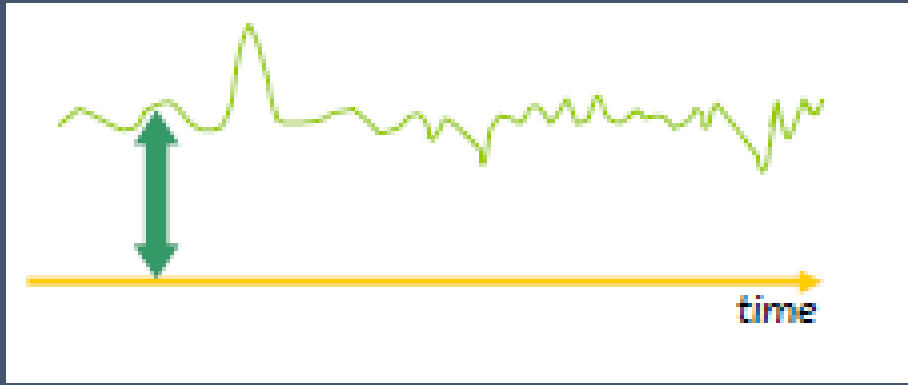
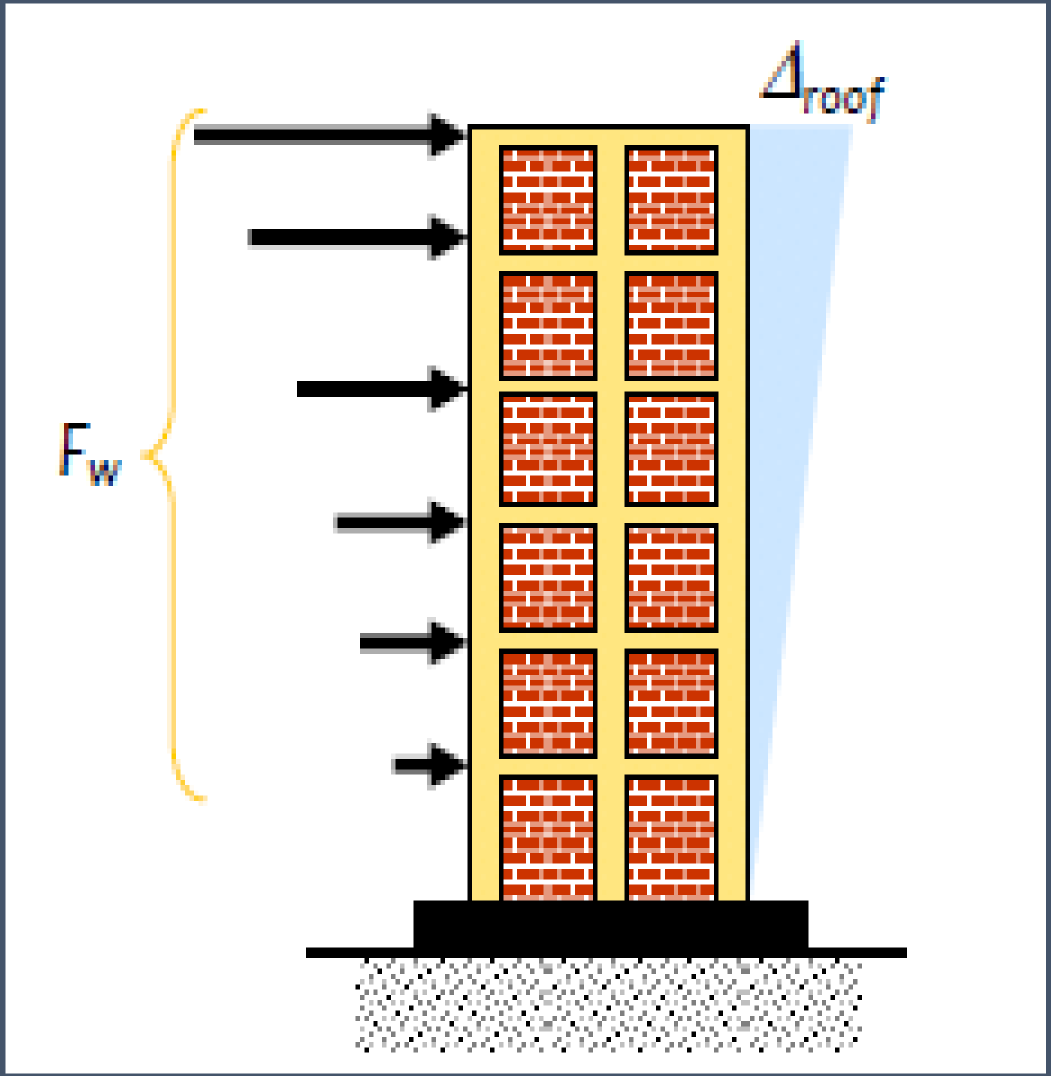
DYNAMIC ACTIONS OF WIND

1. WIND IS FORCE BASED LOADINGS I.E. IN WIND , THE BUILDING IS SUBJECTED TO WIND PRESSURE.
2. WIND FORCES MAY EXPERIENCE SMALL FLUCTUATION IN THE STRESS FIELD.
3. REVERSAL OF STRESSES UNER WIND LOAD OCCUR OVER A LARGE DURATION OF TIME.

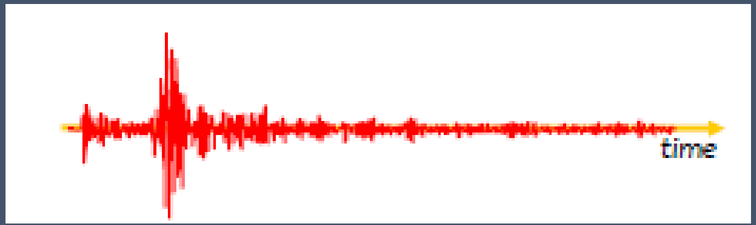


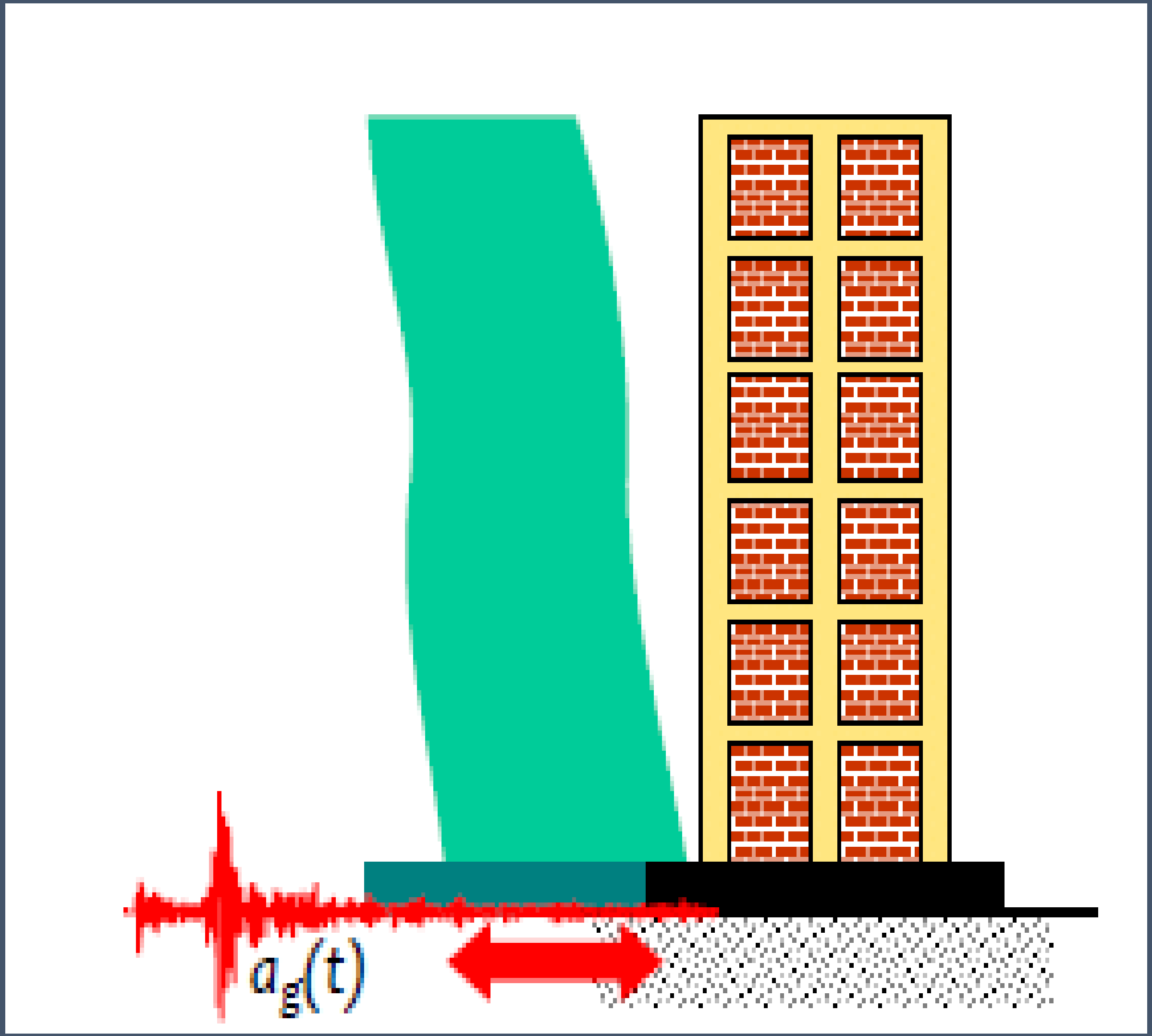


Images Property of GSDMA

DYNAMIC ACTIONS OF EARTHQUAKE

1. IN EARTHQUAKE, IT IS SUBJECTED TO RANDOM MOTION OF GROUND AT ITS BASE, WHICH INDUCES INERTIA FORCES IN THE BUILDINGS I.E. DISPLACEMENT TYPE LOADINGS.
2. MOTION OF GROUND DURING EARTHQUAKE IS CYCLIC ABOUT THE NUETRAL POSITION OF THE STRUCTURE. I.E. ZERO MEAN CYCLIC.
3. STRESSES IN THE BUILDING MAY UNDERGO COMPLEET REVERSAL WITHIN VERY SMALL DURATION OF THE EARTHQUAKE.

