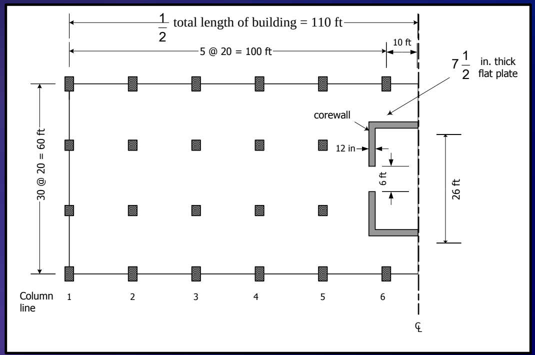


Deflected Shape of Shear Wall-Frame Interactive System

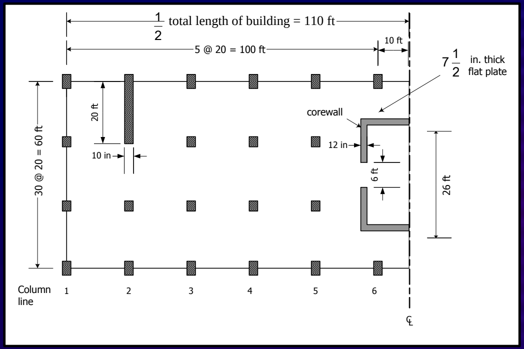


Comparison of Shears and Moments in the Core wall

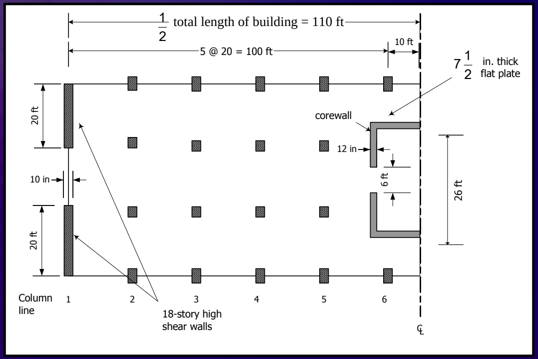
4 Different Layouts for Same Function Requirements



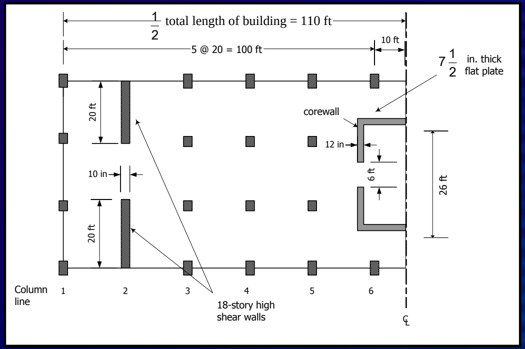
Type A



Type B

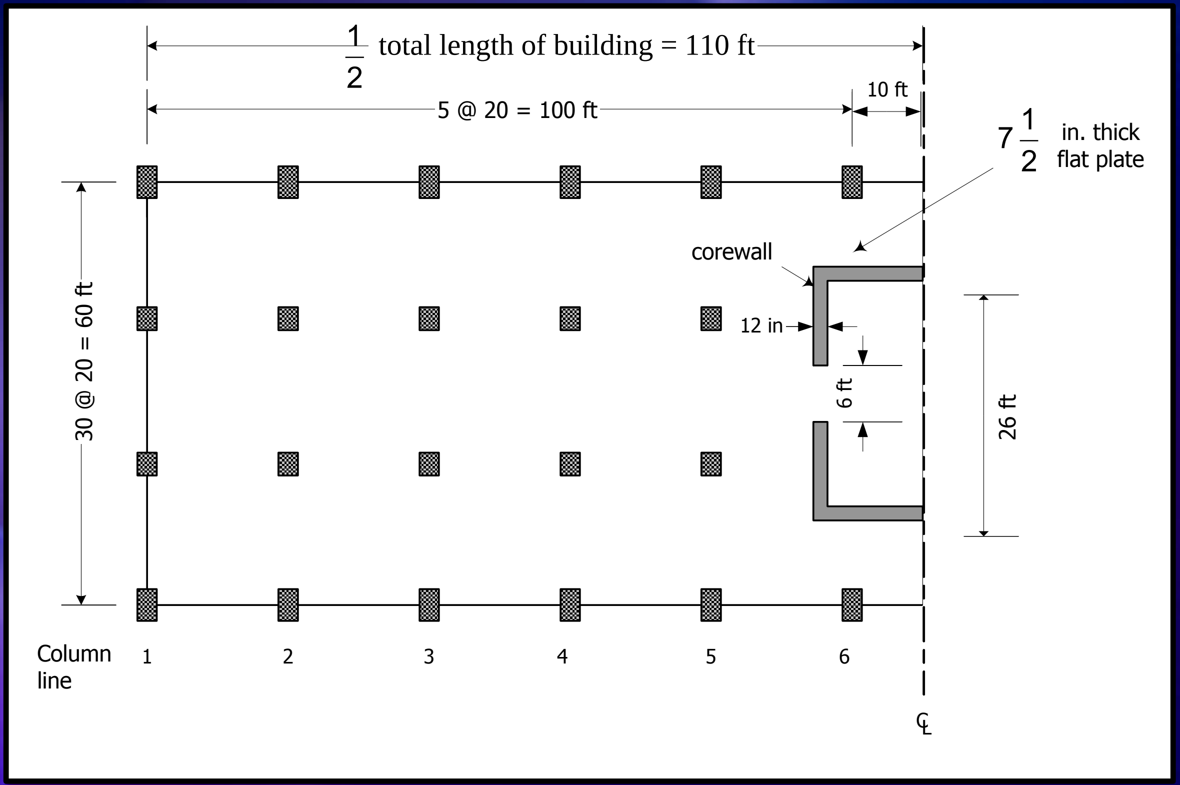


Type C

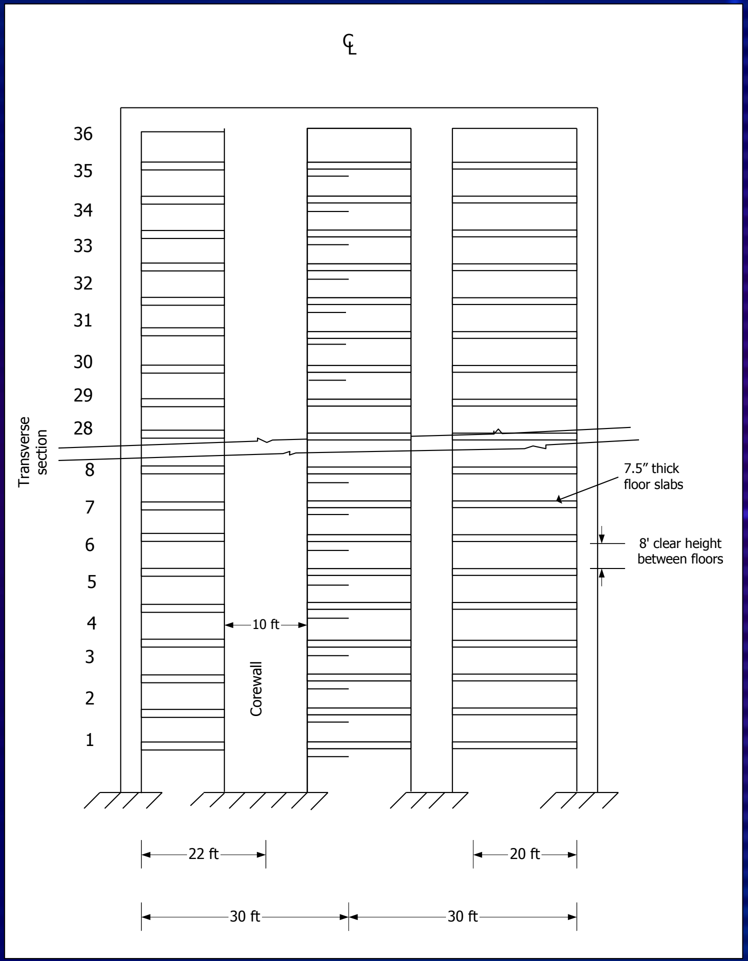


Type D

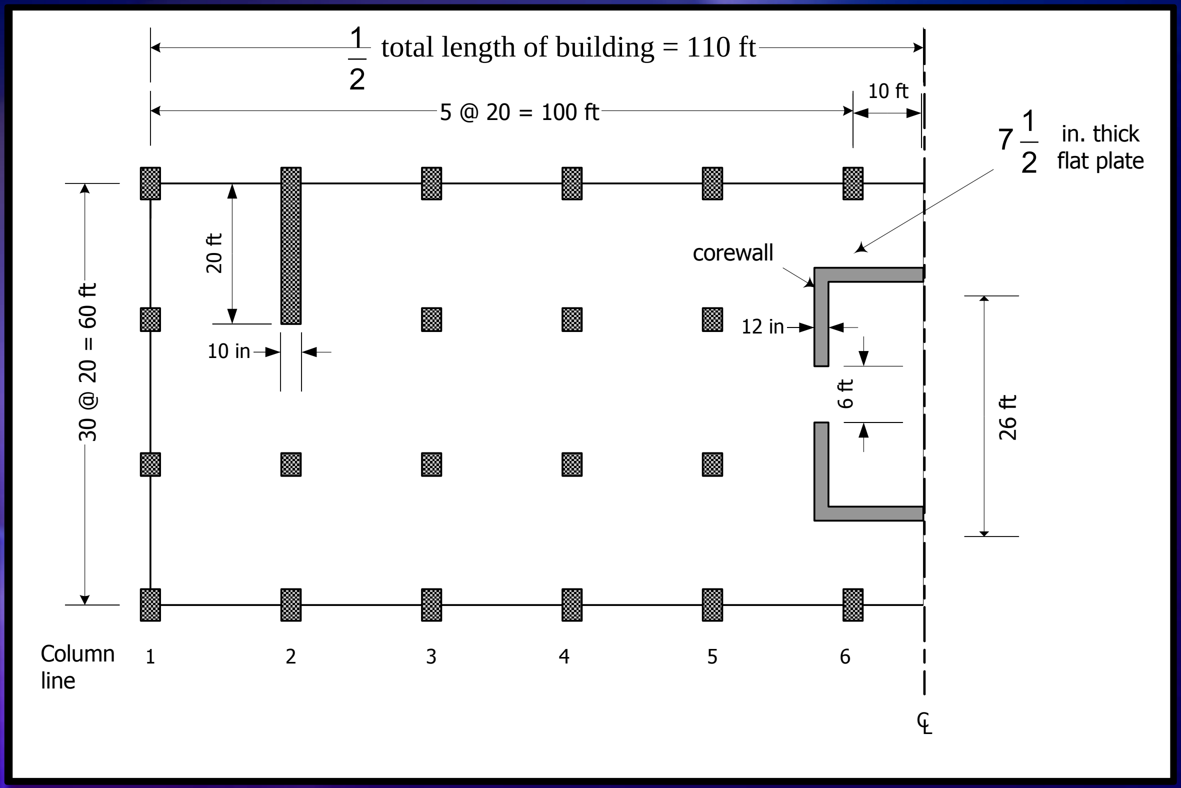
Comparison of… : Type A

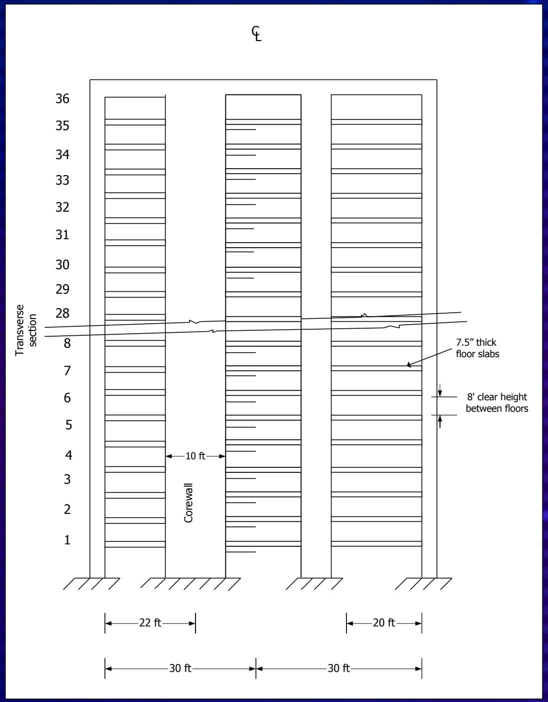


Typical Floor Plan- Structure Type A



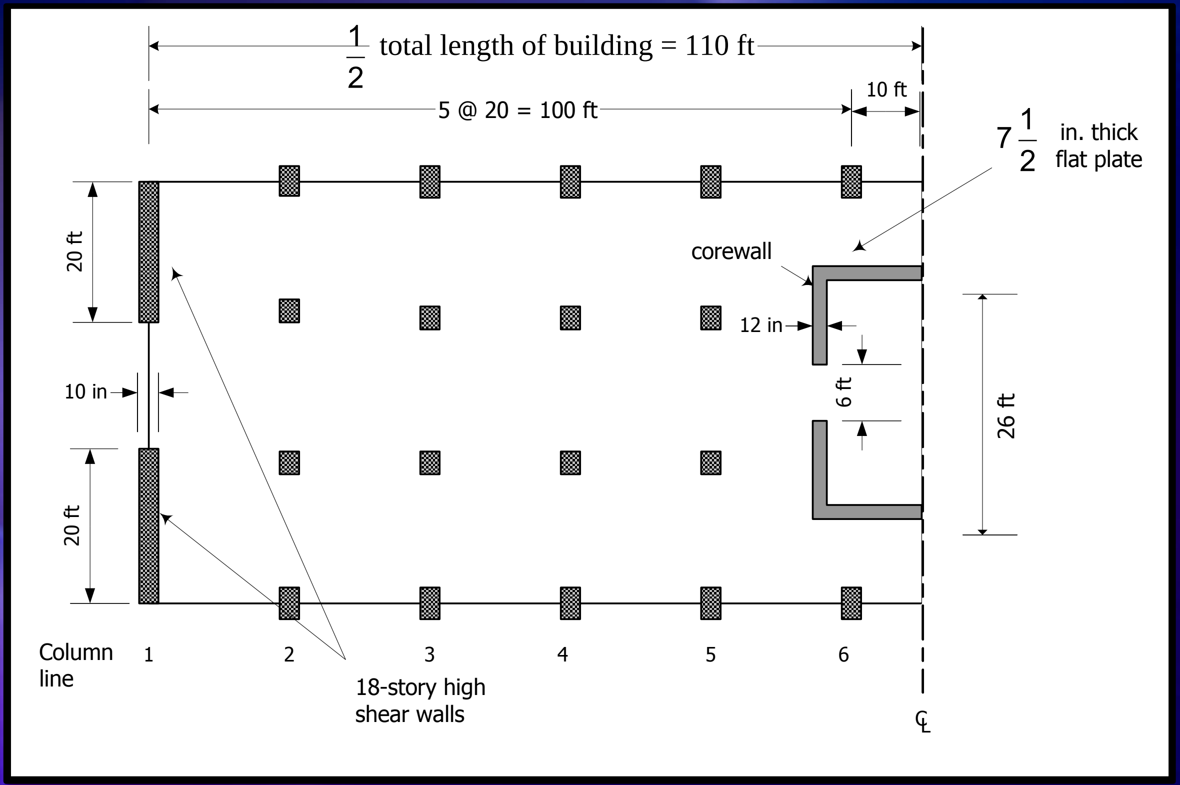
Comparison of… : Type B



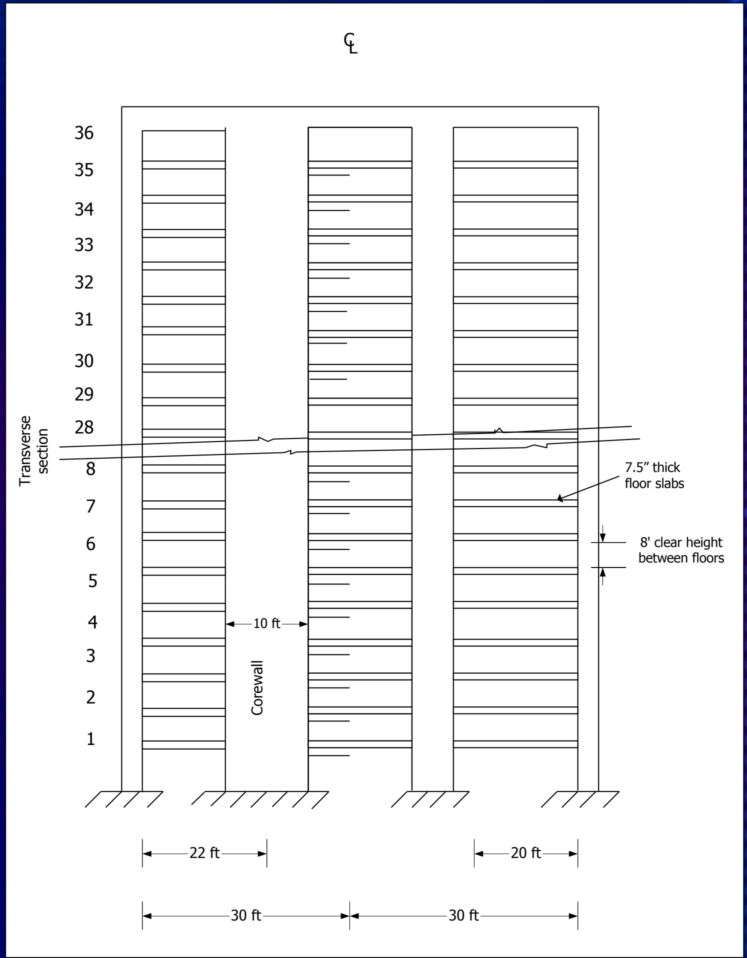


Typical Floor Plan- Structure Type B

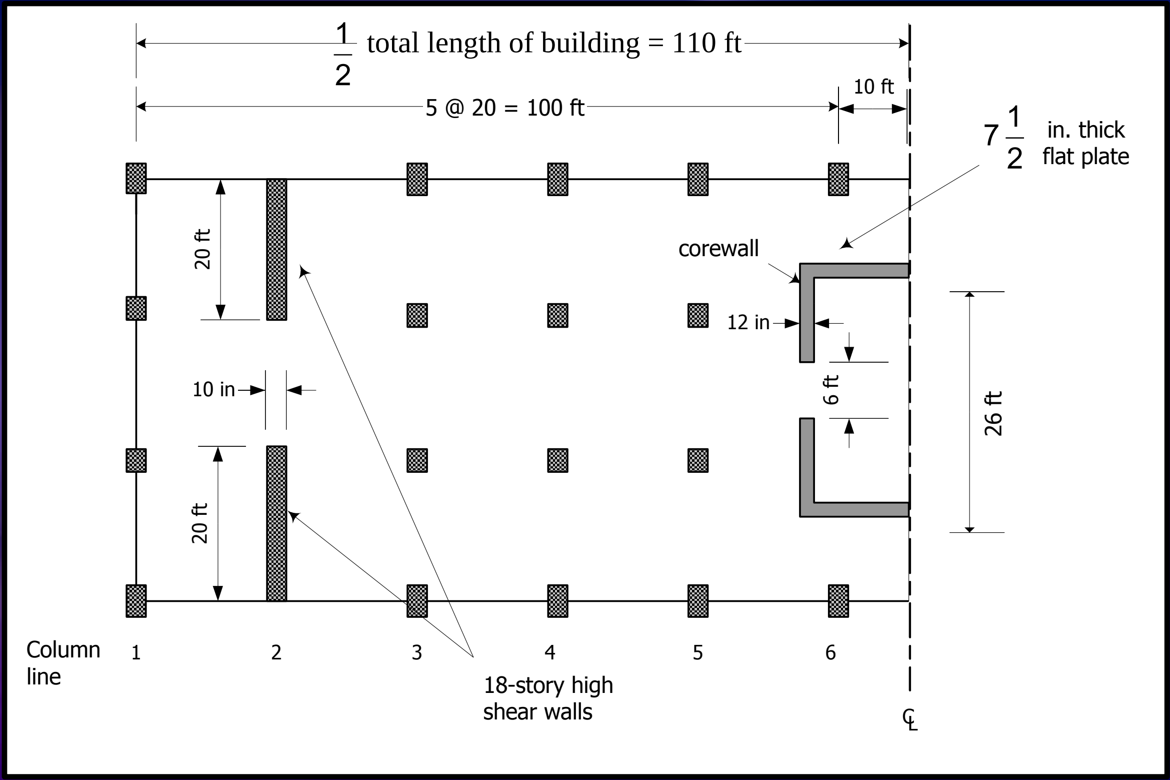
Comparison of… : Type C



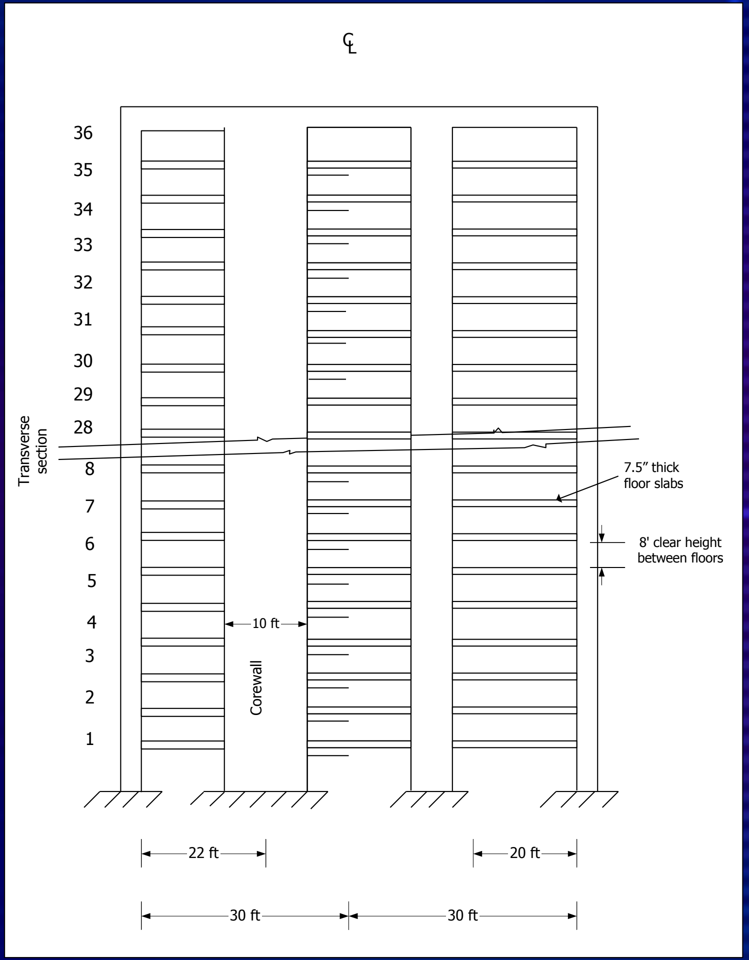
Typical Floor Plan- Structure Type C



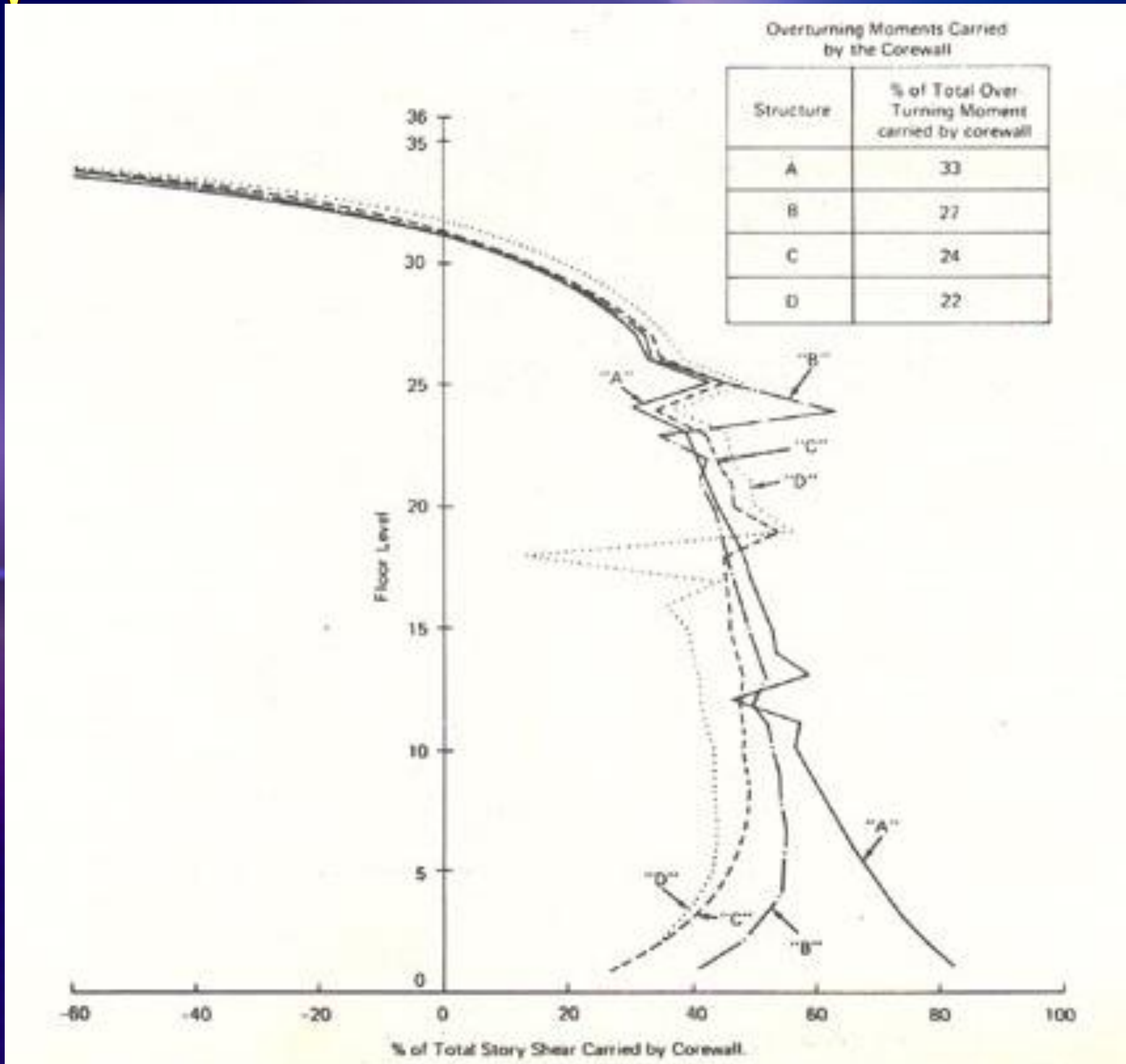
Comparison of… : Type D



Typical Floor Plan- Structure Type D



Comparison of Shears and Moments in the Core wall



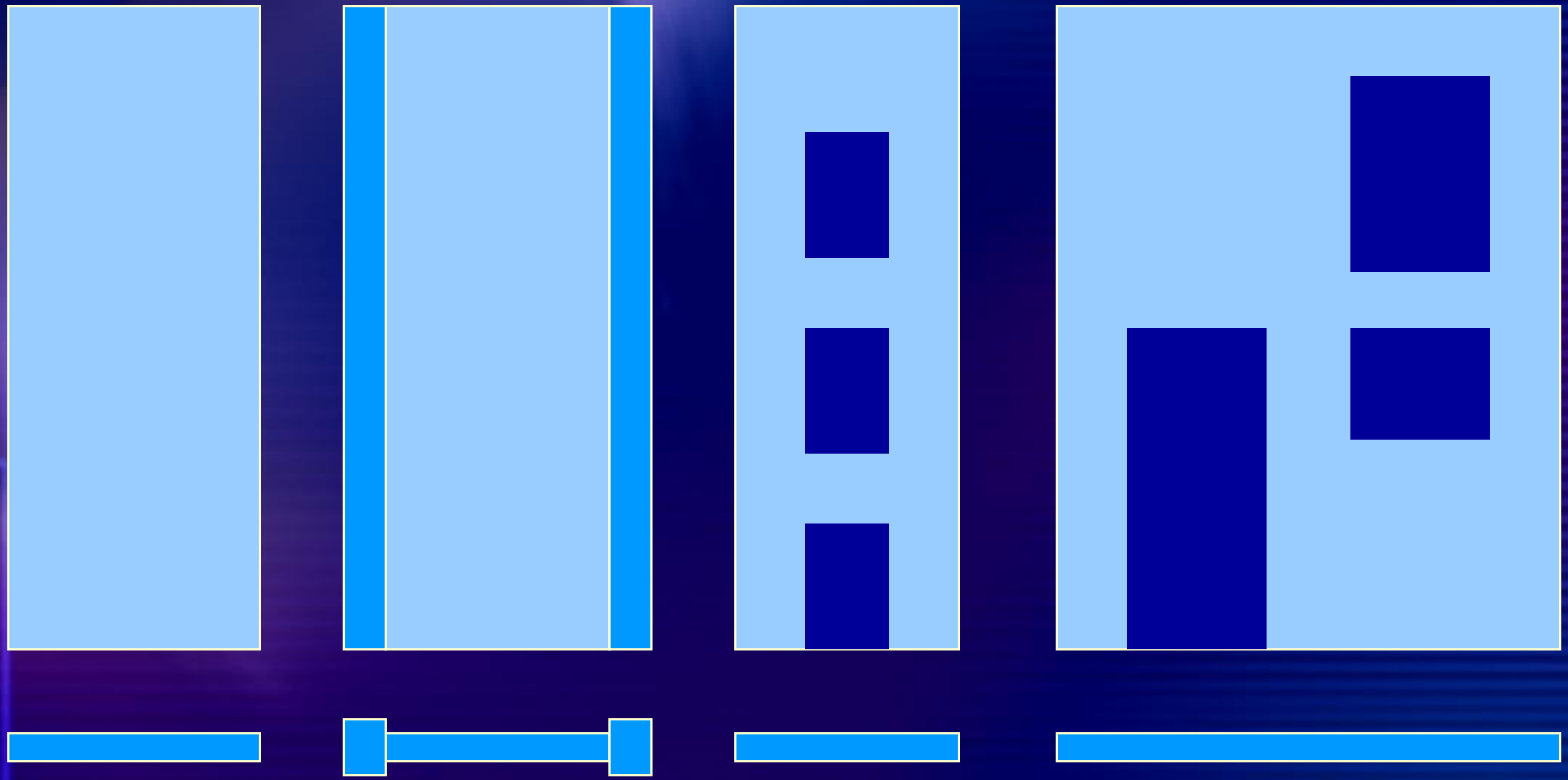
Overturning Moments Carried by the Corewall

Structure	% of Total Over Turning Moment carried by corewall
A	33
B	27
C	24
D	22

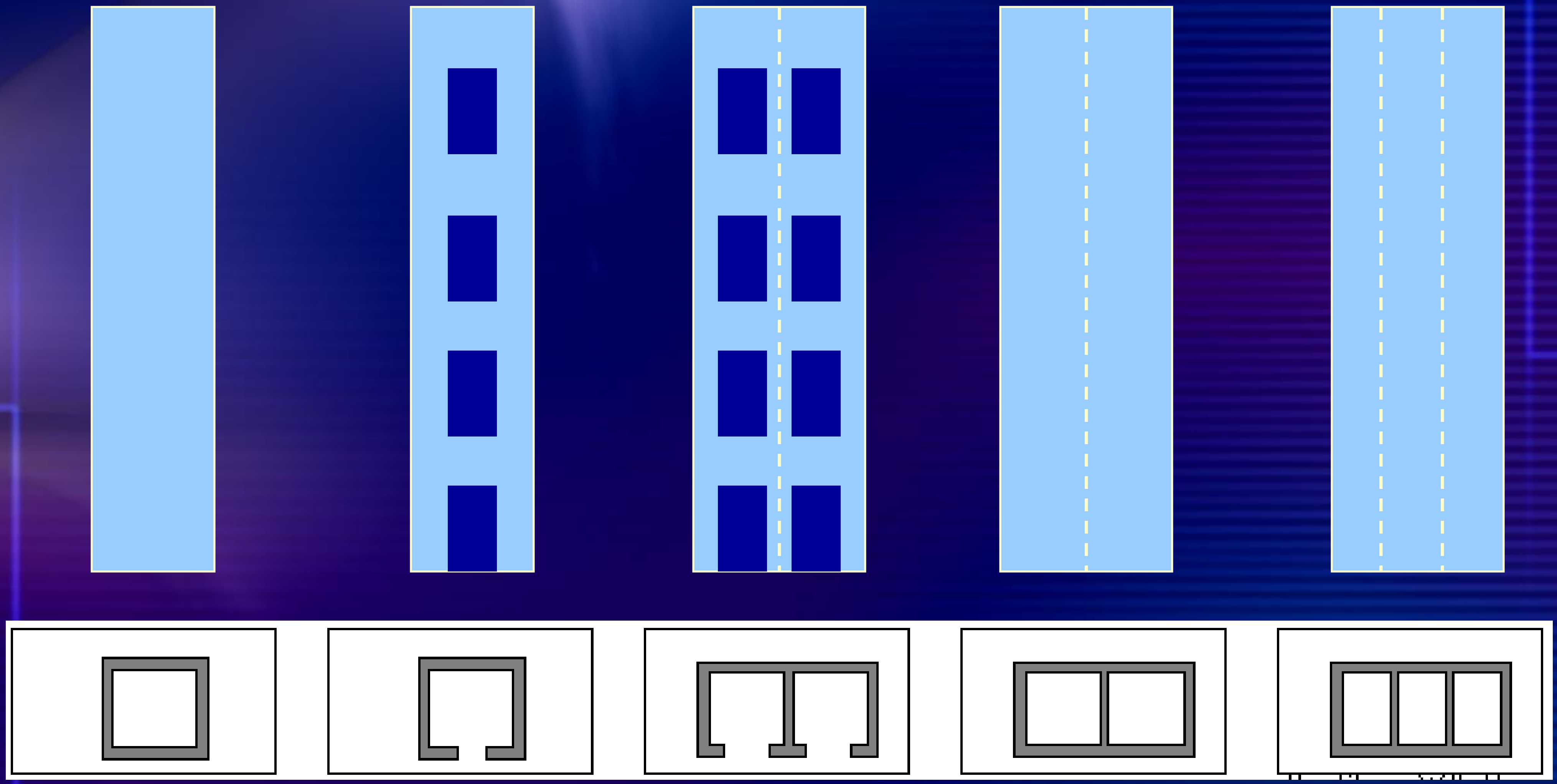
Wall-Frame Interaction: Key Conclusions

- The shear wall deform predominantly in bending mode
- The common assumptions to neglect the frames in lateral load resistance can lead to grossly erroneous results
- Consideration of shear wall-frame interaction leads to a more economic design
- The shear walls should be designed to resist the combined effect of axial, bending and shear
- Layout of the shear walls in plan in very important, both for vertical as well as gravity load

Basic Types of Shear Walls

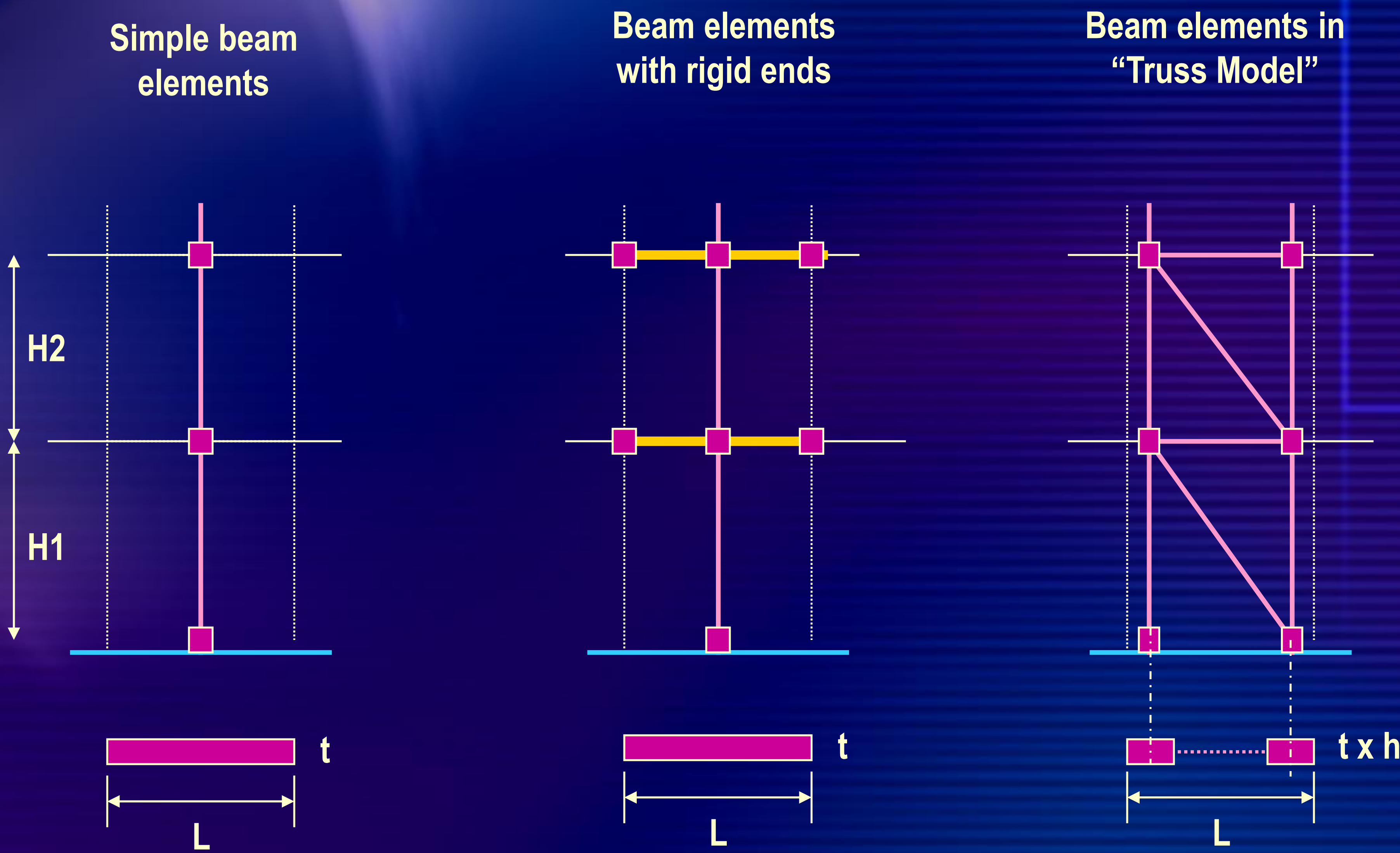


Basic Types of Shear Walls

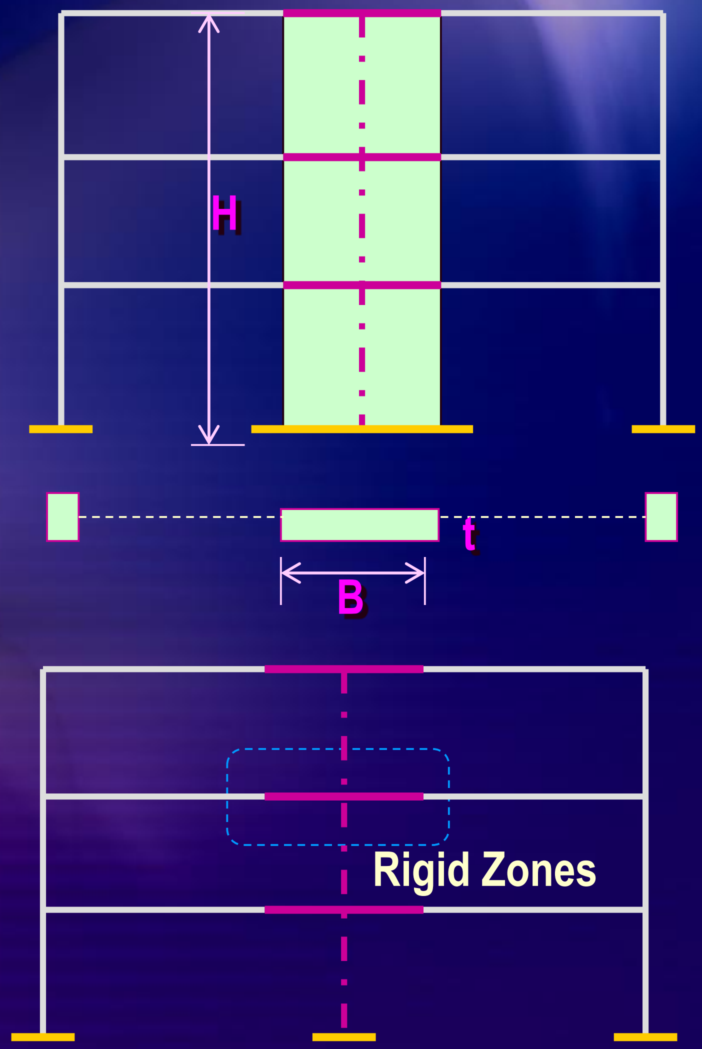


Basic Modeling Options for Shear Walls

Modeling of Walls using 1D Elements

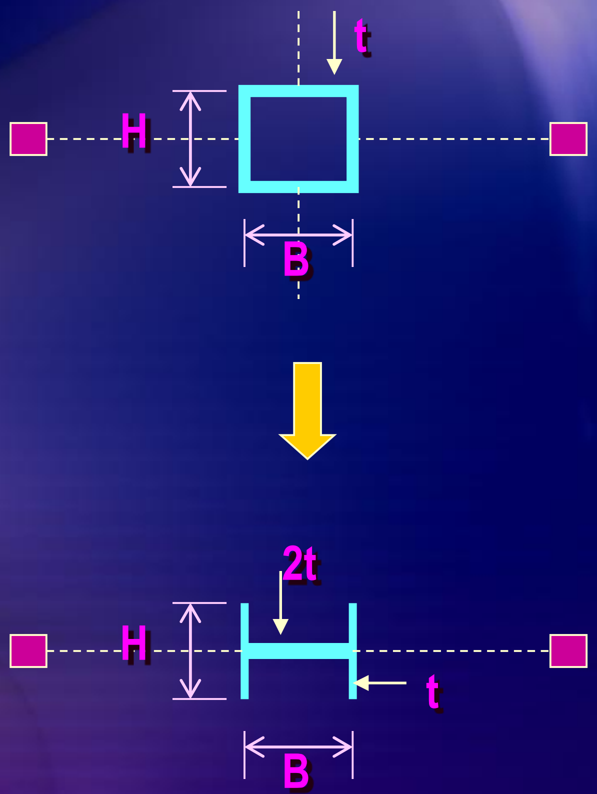


Frame Model for Planer Walls



- Specially Suitable when H/B is more than 5
- The shear wall is represented by a column of section “B x t”
- The beam up to the edge of the wall is modeled as normal beam
- The “column” is connected to beam by rigid zones or very large cross-section

Frame Models for Cellular Walls



- Difficult to extend the concept to Non-planer walls
- Core Wall must be converted to "equivalent" column and appropriate "rigid" elements
- Can be used in 2D analysis but more complicated for 3D analysis
- After the core wall is converted to planer wall, the simplified procedure cab used for modeling

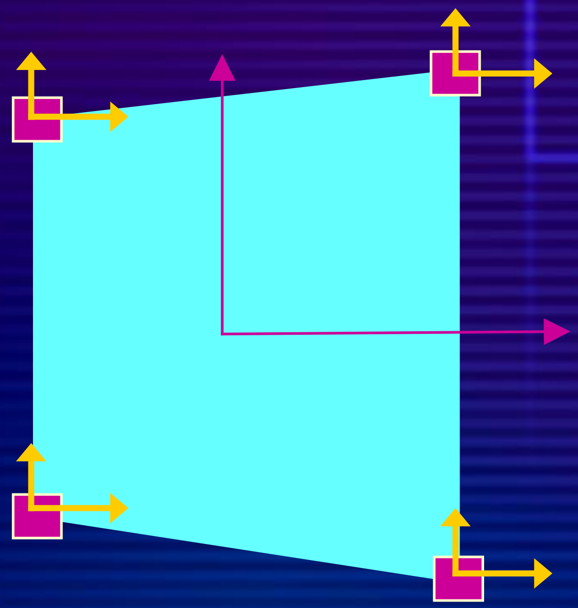
Modeling Walls using 2D Elements

- Walls are subjected to in-plane deformations so 2D elements that have transnational DOF need to be used
- A coarse mesh can be used to capture the overall stiffness and deformation of the wall
- A fine mesh should be used to capture in-plane bending or curvature
- General Shell Element or Membrane Elements can be used to model Shear Walls

Modeling Walls Using Membrane

The Incomplete Membrane Element

Nodes:	**4**
DOFs:	**2 DOFs /Node Ux and Uy**
	2-Translation
Dimension:	**2 dimension element**
Shape:	**Regular / Irregular**
Properties:	**Modulus of Elasticity(E),**
	Poisson ratio(v),
	Thickness(t)

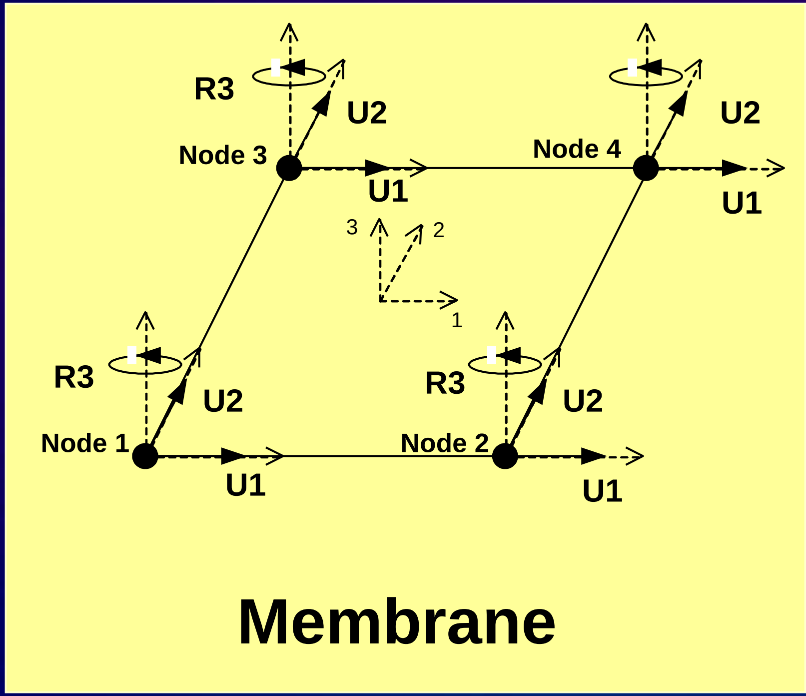


This "Incomplete" Panel or Membrane Element does not connect with Beams completely and rotation DOF of beams and the ends are "Orphaned"

Modeling Walls using Shell Elements

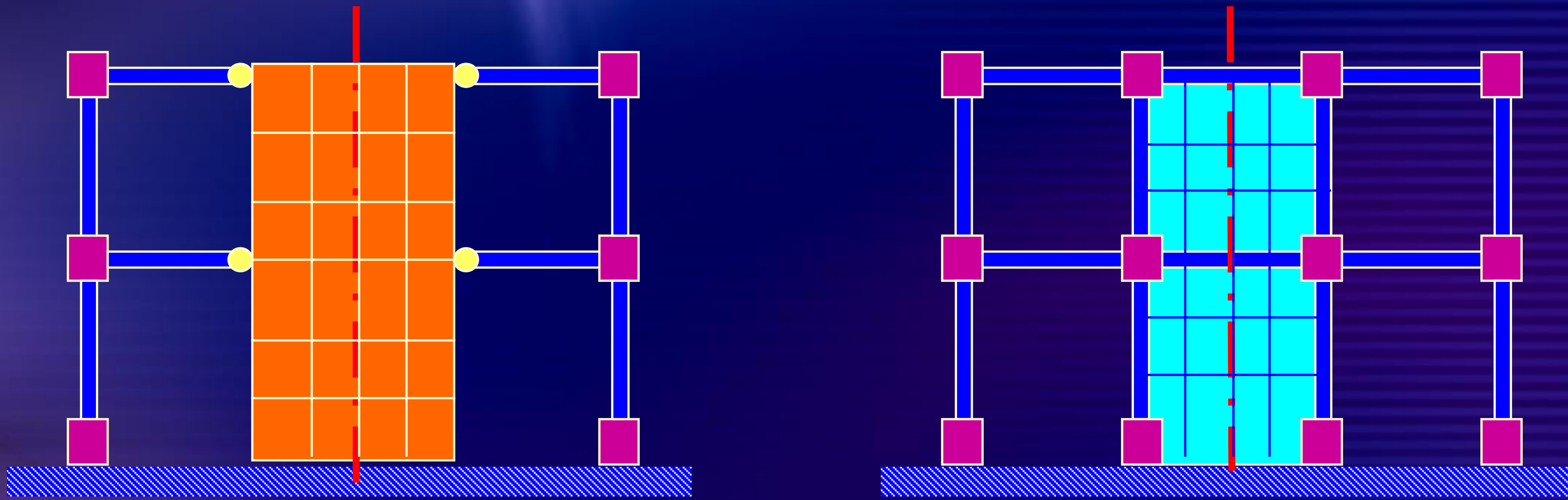
The Complete Membrane Element

Nodes:	**4**
DOFs:	**3 DOFs /Node Ux and Uy and Rz**
	2 Translation, 1 rotation
Dimension:	**2 dimension element**
Shape:	**Regular / Irregular**
Properties:	**Modulus of Elasticity(E),**
	Poisson ratio(v), Thickness(t)



Using Incomplete Membrane Elements

Multiple elements greater accuracy in determination of stress distribution and allow easy modeling of openings



Using *Incomplete Membrane* only

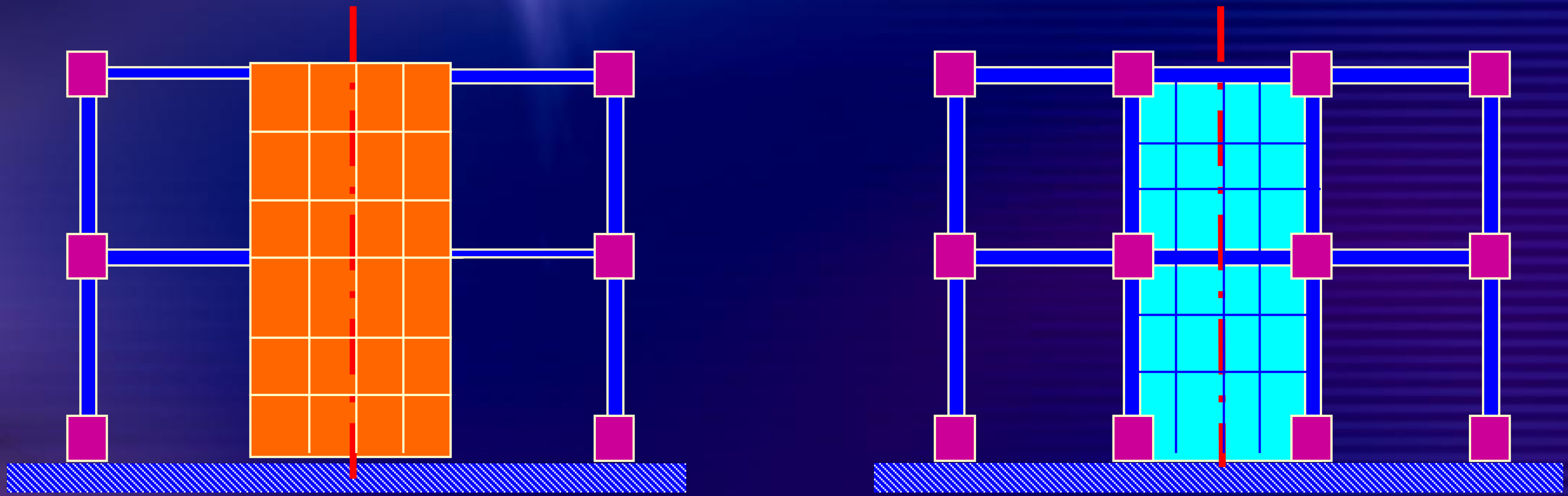
(No Moment continuity with Beams)

Using with Beams and or Columns are Required

(Full Moment continuity with Beams and Columns)

Using Complete Membrane Elements

Multiple elements greater accuracy in determination of stress distribution and allow easy modeling of openings



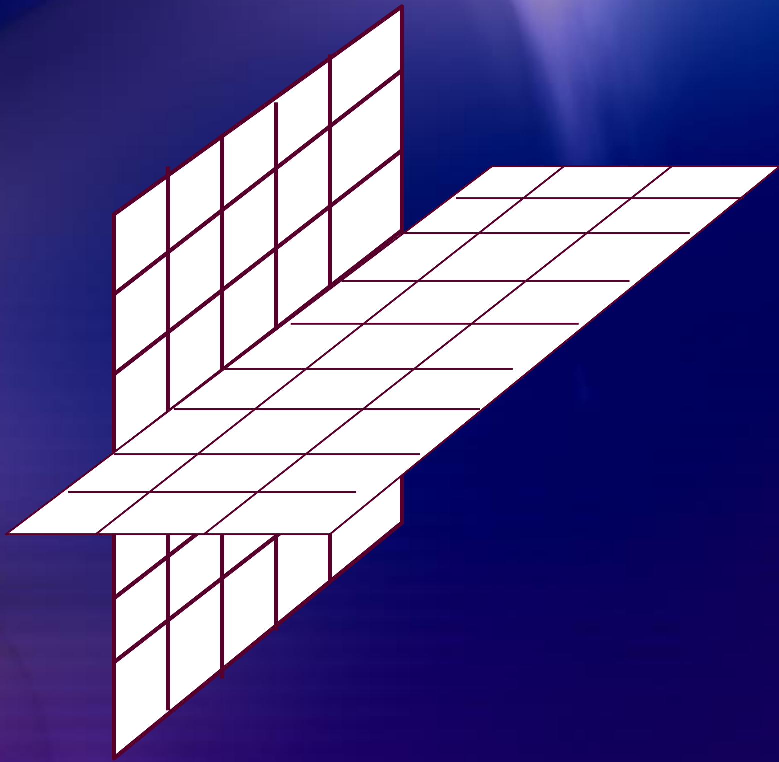
Using *Complete Membrane* only

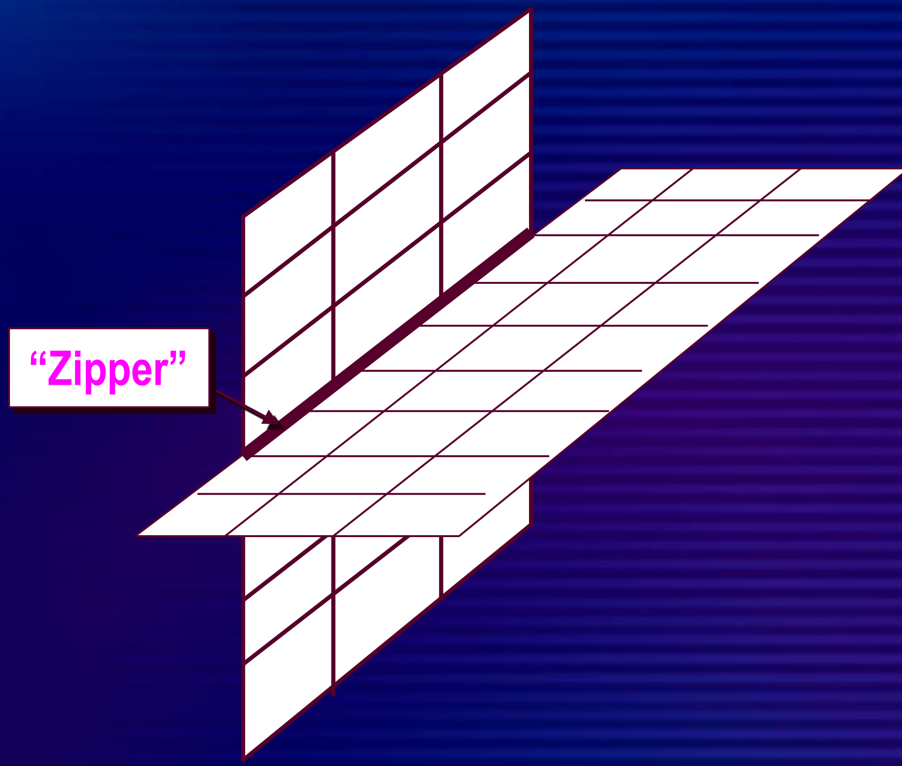
(Moment continuity
with Beams automatically provided)

Using with Beams, Columns is NOT Required

(Full Moment continuity
with Beams and Columns)

Connecting Walls to Slab





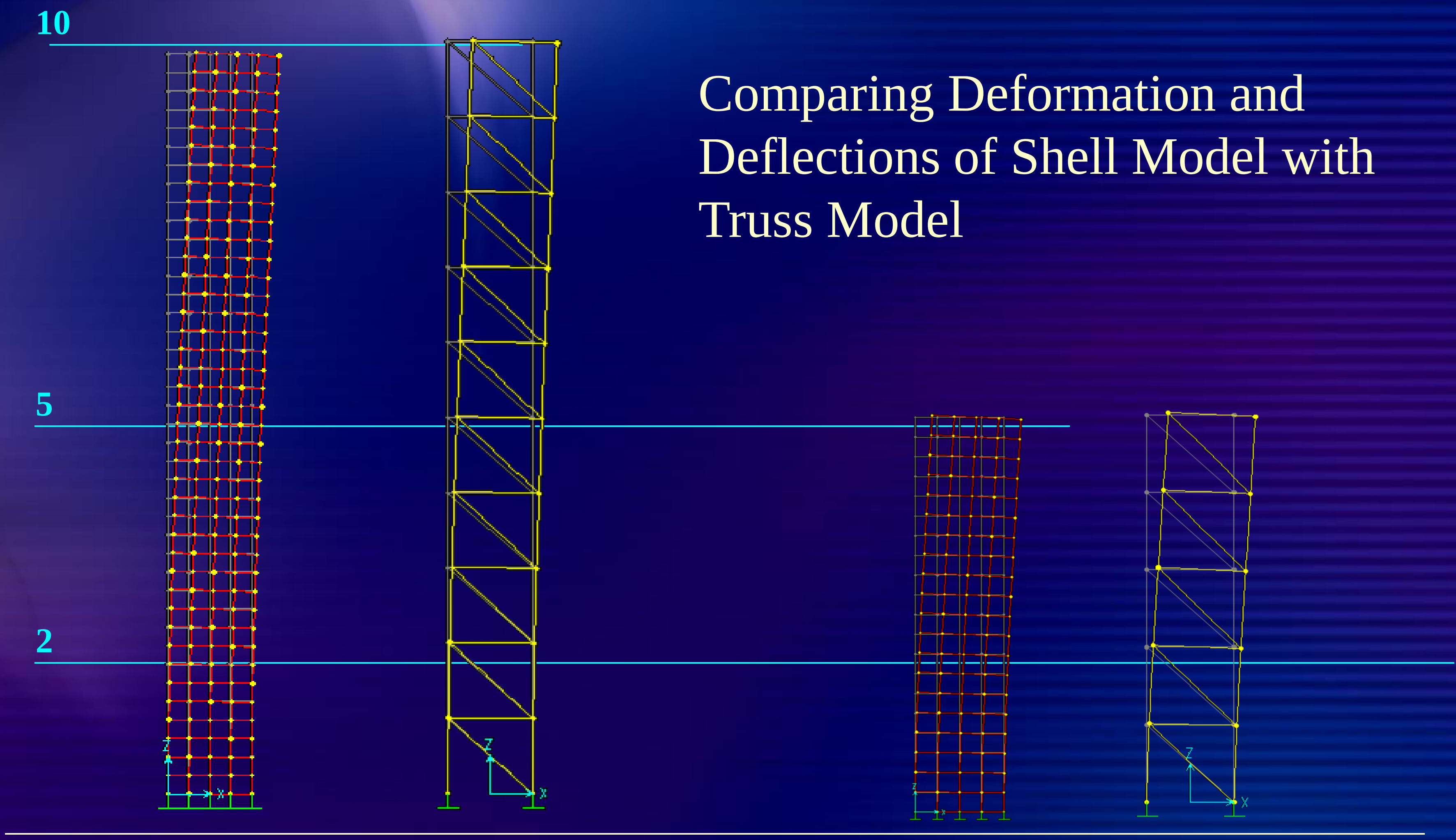
In general the mesh in the slab should match with mesh in the wall to establish connection

Some software automatically establishes connectivity by using constraints or "Zipper" elements

Using Trusses to Model Shear Walls

- **The behavior of shear walls can be closely approximated by truss models:**
  - The vertical elements provide the axial-flexural resistance
  - The diagonal elements provide the shear resistance
- **Truss models are derived from the “strut-tie” concepts**
- **This model represents the “cracked” state of the wall where all tension is taken by ties and compression by concrete**

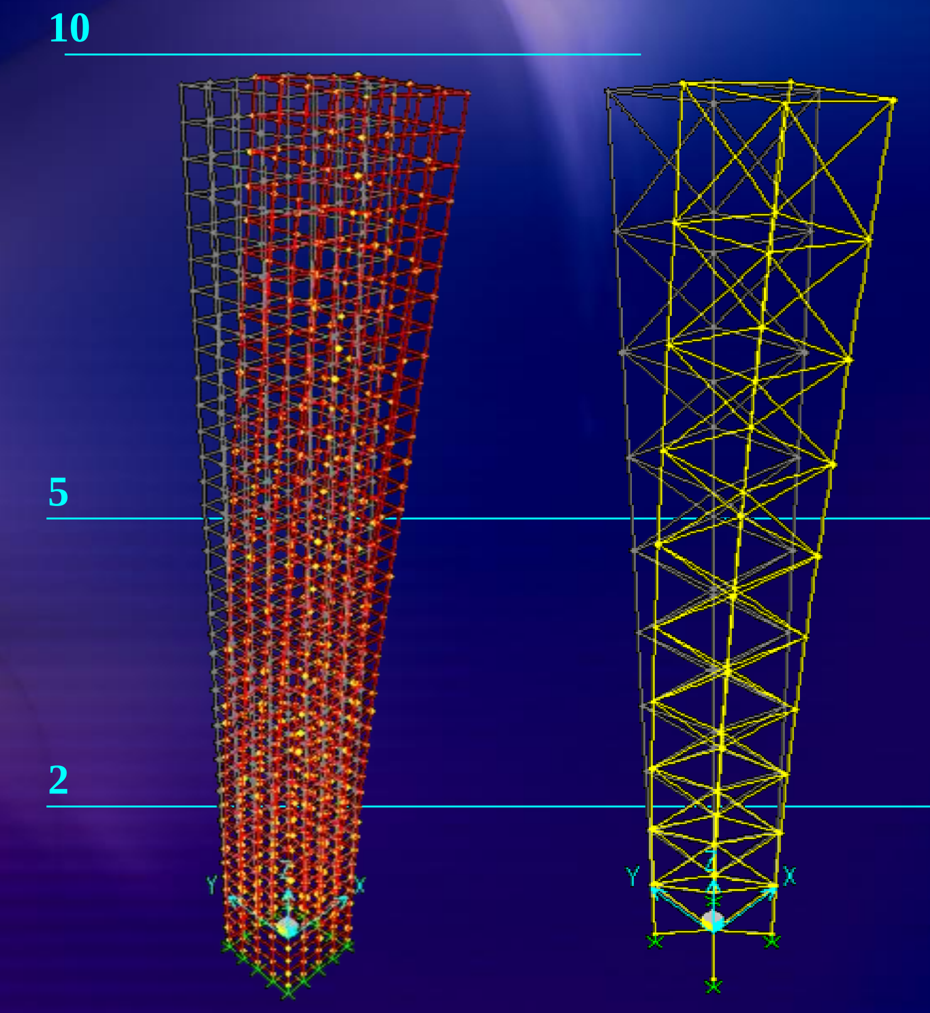
Truss Model for Shear Walls

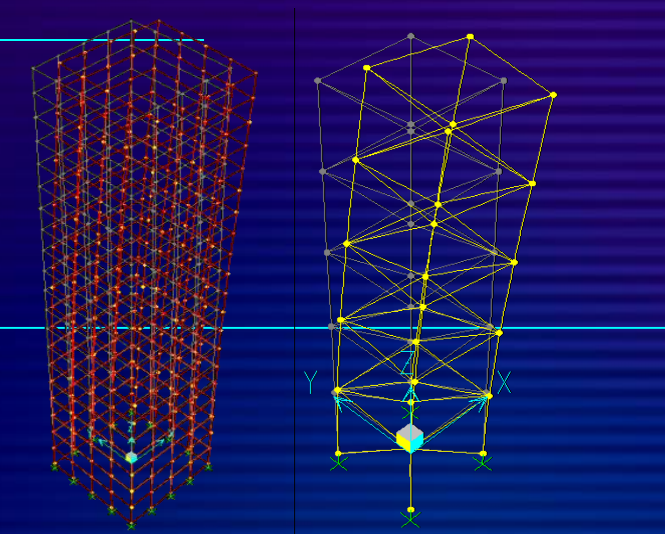


Comparing Deformation and Deflections of Shell Model with Truss Model

Truss Model for Shear Walls

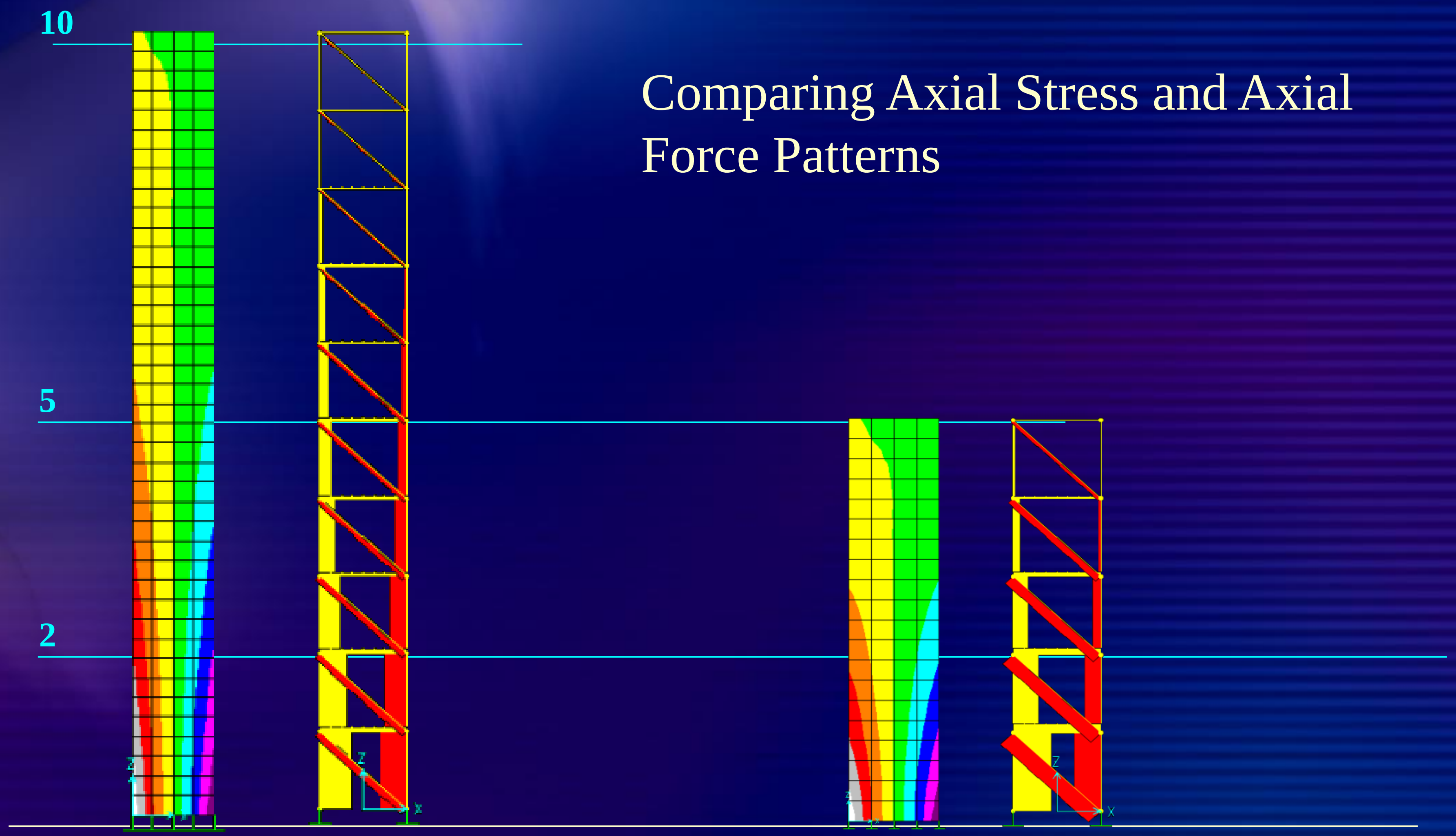
Comparing Deformation and Deflections of Shell Model with Truss Model



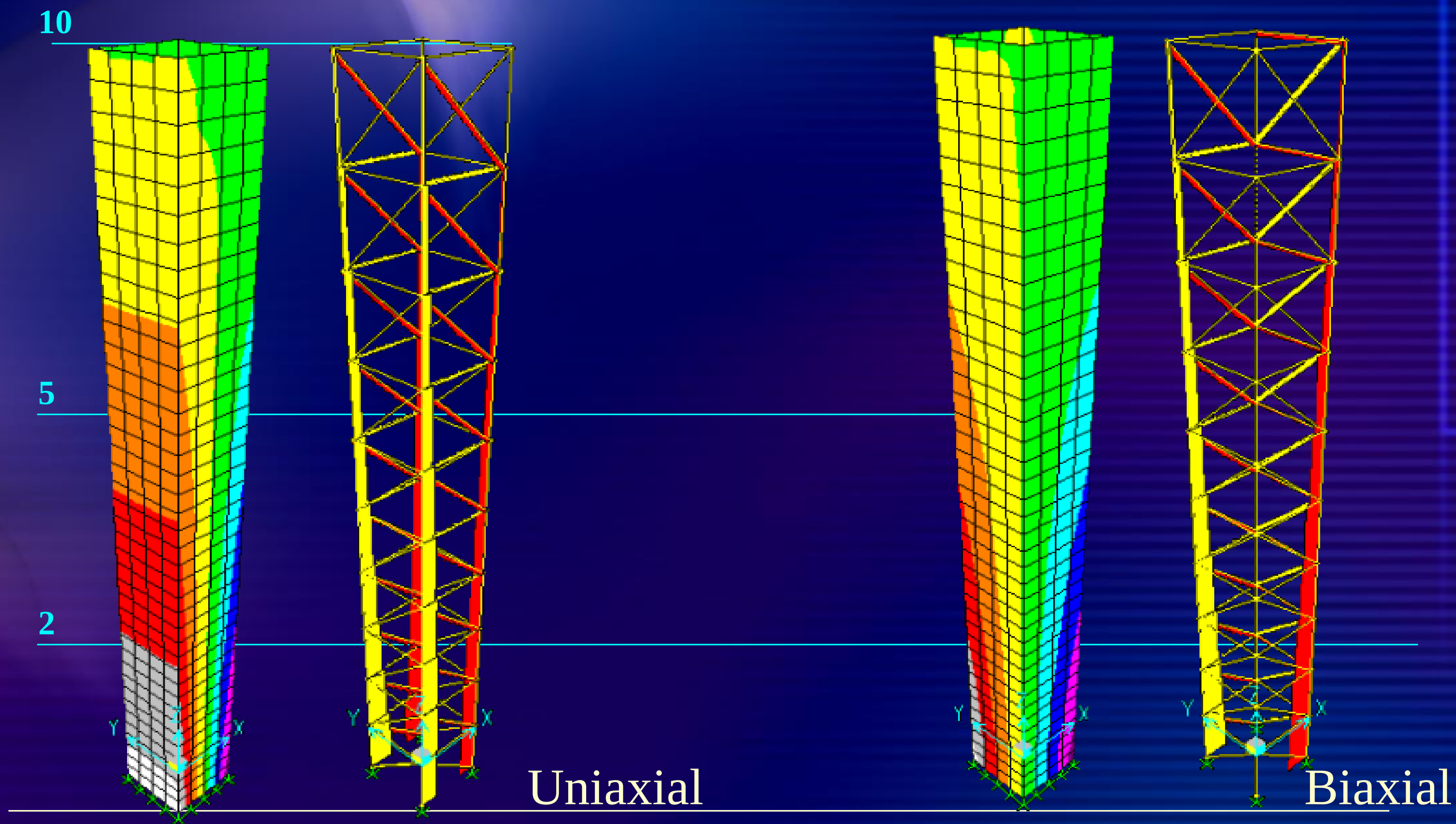


Truss Models for Shear Walls

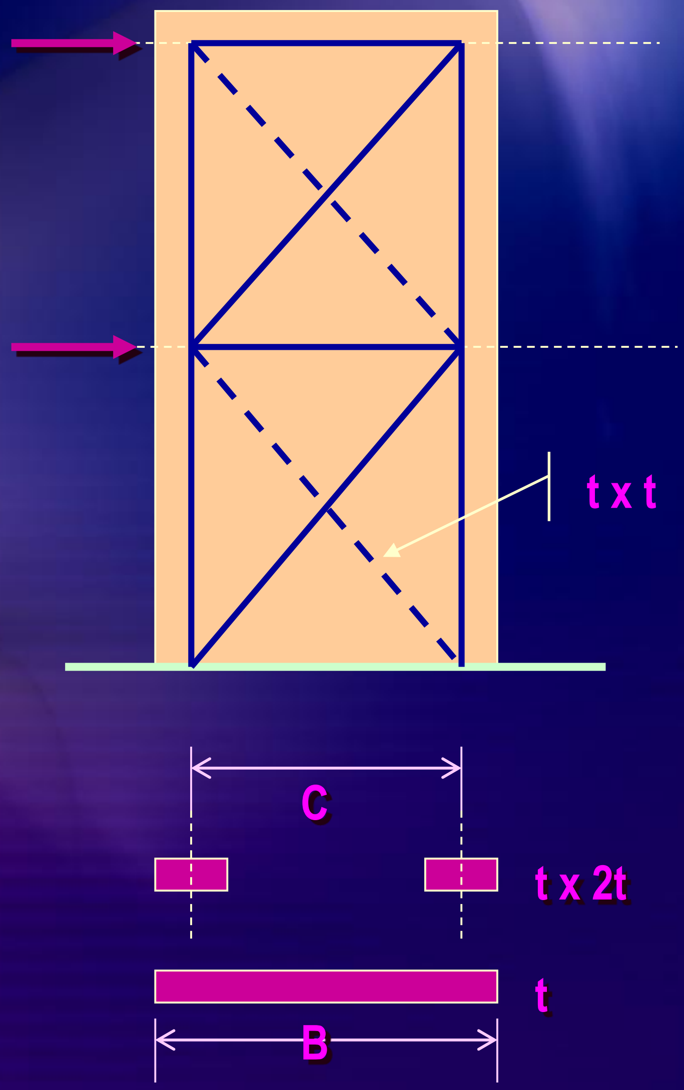
Comparing Axial Stress and Axial Force Patterns