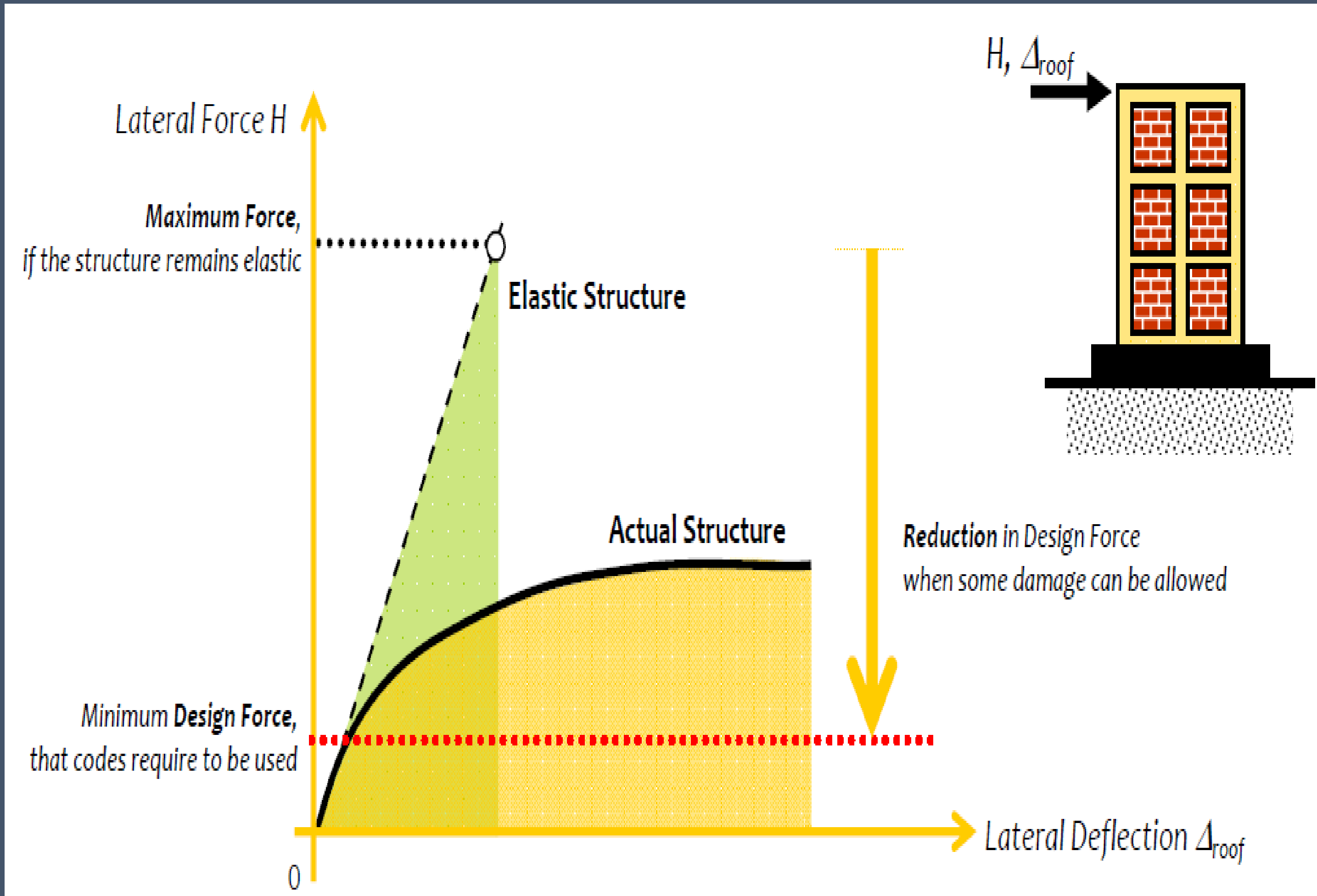




Images Property of GSDMA

BASIC ASPECTS OF SEISMIC DESIGN

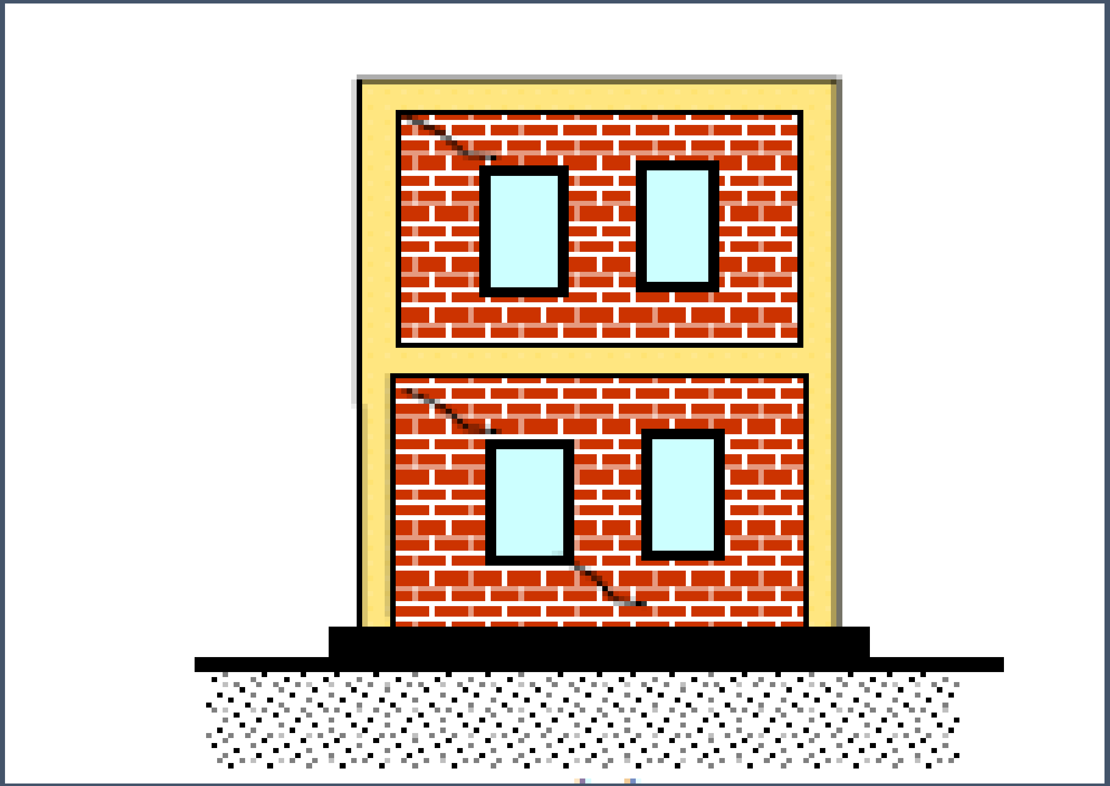
1. THE MASS OF THE BUILDING CONTROLS THE SEISMIC DESIGN.
2. MORE THE MASS OF THE BUILDING, MORE WILL BE THE INERTIA FORCES PRODUCED IN THE BUILDING.
3. BUILDINGS WITH ZERO DAMAGE DURING EARTHQUAKE IS ECONOMICALLY NOT VIABLE.
4. SO BUILDINGS ARE ALLOWED SOME DAMAGE DURING STRONG GROUND SHAKING BY DESIGNING THEM FOR A FRACTION(10%-15%) OF THE FORCE THEY WOULD EXPERIENCE DURING STRONG EARTHQUAKES



TRADITIONAL EARTHQUAKE DESIGN PHILOSOPHY

1. TRADITIONAL EARTHQUAKE-RESISTANT DESIGN PHILOSOPHY REQUIRES THAT NORMAL BUILDINGS SHOULD BE ABLE TO RESIST

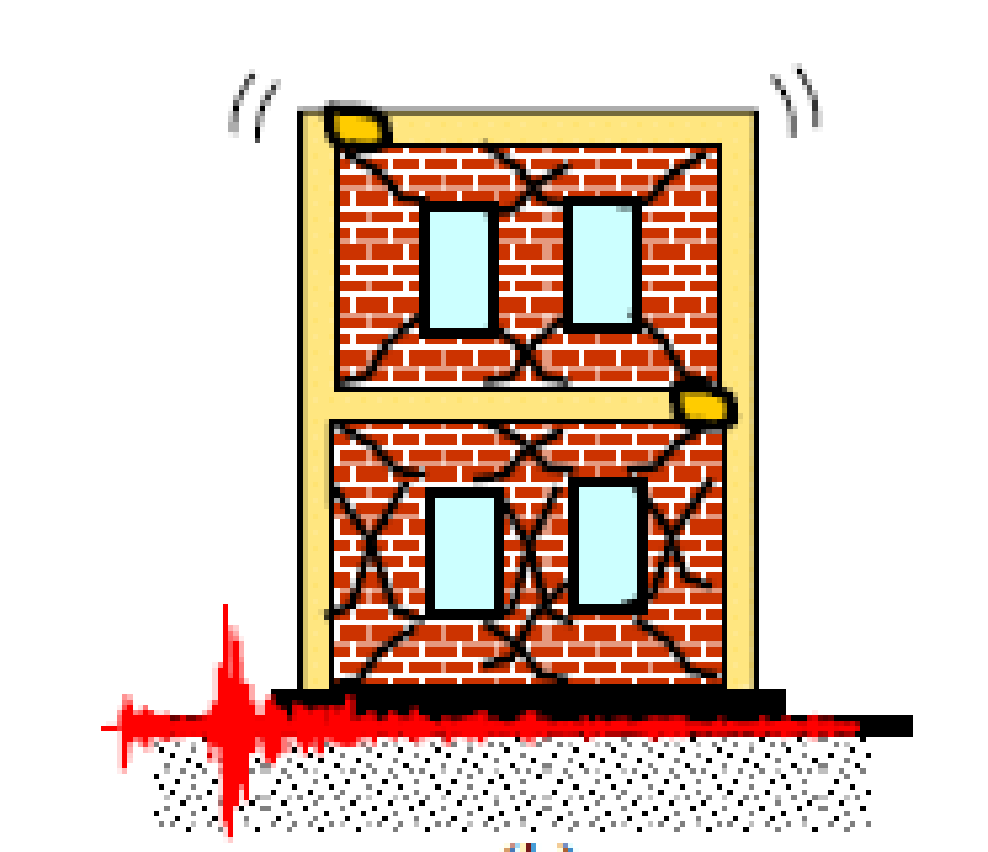
(a) FOR MINOR AND FREQUENT SHAKING –THERE SHOULD BE NO DAMAGE TO THE STRUCTURAL ELEMENTS.



TRADITIONAL EARTHQUAKE DESIGN PHILOSOPHY

1. TRADITIONAL EARTHQUAKE-RESISTANT DESIGN PHILOSOPHY REQUIRES THAT NORMAL BUILDINGS SHOULD BE ABLE TO RESIST

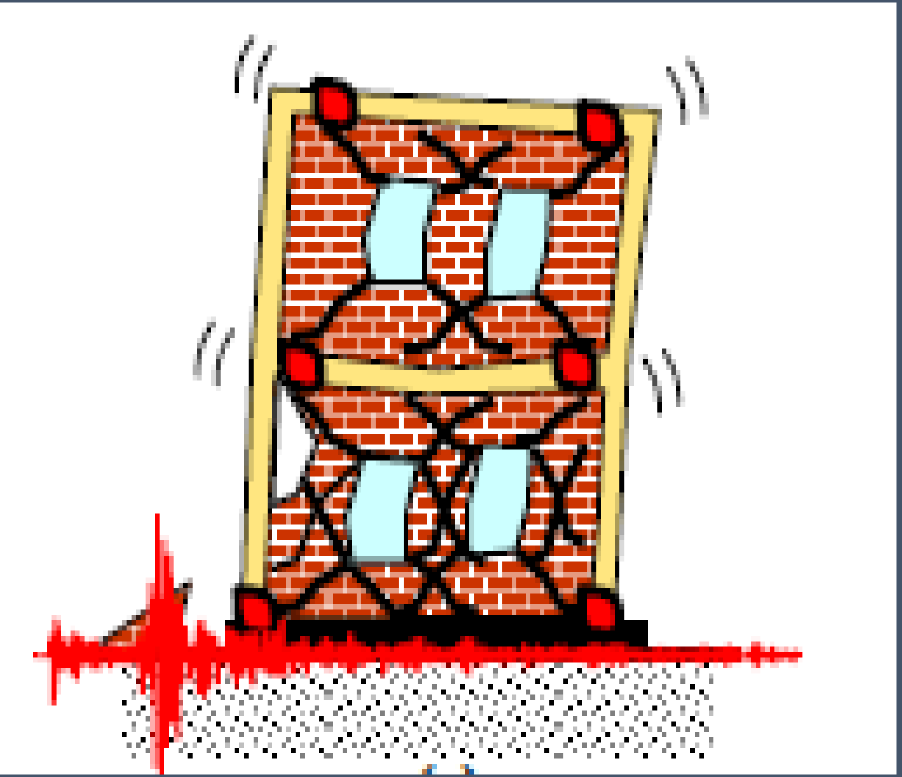
(a) FOR MODERATE SHAKING – MINOR DAMAGE TO THE STRUCTURAL ELEMENTS AND SOME DAMAGE TO THE NON STRUCTURAL ELEMENTS.



TRADITIONAL EARTHQUAKE DESIGN PHILOSOPHY

1. TRADITIONAL EARTHQUAKE-RESISTANT DESIGN PHILOSOPHY REQUIRES THAT NORMAL BUILDINGS SHOULD BE ABLE TO RESIST

(a) FOR SEVERE SHAKING – DAMAGE TO THE STRUCTURAL ELEMENTS WITH **NO** COLLAPSE . THE BUILDING MAY BE UNUSABLE, BUT MAY SAVE THE LIVES OF THE RESIDENTS.