Truss Models for Shear Walls



How to Construct Truss Models



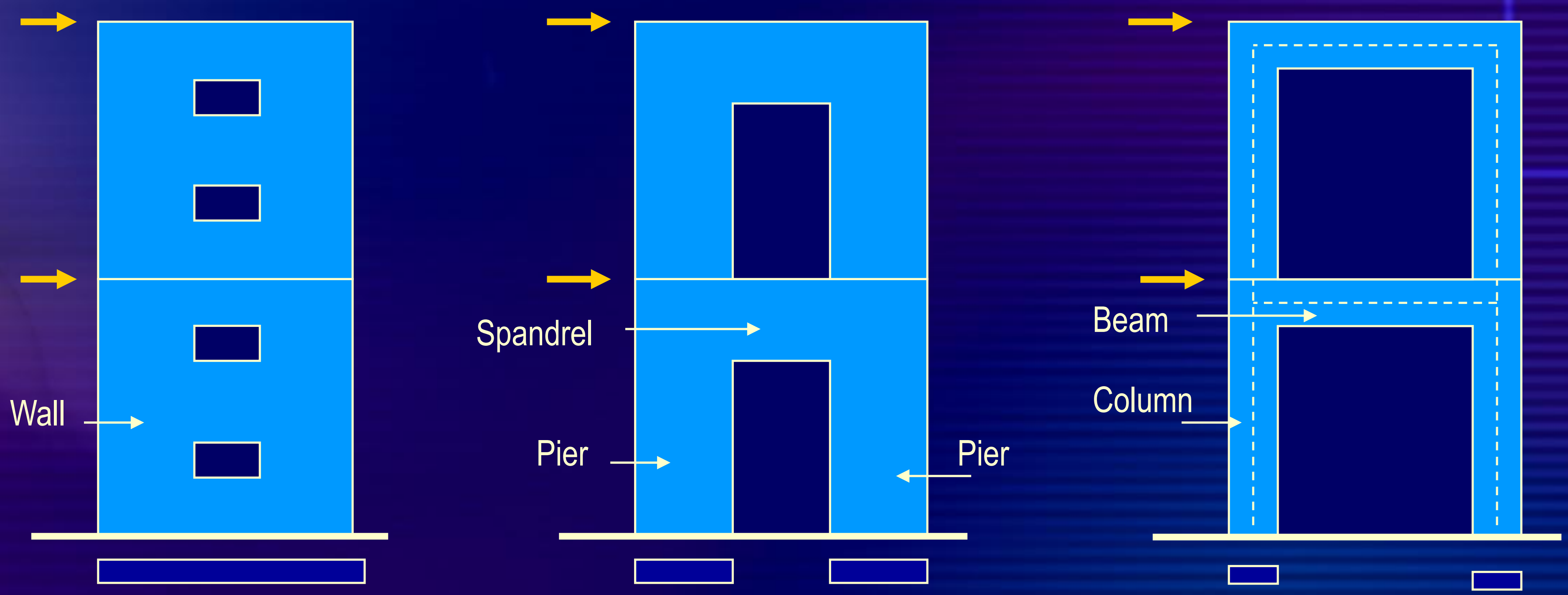
- For the purpose of analysis, assume the main truss layout based on wall width and floor levels
- Initial member sizes can be estimated as t x 2t for main axial members and t x t for diagonal members
- Use frame elements to model the truss. It is not necessary to use truss elements
- Generally single diagonal is sufficient for modeling but double diagonal may be used for easier interpretation of results
- The floor beams and slabs can be connected directly to truss elements

Openings in Shear Walls

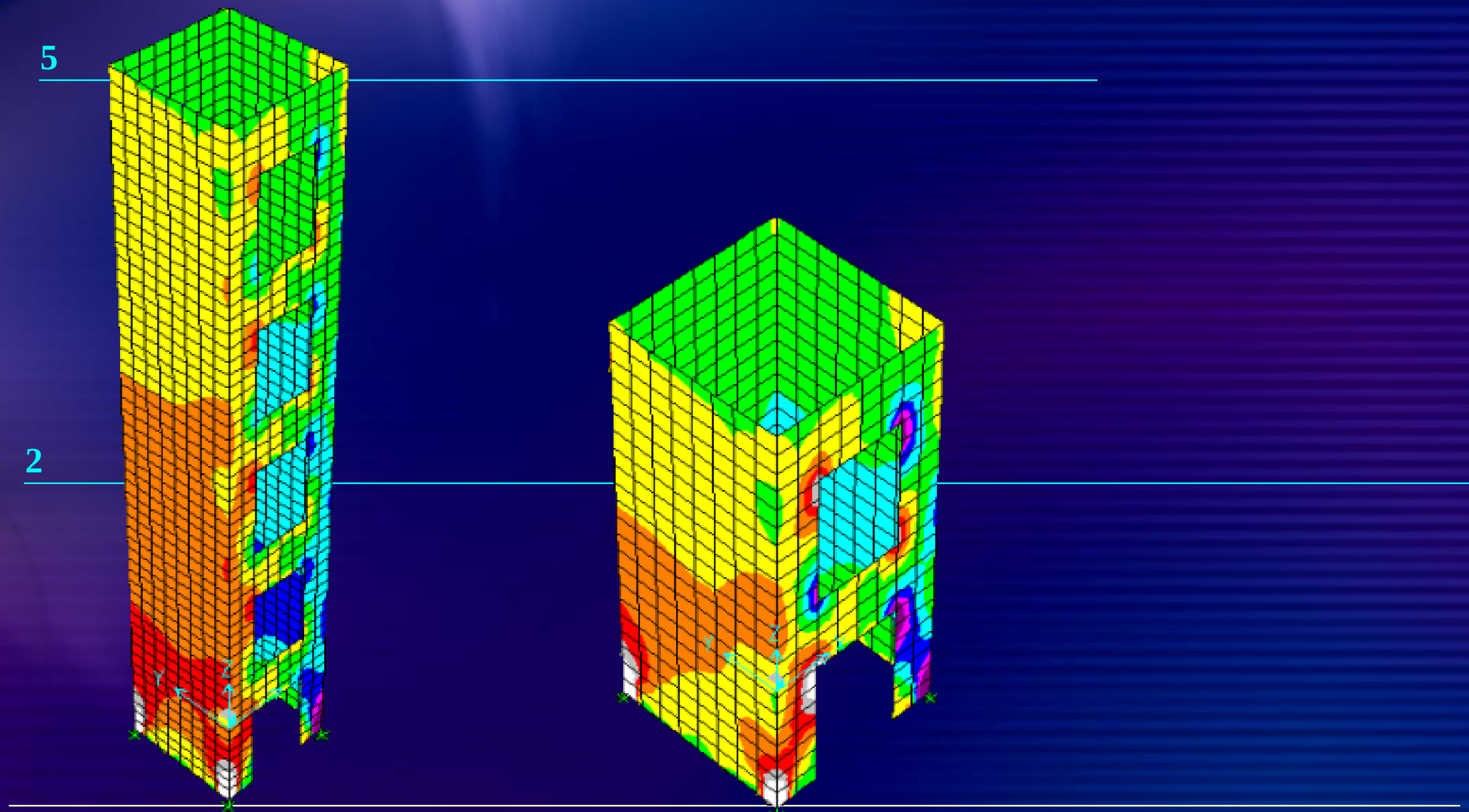
Very Small Openings may not alter wall behavior

Medium Openings may convert shear wall to Pier and Spandrel System

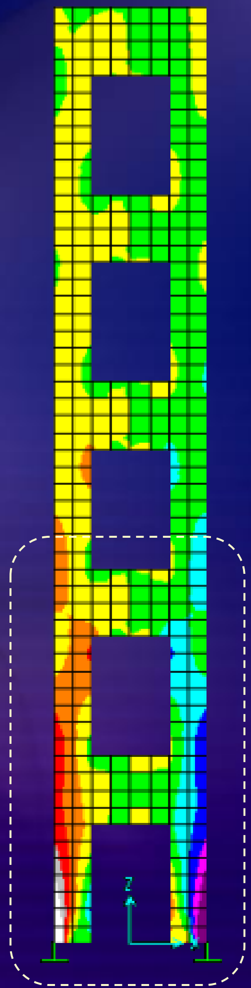
Very Large Openings may convert the Wall to Frame

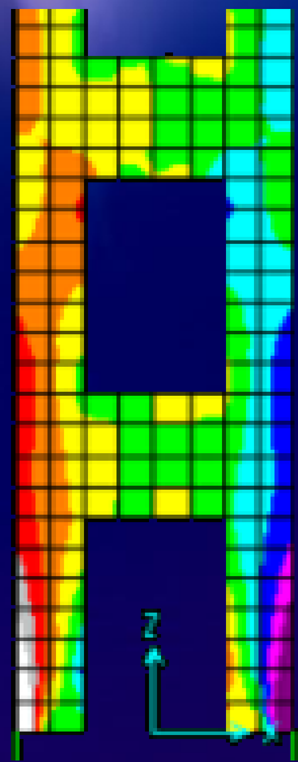


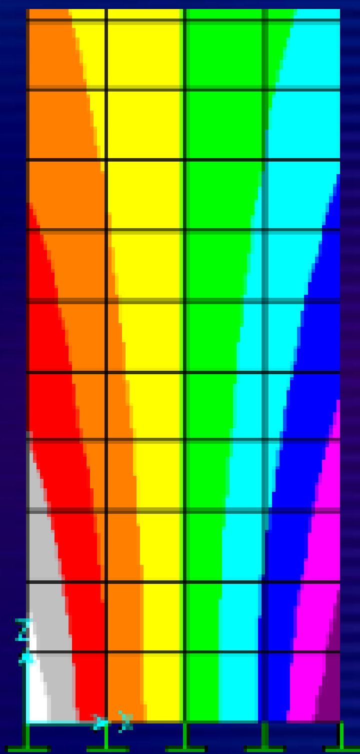
Openings in Shear Walls - Cellular



Openings in Shear Walls - Planer







Modeling Walls with Opening

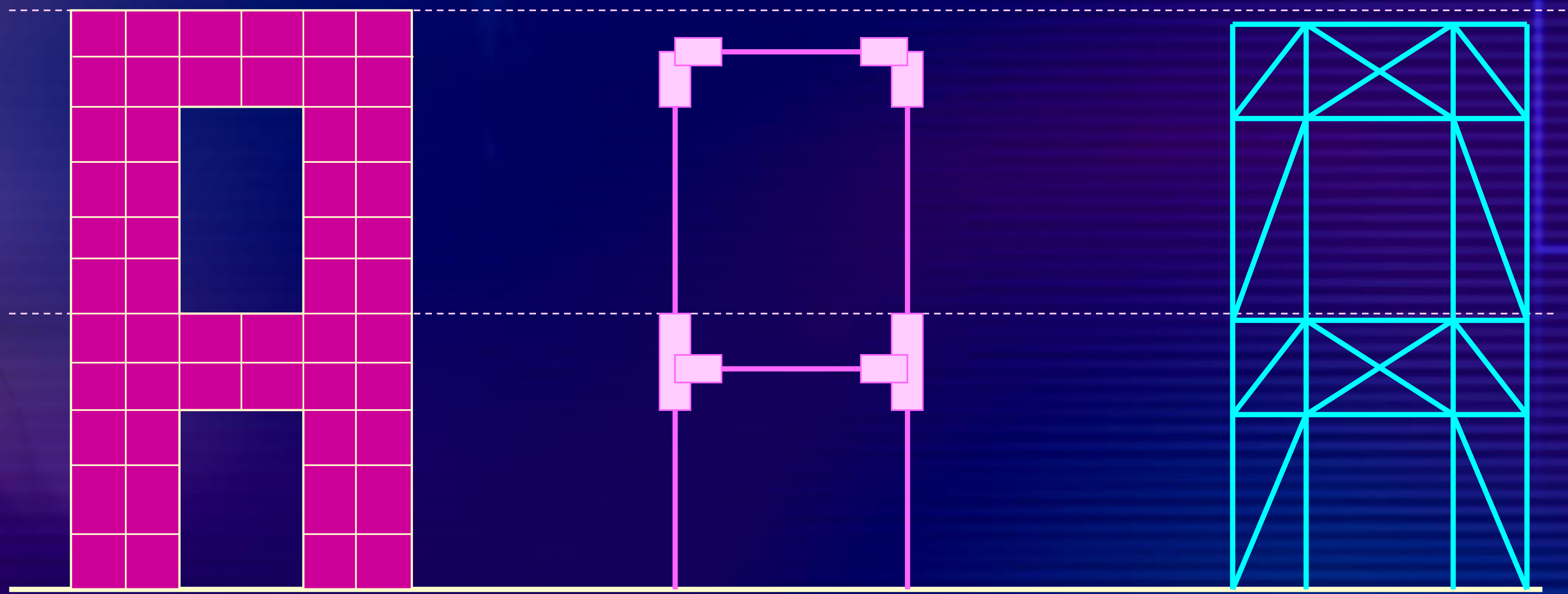
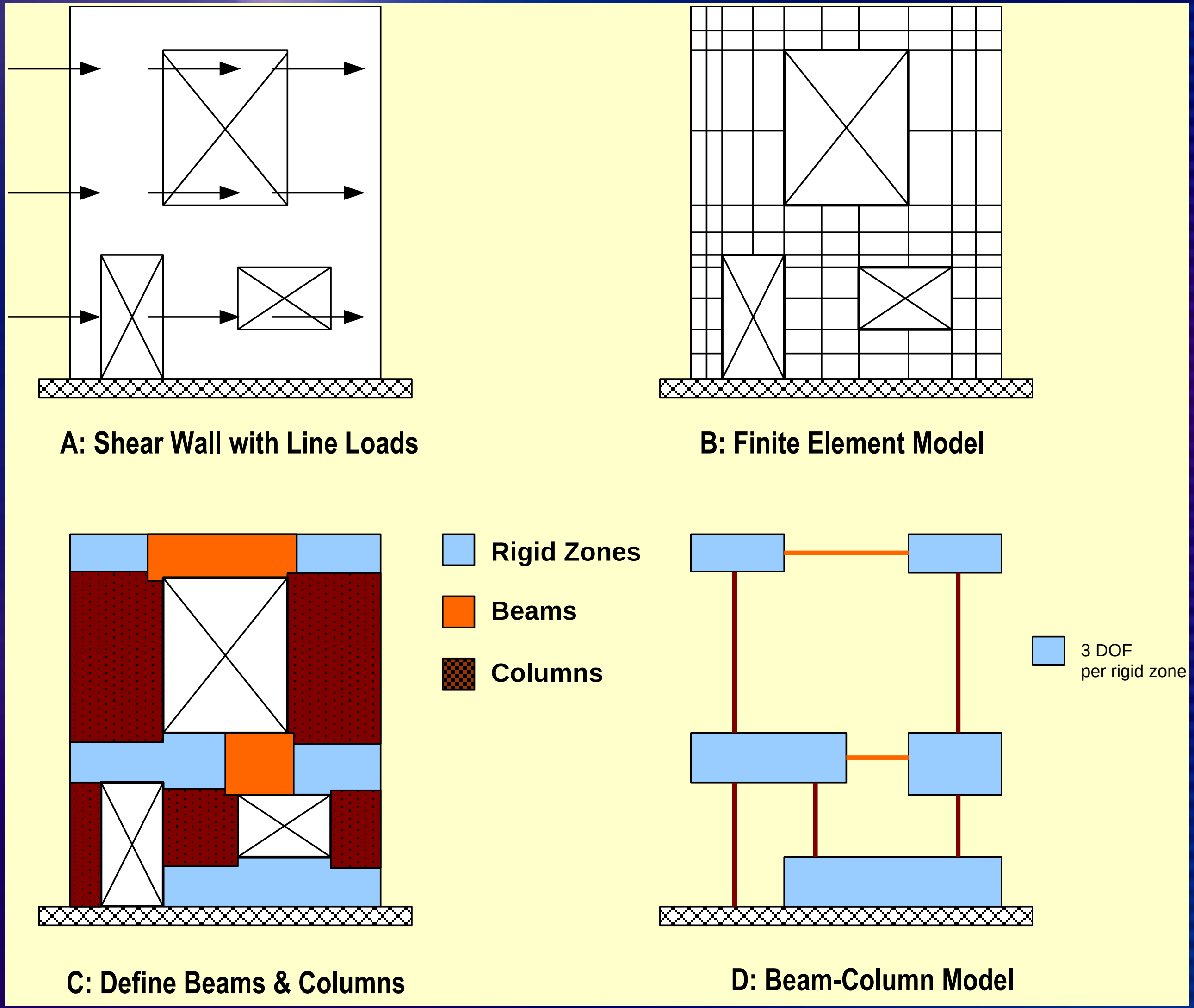


Plate-Shell Model

Rigid Frame Model

Truss Model

Frame Model of Shear Walls



Based on Concept proposed by E.L. Wilson

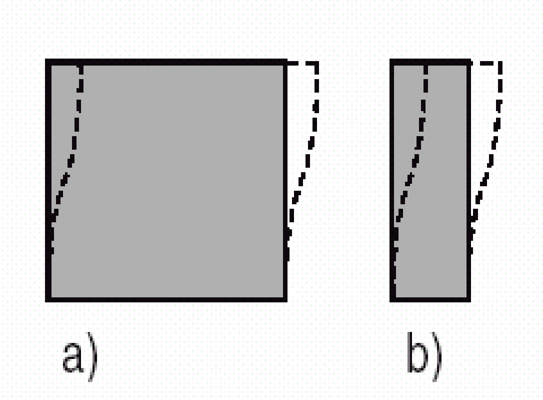
Using Beam-Column to Model Shear Walls

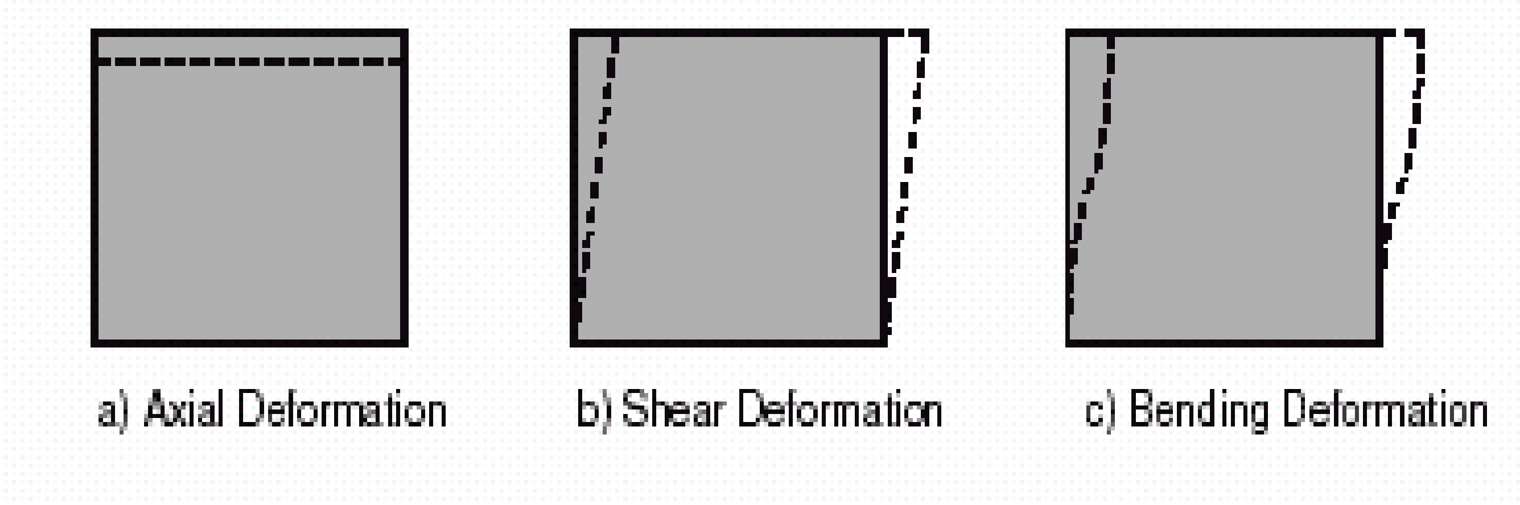
- 4-Node plane element may not accurately capture the linear bending, because constant shear distribution is assumed in formulation but actually shear stress distribution is parabolic

- Since the basic philosophy of RC design is based on cracked sections, it is not possible to use the finite elements results directly for design

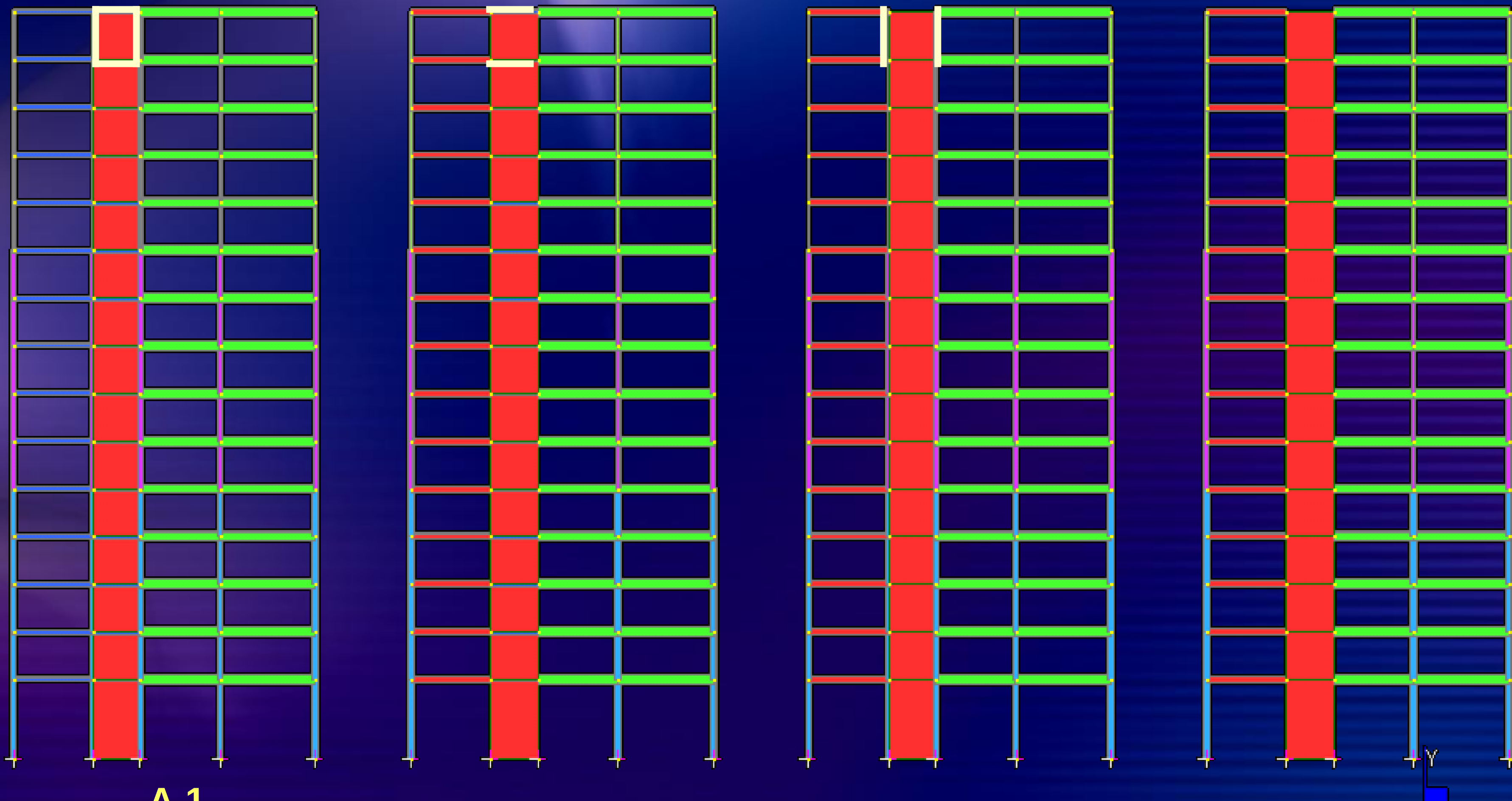
- Very simple model (beam-column) which can also captures the behavior of the structure, The results can be used directly to design the concrete elements.

- Shell Deformations:
  - *Three types of deformation that a single shell element could experience*
  - *A single shell element in the program captures shear and axial deformations well.*
  - *But a single shell element is unable to capture bending deformation.*





Modeling Shear Walls Using Shell Elements



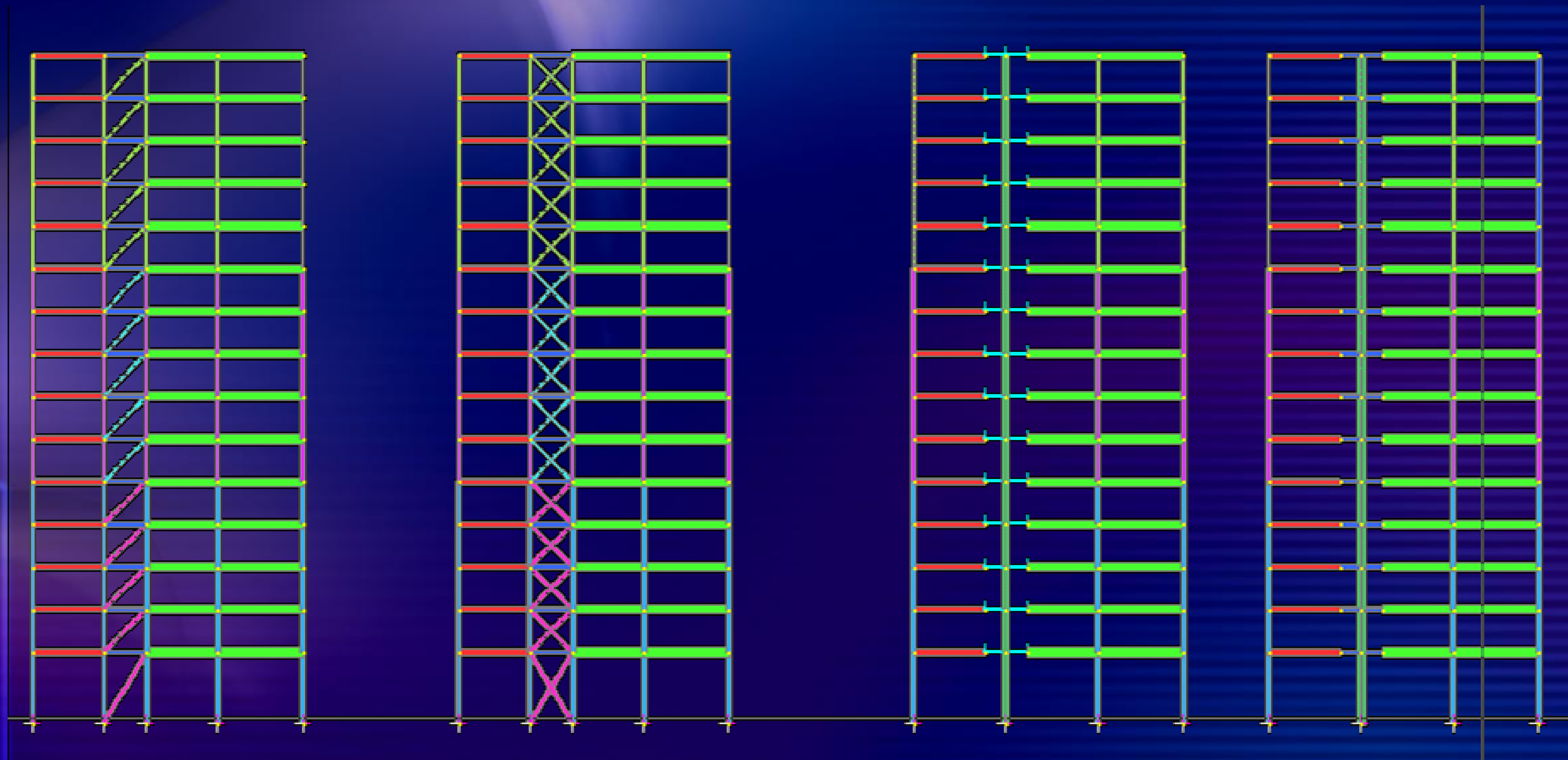
A-1
Plates with Columns and Beams

A-2
Plates with Beams

A-3
Plates with Columns

A-4
Plates Only

Modeling Shear Walls Using Beam Elements



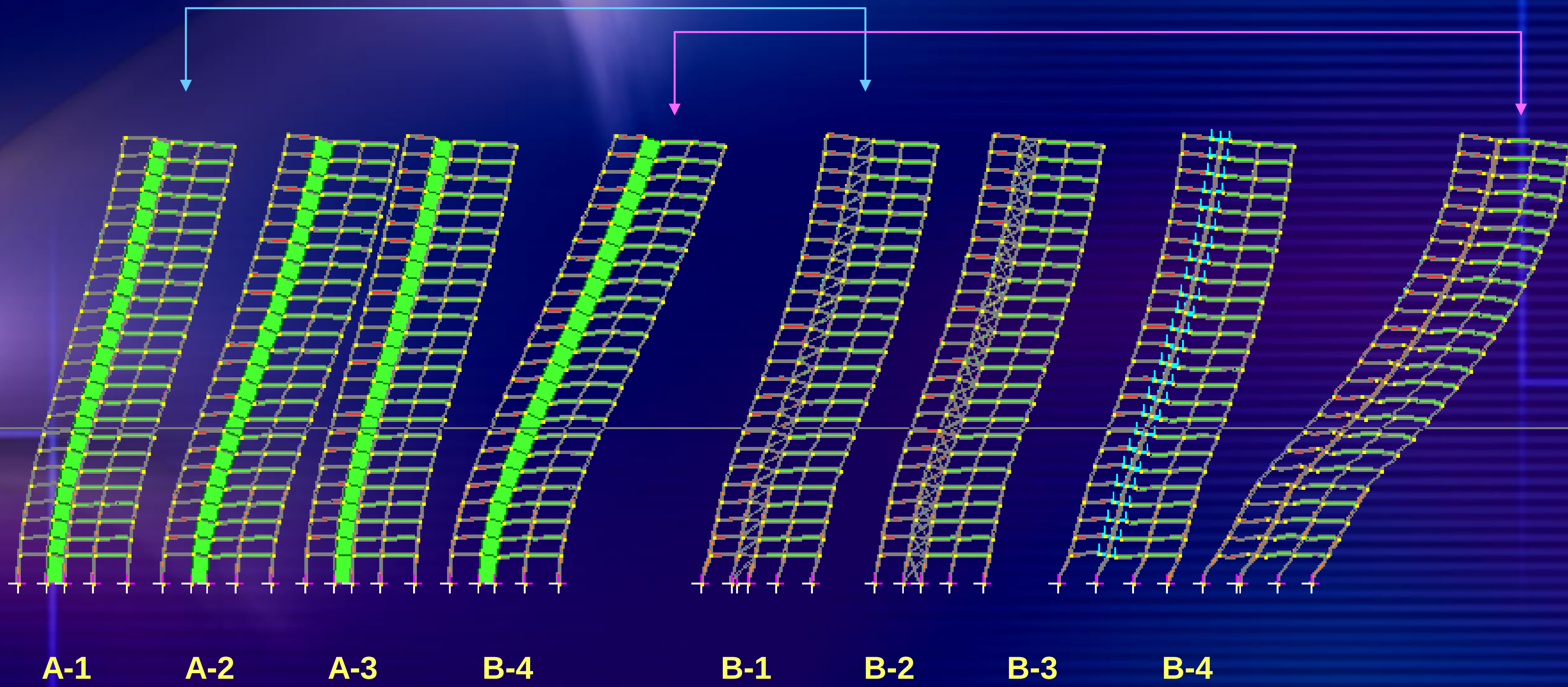
B-1
Single Bracing

B-2
Double Bracing

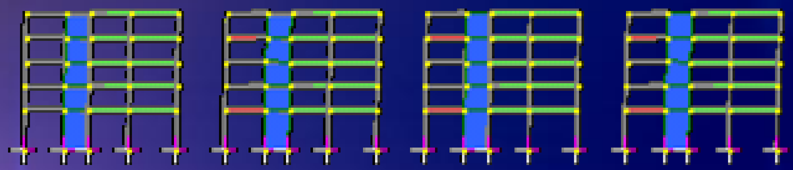
B-3
Column with
Rigid Zones

B-4
Columns with
Flexible Zones

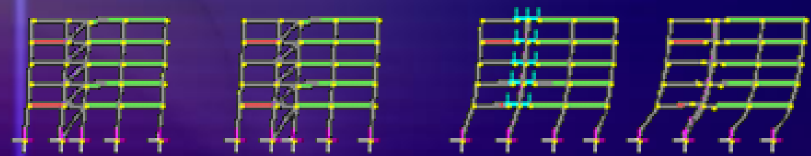
Comparison of Behavior



Comparison of Behavior (5 Floors)

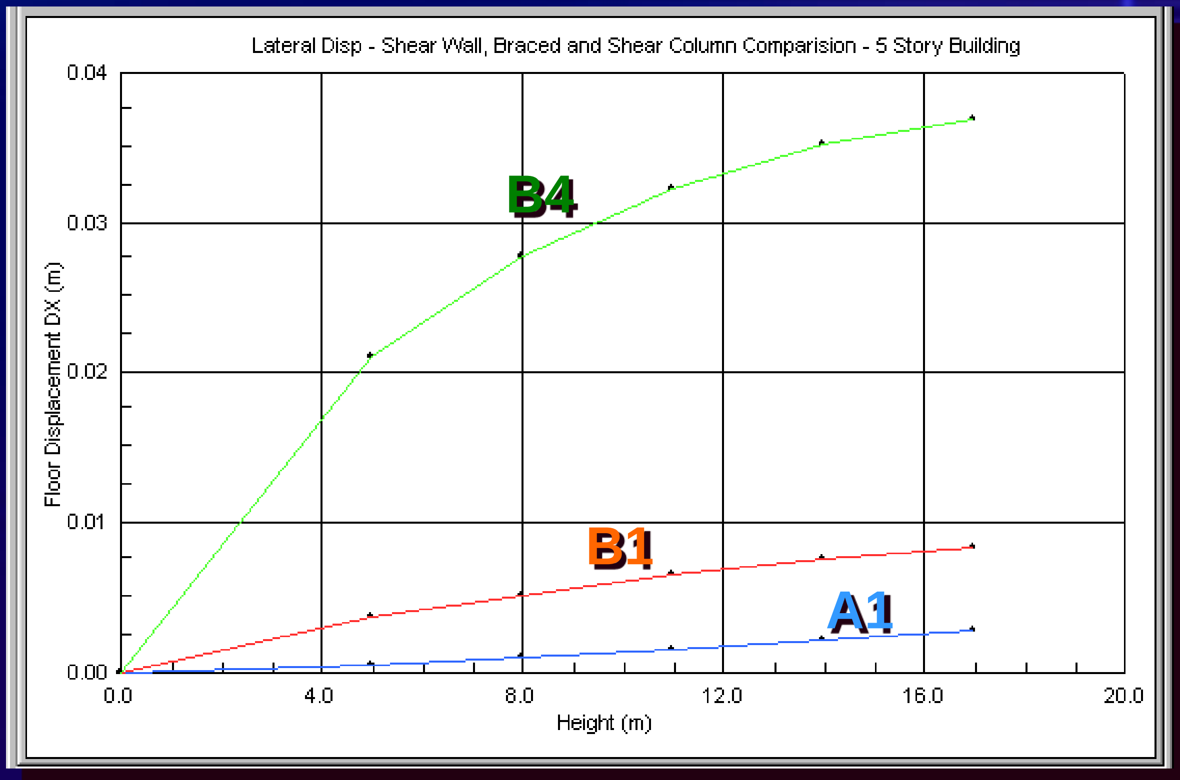


A1

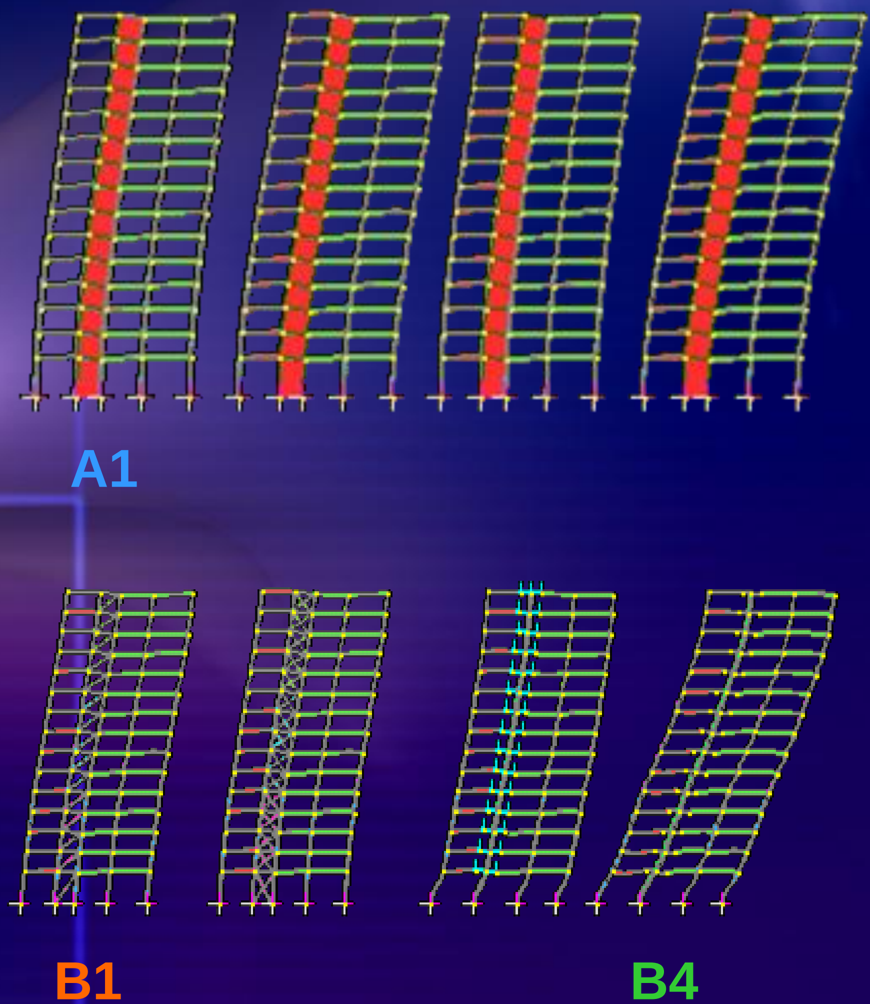


B1

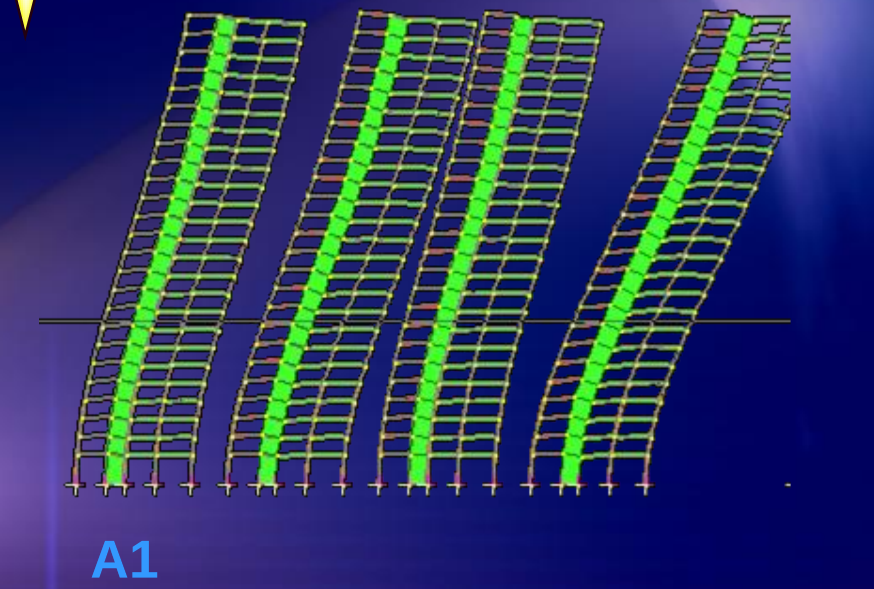
B4

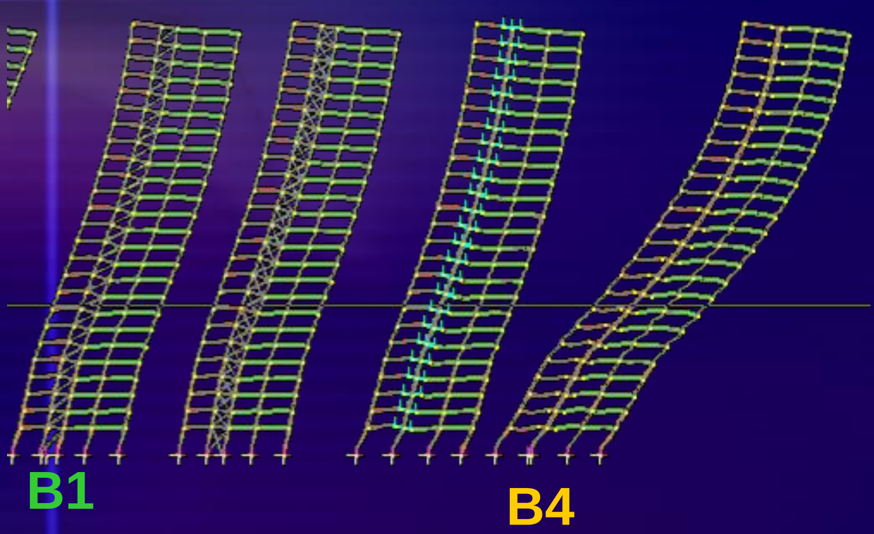


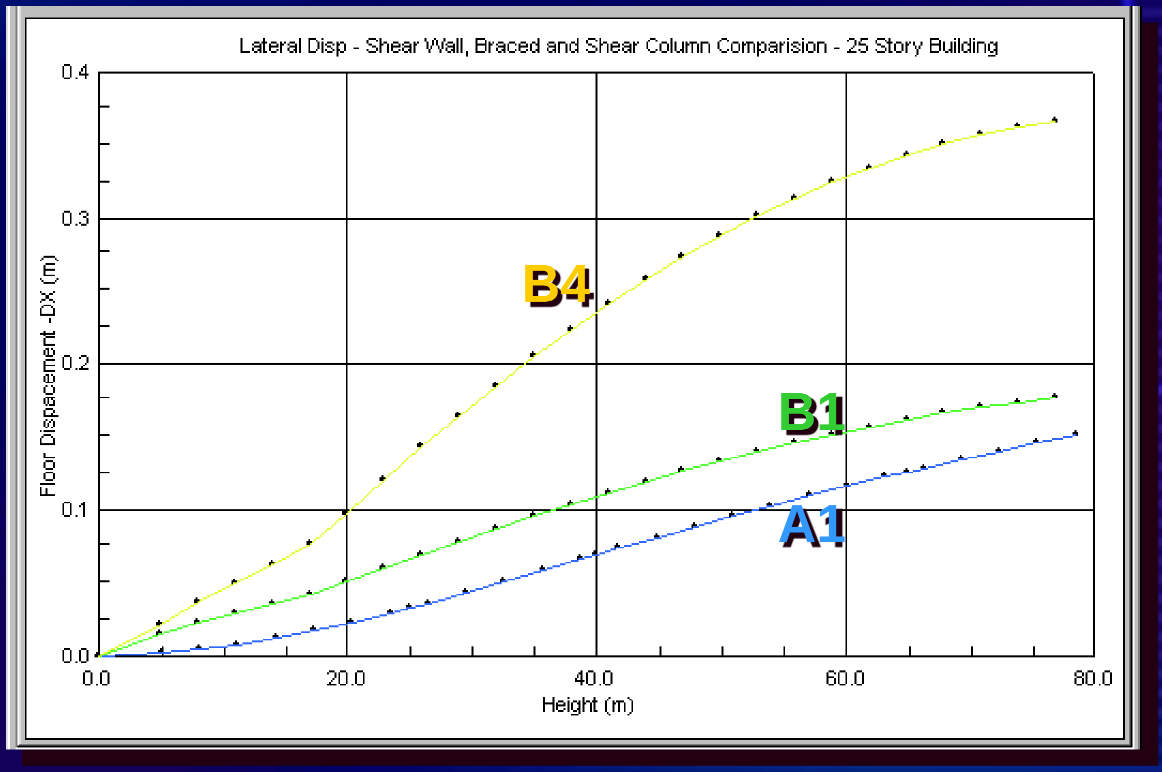
Comparison of Behavior (15 Floors)



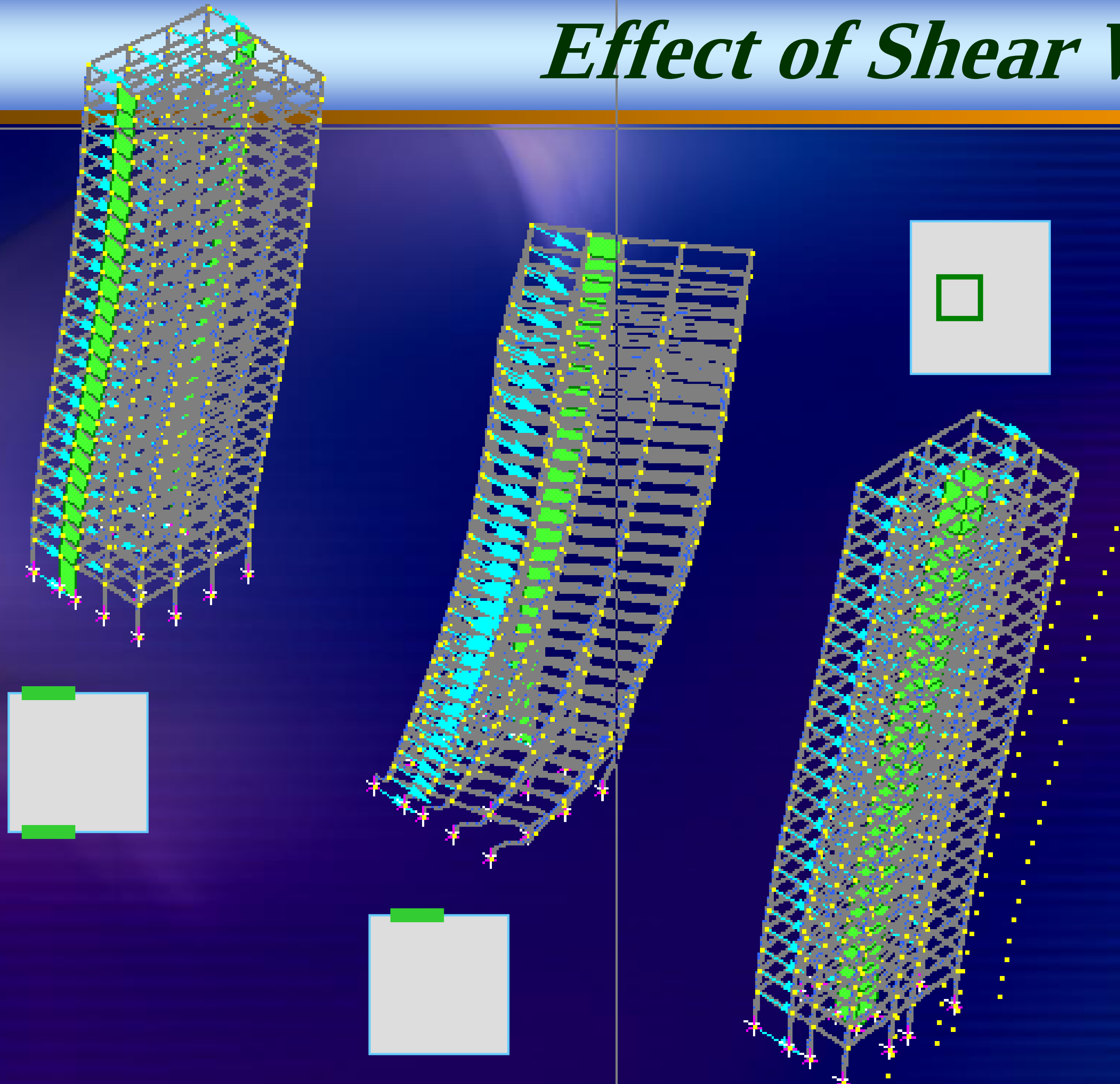
Comparison of Behavior (25 Floors)

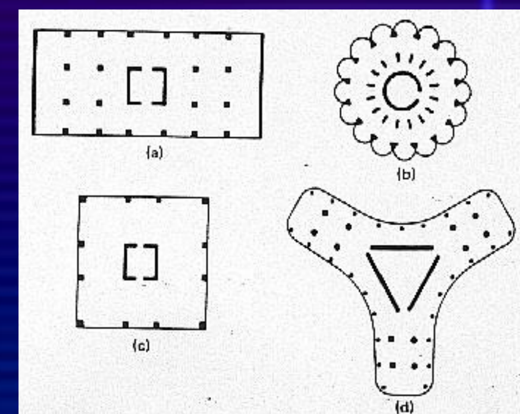






Effect of Shear Wall Location

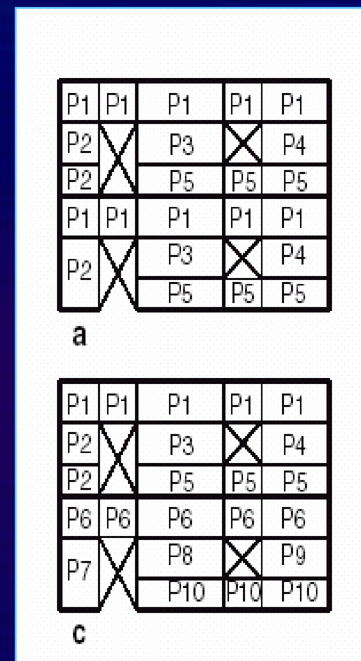


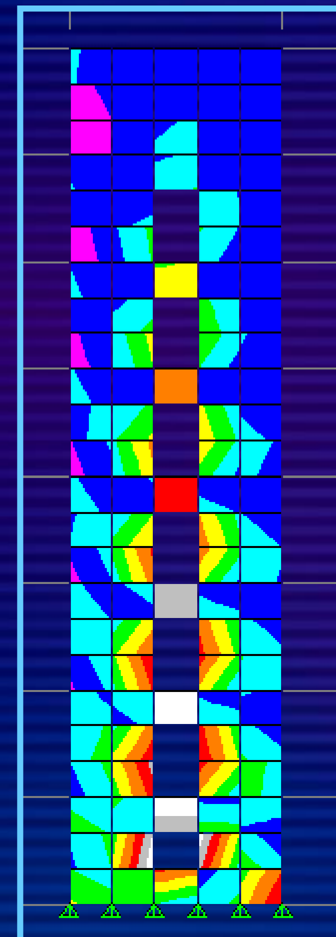


Modeling of Shear Walls In ETABS

Special Considerations/Concepts:

- Zoning
  - *Pier*
  - *Spandrel and*
  - *Boundary Zone*
- Labeling
  - *Pier*
  - *Spandrel*
- Section Types
  - *Simplified Section (C, T or Linear)*
  - *Uniform reinforcing section*
  - *General Sections*



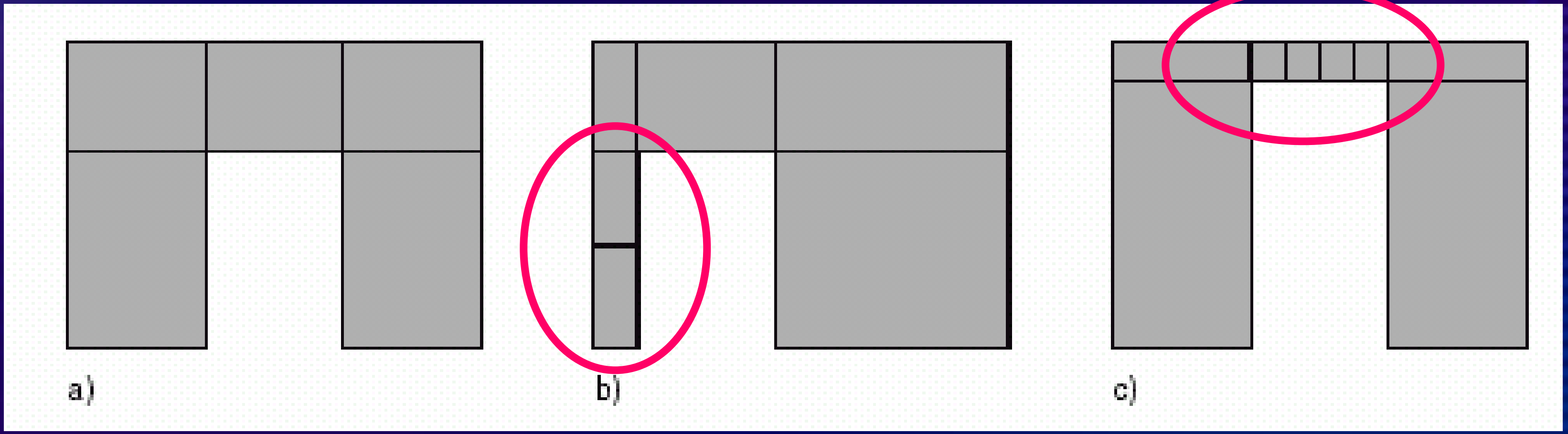


- Wall Meshing and Load Transfer:
  - *Appropriate Meshing and labeling of Shear Walls is the key to proper modeling and design of walls*
  - *No automatic meshing is available for walls (only manual)*
  - *Loads are only transferred to walls at the corner points of the area objects that make up the wall*
  - *Generally the Membrane or Shell type Elements should be used to model walls*

Wall Meshing:

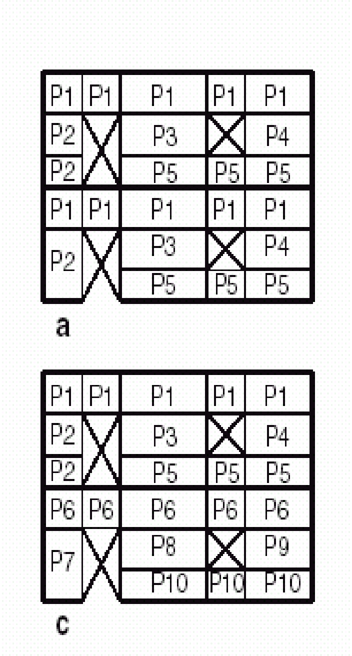
- *Piers and spandrels where bending deformations are significant (slender piers and spandrels), need to mesh the pier or spandrel into several elements*

- *If the aspect ratio of a pier or spandrel one shell element is worse than 3 to 1, consider additional meshing of the element to adequately capture the bending deformation*



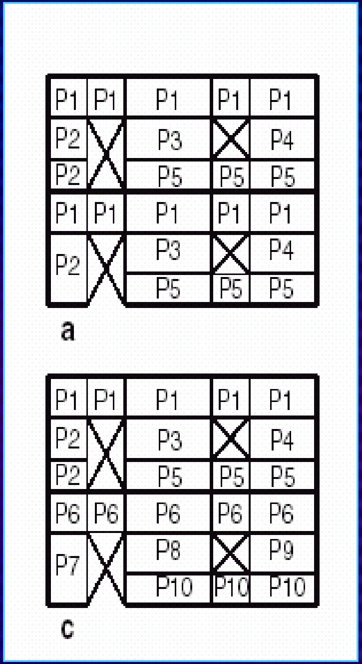
Pier Zone Labeling (Naming/Grouping)

- *Pier labels are assigned to vertical area objects (walls) and to vertical line objects (columns)*
- *Objects that are associated with the same story level and have the same pier label are considered to be part of the same pier.*
- *Must assign a pier element a label before you can get output forces for the element or before you can design the element.*

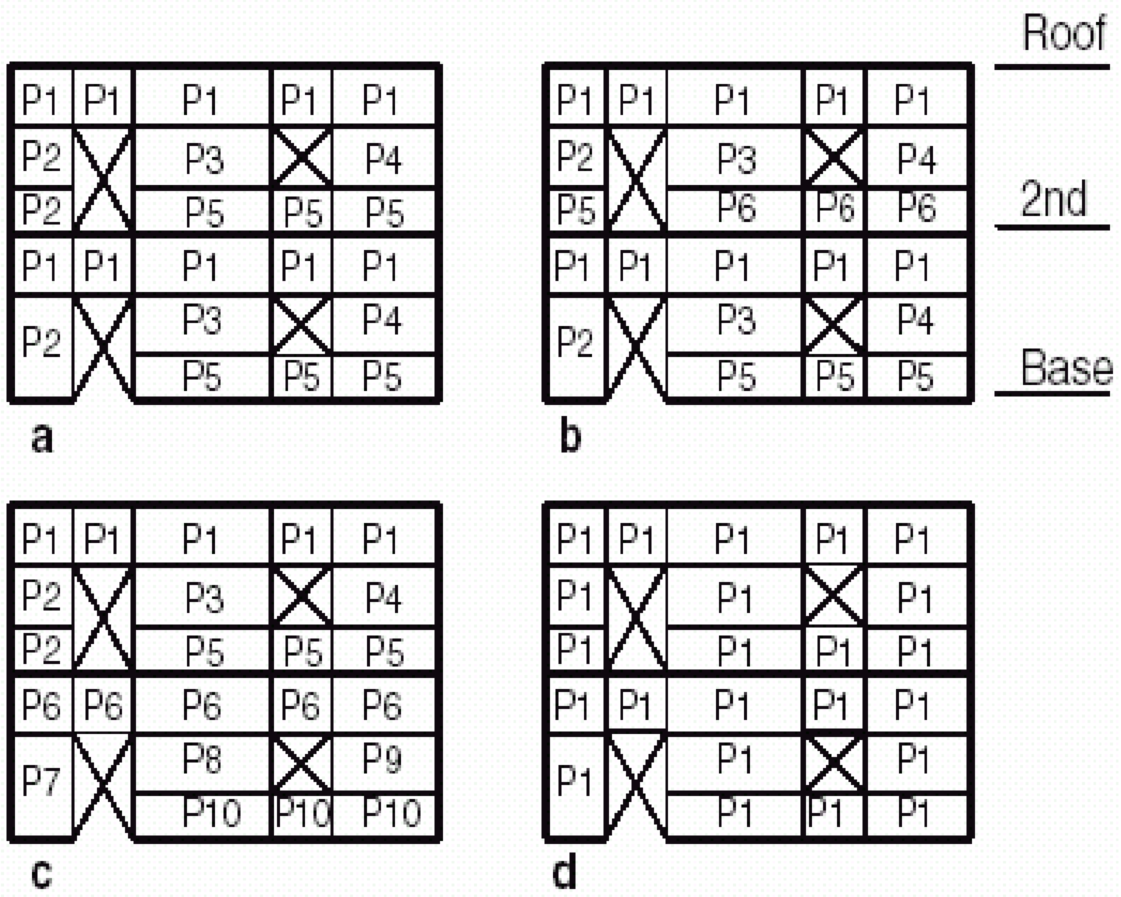


Shear Wall Design – Pier Zones

- *A single wall pier cannot extend over multiple stories*
- *Wall pier forces are output at the top and bottom of wall pier elements*
- *Wall pier design is only performed at stations located at the top and bottom of wall pier elements.*

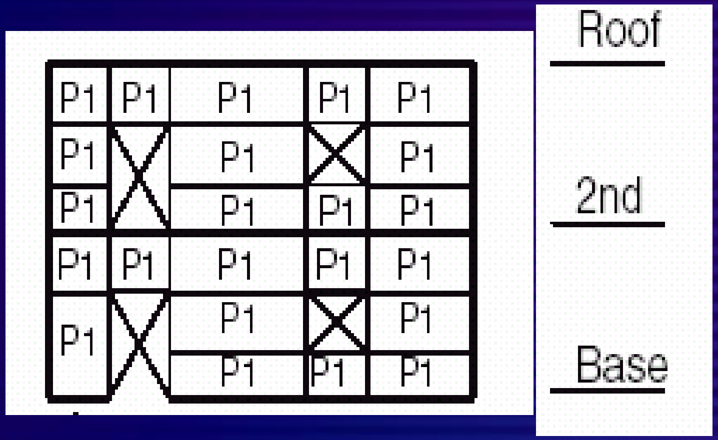


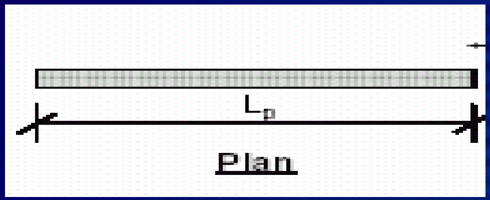
Piers Labeling Examples



General Comments on Case d:

- *All of the area objects given the same label P1*
- *Design is performed across the entire wall at each story level*
- *Wall forces would be provided for the entire wall at each story level*
- *Combined reinforcement is reported at the top and bottom of each floor (3-5 area objects)*

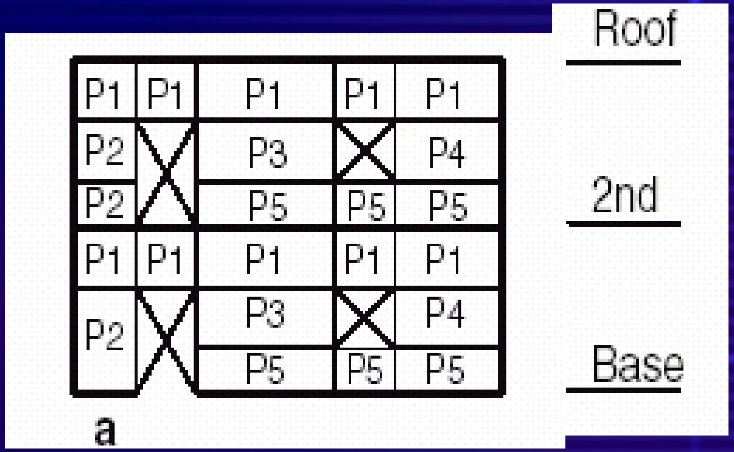




Section for Design at II Floor Top

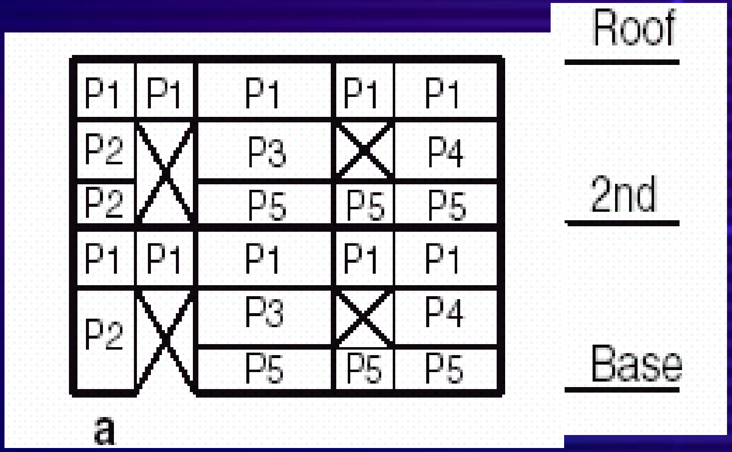
General Comments on Case a:

- *Common way to label piers*
- *At the upper level, Pier P1 is defined to extend all the way across the wall above the openings.*
- *Pier P2 makes up the wall pier to the left of the door opening.*
- *Pier P3 occurs between the door and window openings.*
- *Pier P4 occurs between the window opening and the edge of the wall.*
- *Pier P5 occurs below the window opening between the door and the edge of the wall. A similar labeling of piers occurs at the*
- *lower level.*



General Comments on Case a (Common Way):

- *At the upper level, Pier P1 is defined to extend all the way across the wall above the openings.*
- *Pier P2 makes up the wall pier to the left of the door opening.*
- *Pier P3 occurs between the door and window openings.*
- *Pier P4 occurs between the window opening and the edge of the wall.*
- *Pier P5 occurs below the window opening between the door and the edge of the wall.*
- *A similar labeling of piers occurs at the lower level.*



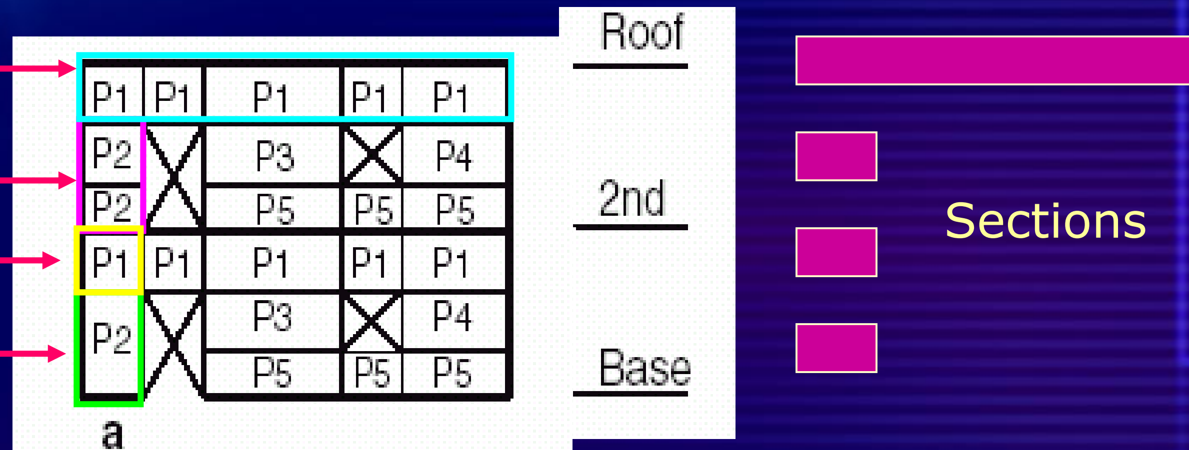
General Comments on Case a (Common Way):

Design pier –1

Design pier –2

Design pier –3

Design pier –4



Output for Each Pier

Uniform Reinforcing Pier Section - Flexural Design (UBC97)

Story ID: STORY8 Pier ID: PW1 X Loc: 432 Y Loc: 0 Units: Kip-in

Flexural Design for P-M2-M3 (RLLF = 1.000)

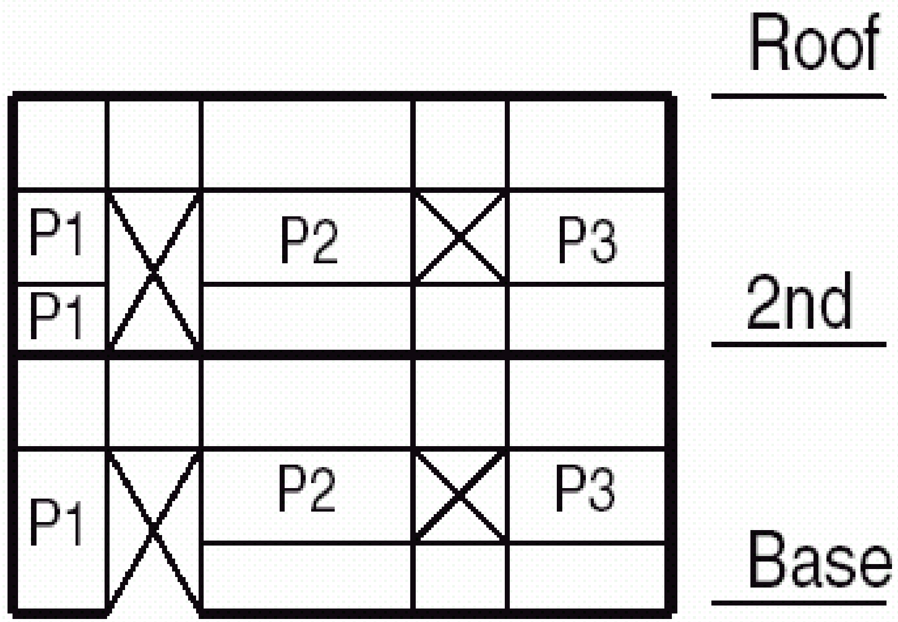
Station Location	Required Reinf Ratio	Current Reinf Ratio	Flexural Combo	Pu	M2u	M3u	Pier Ag
Top	0.0025	0.0029	DWAL2	0.000	0.000	0.000	3456.000
Bottom	0.0025	0.0029	DWAL2	-60.476	0.000	2016.000	3456.000

Shear Design (EQF = 1.000)

Station Location	Rebar in^2/ft	Shear Combo	Pu	Mu	Vu	Capacity phi Vc	Capacity phi Vn
Top Leg 1	103.680	DWAL2	0.000	0.000	14.000	346.225	595.057
Bot Leg 1	0.360	DWAL2	-60.476	2016.000	14.000	353.483	602.315

Spandrel Zone Labeling (Naming/Grouping)

- Spandrel labels are assigned to vertical area objects (walls) and to horizontal line objects (beams)
- Unlike pier elements, a single wall spandrel element can be made up of objects from two (or more) adjacent story levels
- Must assign a spandrel element a label before you can get output forces for the element or before you can design the element

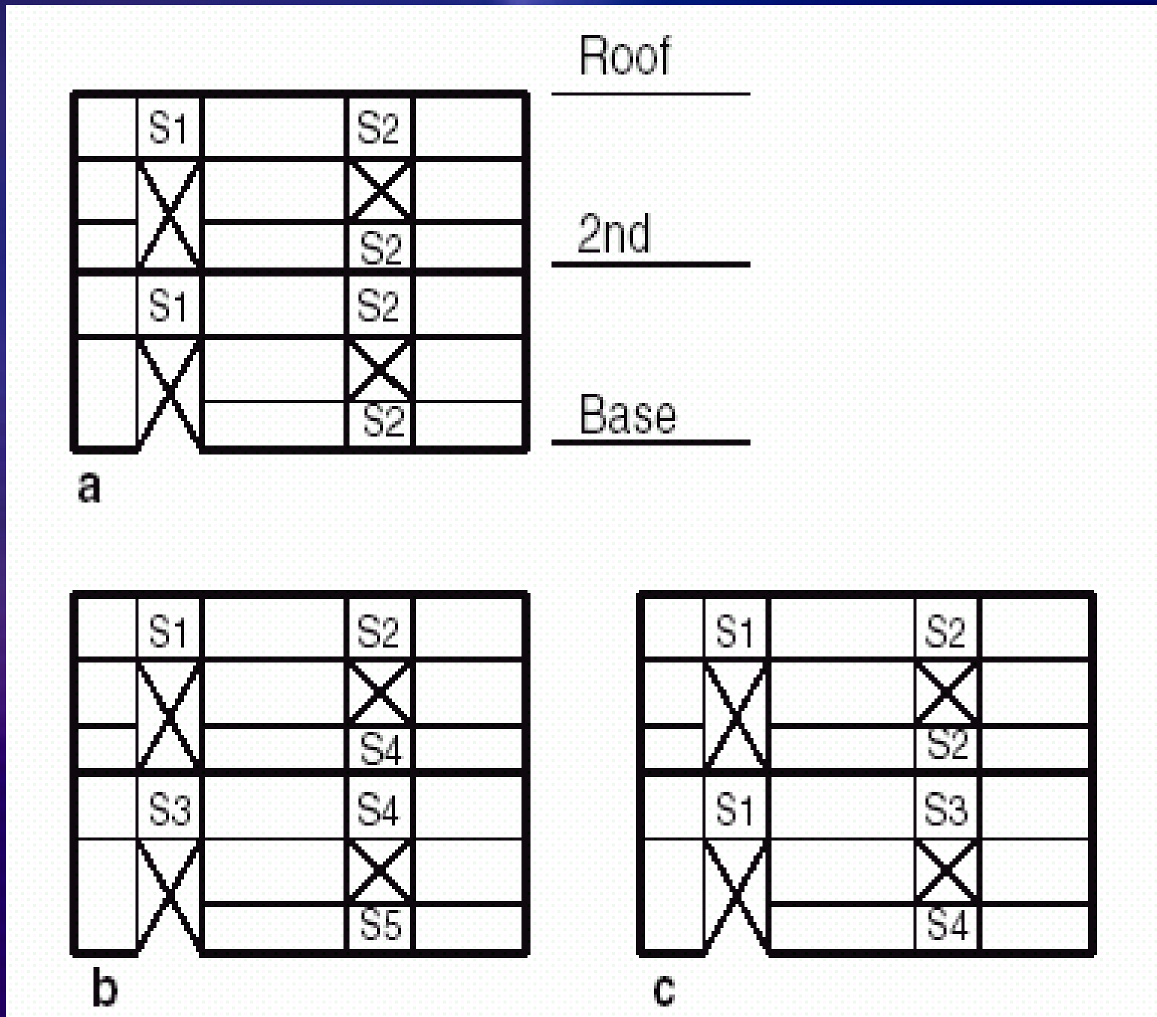


Example of Possibly Incomplete Wall Pier Labeling

Spandrels or Headers

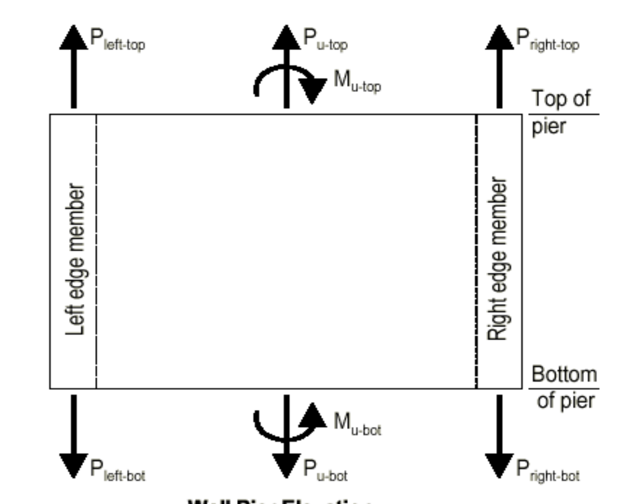
- Wall spandrel forces are output at the left and right ends of wall spandrel Elements
- Wall spandrel design is only performed at stations located at the left and right ends of wall spandrel elements
- Multiple wall spandrel labels cannot be assigned to a single area object.