WE ALWAYS DESIGN

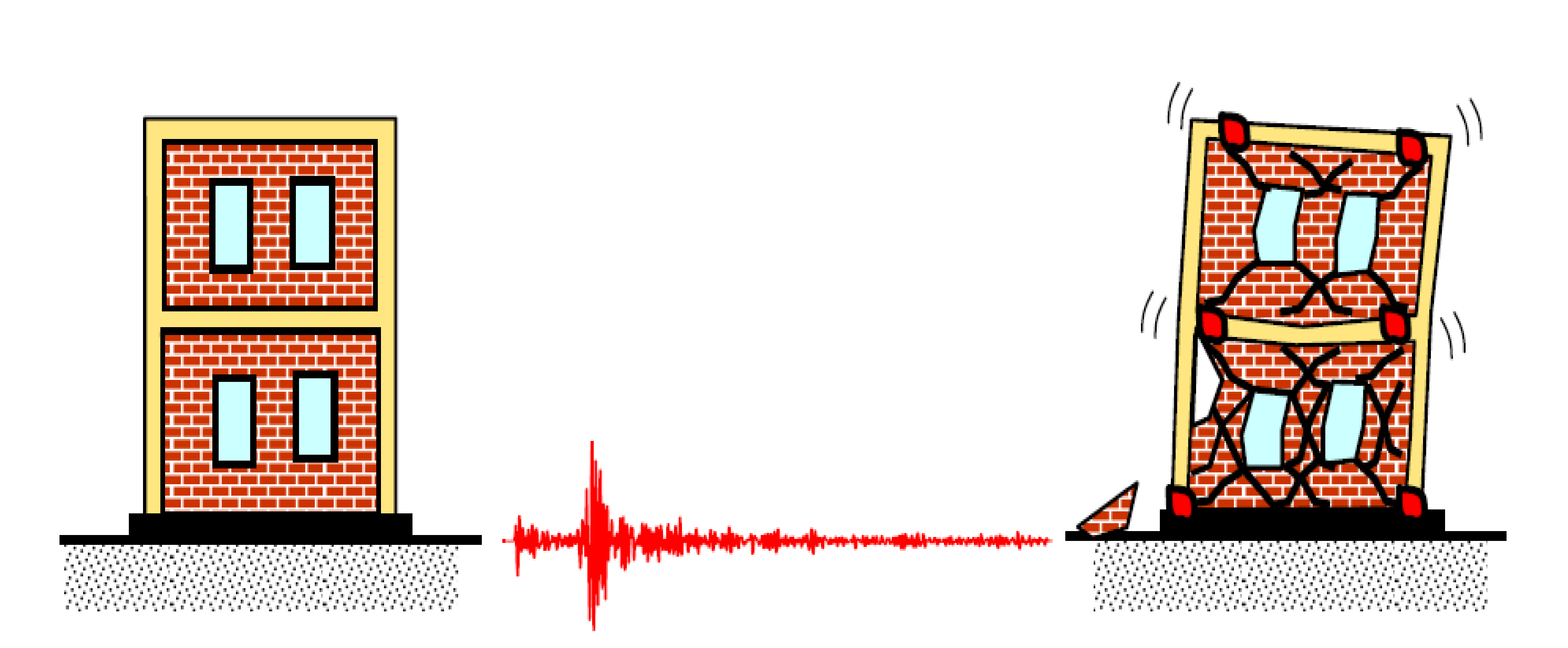
EARTHQUAKE RESISTANT DESIGN

AND **NOT**

EARTHQUAKE PROOF DESIGN

WHAT DO WE MEAN ?

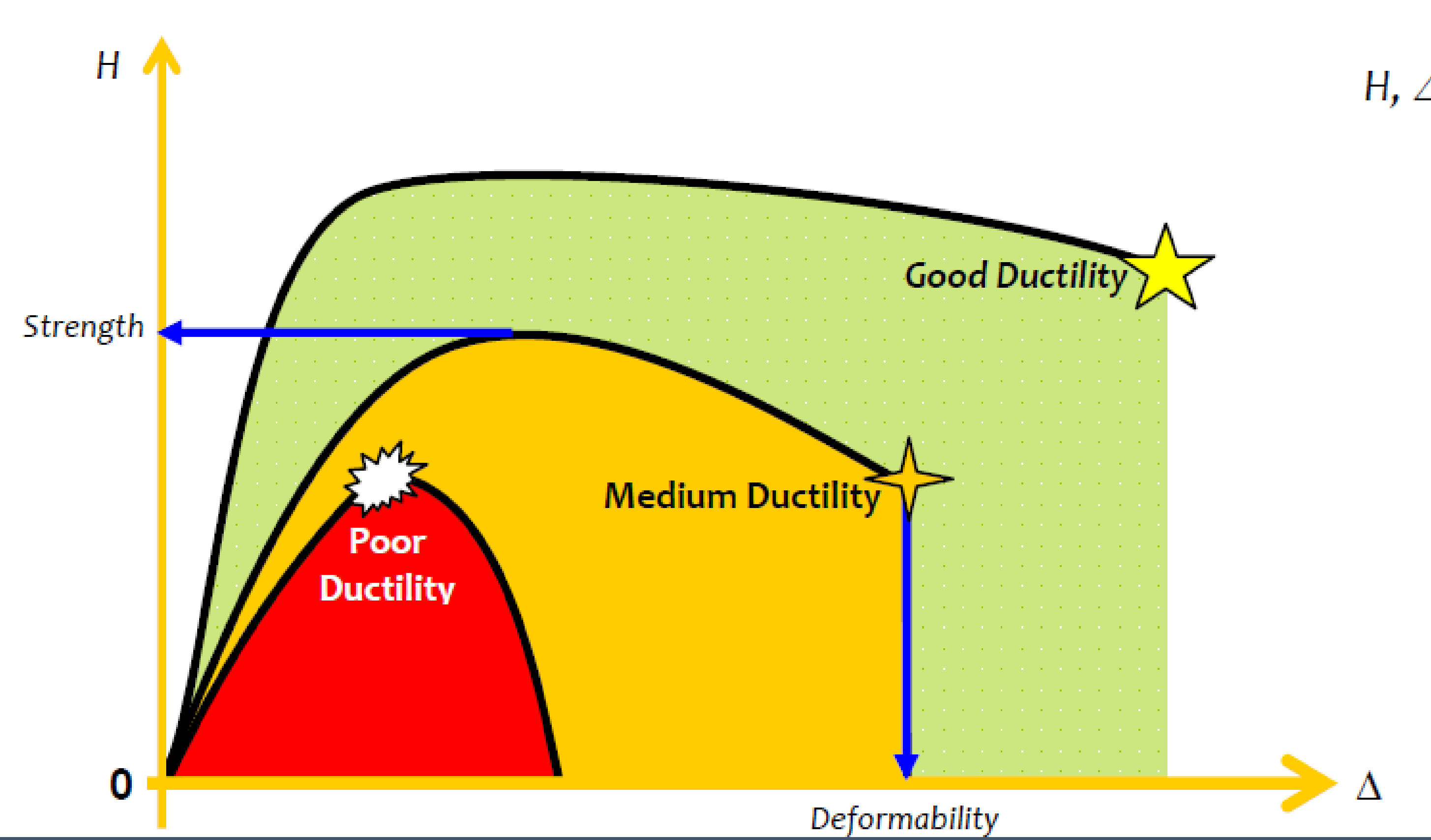
- 1 DAMAGE IS EXPECTED DURING EARTHUAKE IN NORMAL CONSTRUCTION.



https://www.udemy.com/etabscourse/

HERE COMES THE DUCTILITY TO SAVE US

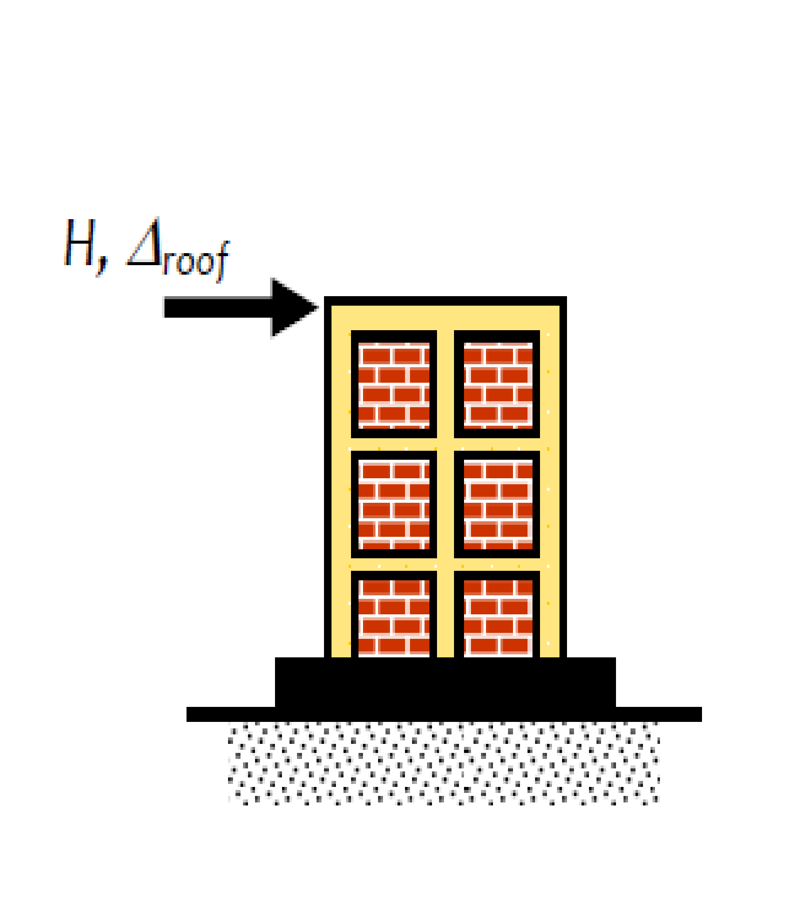
- 1. THE BUILDINGS SHOULD BE DESIGNED FOR FRACTION OF THE ELASTIC LVEL OF SEISMIC FORCE.
- BY PROVIDING DUCTILITY, BUILDINGS CAN WITHSTAND LARGE DISPLACEMENT WITHOUT COLLAPSE AND UNDUE LOSS OF STRENGTH.



Images Property of GSDMA

DESIGN FOR EARTHQUAKE FORCES ?

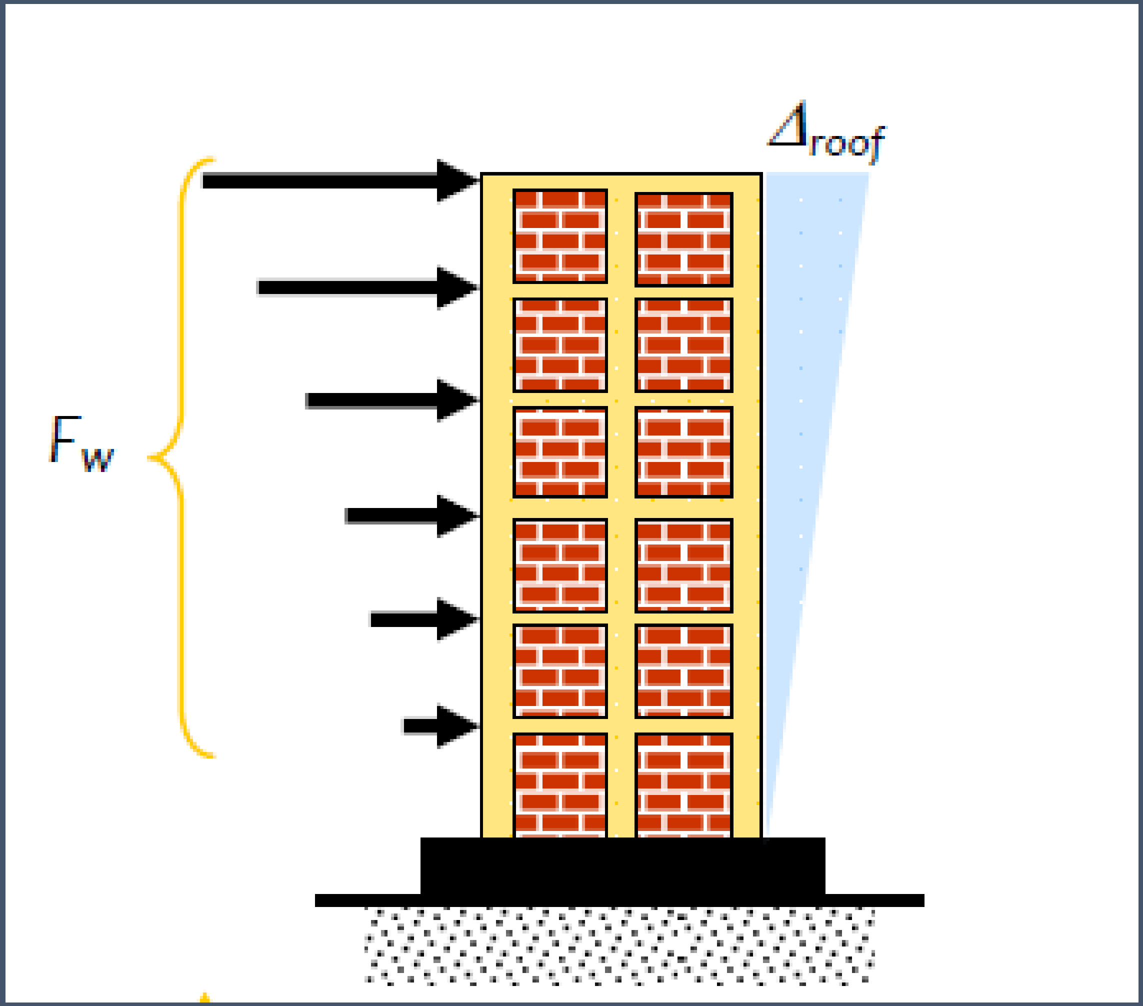
- 1. EARTHQUAKE SHAKING REQUIRES THE BUILDING TO BE CAPABLE OF RESISTING CERTAIN RELATIVE DISPLACEMENT DUE TO IMPOSED DISPLACEMENT AT BASE.
- IN SEISMIC DESIGN
- ELASTIC BEHAVIOR IS REQUIRED FOR SPECIAL BUILDINGS LIKE NUCLEAR POWER PLANTS
- INELASTIC BEHAVIOR IS REQUIRED FOR NORMAL BUILDINGS LIKE RESIDENTIAL OR PUBLIC ACCESS BUILDINGS.