Examples: Spandrel Labeling

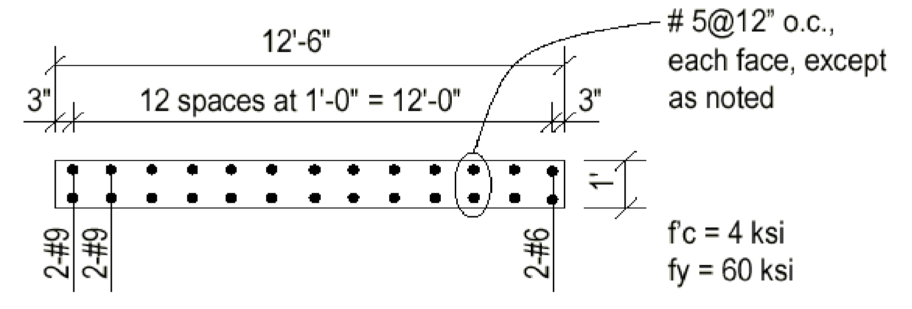


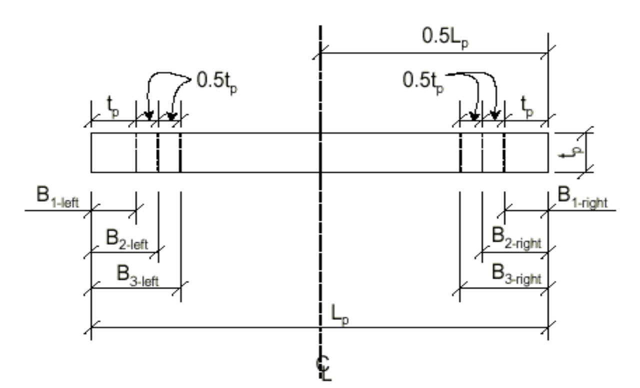
Concrete Shear Wall Design

- Fully integrated wall pier and spandrel design
- ACI, UBC and Canadian Codes
- Design for static and dynamic loads
- Automatic integration of forces for piers and spandrel



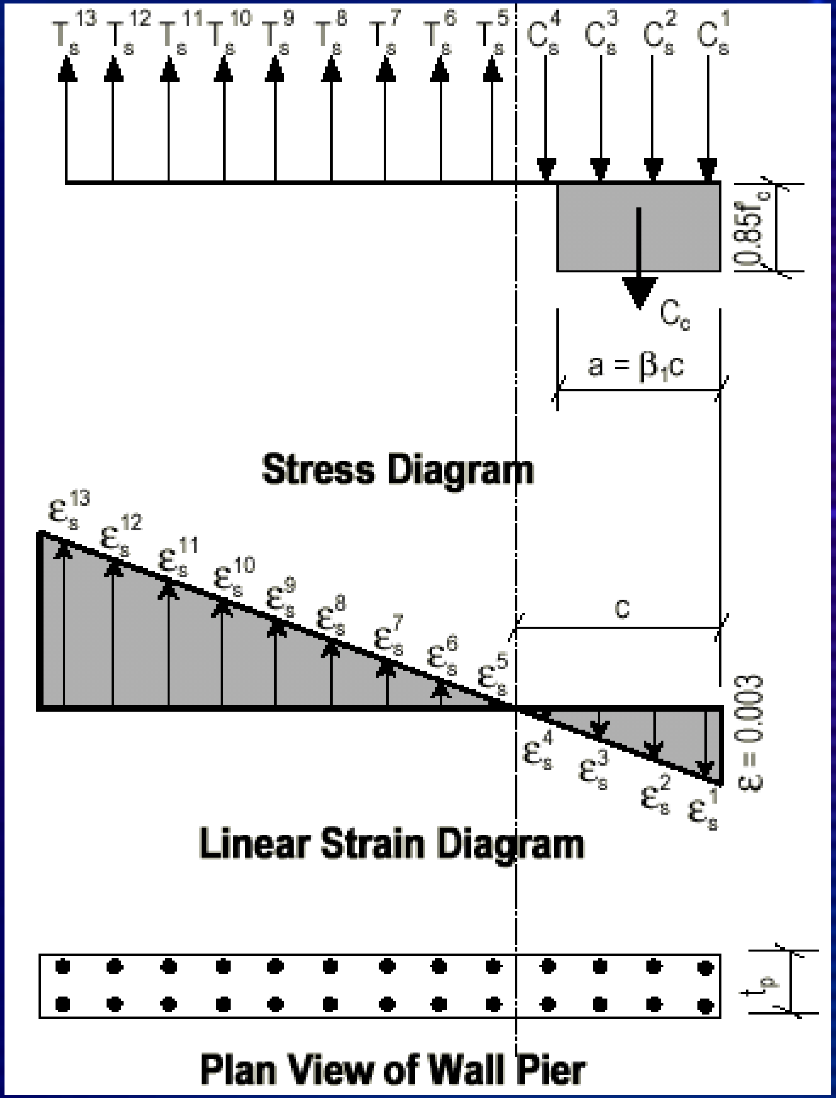
Wall Pier Elevation



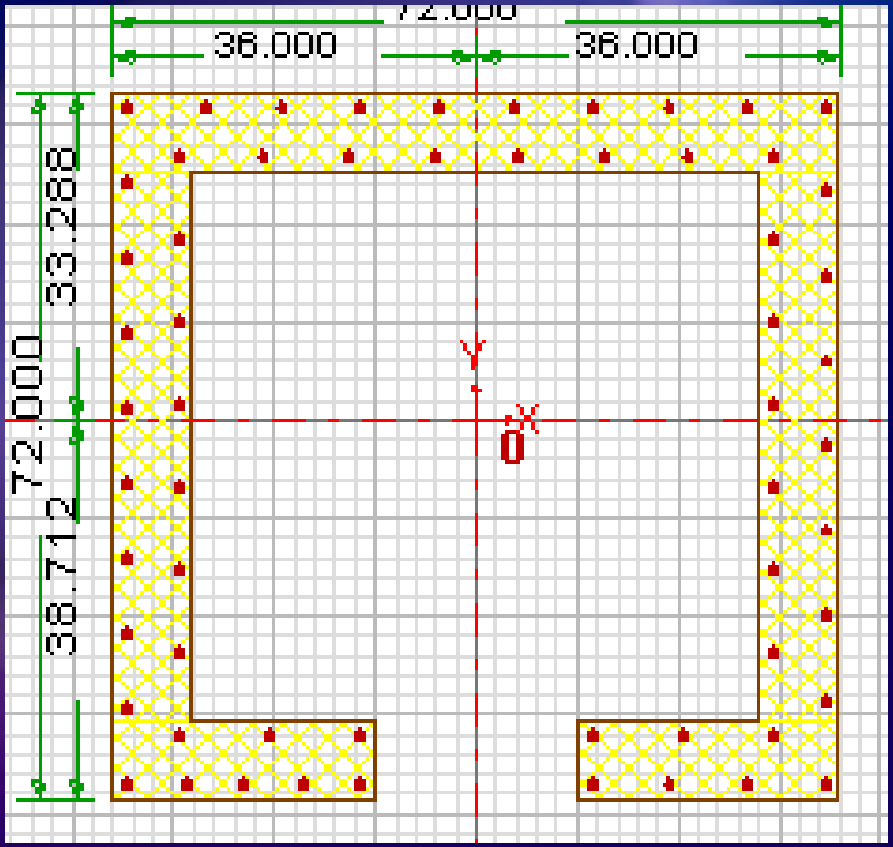


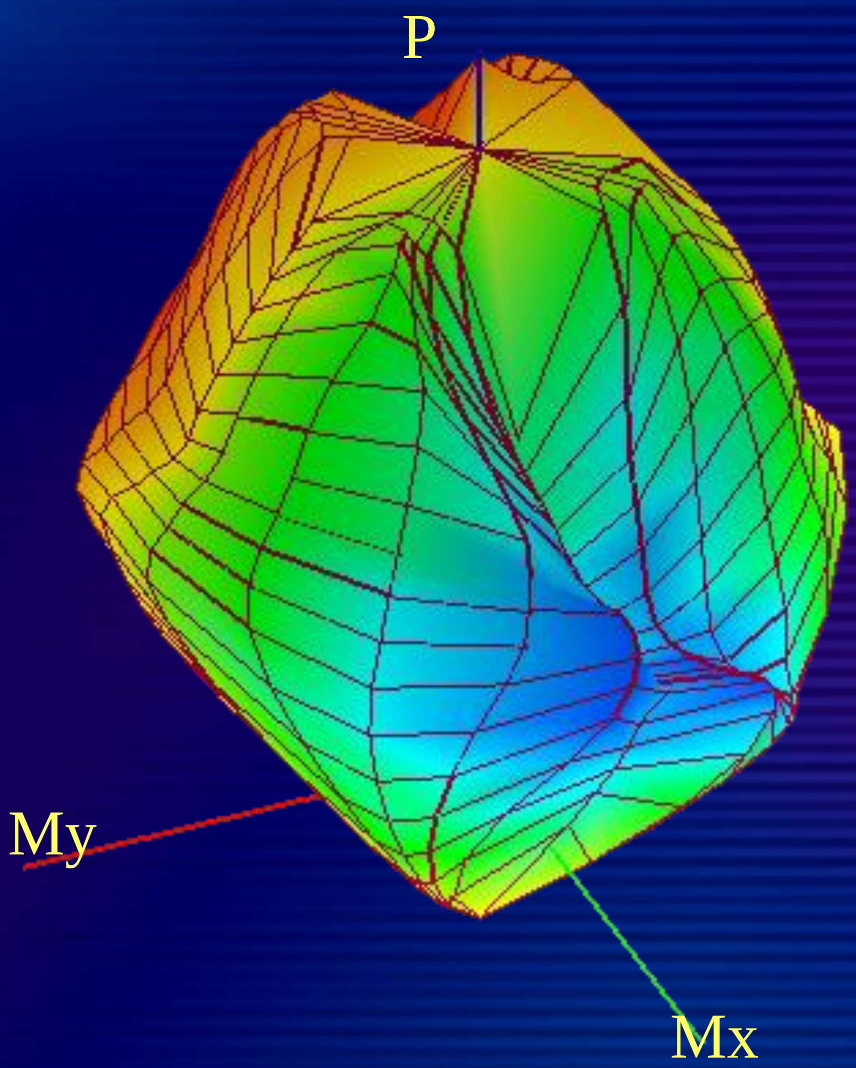
Wall Pier Plan

- **Design based on :**
  - Equilibrium Conditions
  - Strain Compatibility Principle
  - Linear Strain Variation



Interaction Surface for Shear Walls





Concrete Shear Wall Design

- 2D wall pier design and boundary-member checks
- 2D wall spandrel design
- 3D wall pier check for provided reinforcement
- Graphical Section Designer for concrete rebar location
- Graphical display of reinforcement and stress ratios
- Interactive design and review
- Summary and detailed reports including database formats

Shear Wall - Typical Design Process

1. While modeling define Shear Wall elements

2. Choose the Shear Wall design code and review other related preferences and revise them if necessary

3. Assign pier and spandrel labels

3. Run the building analysis

4. Assign overwrites

5. Select Design Combos

6. Start Designing Walls

Shear Wall - Typical Design Process

7. View Design Input and Output Information

8. Design the Member Interactively

9. Print Design Report

10. Change Design Section if Required

11. Re-run Design and Re-analyze if needed

12. Repeat the Above Cycle

Shear Wall Design – Output

Table 1 Shear Wall Design Output Summary

COLUMN HEADING	DESCRIPTION
Simplified Pier Section Design	
Story Label	Label of the story level associated with the pier.
Pier Label	Label assigned to the pier.
Station Location	This is either Top or Bottom to designate the top or the bottom of the pier.
Edge Memb Left	The length of the user-defined edge member, DB1, or the length of the program-determined edge member at the left side of the pier.
Edge Memb Right	The length of the user-defined edge member, DB1, or the length of the program-determined edge member at the right side of the pier.
As Left	The required area of steel at the center of the edge member at the left side of the pier. Note that the area of steel reported here is the maximum of the required tension steel and the required compression steel.
As Right	The required area of steel at the center of the edge member at the right side of the pier. Note that the area of steel reported here is the maximum of the required tension steel and the required compression steel.
Av Shear	The required area per unit length (height) of horizontal shear reinforcing steel in the pier.
B-Zone Length	This item applies only to codes that consider boundary zones. This is a required length, such as 22.762 inches, or it is "Not Needed," or it is "Not Checked." Not Needed indicates that boundary elements are not required. Not Checked means that no check for boundary elements is performed by the program.

Shear Wall Design – Output

Uniform Reinforcing Pier Sections - Design	
Story Label	Label of the story level associated with the pier.
Pier Label	Label assigned to the pier.
Sta Loc	This is either Top or Bot to designate the top or the bottom of the pier.
Edge Bar	The size of the uniformly spaced edge bars.
End Bar	The size of the end and corner bars.
Edge Spacing	The spacing of the uniformly spaced edge bars.
Required Ratio	The maximum required ratio of reinforcing for the pier. This is equal to the total area of vertical steel in the pier divided by area of the pier.
Current Ratio	The ratio of the actual reinforcing specified in the Section Designer section divided by the area of the Section Designer section. This ratio is provided as a benchmark to help you understand how much reinforcing is actually required in the section.
Pier Leg	The pier leg to which the associated shear and boundary zone output applies.
Shear Av	The maximum area per unit length (height) of horizontal reinforcing steel required to resist shear in the specified pier leg
B-Zone Length	This item applies only to codes that consider boundary zones. This is a required length, such as 22.762 inches, or it is "Not Needed," or it is "Not Checked." Not Needed indicates that boundary elements are not required. Not Checked means that no check for boundary elements is performed by the program.
	tion. This ratio is provided as a benchmark to help you understand how much reinforcing is actually required in the section.
Pier Leg	The pier leg to which the associated shear and boundary zone output applies.
Shear Av	The maximum area per unit length (height) of horizontal rein-

Shear Wall Design – Output

Uniform Reinforcing Pier Sections - Check	
Story Label	Label of the story level associated with the pier.
Pier Label	Label assigned to the pier.
Sta Loc	This is either Top or Bot to designate the top or the bottom of the pier.
Edge Bar	The size of the uniformly spaced edge bars.
End Bar	The size of the end and corner bars.
Edge Spacing	The spacing of the uniformly spaced edge bars.
Pier Leg	The pier leg to which the associated shear and boundary zone output applies.
D/C Ratio	The maximum demand/capacity ratio for the pier.
Shear Av	The maximum area per unit length (height) of horizontal reinforcing steel required to resist shear in the specified pier leg
B-Zone Length	This item applies only to codes that consider boundary zones. This is a required length, such as 22.762 inches, or it is "Not Needed," or it is "Not Checked." Not Needed indicates that boundary elements are not required. Not Checked means that no check for boundary elements is performed by the program.

Shear Wall Design – Output

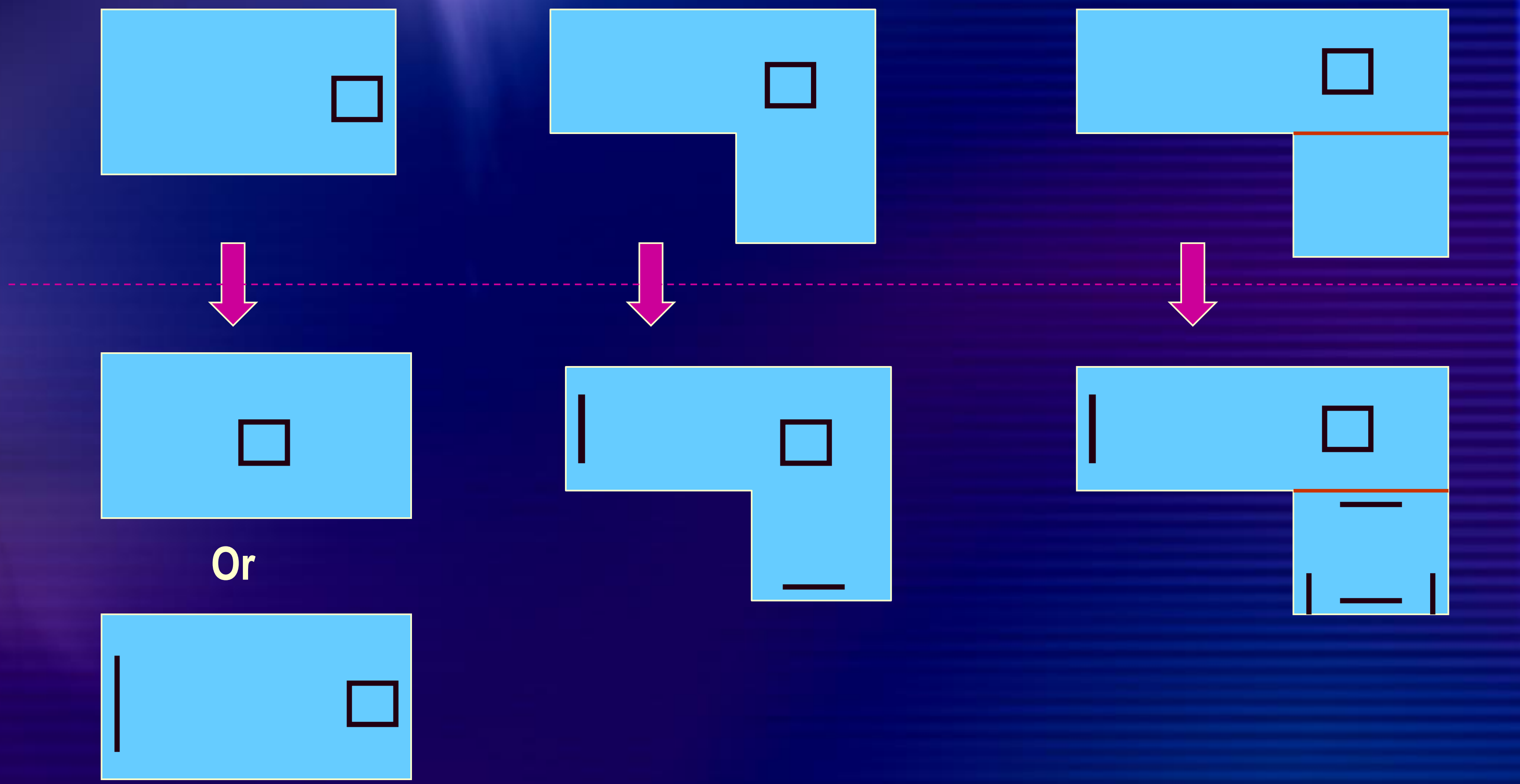
Spandrel Design	
Story Label	Label of the story level associated with the spandrel.
Spandrel Label	Label assigned to the spandrel.
Station Location	This is either Left or Right to designate the left end or the right end of the spandrel.
L/d Ratio	The length of the spandrel divided by the depth.
Shear Vc	The concrete shear capacity used in the spandrel design. See "Determine the Concrete Shear Capacity" in Technical Note Spandrel Shear Design UBC 97, "Determine the Concrete Shear Capacity" in Technical Note Spandrel Shear Design ACI318-99, or "Determine the Concrete Shear Capacity" in Technical Note Spandrel Shear Design BS8110-89 for more information.
Required Reinforcing Steel	
M{top}	The required area of flexural reinforcing steel at the top of the spandrel.
M{bot}	The required area of flexural reinforcing steel at the bottom of the spandrel.
Av	The required area per unit length of vertical shear reinforcing steel in the spandrel.
Ah	The required area per unit length (height) of horizontal shear reinforcing steel in the spandrel.
Avd	The required area of diagonal shear reinforcing steel in the spandrel. This item is only calculated for seismic piers.

The Basic Issues

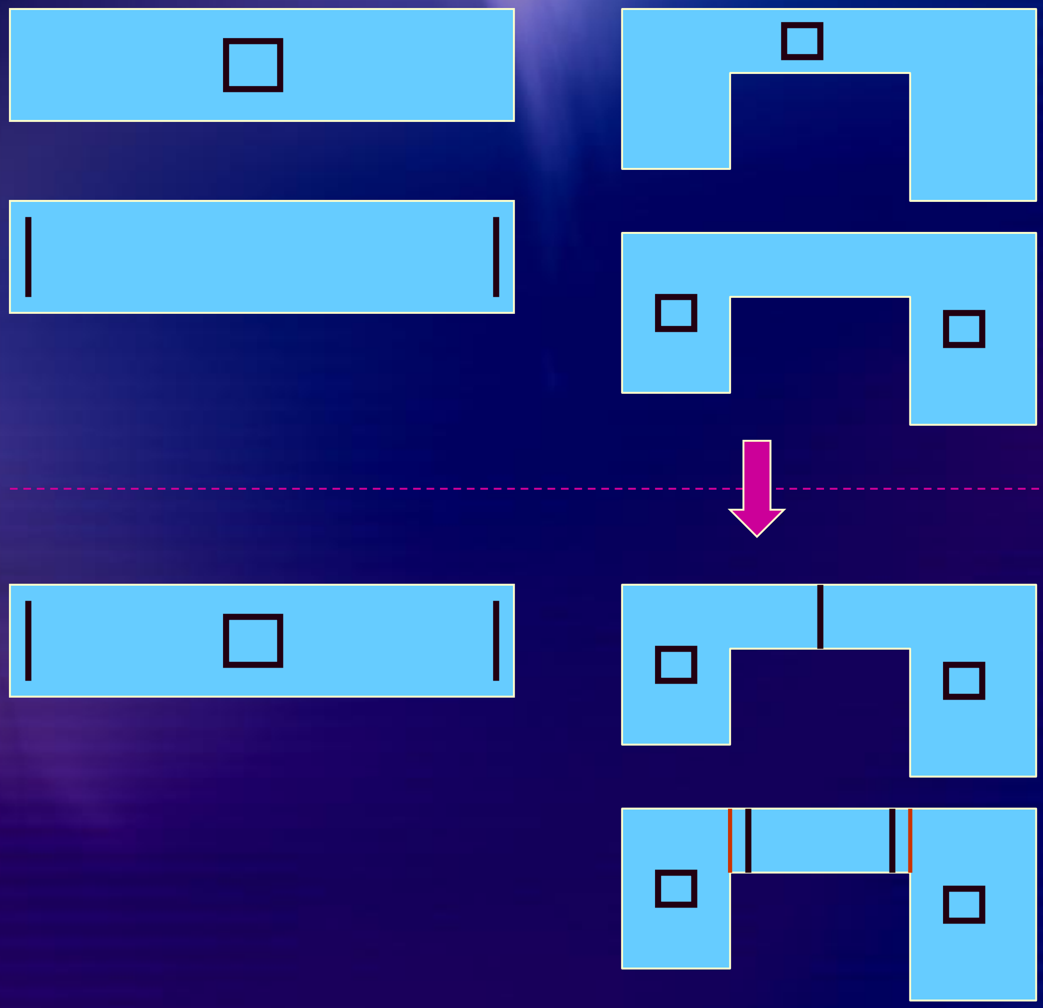
- What is a Shear Wall?
- Modeling and analysis issues
  - **Transfer of loads to shear walls**
  - **Modeling of shear walls in 2D**
  - **Modeling of shear Walls in 3D**
  - **Interaction of shear-walls with frames**

- Design and detaining issues
  - **Determination of rebars for flexure**
  - **Determination of rebars for shear**
  - **Detailing of rebars near openings and corners**
  - **Design and detailing of connection between various components of cellular shear walls**