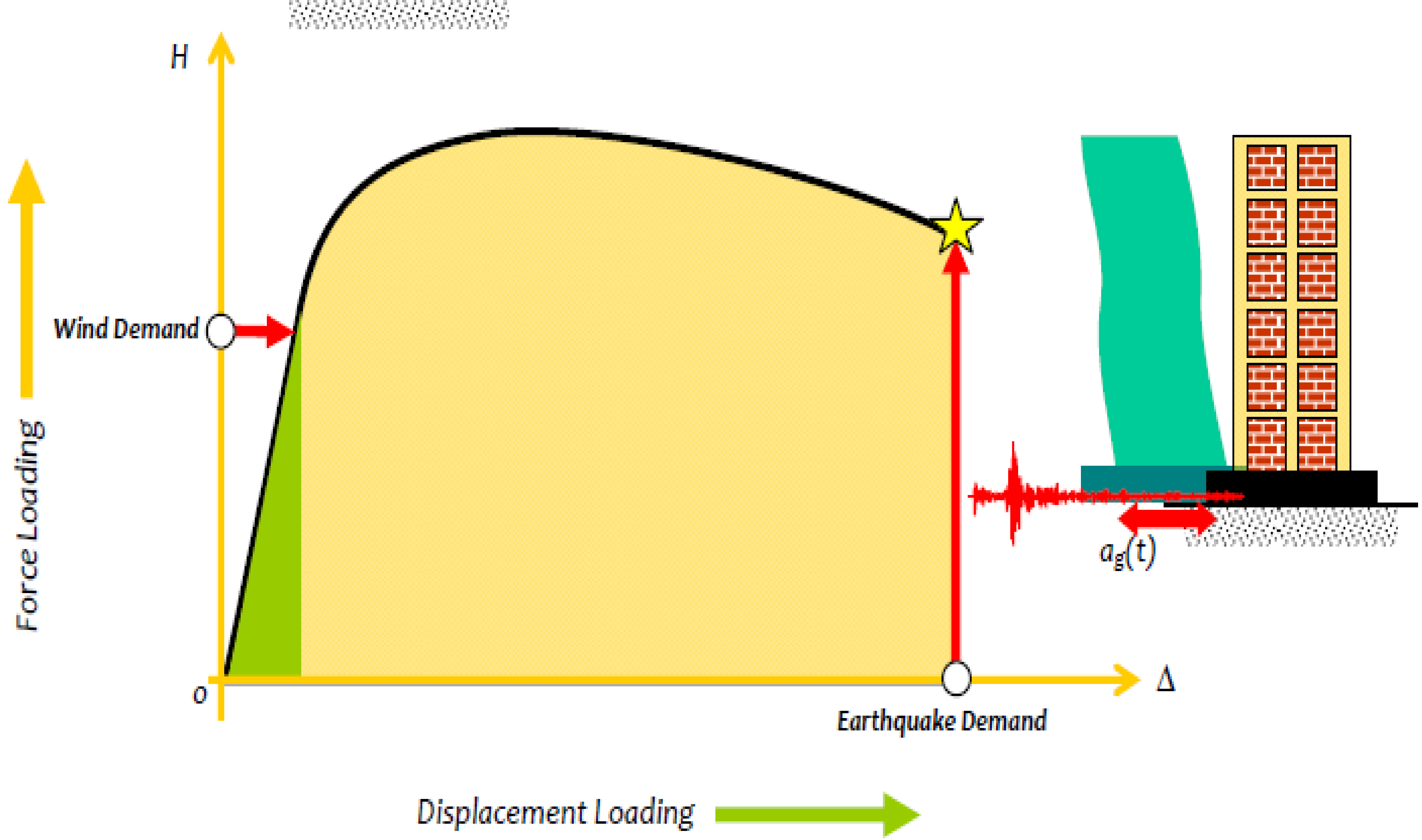
Images Property of GSDMA

DESIGN FOR WIND FORCES

- 1. WIND REQUIRES BUILDINGS TO BE CAPABLE OF RESISTING CERTAIN LEVEL OF FORCES APPLIED ON IT.



Images Property of GSDMA



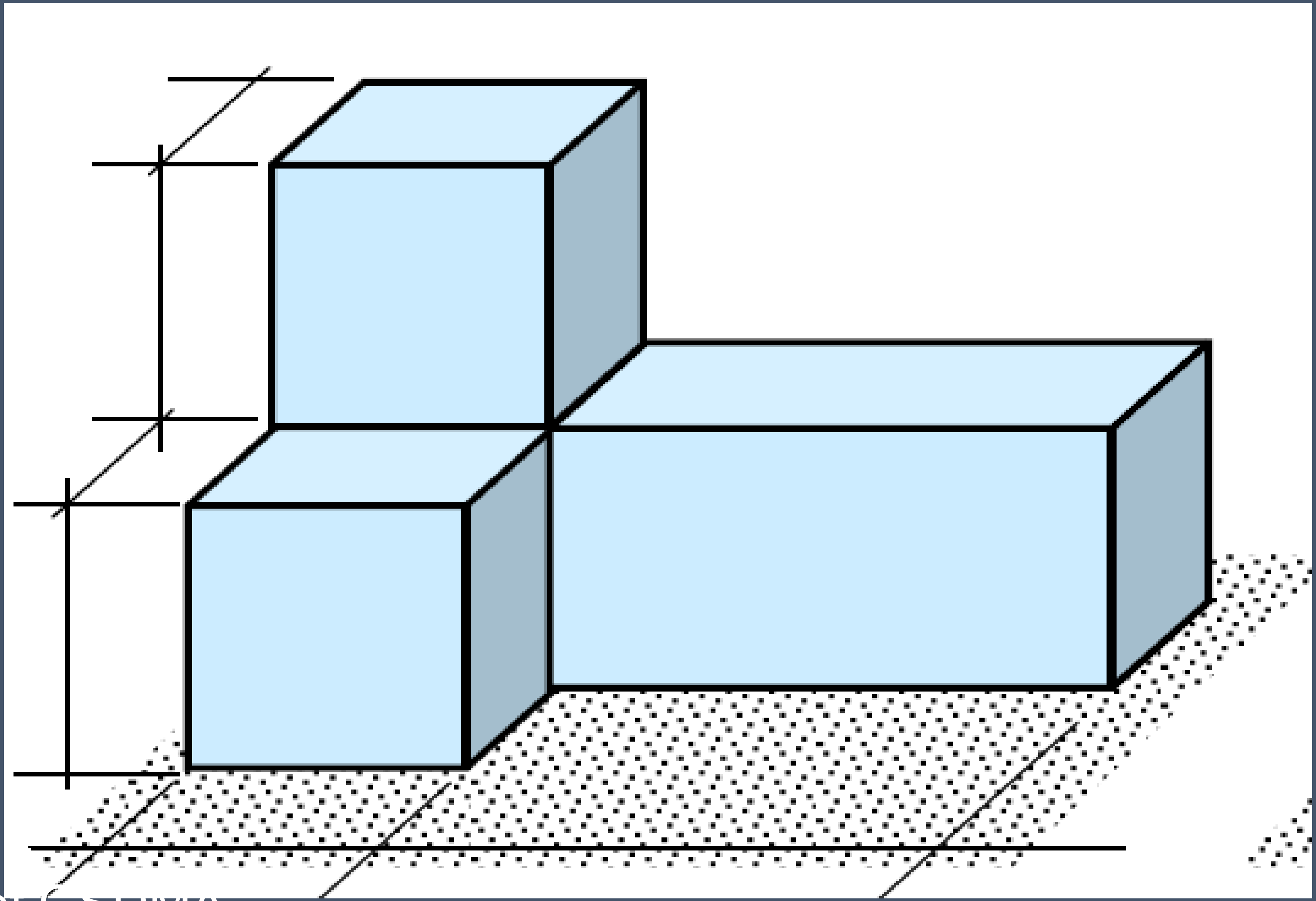
H
Wind Demand
Force Loading
o
Δ
Earthquake Demand
$a_g(t)$
Displacement Loading

CSSD RULE

- THE BASIC MANTRA TO BE FOLLOWED FOR THE EARTHQUAKE RESISTANT DESIGN OF THE STRUCTURES ARE FOUR LETTERS.
- C – SEISMIC STRUCTURAL **C**ONFIGURATION
- S- LATERAL **S**TIFFNESS
- S- LATERAL **S**TRENGTH
- D – **D**UCTILITY OF THE STRUCTURE