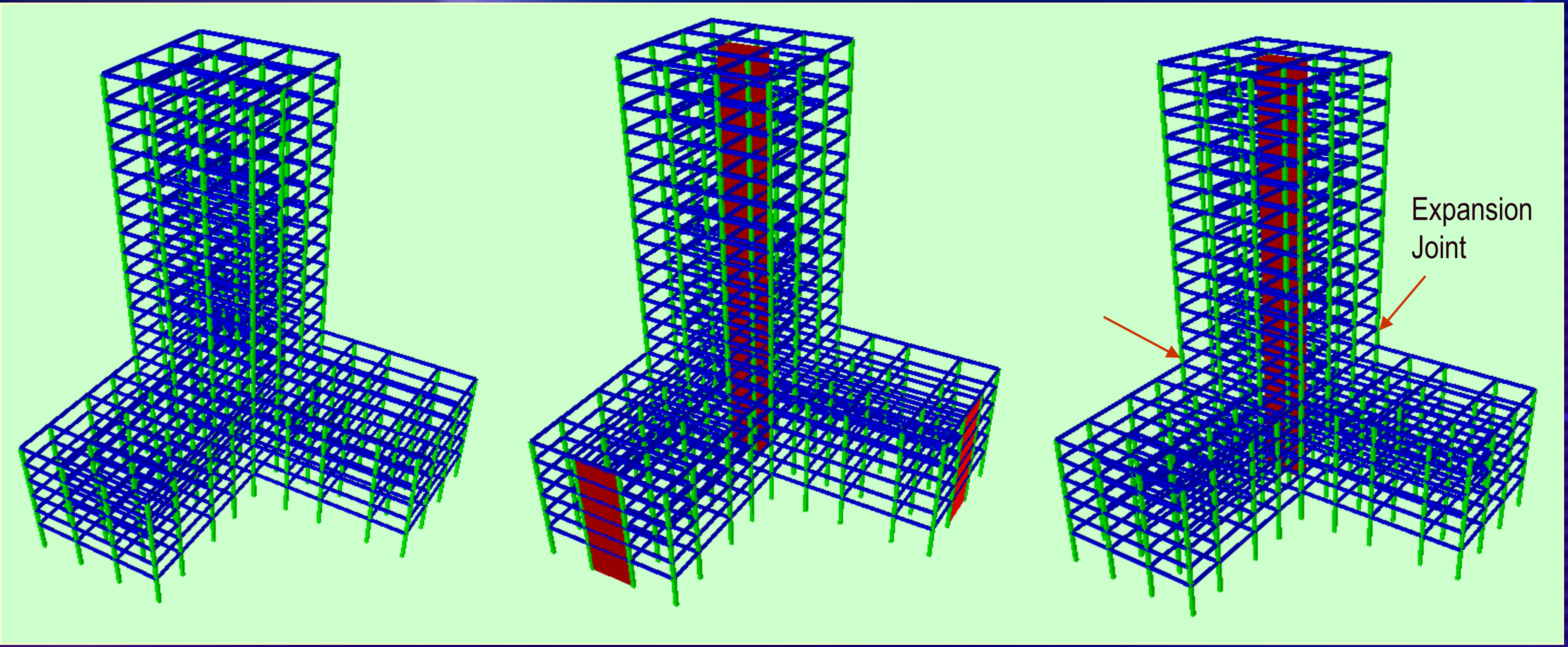
Avoid Eccentricity in Plan



Reduce In-plane Bending in Floor



Vertical Irregularity



No Shear Walls

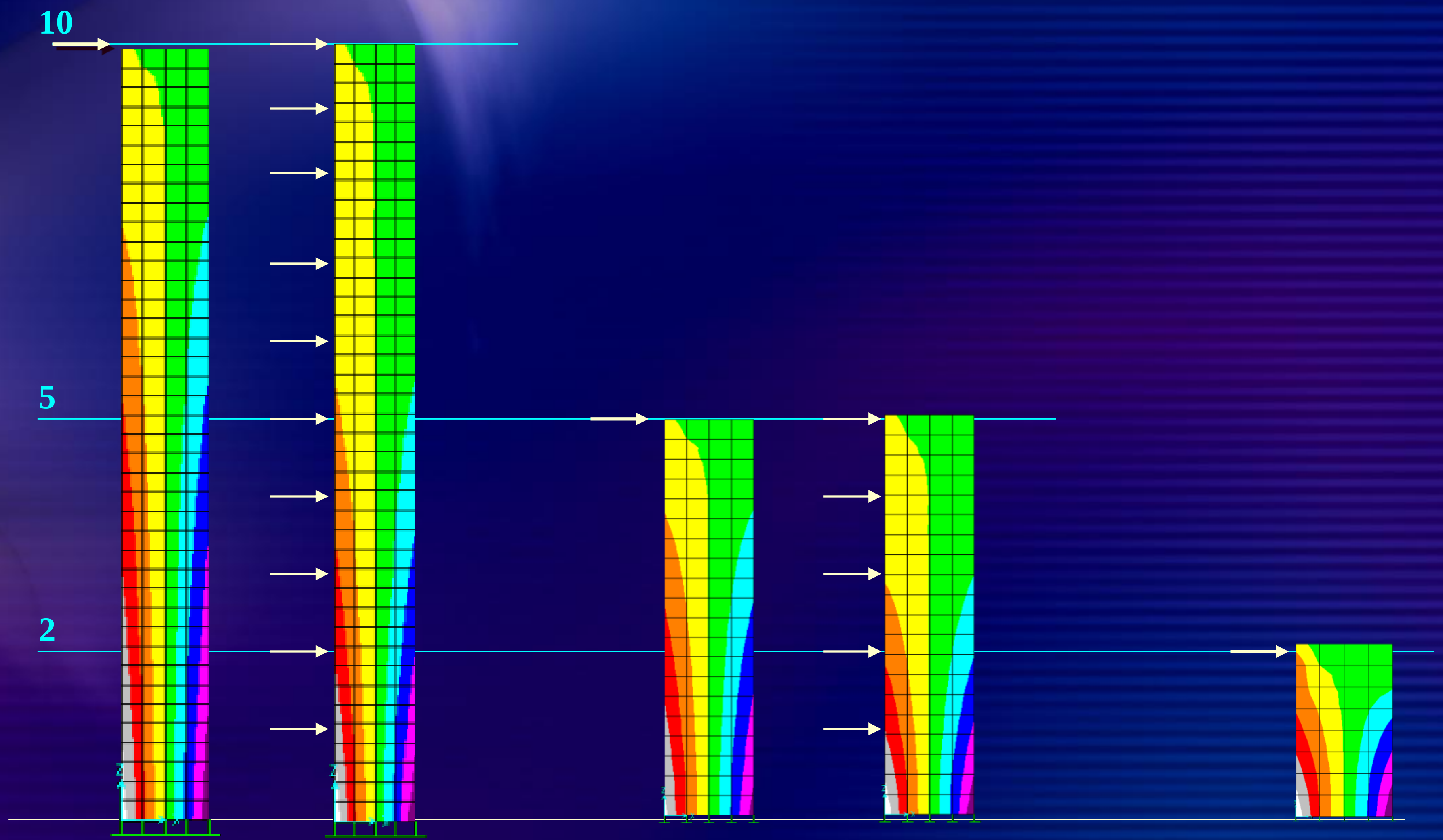
Balanced Shear Walls at All Levels

Using Expansion Joints to eliminate some walls

Using Efficient Building Plan Shape

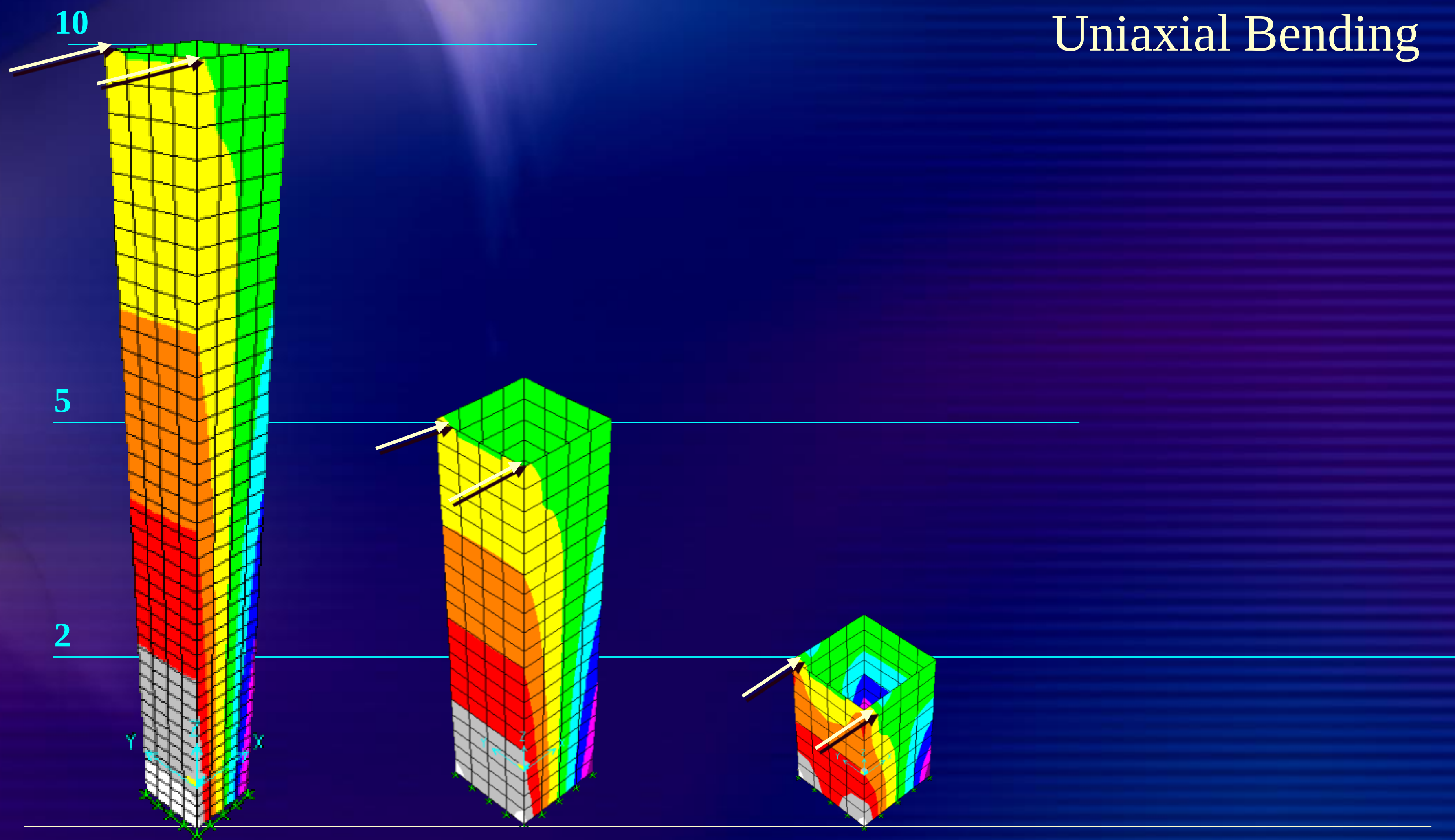
Design of Shear Walls

Axial Stresses in Planer Walls

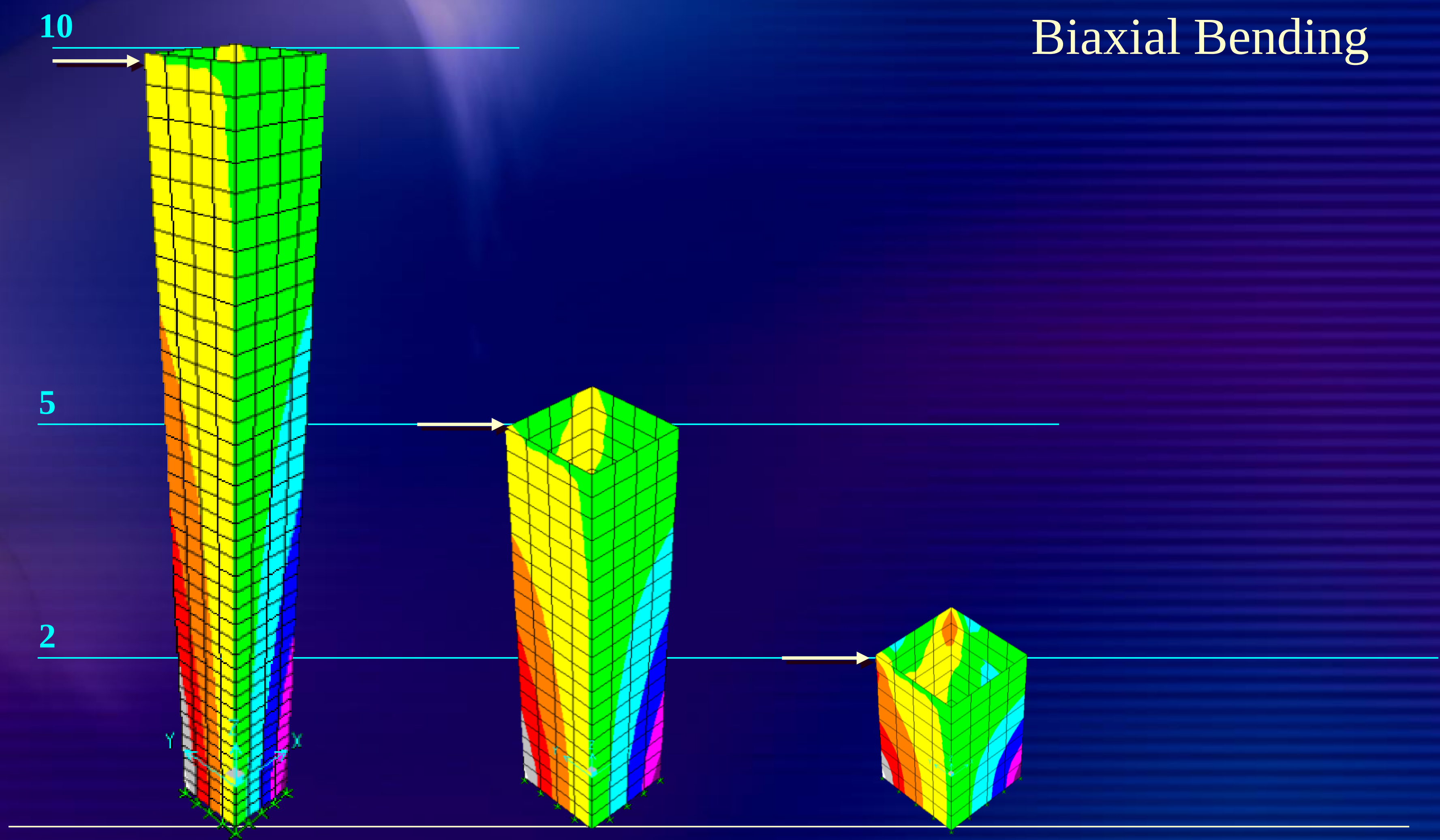


Axial Stresses in Cellular Walls

Uniaxial Bending

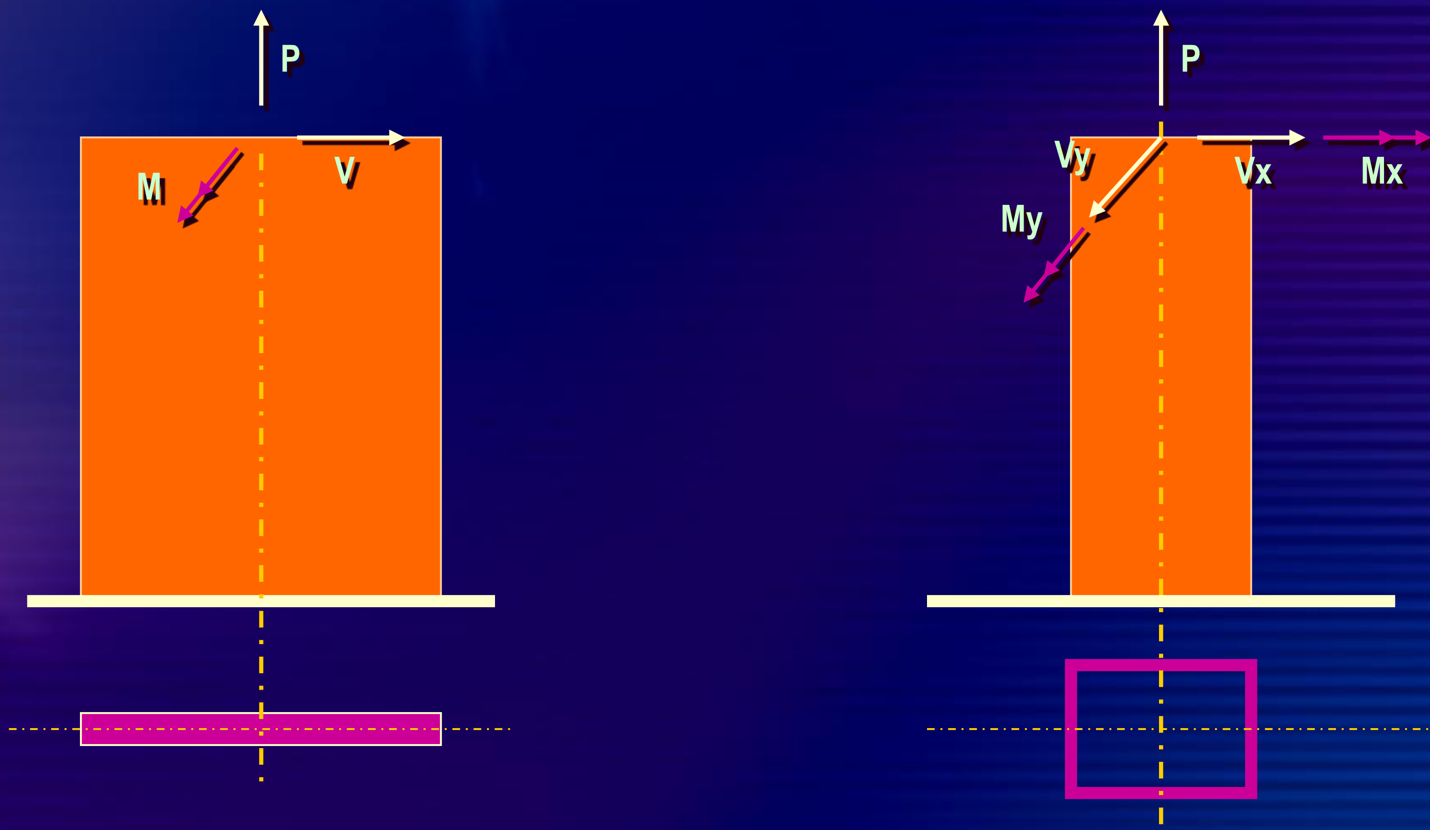


Axial Stresses in Cellular Walls

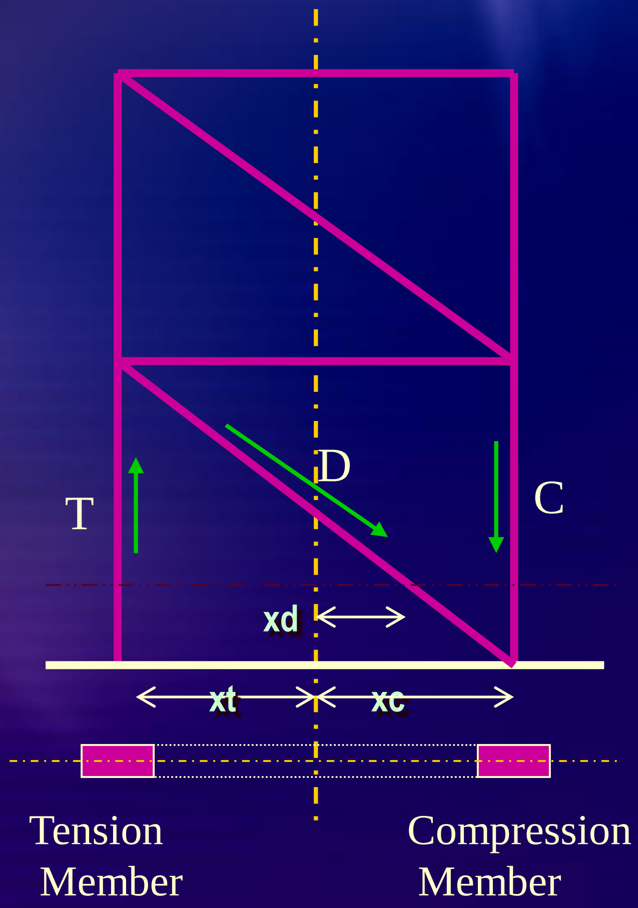


Getting Result from Frame Model

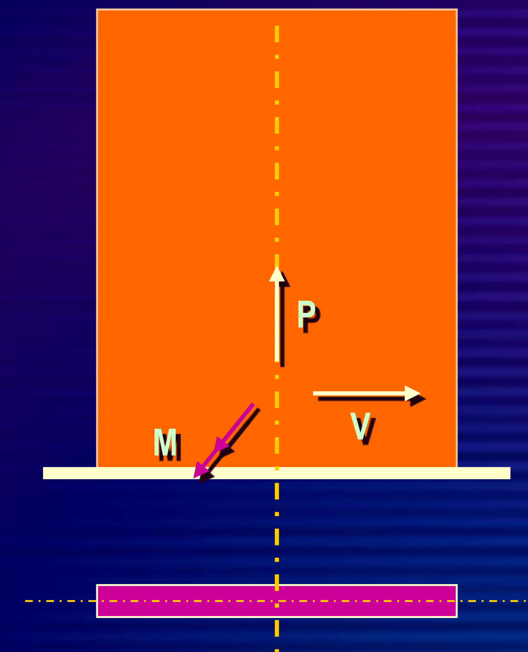
Design actions (P, Mx, My and V) are obtained directly



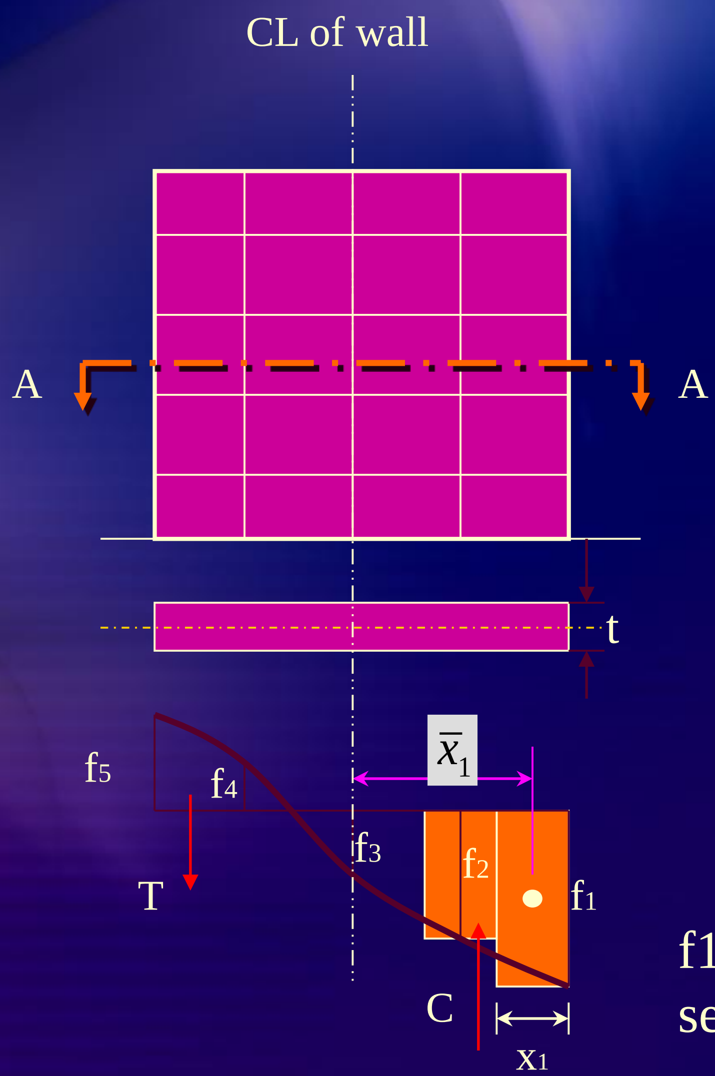
Getting Results from Truss Model

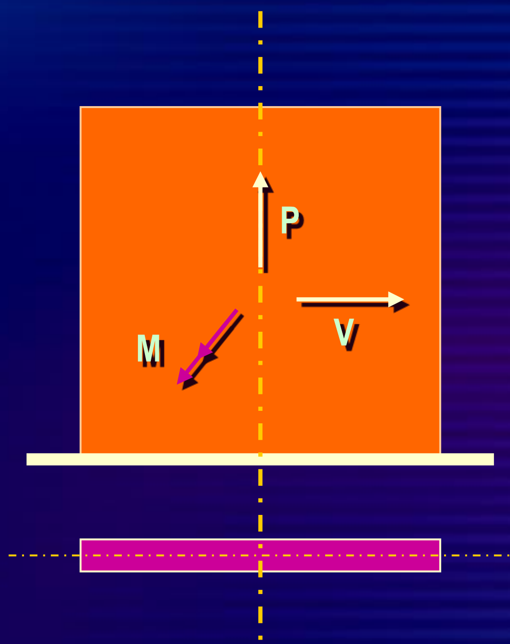


$$P = T + C + D\sin(\theta)$$
$$M = Tx_t + Cx_c + D\sin(\theta)x_d$$
$$V = D\cos(\theta)$$



Getting Results From Shell Model





$$F_i = A_i f_i$$

$$P = \sum_{i=1}^{n} F_i$$

$$M = \sum_{i=1}^{n} F_i x_i$$

$$V = \sum_{i=1}^{n} A_i v_i$$

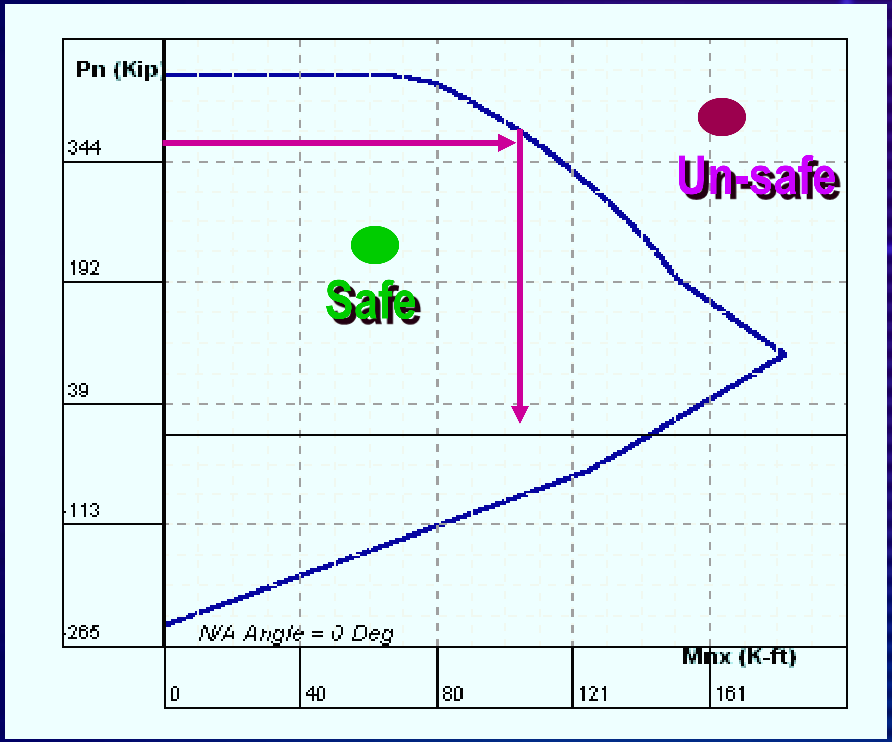
f1, f2, …..fn are the nodal stresses at section A-A , obtained from analysis

Interaction Curves - Uniaxial

The curve is generated by varying the neutral axis depth

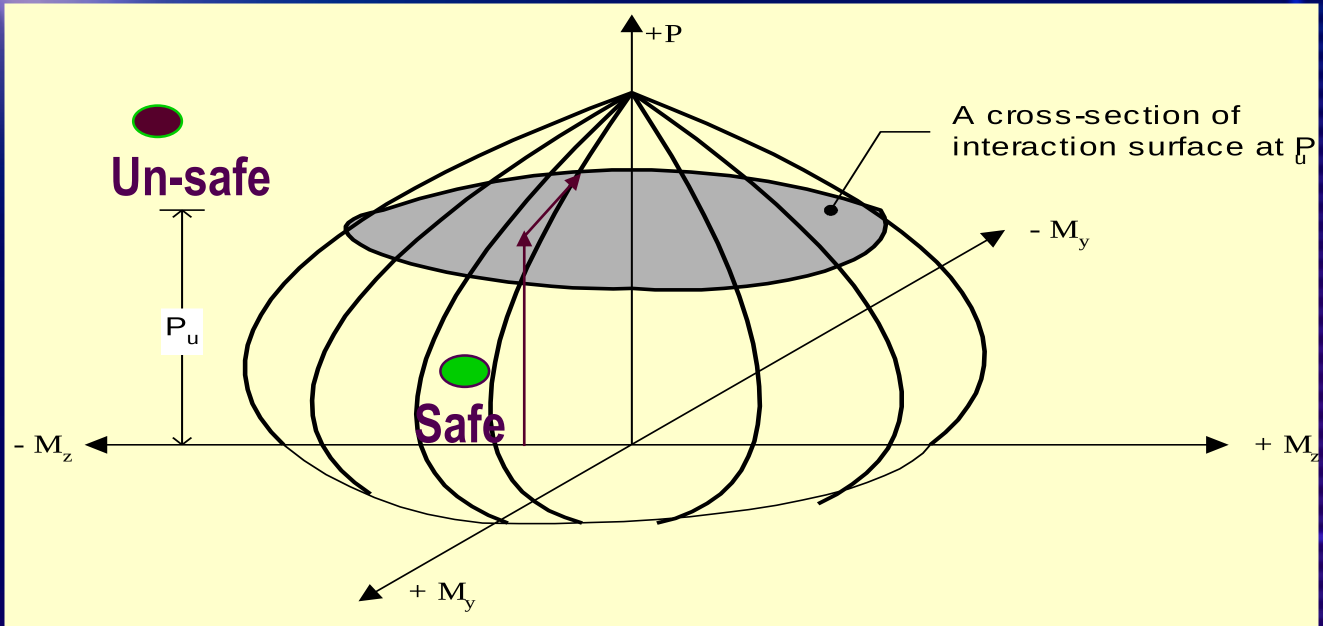
$$N_{nx} = \phi \left[\int_A f_c(\varepsilon) da + \sum_{i=1}^{Nb} f_{si} A_{si} \right]$$

$$M_{ny} = \phi \left[\int_z \int_A f_c(\varepsilon) da.dz + \sum_{i=1}^{Nb} f_{si} A_{si} d_{zi} \right]$$



Interaction Surface - Biaxial

The surface is generated by changing Angle and Depth of Neutral Axis

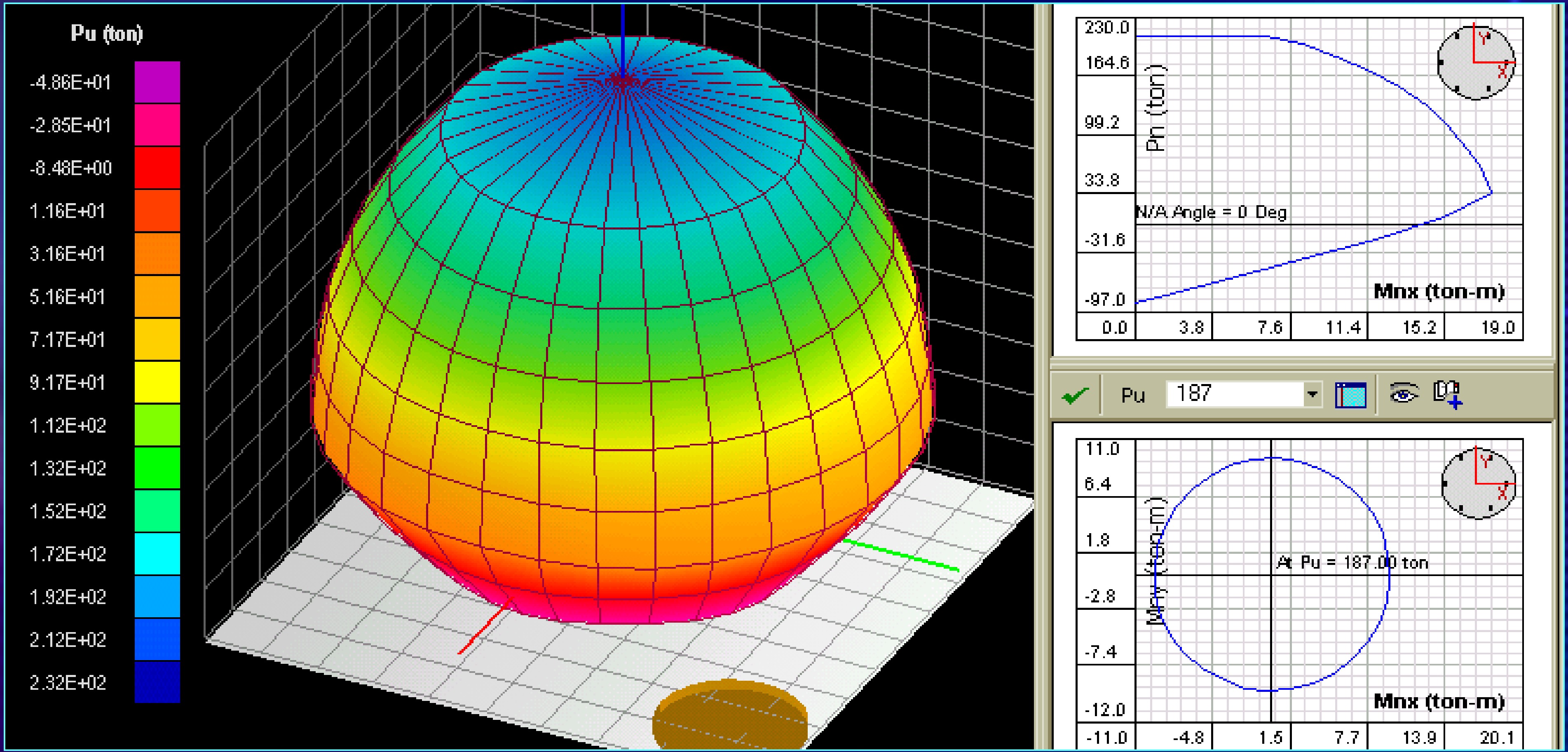


$$N_z = \phi_1 \left[\frac{1}{\gamma_1} \int_x \int_y \sigma(x,y) dx\, dy \;\ldots + \frac{1}{\gamma_2} \sum_{i=1}^{n} A_i \sigma_i (x,y) \;\ldots \right]$$

$$M_x = \phi_2 \left[\frac{1}{\gamma_1} \int_x \int_y \sigma(x,y) dx\, dy . y \;\ldots + \frac{1}{\gamma_2} \sum_{i=1}^{n} A_i \sigma_i (x,y) \; y_i \ldots \right]$$

$$M_y = \phi_3 \left[\frac{1}{\gamma_1} \int_x \int_y \sigma(x,y) dx\, dy . x \;\ldots + \frac{1}{\gamma_2} \sum_{i=1}^{n} A_i \sigma_i (x,y) \; x_i \ldots \right]$$

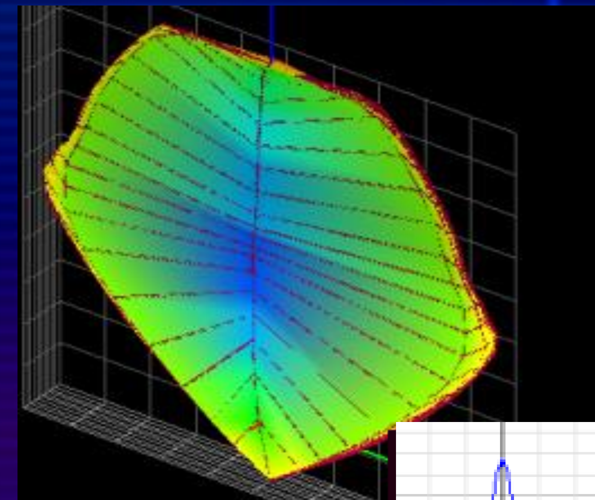
Interaction Surface and Curves

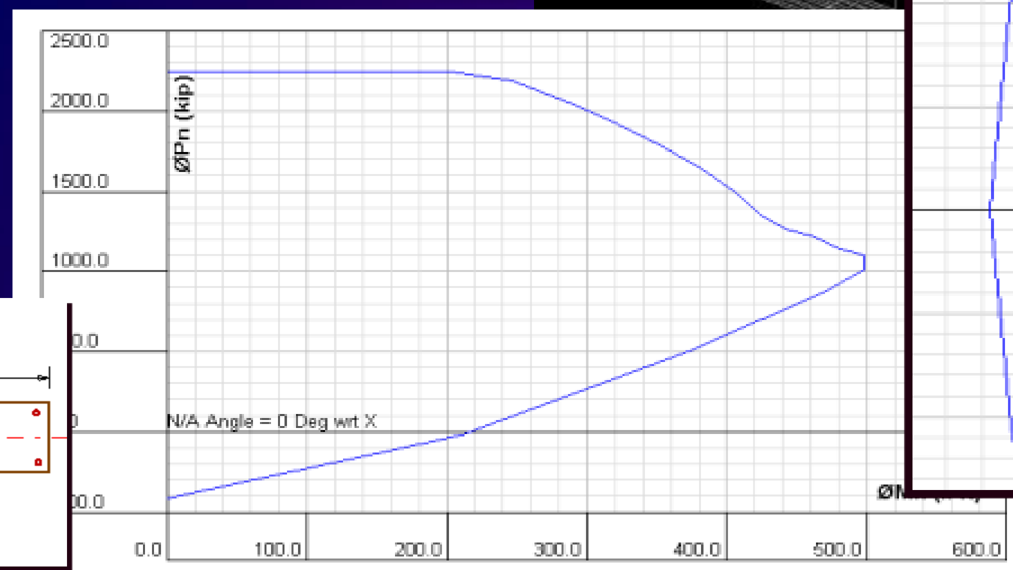


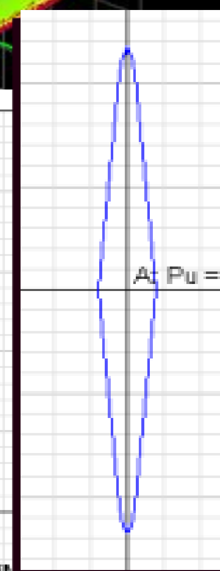
Narrow Planner Walls

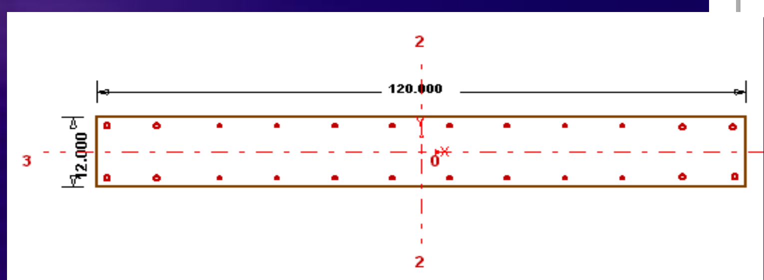
The capacity is almost completely un-axial

Moment capacity can be increased by providing Rebars at the corners



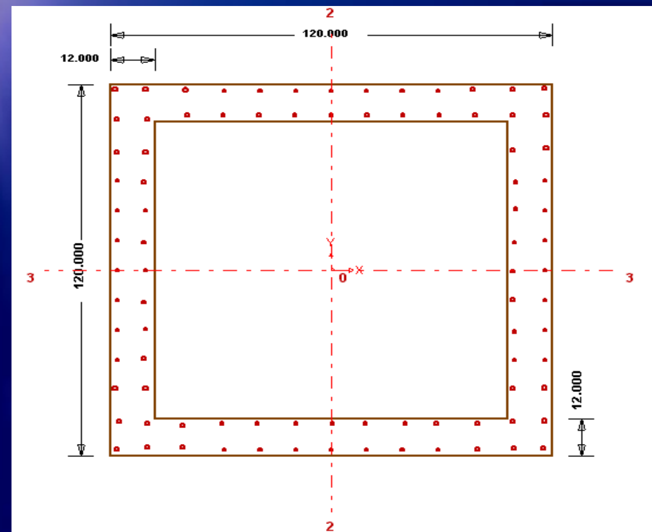


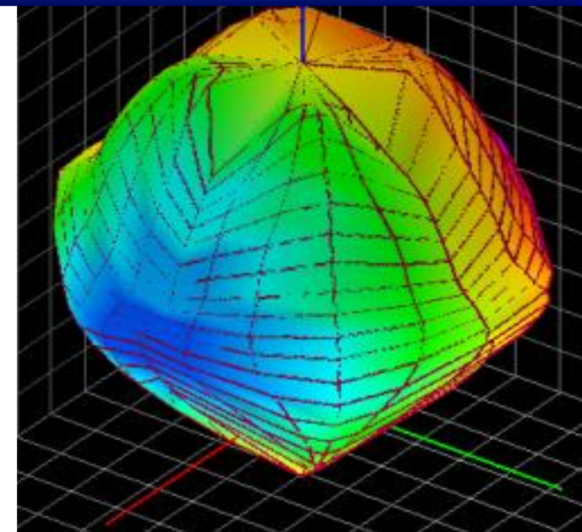


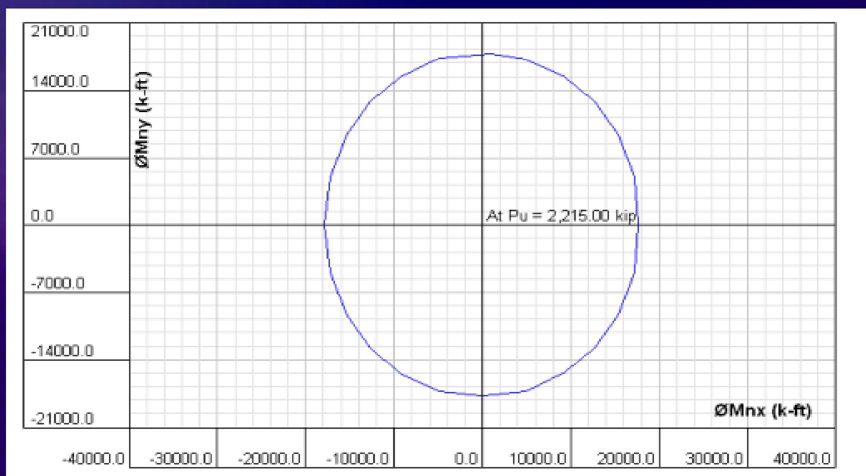


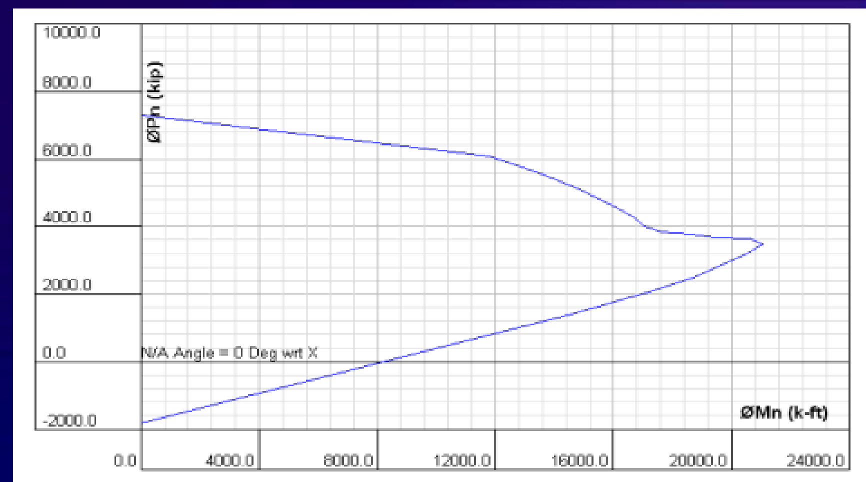
Cellular Wall – No Opening

The capacity is almost completely biaxial

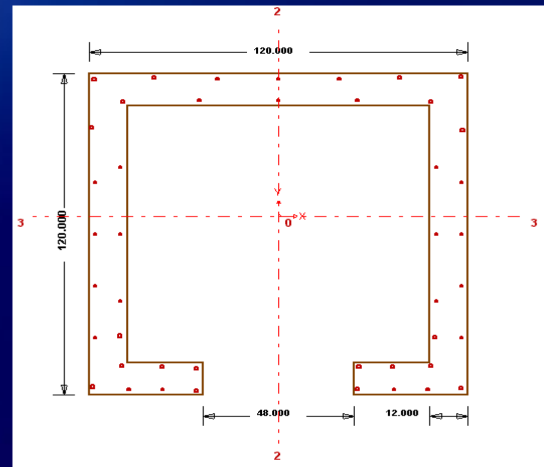


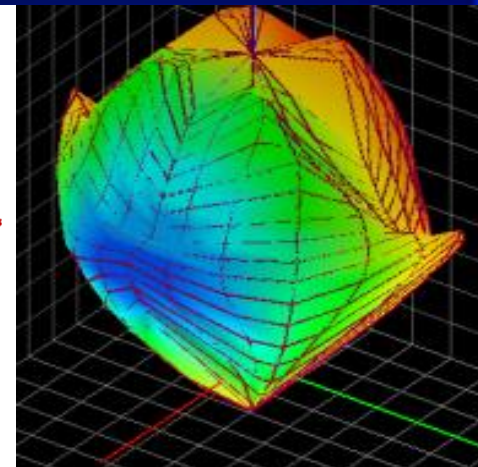


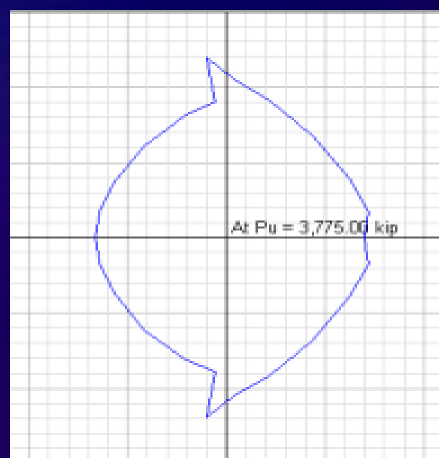


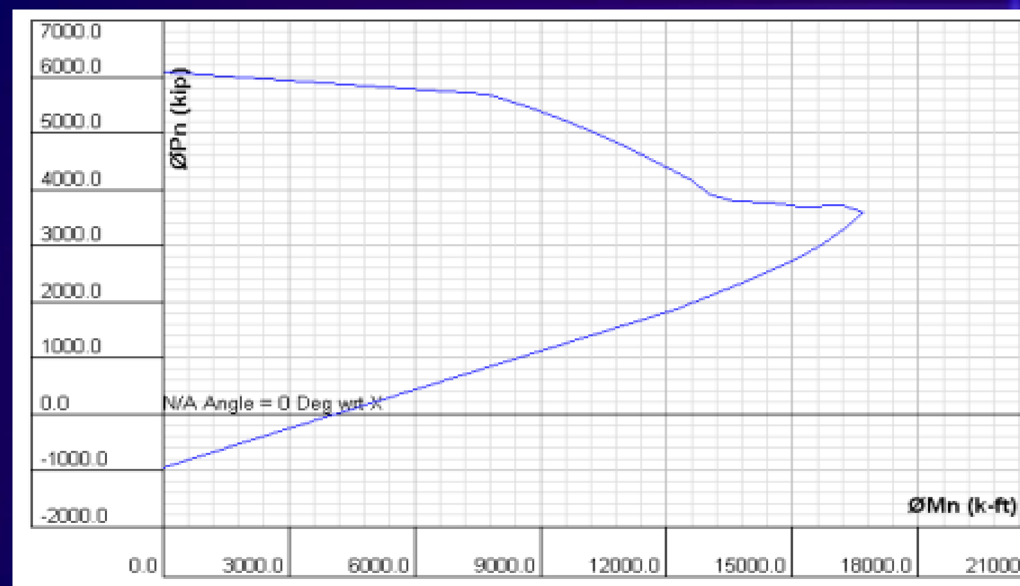


Single Cell Walls

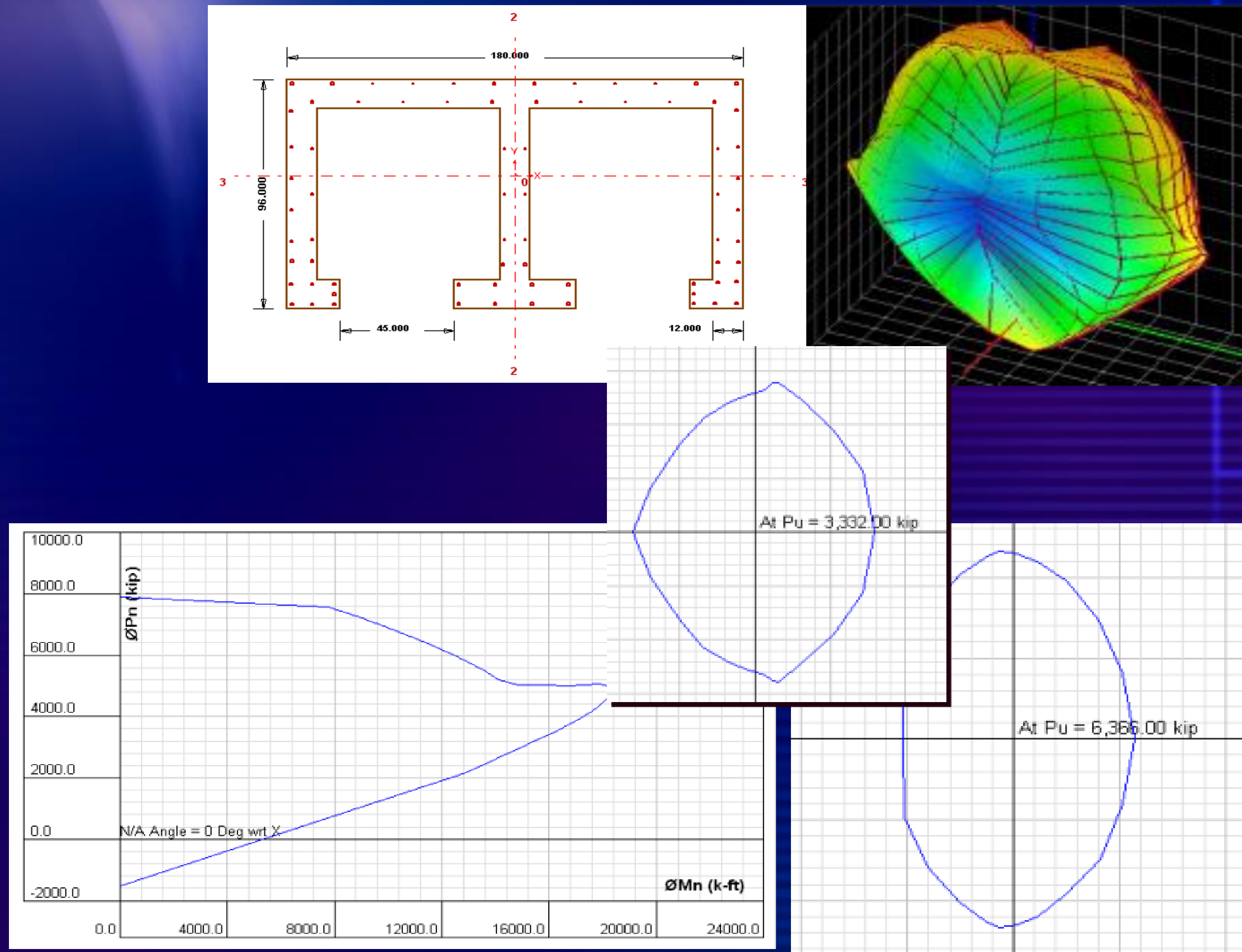




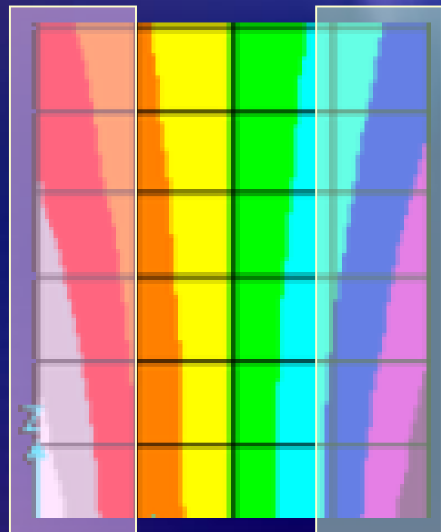


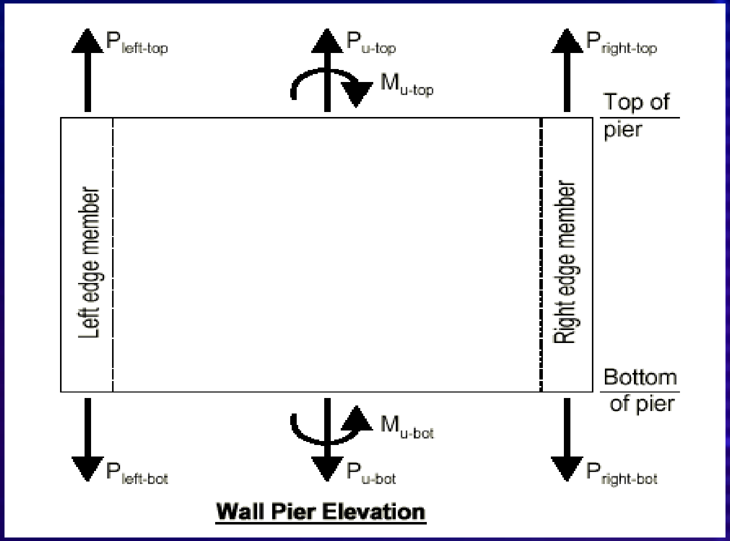


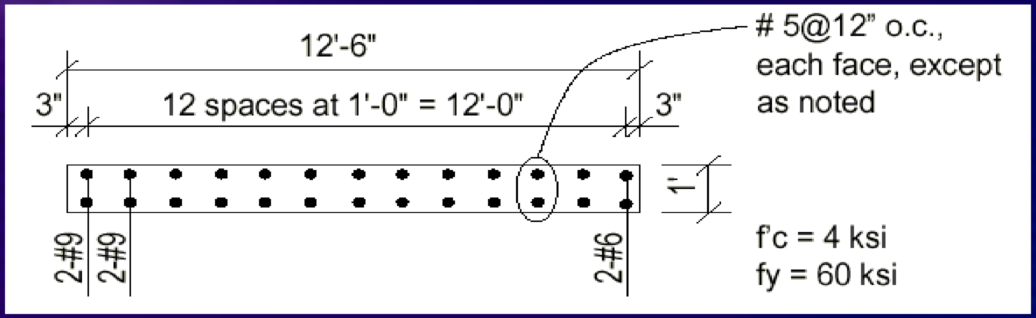
Double Cell Walls

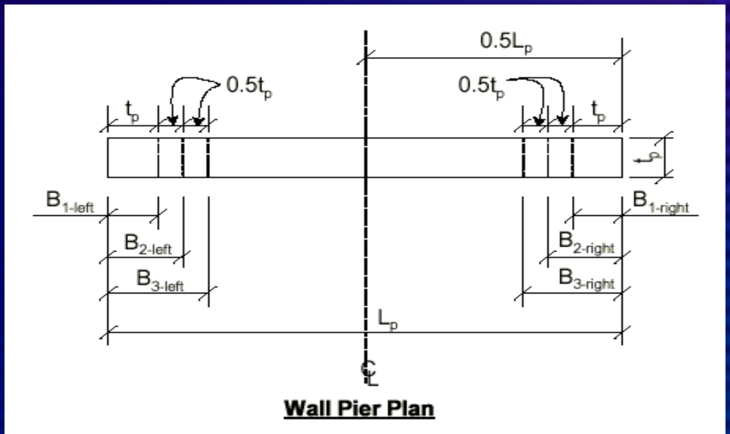


Designing as Axial Zones

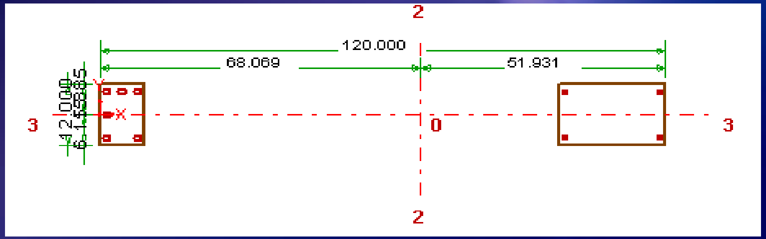


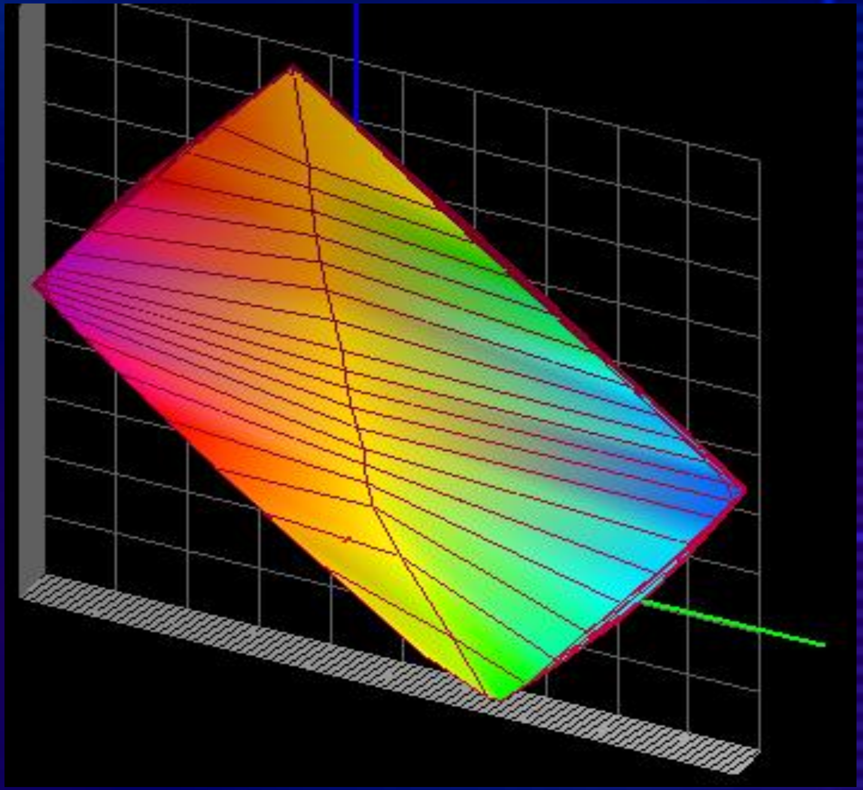




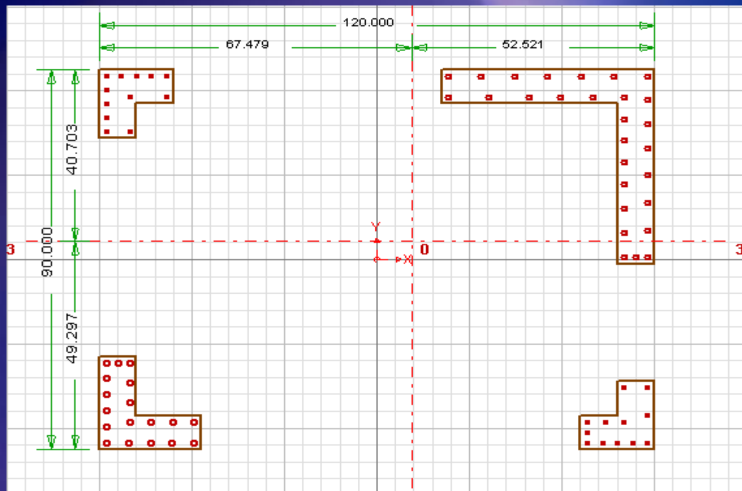


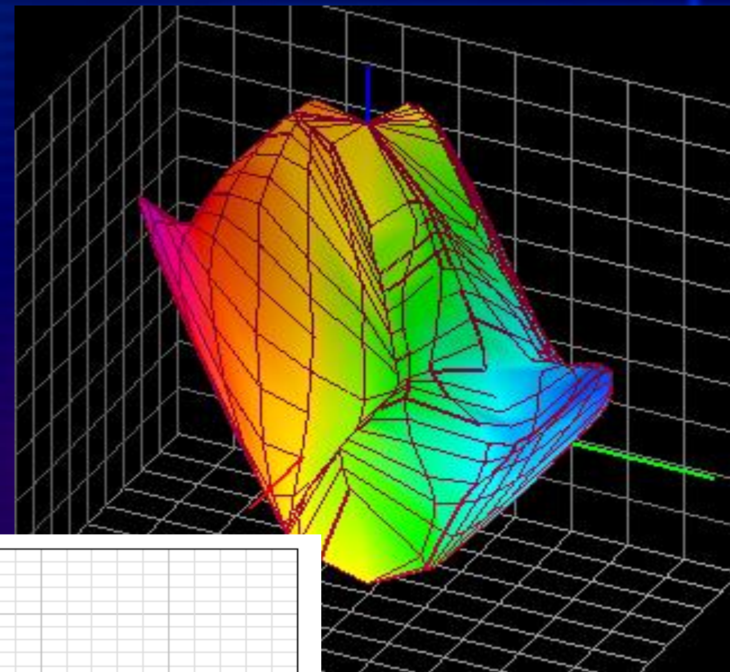
Axial Zone Model – Planer Wall

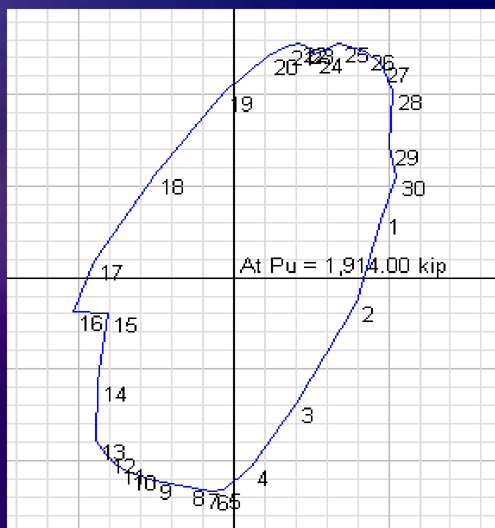


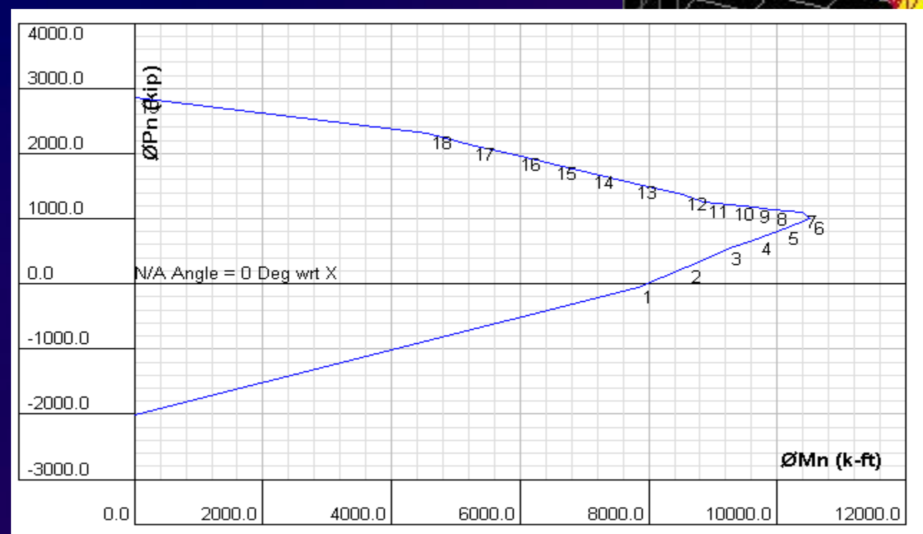


Axial Zones for Box Wall

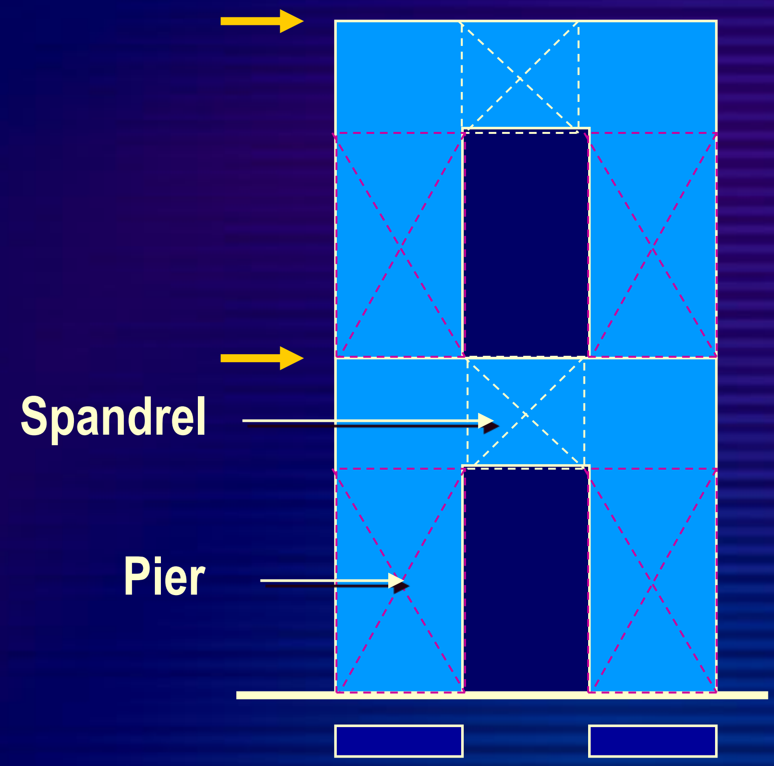






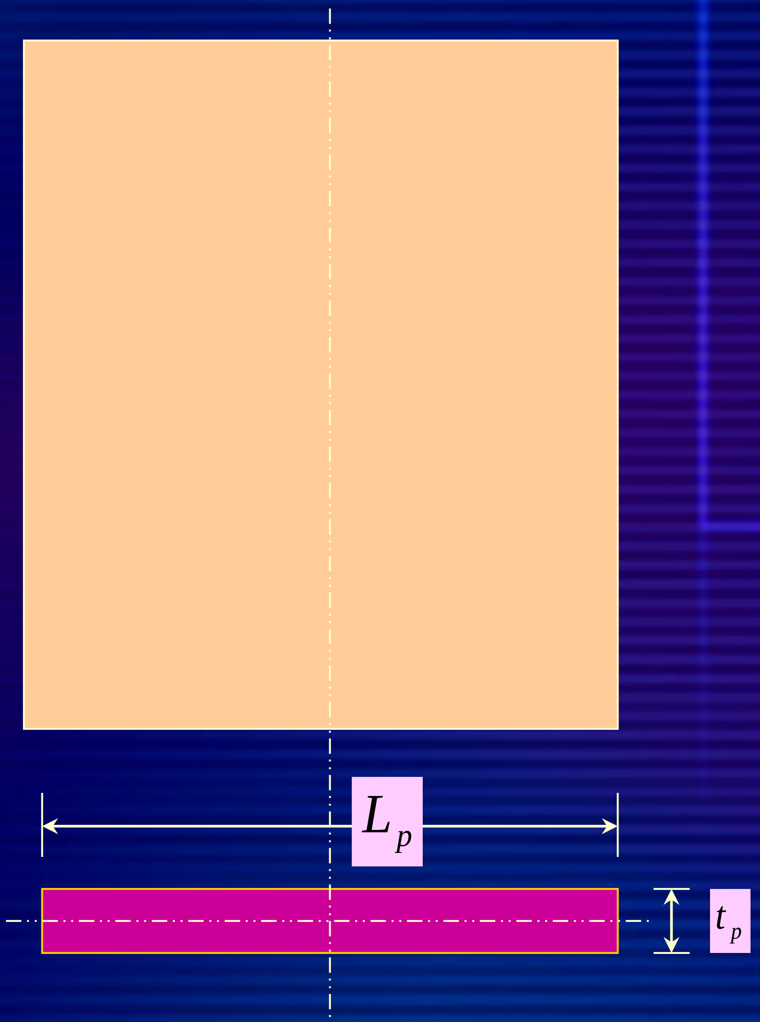


Shear Design



Shear Design of Pier

- Determine Concrete shear capacity, Vc
- Check if Vc exceeds the limit, if it does, section needs to be revised
- Determine steel Rebars for Vs=V-Vc
- Check additional steel for seismic requirements



ACI Equations for Pier Design

Basic Concrete Shear Capacity

$$V_c = 3.3 R_{LW} \sqrt{f'_c}\, t_p \left(0.8 L_p\right) - \frac{P_u \left(0.8 L_p\right)}{4 L_p}$$

Concrete not to Exceed the limit

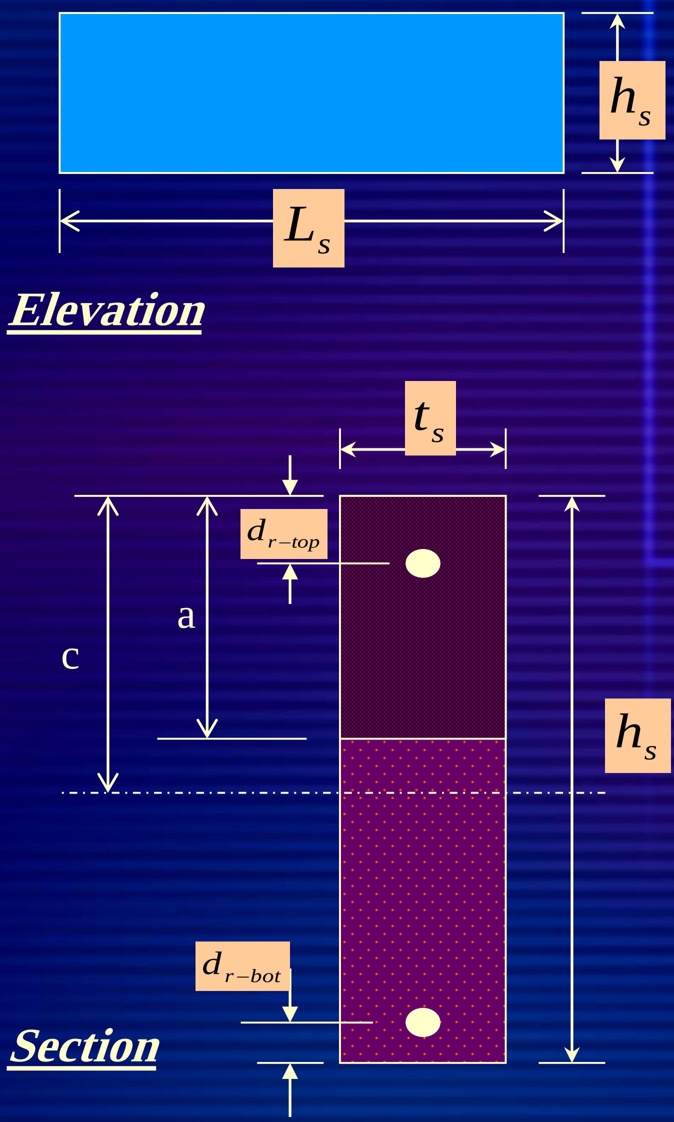
$$V_c \le \left[0.6 R_{LW} \sqrt{f'_c} + \frac{L_p \left(1.25 R_{LW} \sqrt{f'_c} - 0.2 \frac{P_u}{L_p t_p} \right)}{Abs\left(\frac{M_u}{V_u}\right) - \frac{L_p}{2}} \right] t_p \left(0.8 L_p\right)$$

Area of Steel Computed as

$$A_v = \frac{\frac{Abs\left(V_u\right)}{\phi} - V_c}{f_{ys}\left(0.8 L_p\right)} \qquad \frac{Abs\left(V_u\right)}{\phi} \le 10 R_{LW} \sqrt{f'_c}\, t_p \left(0.8 L_p\right)$$

Shear Design for Spandrel

- Determine Concrete shear capacity, Vc
- Check if Vc exceeds the limit, if it does, section needs to be revised
- Determine steel Rebars for Vs=V-Vc
- Check additional steel for seismic requirements



ACI Equations for Spandrel Design

Basic Concrete Shear Capacity

$$V_c = 2R_{LW}\sqrt{f_c'}\,t_s d_s$$

Concrete not to Exceed the limit

$$V_s = V_n - V_c = \frac{V_u}{\phi} - V_c$$

Area of Steel Computed as

$$A_v = \frac{V_s}{f_{ys} d_s} \qquad V_s \le 8R_{LW}\sqrt{f_c'}\,t_s d_s$$

Check for minimum steel and spacing etc.

ACI Equations for Spandrel Design

When $\frac{L_s}{d_s} > 5$ and $\frac{V_u}{\phi} > 0.5V_c$

$$A_{v\,min} = \frac{50t_s}{f_{ys}}$$

$$A_{h\,min} = 0$$

When $\frac{L_s}{d_s} > 5$ and $\frac{V_u}{\phi} \le 0.5V_c$

$$A_{v\,min} = A_{h\,min} = 0$$

When $2 \le \frac{L_s}{d_s} \le 5$ Check

$$\frac{V_u}{\phi} \le \frac{2}{3}\left(10 + \frac{L_s}{d_s}\right) R_{LW} \sqrt{f_c'}\, t_s d_s$$

$$A_{v\,min} = 0.0015t_s$$

$$A_{h\,min} = 0.0025t_s$$

Notations for Shear Design

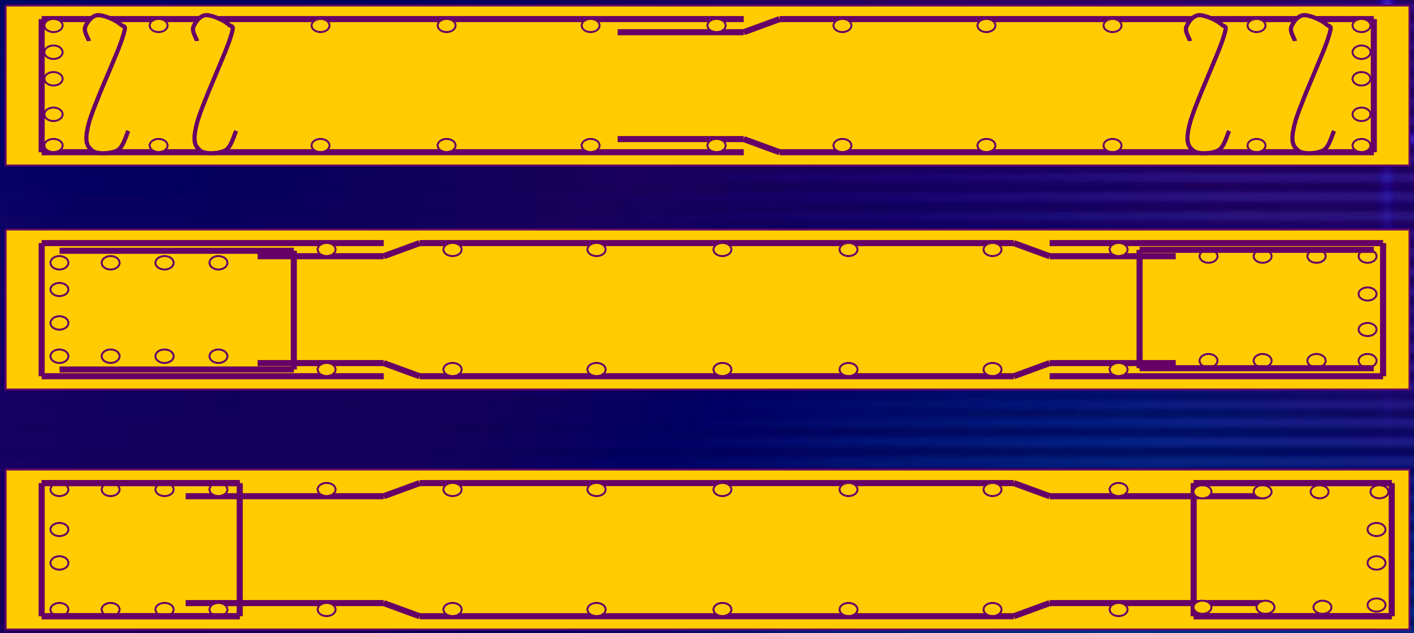
L_s	= Length of Spandrel
t_s	= Thickness of Spandrel
d_{r-top}	= Distance from top of spandrel to the centroid of top reinforcing
d_{r-bot}	= Distance from bottom of spandrel to the centroid of bottom reinforcing
h_s	= Total depth of spandrel
R_{LW}	= Shear reduction factor as specified in the concrete material properties for light weight concrete.
d_s	= Effective depth of spandrel
V_s	= Portion of Shear force in spandrel carried by reinforcing steel
V_c	= Portion of Shear force in spandrel carried by concrete

- Place more reinforcement at the ends and distribute the remaining in the middle portion
- Confine the Rebars at the end for improved ductility and increased moment capacity

Option -1

Option -2

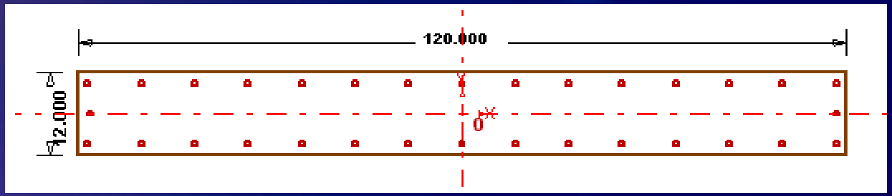
Option -3

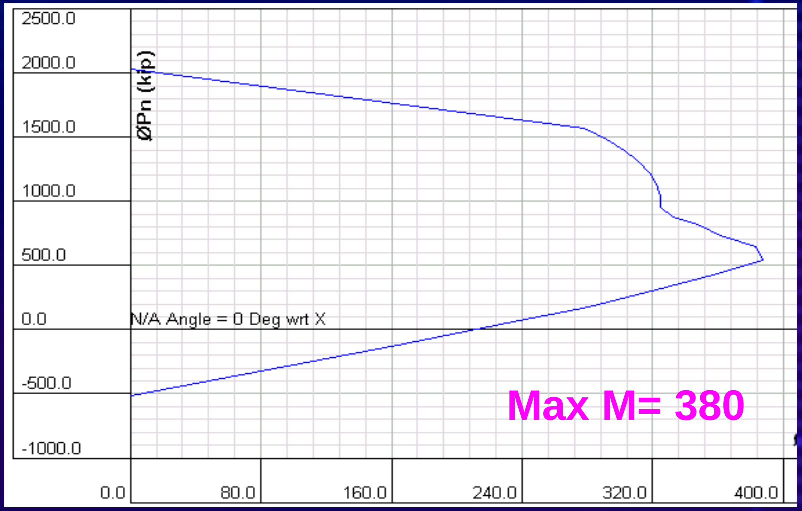


Effect of Rebar Layout

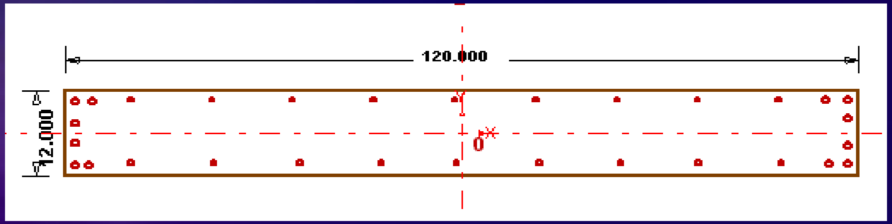
Moment Capacity for 1% Rebars

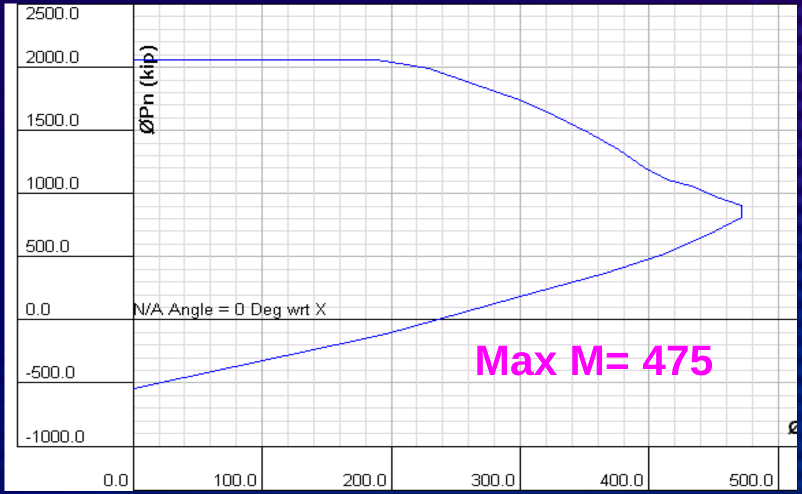
a) Uniform Distribution





b) Concentrated Bars

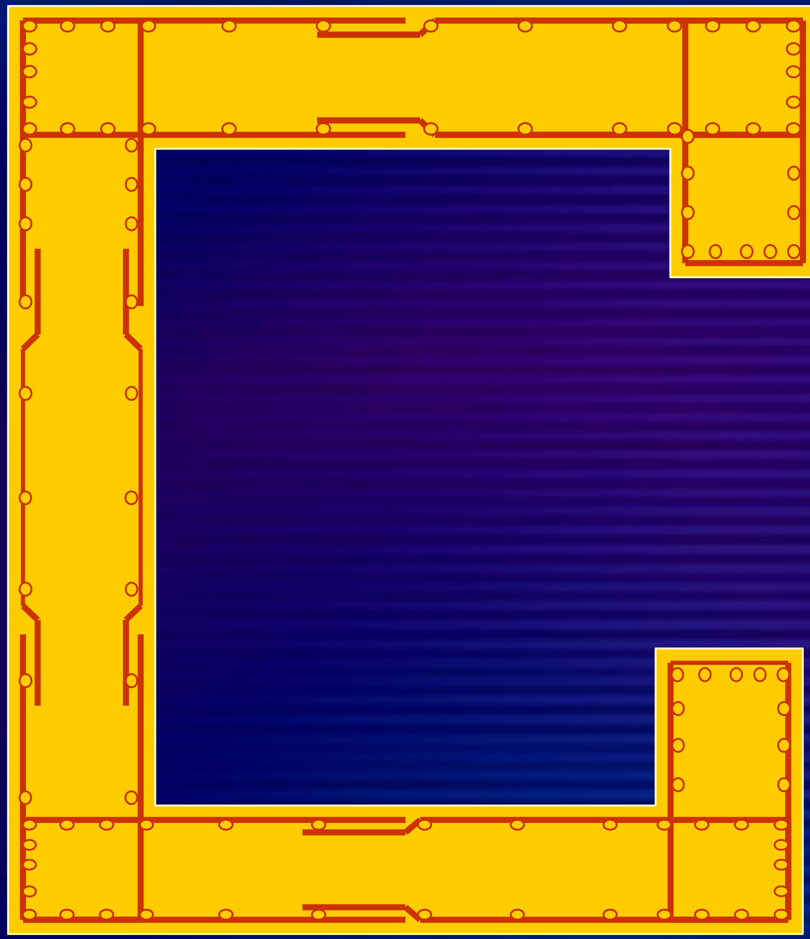




Nearly 25% increase for same steel

Wall Section

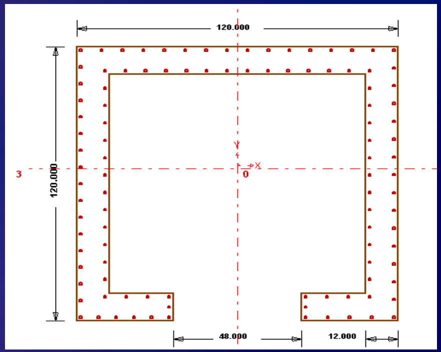
- Place more reinforcement at the corners and distribute the remaining in the middle portion
- Confine the Rebars at the corners for improved ductility and increased moment capacity
- Provide U-Bars at the corners for easier construction and improved laps