1. SEISMIC STRUCTURAL CONFIGURATION

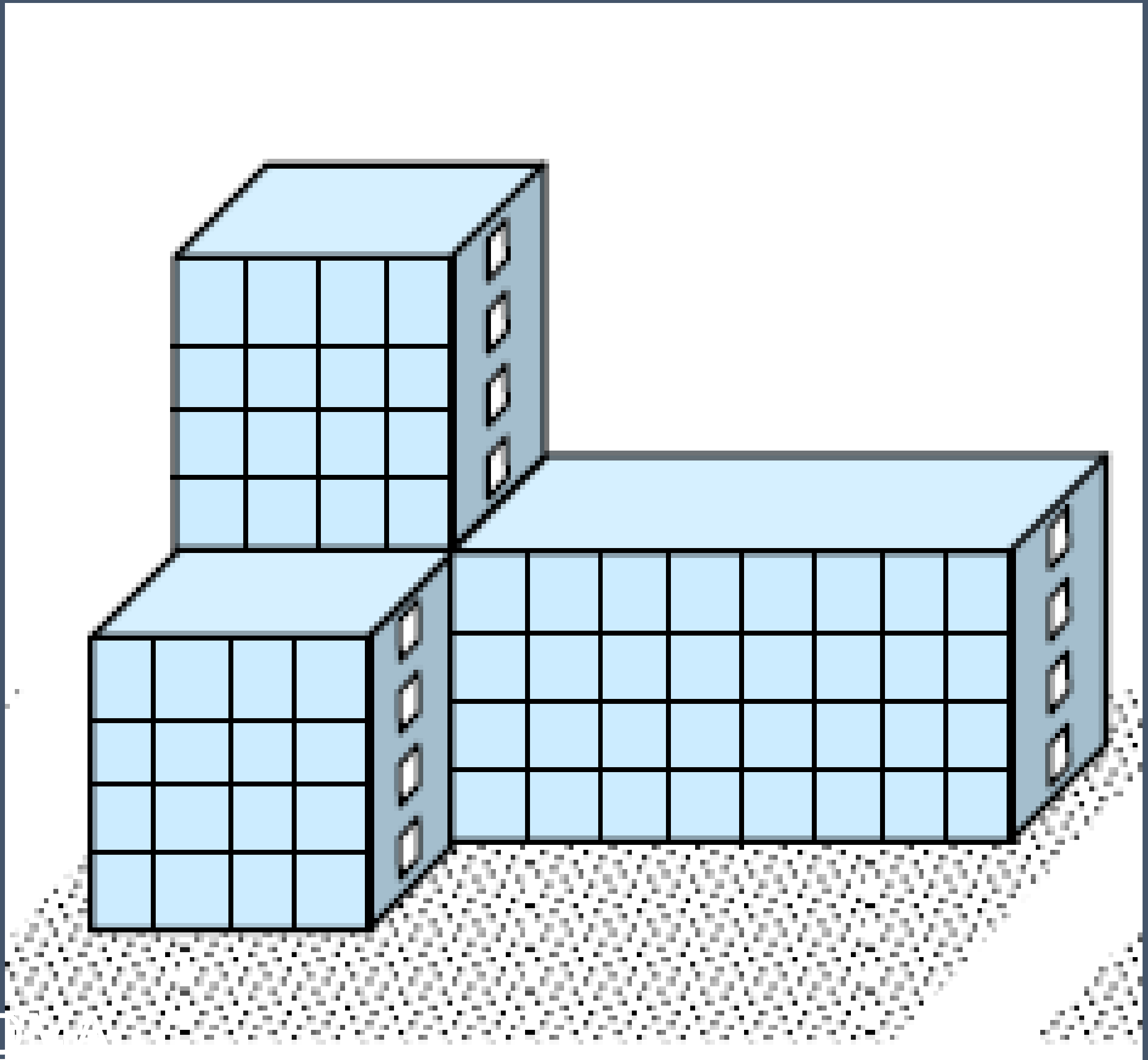
- (A) GEOMETRY, SHAPE AND SIZE OF THE BUILDING,



Images Property of GSDMA

1. SEISMIC STRUCTURAL CONFIGURATION

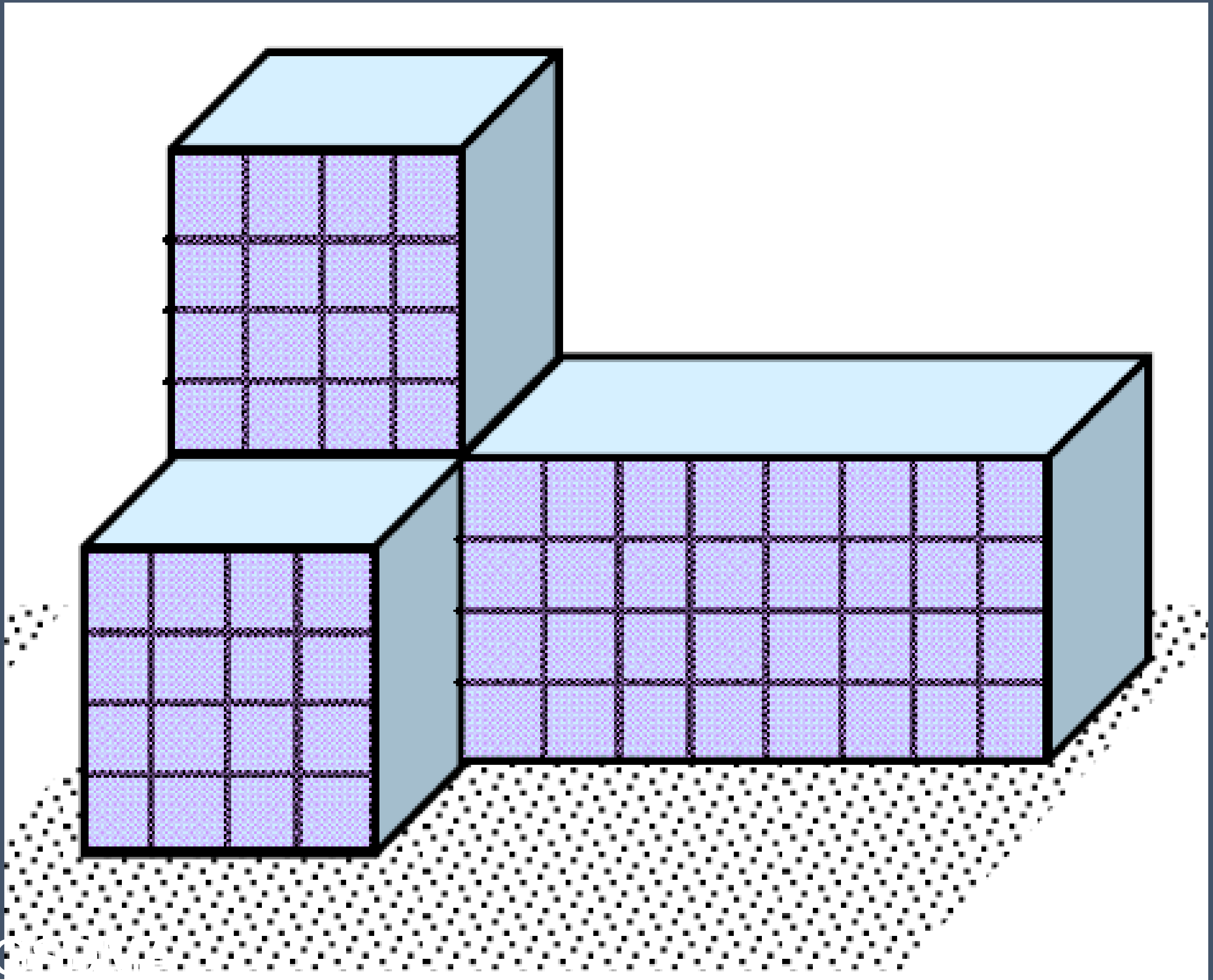
(B) LOCATION AND SIZE OF STRUCTURAL ELEMENTS,



Images Property of GSDMA

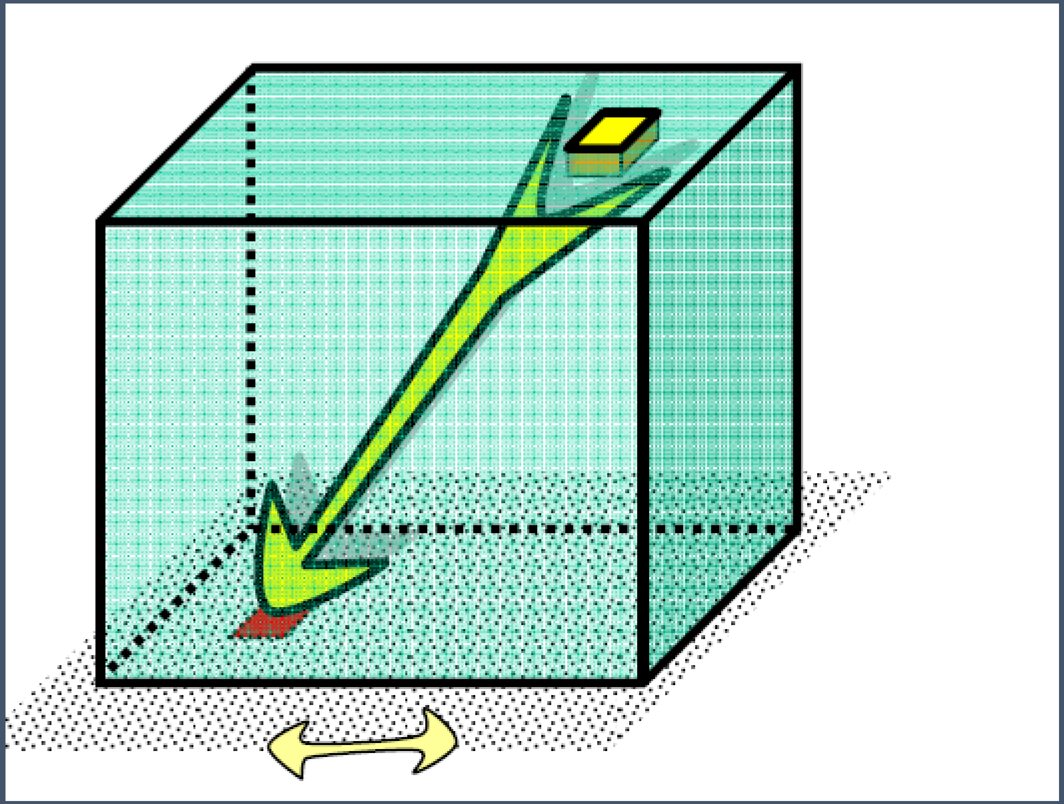
1. SEISMIC STRUCTURAL CONFIGURATION

(C) LOCATION AND SIZE OF SIGNIFICANT NON-STRUCTURAL ELEMENTS



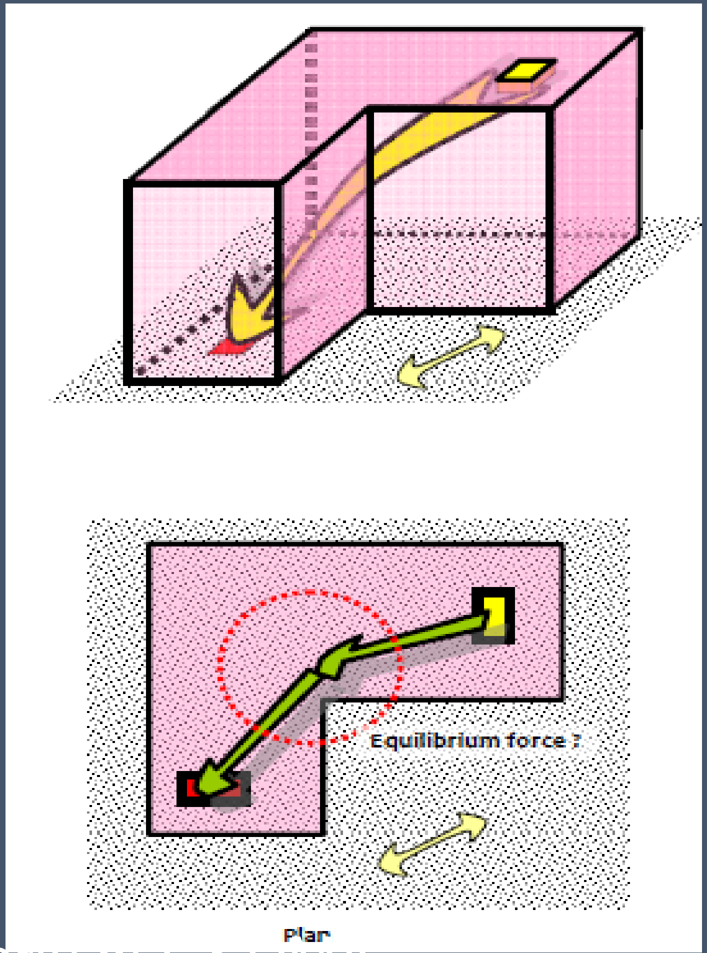
1. SEISMIC STRUCTURAL CONFIGURATION

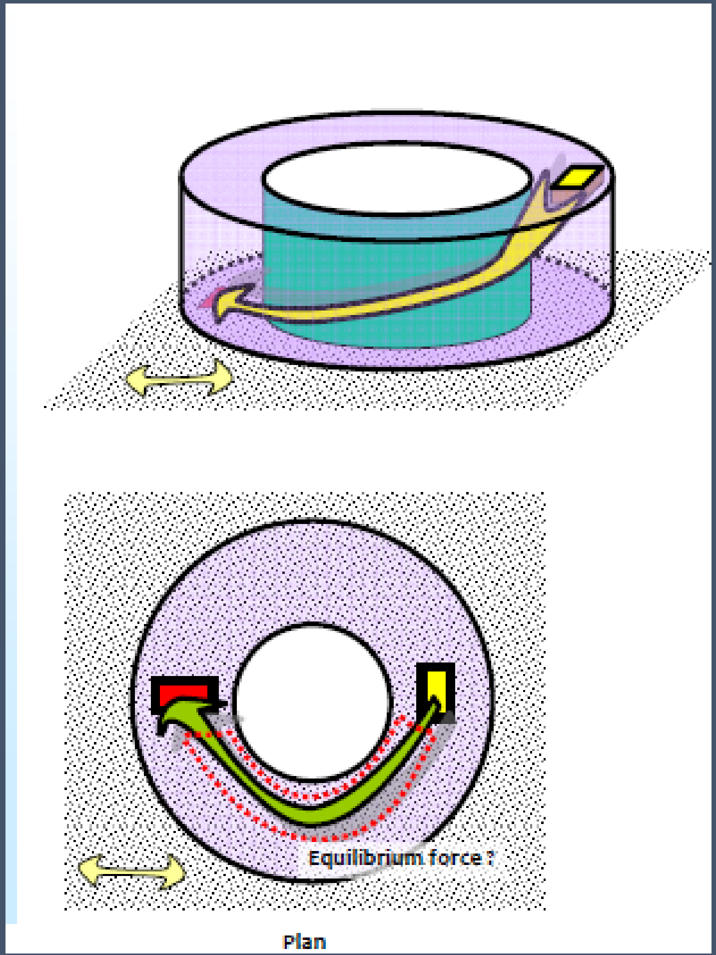
1. STRUCTURES WITH SIMPLE CONFIGURATION I.E. RECTANGULAR PLANS AND STRAIGHT ELEVATIONS PERFORM WELL DURING EARTHQUAKE.
2. INERTIA FORCES ARE TRANSFERRED STRAIGHT WITHOUT ANY BENDS .