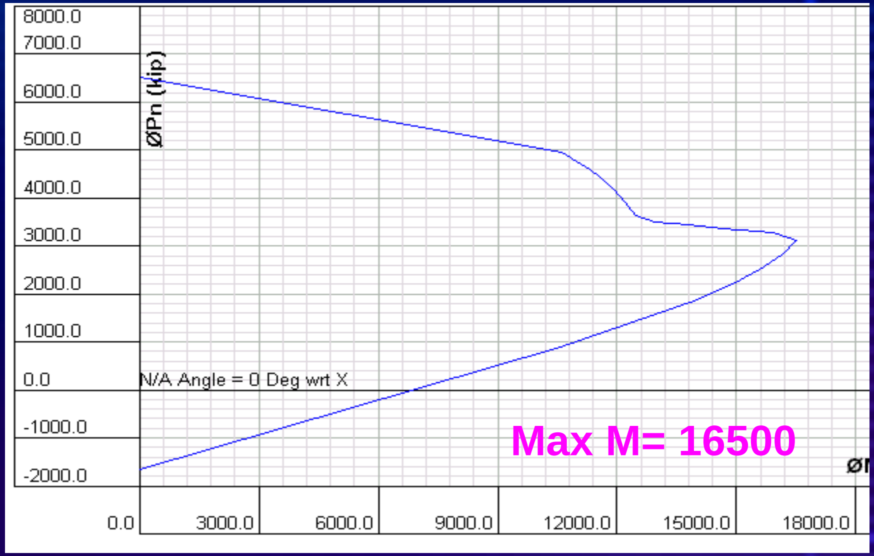


Effect of Rebar Layout

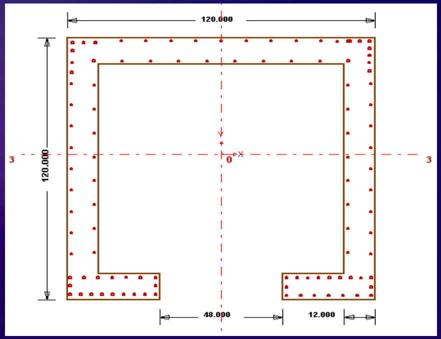
Moment Capacity for 1% Rebars

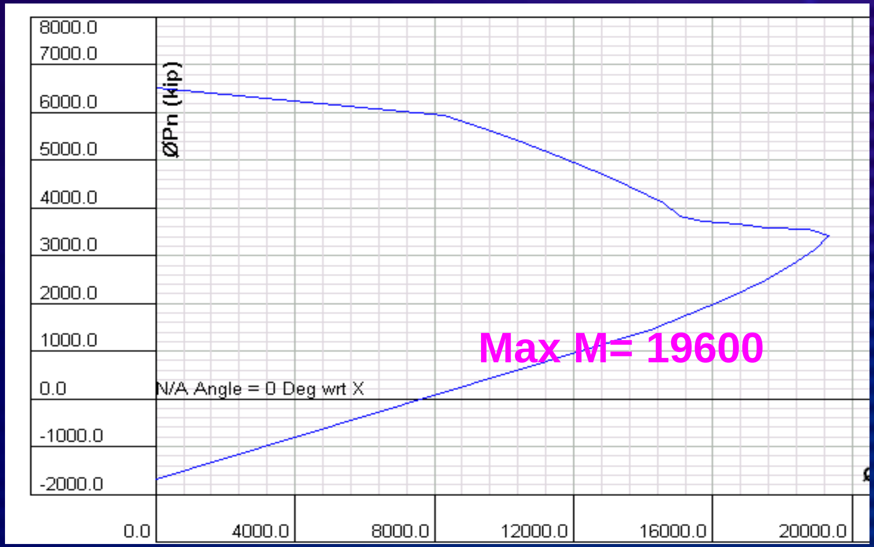
a) Uniform Distribution





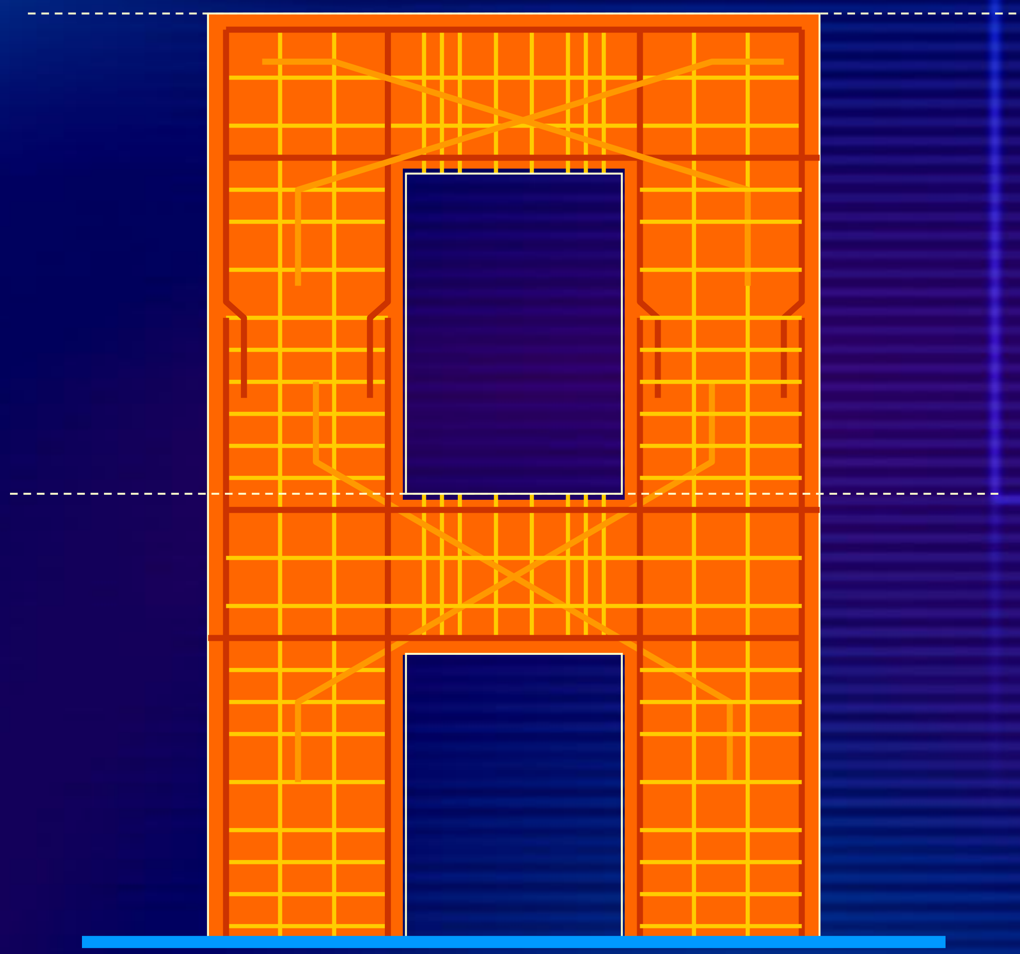
b) Concentrated Bars





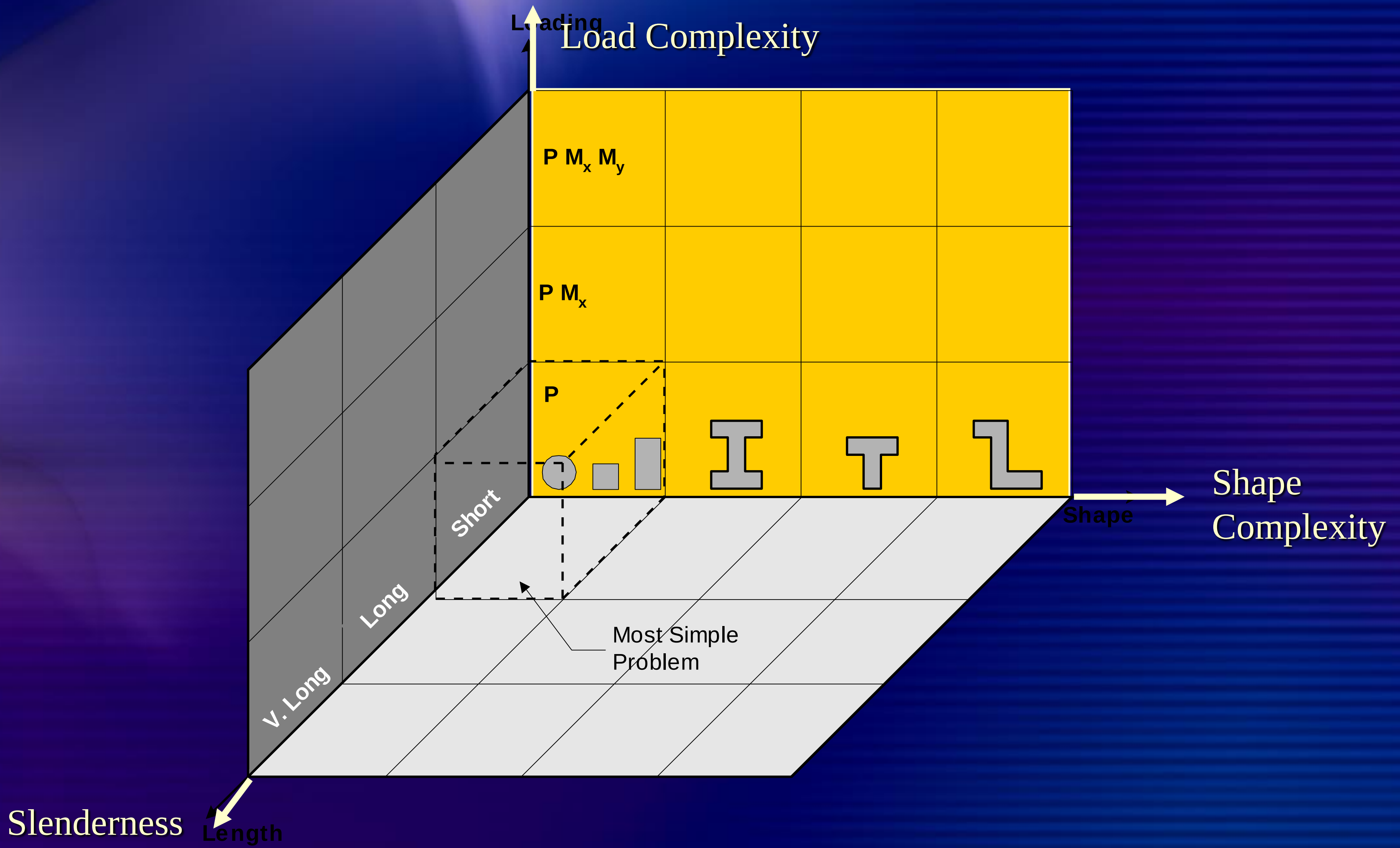
Nearly 20% increase for same steel

Rebar Detailing For Openings

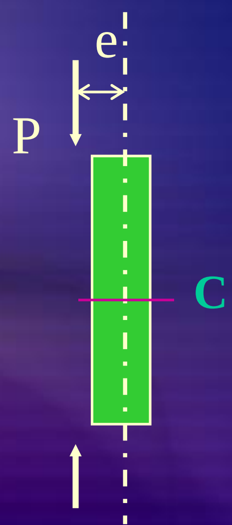


Slenderness of Columns

Complexity in the Column Design

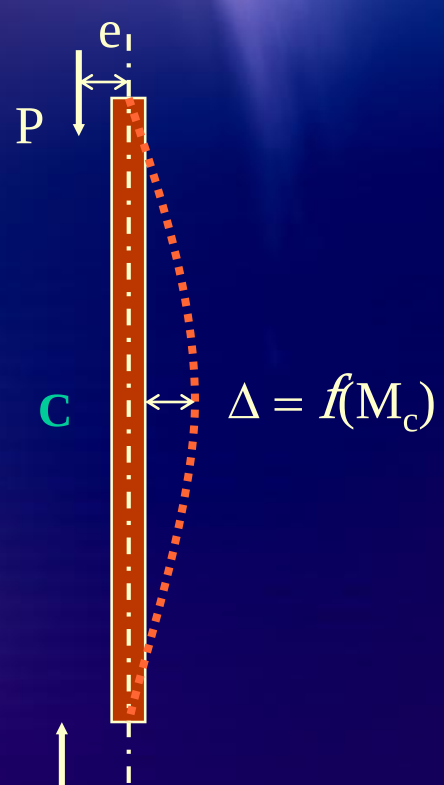


What is Slenderness Effect



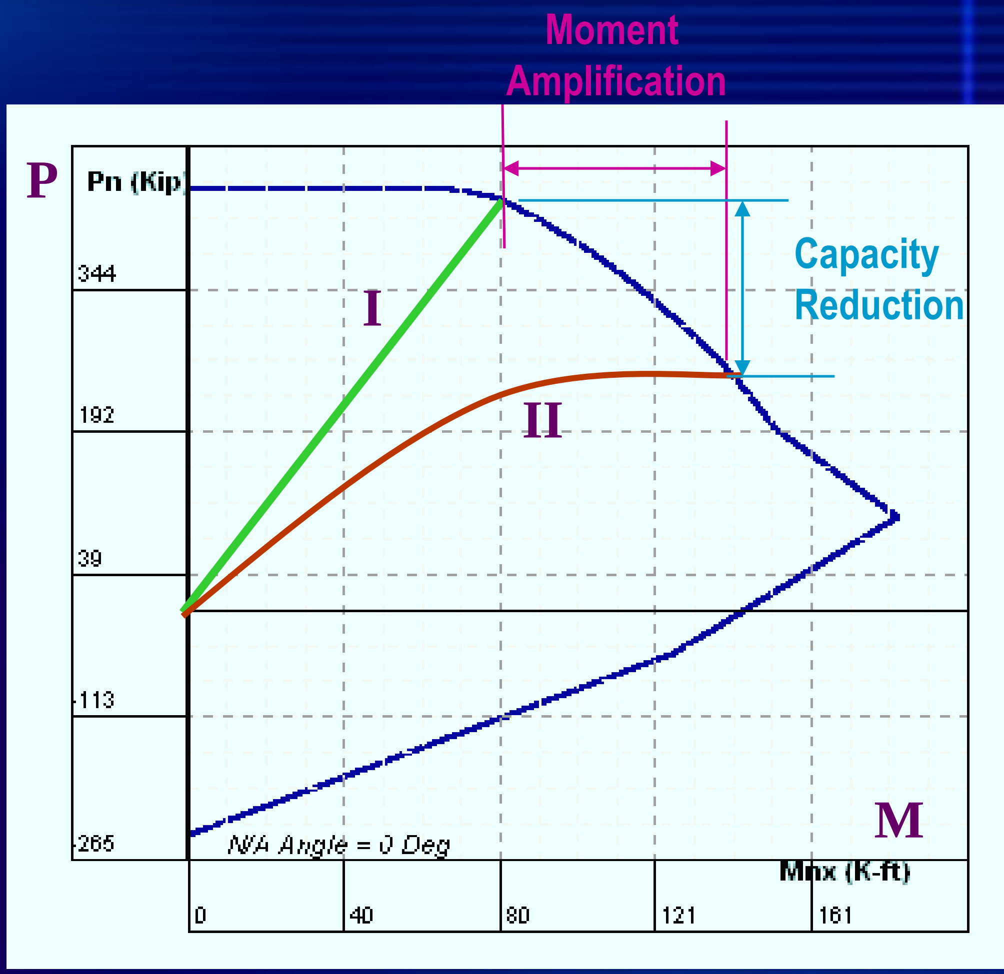
I. $M_c = P.e$

Short Column



II : $M_c = P(e + \Delta)$

Long Column



Column Capacity (P-M)

Factors Effecting Slenderness Effect

- **"Effective" Length**
  - Actual Length
  - End Framing and Boundary Conditions
  - Lateral Bracing Conditions
- **"Effective" Stiffness**
  - Cross-sections Dimensions and Proportions
  - Reinforcement amount and Distribution
  - Modulus of Elasticity of Concrete and Steel
  - Creep and Sustained Loads
- **Loads**
  - Axial Load
  - End Moments and Moments along the Length

ACI Moment Magnification Summary

Final Design Moment

Larger Non- Sway Moment

Larger Sway Moment

$$M_m = M_{ns}\delta_{ns} + M_s\delta_s$$

$$\delta_{ns} = \frac{C_m}{1 - \dfrac{P_u}{0.75\,P_C}}$$

a) $\delta_s = \dfrac{1}{1 - \dfrac{\sum P_u \Delta_0}{V_u l_c}} \geq 1.0$

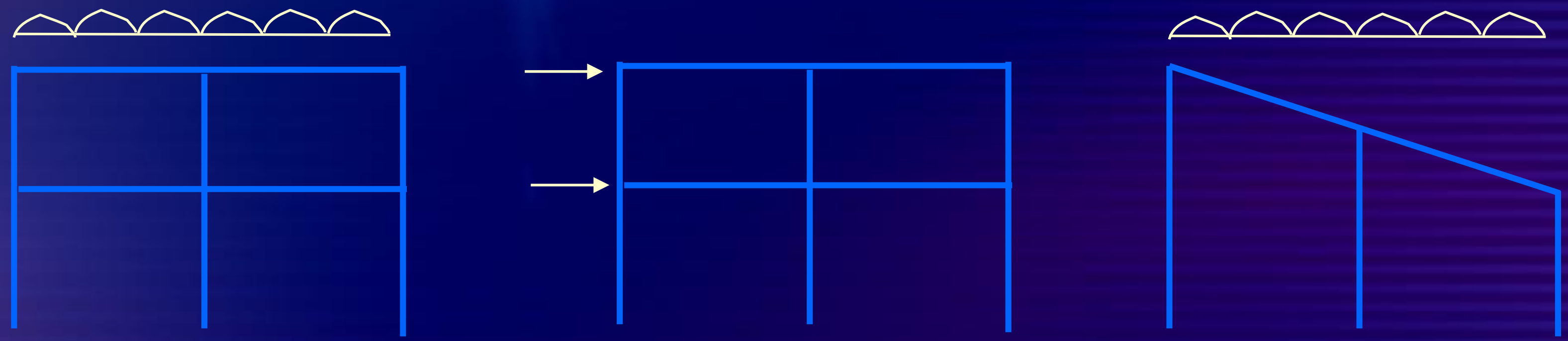
If $\delta_s > 1.5$ then

b) $\delta_s = \dfrac{1}{1 - \dfrac{\sum P_u}{0.75 \sum P_c}} \geq 1$

$$C_m = 0.6 + 0.4\frac{M1}{M2} \geq 0.4 \qquad P_C = \frac{\pi^2 (EI)}{(Kl_U)^2}$$

What is Sway …

– Sway is dependent upon the structural configuration as well as type of loading

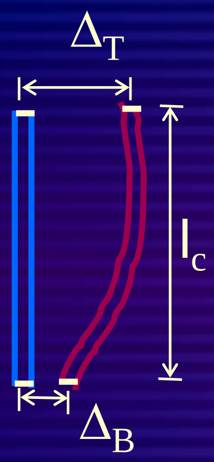


Non Sway **Sway** **May be Sway**

– **For Non-sway Frames (Very rigid or braced)**	$\delta_s = 1.0$ $\delta_{ns} \geq 1.0$
– **For Sway Frames (Open frames, not braced, Depends on loads also)**	$\delta_s \geq 1.0$ $\delta_{ns} \geq 1.0$

- **Appreciable relative moment of two ends of column**

$$Sway\Delta_0 = \frac{\left|\Delta_T - \Delta_B\right|}{l_c}$$



- **Sway Limits**

$$a)\ EI_{Bracing\ walls} > 6EI_{Columns}$$

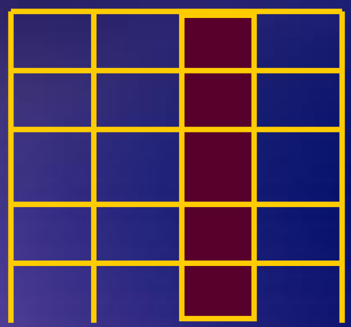
$$b)\ E\frac{P_U\Delta_0}{V_U l_C} < 0.05$$

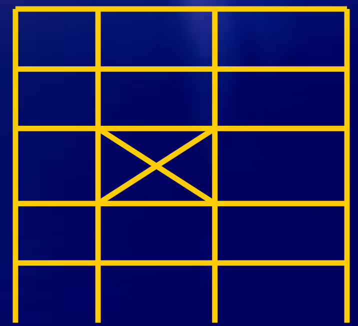
$$c)\ \frac{M_m}{M} < 1.05$$

Frame considered as "Non-Sway"

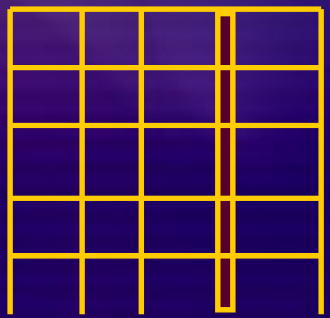
… More on Sway

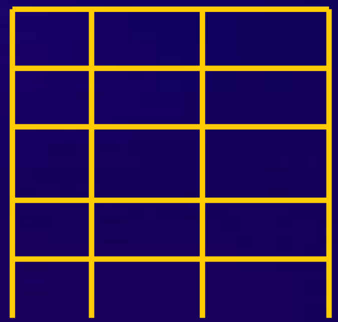
- Braced Column (Non-Sway)





- Unbraced Column (Sway)





- Most building columns may be considered “Non-Sway” for gravity loads
- More than 40% of columns in buildings are “Non-Sway” for lateral loads
- Moment Magnification for “Sway” case is more significant, more complicated and more important

Calculation of δ_{ns} (Non-Sway)

$$\delta_{ns} = \frac{C_m}{1 - \dfrac{P_u}{0.75\,P_C}}$$

Moment curvature Coefficient

Applied column load

Critical buckling load

$$P_C = \frac{\pi^2 (EI)}{(K l_U)^2}$$

Flexural Stiffness

Effective Length Factor

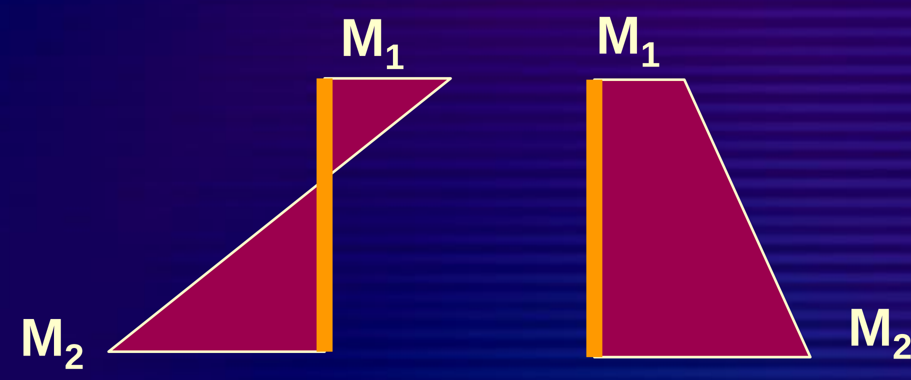
The C_m Factor

The Moment and Stress Amplification Factors are derived on the basis of pin-ended columns with single moment curvature.
(C_m = 1.0)

For other Moment Distribution, the correction factor C_m needs to be computed to modify the stress amplification.

C_m = 0.4 to 1.0

$$C_m = 0.6 + 0.4\frac{M1}{M2} \geq 0.4$$

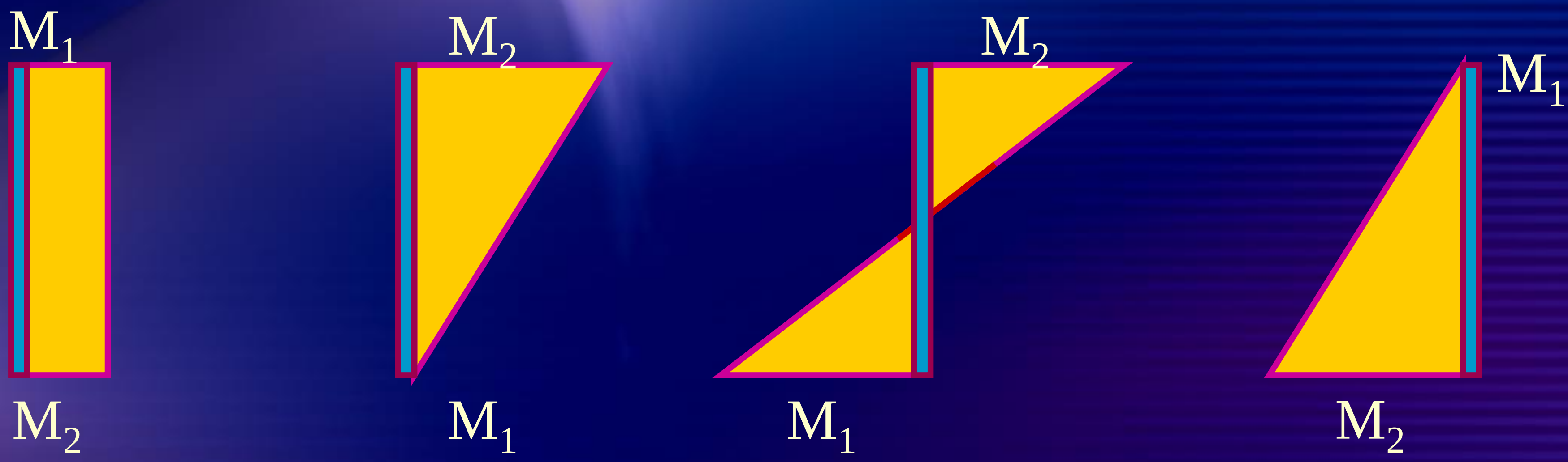


M1/M2
Positive

M1/M2
Negative

M1 is the smaller End Moment
M2 is the larger End Moment

More about C_m Factor



$M_1 = -M$
$M_2 = M$

$M_1 = 0$
$M_2 = M$

$M_1 = M$
$M_2 = M$

$M_1 = 0$
$M_2 = M$

$$\frac{M_1}{M_2} = -1$$

$$\frac{M_1}{M_2} = 0$$

$$\frac{M_1}{M_2} = 1$$

$$\frac{M_1}{M_2} = 0$$

Cm = 1.0

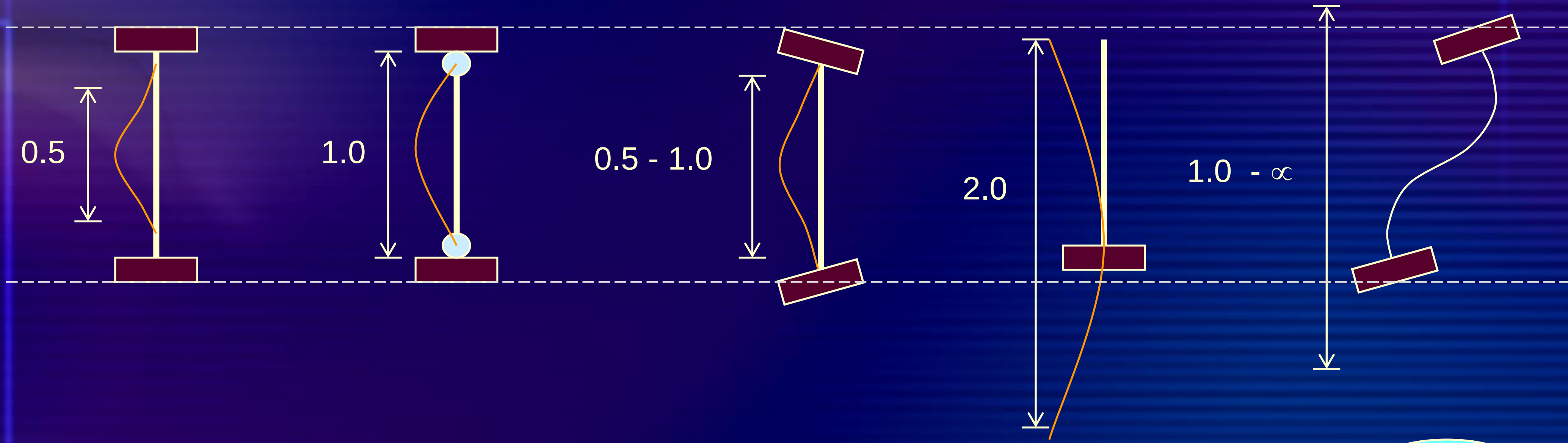
Cm = 0.6

Cm = 0.2

Cm = 0.6

Effective Length Factor, K

- To account for "Axial-Flexural Buckling"
- Indicates the "total bent" length of column between inflection points
- Can vary from 0.5 to Infinity
- Most common range   0.75 to 2.0



… Determination of K

- **Members Part of Framed Structure**

Unbraced Frames	$K = \dfrac{20 - G_m}{20}\sqrt{1 + G_m} \qquad for\ G_m < 2$ $K = 0.9\sqrt{(1 + G_m)} \qquad for\ G_m \geq 2$
Braced Frames (smaller of)	$K = 0.7 + 0.05(G_T + G_B) \leq 1.0$ $k = 0.85 + 0.05 G_m \leq 1.0$

$$G = \frac{\sum(EI/L_C) \quad Columns}{\sum(EI/L) \quad Beams}$$

$K \ \alpha \ G \qquad G\ Increase,\ K\ Increases$

$G_T = Top\ End$

$G_B = Bottom\ End$

$G_m = Minimum\ of\ G_T\ and\ G_B$

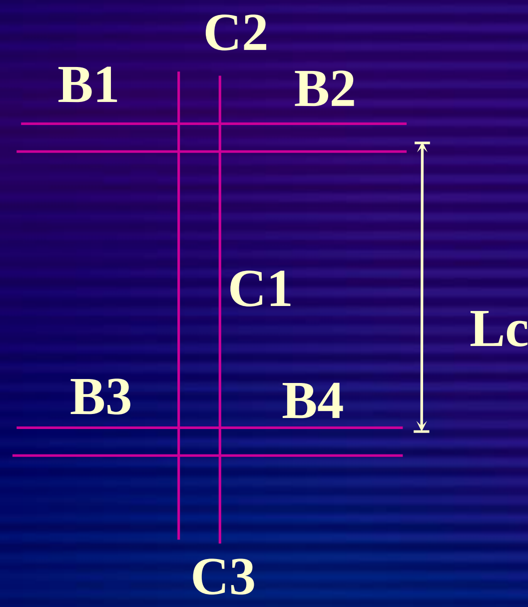
- **Isolated Members**

		Top End		
		Fix	**Pin**	**Free**
Bottom End	**Fix**	**0.5**	**0.8**	**2.0**
	Pin	**0.8**	**1.0**	**Unstable**
	Free	**2.0**	**Unstable**	**Unstable**

$$\psi = \frac{\sum (EI/l_C) \quad \text{Columns}}{\sum (EI/l) \quad \text{Beams}}$$

$$K \alpha\ \psi \qquad \psi\ \text{Increase}, K\ \text{Increases}$$

- How about “I” Gross? Cracked? Effective?
- ACI Rules   Beams I = 0.35 Ig, Column I = 0.7Ig



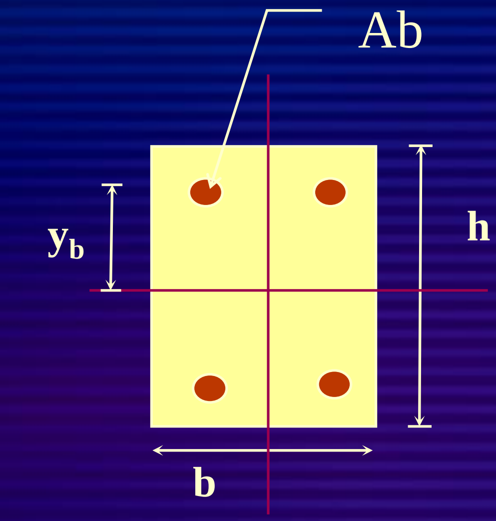
$$Example = \psi_T = \frac{E(I_{C1} + I_{C2})}{E(I_{B1} + I_{B2})}$$

E for column and beams may be different

Determination of Stiffness EI

$$EI = \frac{0.2E_C I_g + E_s I_{se}}{1+\beta_d}$$

$$or \quad = \frac{0.4E_C I_g}{1+\beta_d}$$



- **Attempt to include,**
  - Cracking, Variable E, Creep effect
  - Geometric and material non linearity

$$I_g = \frac{bh^3}{12}$$

$$I_{se} = \sum A_b . y_b^2$$

- **I_g = Gross Moment of Inertia**
- **I_{se} = Moment of Inertia of rebars**

□ **β_d = Effect of creep for sustained loads. = P_{ud}/P_u**

Slenderness procedure for Buildings

$$Q = \frac{\sum P_U \Delta_0}{V_U l_C}$$

$$\sum P_U = P_{U1} + P_{U2} + P_{U3} \ldots\ldots$$

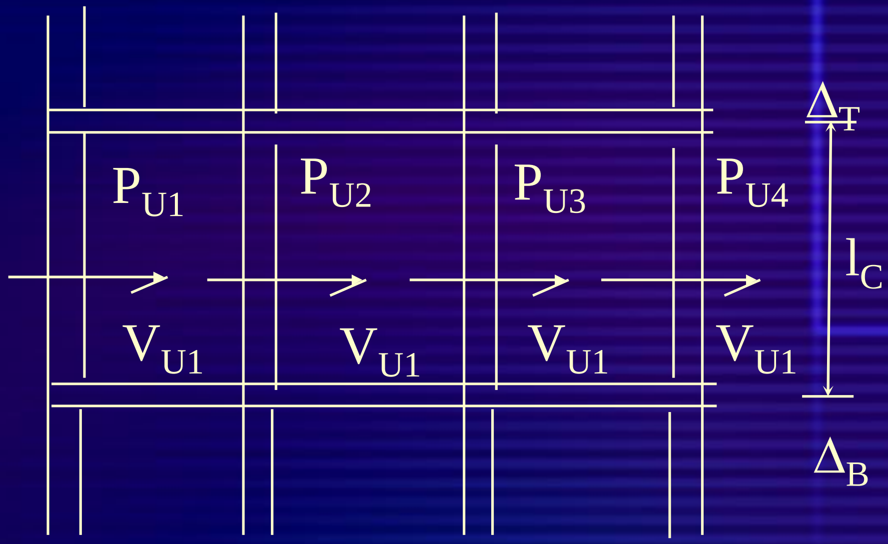
$$\Delta_0 = \Delta_T - \Delta_B$$

$$V_U = V_{U1} + V_{U2} + V_{U3} \ldots\ldots$$

$$l_C = Clear\ storey\ height\ (average)$$

$$If\ Q \leq 0.05\ :\ Non-sway\ case$$

$$Q > 0.05\ :\ Sway\ Case$$



- **Basic Equation for Slender Columns**

$$M_m = M_i + Na_u$$

Initial Moment form elastic analysis

M_{add}, Additional moment due to deflection

Calculation of Deflection a_u

$$a_u = \beta_a K h$$

Load correction factor

Column Dimension along deflection

Length Correction Factor

$$K = \frac{N_{uz} - N}{N_{uz} - N_{bal}} \leq 1$$

Applied column load

Axial capacity at balanced conditions

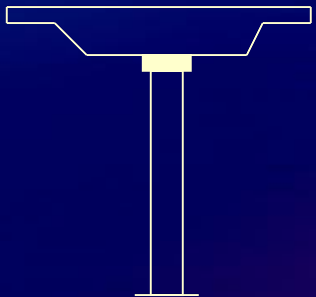
Axial Capacity for M = 0 $N_{uz} = 0.45 f_{cu} A_c + 0.95 A_{sc} f_y$

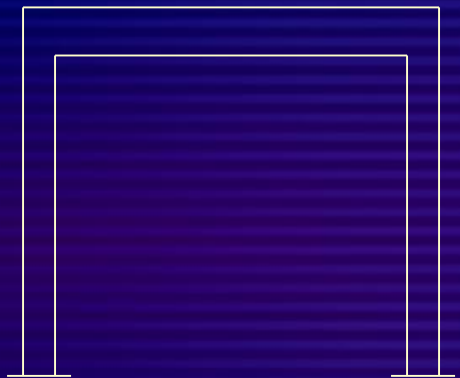
$$\beta_a = \frac{1}{2000}\left(\frac{l_e}{b}\right)^2$$

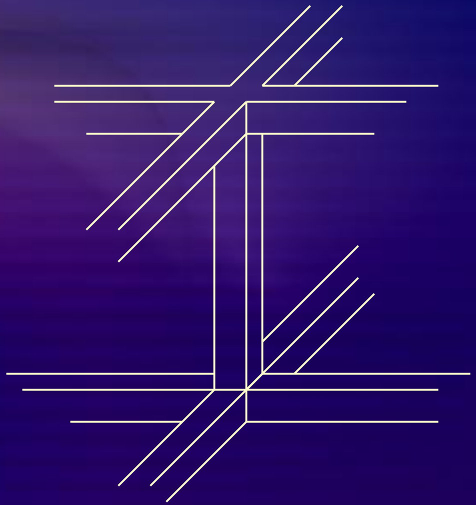
Effective Length = βl_o (From Table 3.21 and 3.22)

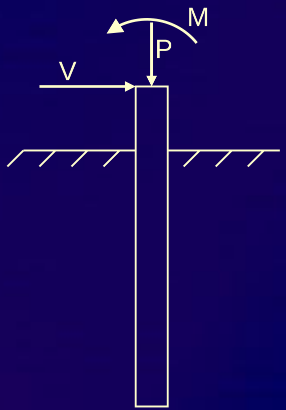
Smaller dimension

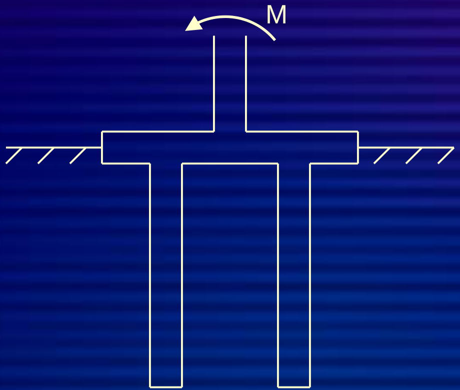
Some Special Cases



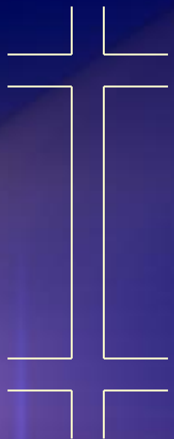


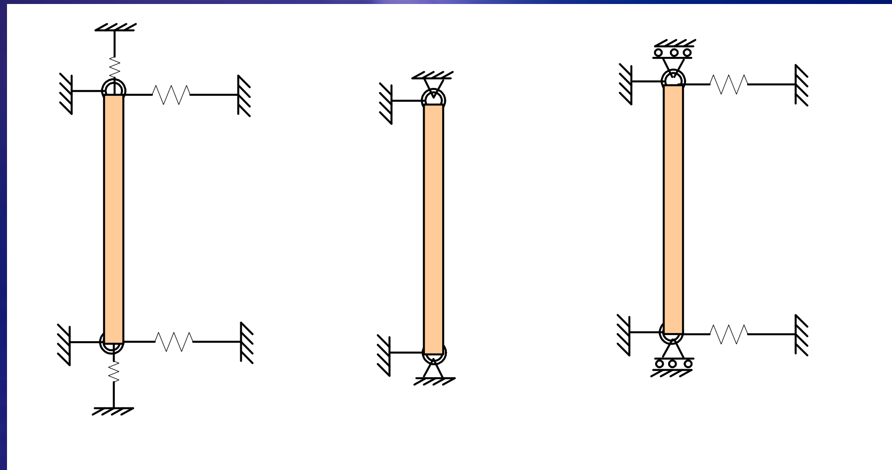


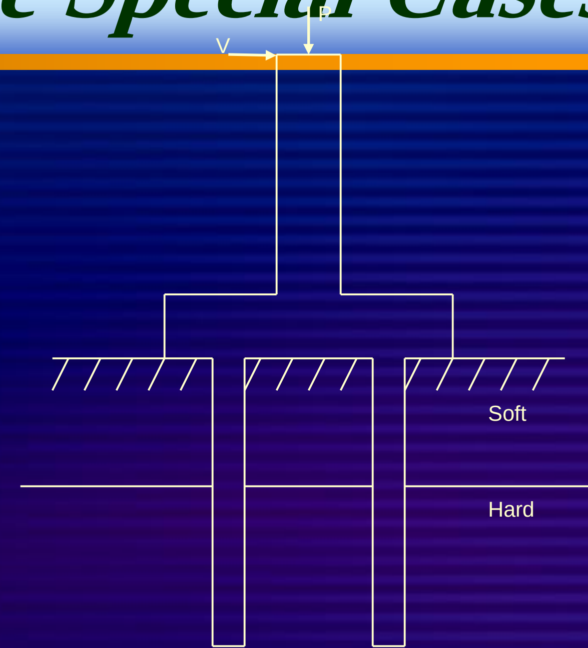




Some Special Cases







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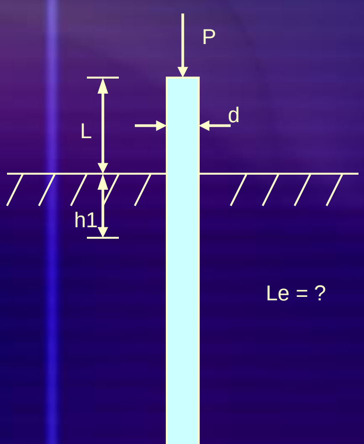
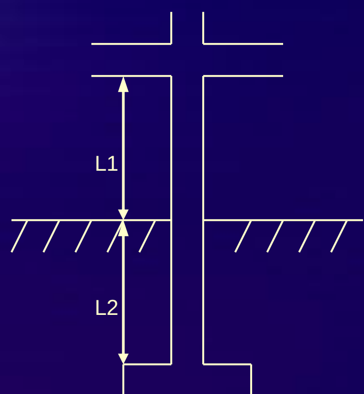


(a)



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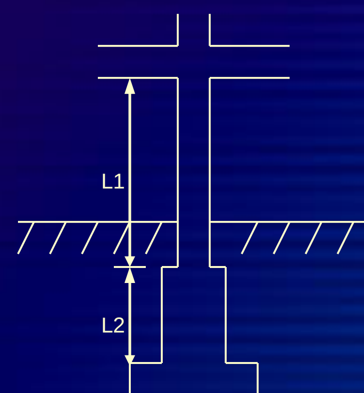

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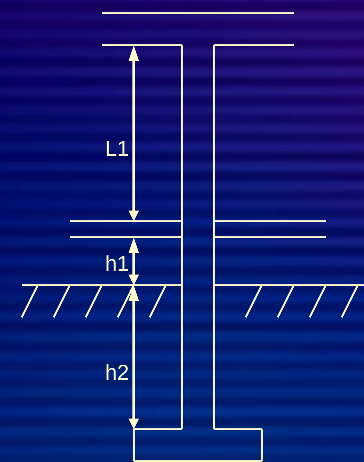

(d)