1. SEISMIC STRUCTURAL CONFIGURATION

1. STRUCTURES WITH COMPLEX CONFIGURATION I.E. SETBACKS AND GEOMETRIC OPENINGS DO NOT PERFORM WELL DURING EARTHQUAKE.
2. INERTIA FORCES HAVE TO BEND BEFORE REACHING THE GROUND



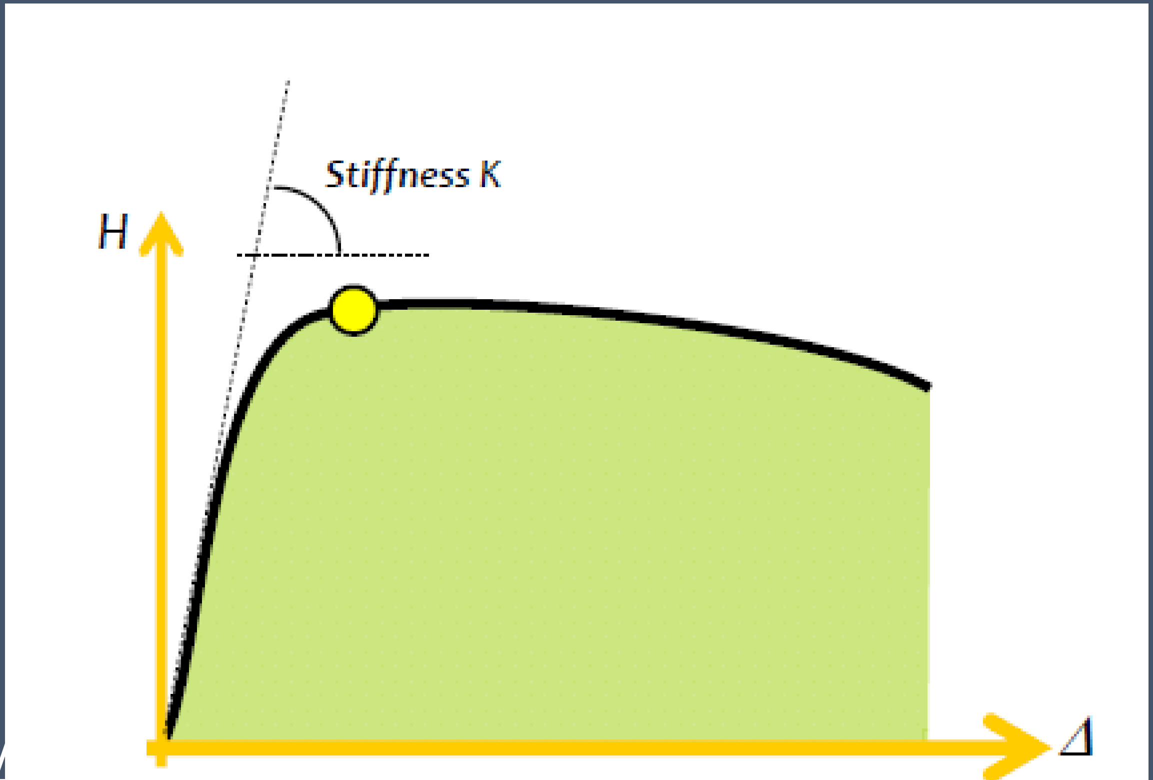


Images Property of GSDMA

https://www.udemy.com/etabscourse/

2. LATERAL STIFFNESS

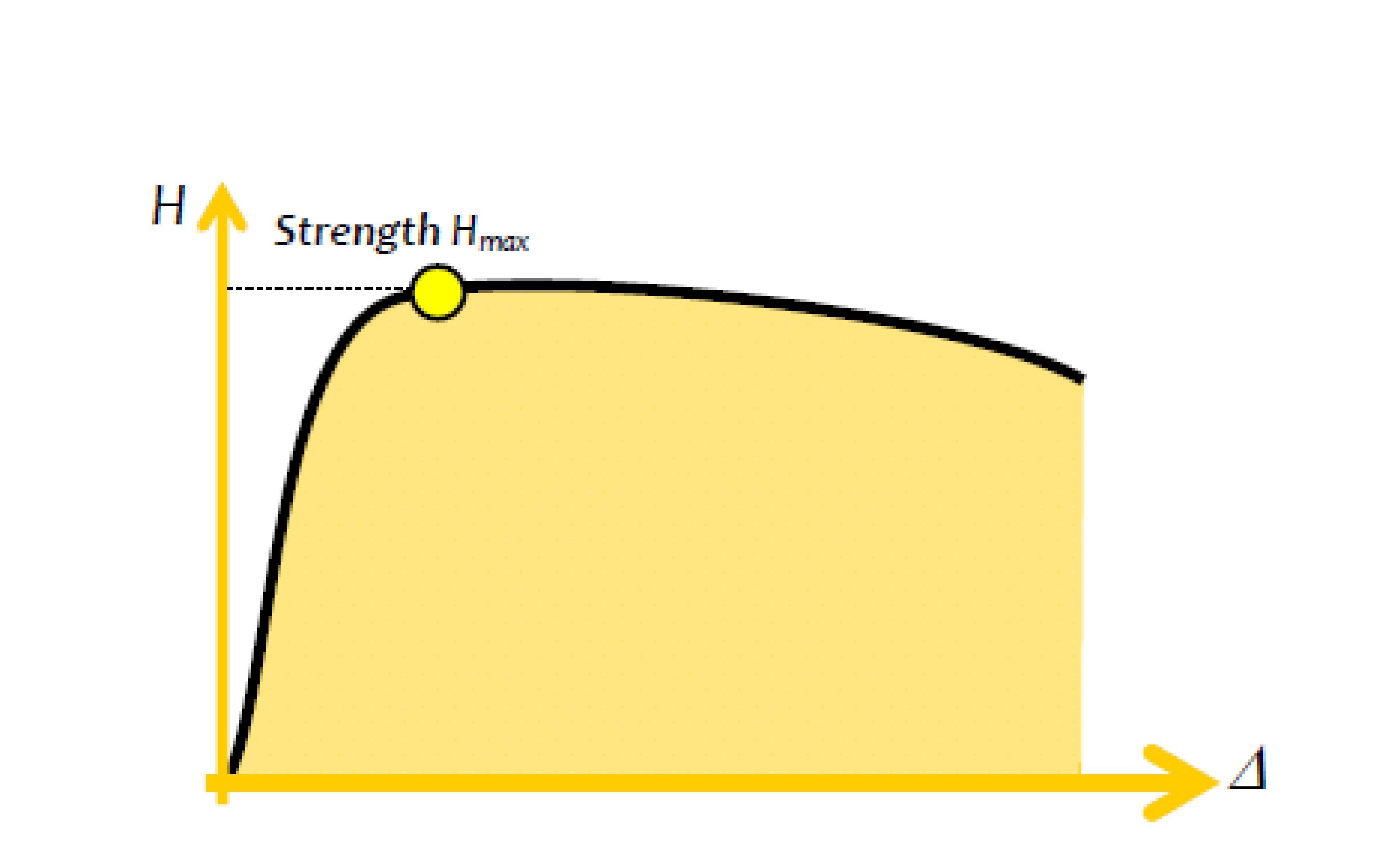
- LATERAL STIFFNESS IS THE RIGIDITY OF AN OBJECT — THE EXTENT TO WHICH IT RESISTS DEFORMATION IN RESPONSE TO AN APPLIED EARTHQUAKE FORCES.
- THE COMPLEMENTARY CONCEPT IS FLEXIBILITY - THE MORE FLEXIBLE AN OBJECT IS, THE LESS STIFF IT IS.
- STIFFNESS OF THE STRUCTURE DECREASES WITH THE INCREASE IN DAMAGE OF THE STRUCTURE.



Images Property of GSDM

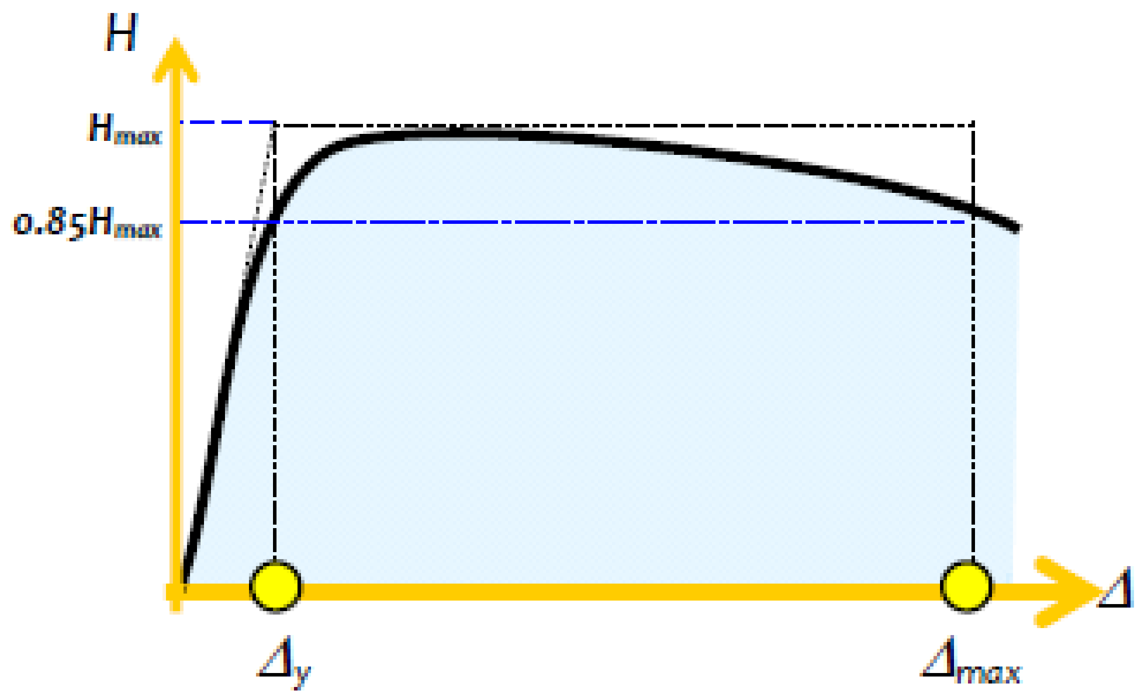
3. LATERAL STRENGTH

- LATERAL STRENGTH REFERS TO THE MAXIMUM RESISTANCE THAT THE BUILDING OFFERS DURING ITS ENTIRE HISTORY OF RESISTANCE TO RELATIVE DEFORMATION.



4. DUCTILITY OF THE STRUCTURE

- **DUCTILITY TOWARDS LATERAL DEFORMATION REFERS THE RATIO OF THE MAXIMUM DEFORMATION AND THE IDEALIZED YIELD DEFORMATION. THE MAXIMUM DEFORMATION CORRESPONDS TO THE MAXIMUM DEFORMATION SUSTAINED BY IT.**



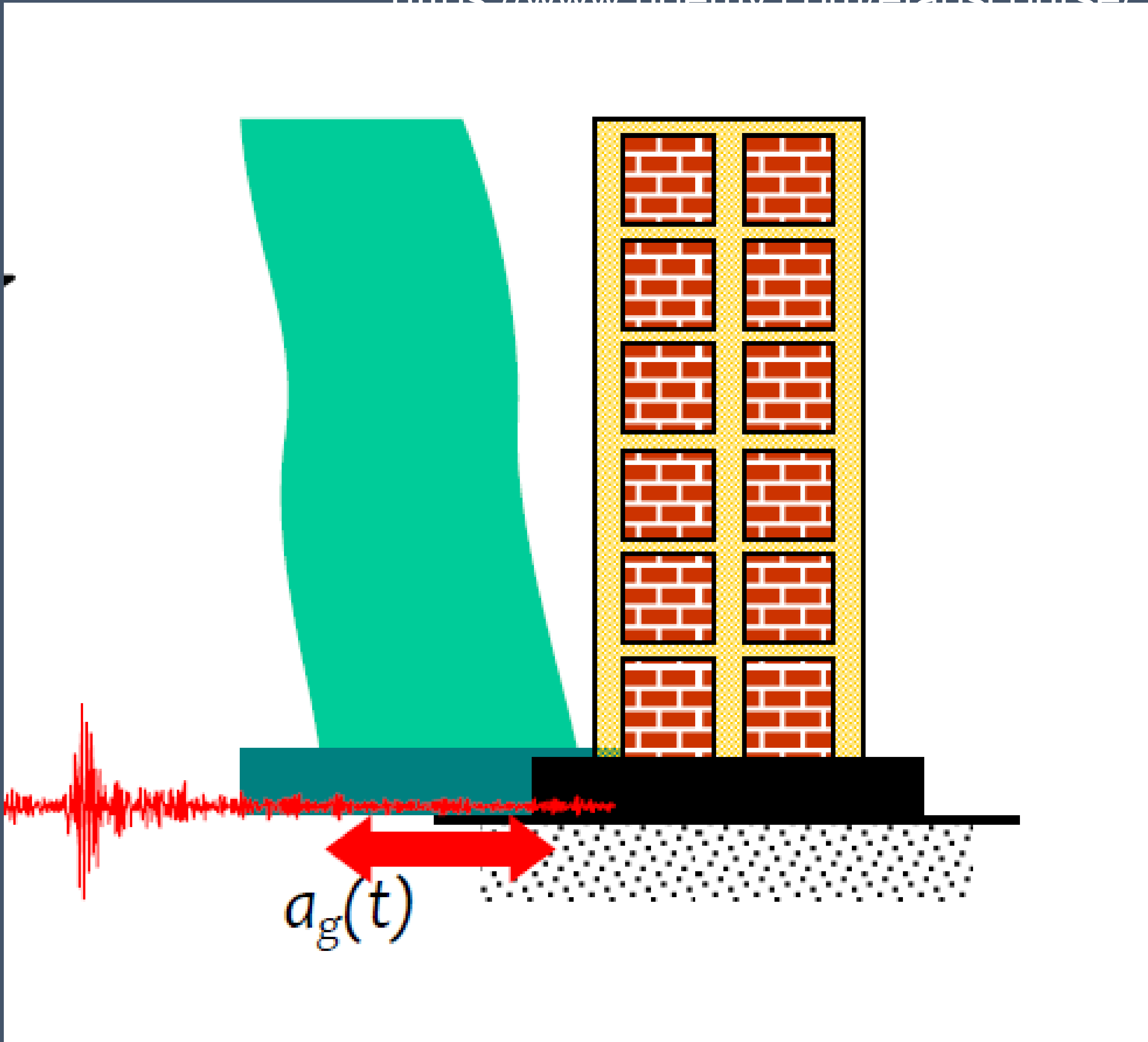
$$\text{Ductility} = \frac{\Delta_{max}}{\Delta_y}$$

SUMMARY OF CSSD RULE

GOOD SEISMIC CONFIGURATION – BUILDINGS SHOULD HAVE GOOD SEISMIC CONFIGURATION WITH NO COMPLEXITIES.

- **GOOD LATERAL STIFFNESS -** IN BOTH OF THE DIRECTIONS SO THAT IT DOES NOT SWAY MUCH AND DAMAGE TO BE MINIMUM.
- **GOOD LATERAL STRENGTH -** IN BOTH OF THE DIRECTIONS TO RESSIT GROUND SHAKING WITH MINIMUM DAMAGE AND NOT EXCESSIVE STRENGTH TO KEEP THE STRUCTURE ECONOMICALLY VIABLE. THIS BAALNCE IS VERY IMPORTANT FOR STRUCTURAL ENGINEERS.
- **GOOD DUCTILITY -** TO ACCOMMODATE THE LATERAL DEFORMATION BETWEEN BASE AND THE ROOF ODF THE BUILDING.

ALL BUILDINGS ARE JUST VERTICAL CANTILEVERS PROJECTING OUT FROM THE SURFACE OF THE EARTH.



Images Property of GSDMA

THREE PRINICIPAL BEHAVIOR FOR EARTHQUAKE RESISTANT BUILDINGS

- THEY SHOULD BE STRONG ENOUGH TO NOT SUSTAIN ANY DAMAGE DURING WEAK EARTHQUAKE SHAKING.
- THEY SHOULD BE STIFF ENOUGH TO NOT SWING TOO MUCH, EVEN DURING WEAK EARTHQUAKES.
- THEY SHOULD NOT COLLAPSE DURING THE EXPECTED STRONG EARTHQUAKE SHAKING TO BE SUSTAINED BY THEM EVEN WITH SIGNIFICANT STRUCTURAL DAMAGE.

A REMARKABLE QUOTE - *by Nathan M. Newmark and Emilo Rosenbleuth*

- *If a civil engineer is to acquire fruitful experience in a brief span of time, expose him to the concepts of earthquake engineering, no matter if he is later not to work in earthquake country.”*

SEVEN STEPS OF STRUCTURAL DESIGN

1. • ADOPT A SIMPLE GOMETRY AND WELL PROPORTIONED STRUCTURAL ARRANGEMENT.

2. • ADOPT A STRONG STRUCTURAL SYSTEM THAT CAN RESIST BOTH VERTICAL AND LATERAL LOADS.

3. • DETERMINE THE PRELIMINARY SIZING OF INDIVIDUAL STRUCTURAL ELEMENTS BASED ON THE ACCEPTABLE SLENDERNESS RATIOS AND MINIMUM REINFORCEMENT REQUIREMENTS.

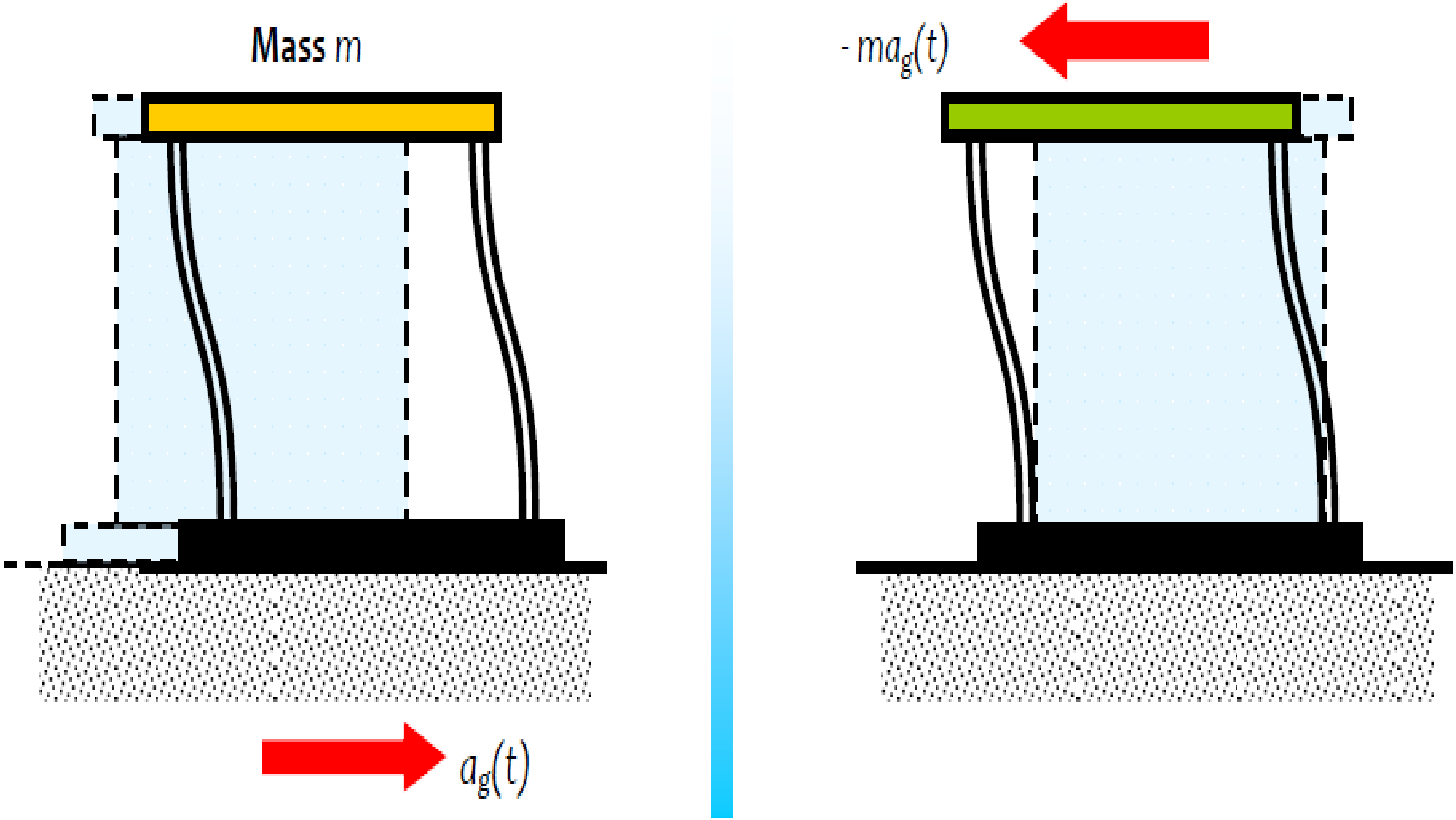
4. • IDENTIFY A DESIRED COLLAPSE MECHANISM IN WHICH THE BUILDING SHOULD DEFORM IN, UNDER THE EXTREME CONDITION OF COLLAPSE, FOR EXTREME CASE. USUALLY, IN FRAME STRUCTURES, PLASTIC MOMENT HINGES ARE DESIRED AT THE ENDS OF THE BEAMS WITH GOOD ROTATIONAL DUCTILITY.

5. • PREPARE A BASIC STRUCTURAL ANALYSIS MODEL OF THE BUILDING. IMPOSE A HORIZONTAL DEFORMATION ON THE BUILDING CORRESPONDING TO PERMISSIBLE INTER-STOREY DRIFT AT ALL STOREYS, AND PERFORM AN ELASTIC ANALYSIS OF THE BUILDING

6. • PERFORM SEISMIC DESIGN OF ALL STRUCTURAL ELEMENTS OF THE BUILDING I.E. SLABS, BEAMS, COLUMNS, STRUCTURAL WALLS, FOUNDATION ETC.

7. • ESTIMATE THE FUNDAMENTAL TRANSLATIONAL NATURAL PERIOD T OF THE BUILDING, AND CALCULATE THE DESIGN SEISMIC BASE SHEAR VB ON THE BUILDING.. APPLY THE DESIGN SEISMIC BASE SHEAR VB ON THE STRUCTURAL ANALYSIS MODEL OF THE BUILDING. AND, CHECK THE ADEQUACY OF THE DESIGN OF ALL STRUCTURAL ELEMENTS, INCLUDING BEAM-COLUMN AND BEAM-WALL JOINTS.

ACCELERATION TIME HISTORY AT THE BASE OF A BUILDING IS CONVERTED TO A FORCE TIME HISTORY FOR THE MASS OF THE BUILDING WITH THE BASE FIXED



IMPORTANT TERMS USED IN SEISMIC DESIGN CODES

- IN THE FORCE BASED EARTHQUAKE RESISTANT DESIGN, CODES REPRESENT THE EARTHQUAKE-INDUCED INERTIA FORCES IN THE FORM OF DESIGN *EQUIVALENT STATIC* LATERAL FORCE. THIS FORCE IS CALLED AS THE ***SEISMIC DESIGN BASE SHEAR V_B***
- THIS FORCE DEPENDS ON THE SEISMIC HAZARD AT THE SITE OF THE BUILDING REPRESENTED BY THE ***SEISMIC ZONE FACTOR Z.***
- CODES TEND TO ADOPT THE ***IMPORTANCE FACTOR I*** FOR INCREASING THE ELASTIC RANGE OF THE BUILDINGS.
- THE NET SHAKING OF A BUILDING IS A COMBINED EFFECT OF THE ENERGY CARRIED BY THE EARTHQUAKE AT DIFFERENT FREQUENCIES AND THE NATURAL PERIODS OF THE BUILDING. WHICH IS DENOTED BY ***STRUCTURAL FLEXIBILITY FACTOR SA/G.***
- TO MAKE NORMAL BUILDINGS ECONOMICAL, DESIGN CODES ALLOW SOME DAMAGE FOR REDUCING COST OF CONSTRUCTION WITH THE HELP OF ***RESPONSE REDUCTION FACTOR R***, WHICH IS HIGHER FOR DUCTILE BUILDINGS AND SMALLER FOR BRITTLE ONES.

INDIAN STANDARD IS 1893-2016

- As per the Indian Seismic Code IS:1893 (Part 1) - 2016, *Design Base Shear VB* is given by:

$$V_B = A_h W = \frac{ZI}{2R}\left(\frac{S_a}{g}\right)W$$

- Z = SEISMIC ZONE FACTOR
- I = IMPORTANCE FACTOR
- R = RESPONSE REDUCTION FACTOR
- Sa/g = DESIGN ACCELERATION SPECTRUM VALUE.

Sa/g THE *DESIGN ACCELERATION SPECTRUM VALUE* AS PER IS 1893-2016

$$\frac{S_a}{g} = \begin{cases} \begin{cases} 2.5 & 0.00 < T < 0.40 \\ \dfrac{1.00}{T} & 0.40 < T < 4.00 \end{cases} & \text{for Soil Type I : rocky or hard soil sites} \\ \begin{cases} 2.5 & 0.00 < T < 0.55 \\ \dfrac{1.36}{T} & 0.55 < T < 4.00 \end{cases} & \text{for Soil Type II : medium soil sites} \\ \begin{cases} 2.5 & 0.00 < T < 0.67 \\ \dfrac{1.67}{T} & 0.67 < T < 4.00 \end{cases} & \text{for Soil Type III : soft soil sites} \end{cases},$$

Seismic Zone Factor *Z* as per IS:1893 (Part 1) - 2016

Seismic Zone	V	IV	III	II
Z	0.36	0.24	0.16	0.10

Note:
The zone in which a building is located can be identified from the Seismic Zone Map of India given in IS:1893-2007, sketched in Figure 2.1.

IMPORTANCE FACTOR I AS PER IS 1893-2016

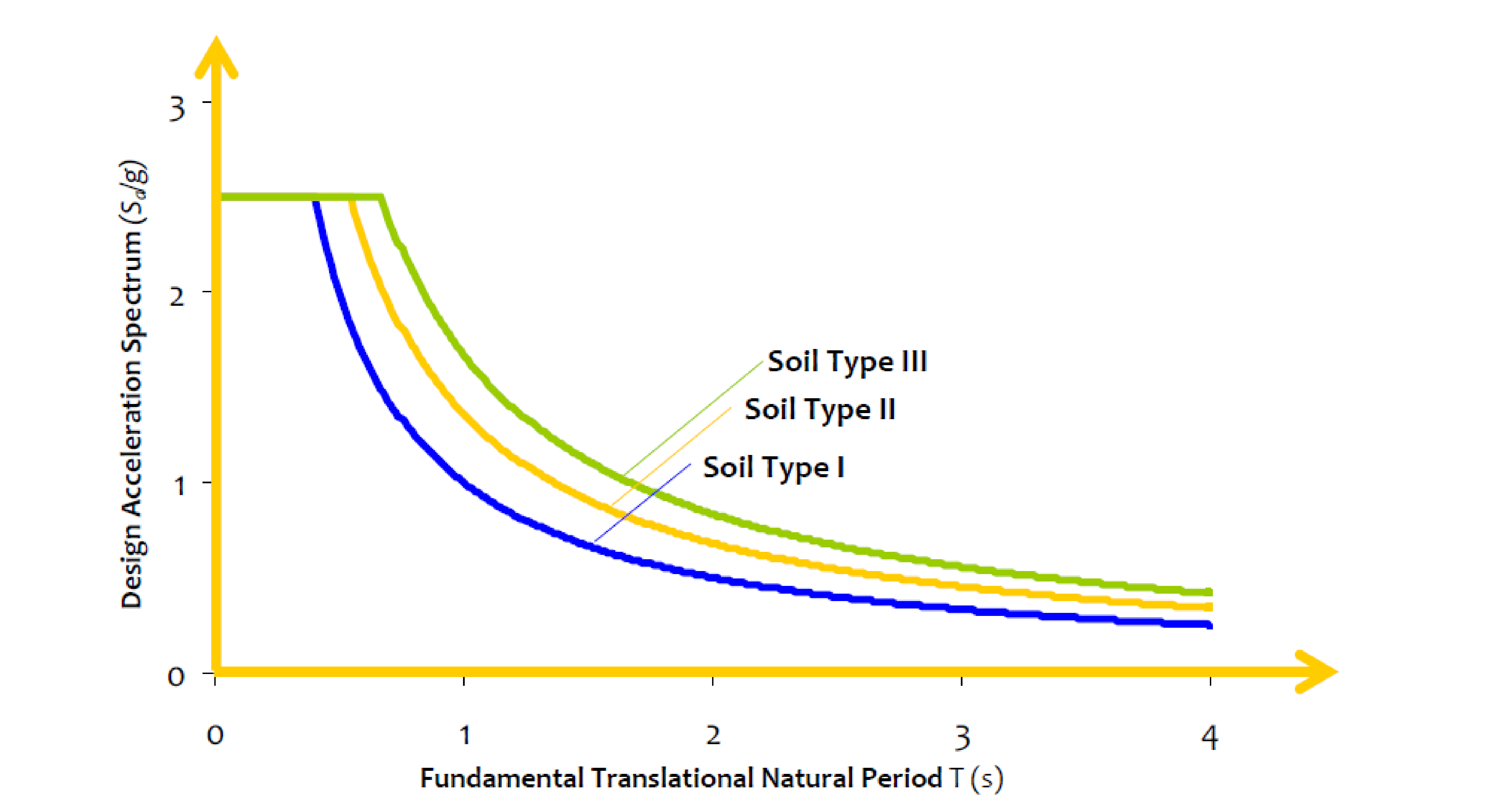
Building	*Importance Factor I*
Normal Buildings	*1.0*
Important Buildings (*e.g.*, Critical buildings required to be functional after an earthquake, Lifeline buildings associated with utilities, like water, power & transportation)	*1.5*

RESPONSE REDIUCTION FACTOR AS PER IS1893-2016

Lateral Load Resisting System	*R*
Building Frame Systems	
Ordinary RC moment resisting frame (OMRF)	3.0
Special RC moment-resisting frame (SMRF)	5.0
Steel frame with (a) Concentric braces (b) Eccentric braces	 4.0 5.0
Steel moment resisting frame designed as per SP 6 (6)	5.0
Buildings with Shear Walls	
Ordinary reinforced concrete shear walls	3.0
Ductile shear walls	4.0
Buildings with Dual Systems	
Ordinary shear wall with OMRF	3.0
Ordinary shear wall with SMRF	4.0
Ductile shear wall with OMRF	4.5
Ductile shear wall with SMRF	5.0

https://www.udemy.com/etabscourse/

DESIGN ACCELERATION SPECTRUM CURVE AS PER IS1893-2016



Images Property of GSDMA

DYNAMIC CHARACTERISTICS OF THE BUILDING

THE IMPORTANT DYNAMIC CHARACTERISTICS OF BUILDINGS ARE ***MODES OF OSCILLATION* AND *DAMPING*.**

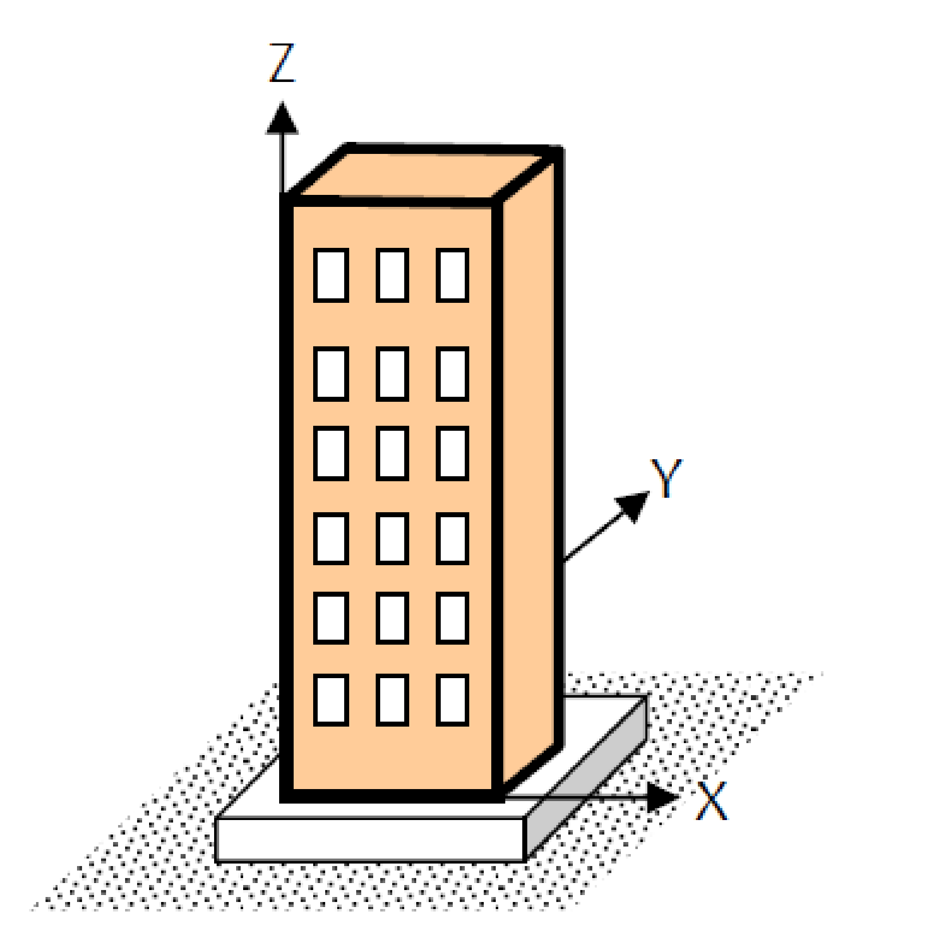
A MODE OF OSCILLATION OF A BUILDING IS DEFINED BY ASSOCIATED *NATURAL PERIOD* AND *DEFORMED SHAPE* IN WHICH IT OSCILLATES.

WHAT IS NATURAL PERIOD OF THE BUILDING ?

*T*HE TIME TAKEN BY IT TO UNDERGO ONE COMPLETE CYCLE OF OSCILLATION UNDER THE APPLICATION OF A LATERAL FORCE

IT IS AN INHERENT PROPERTY OF A BUILDING CONTROLLED BY ITS **MASS *M* AND STIFFNESS *K*.**

$$T_n = 2\pi\sqrt{\frac{m}{k}}\,;$$



T_N = SECONDS

M = MASS OF THE BUILDING

K = STIFFNESS OF THE BUILDING

RELATIONSHIP BETWEEN MASS ,STIFFNESS AND TIME PERIODS

TIME PERIOD IS DIRECTLY PROPORTIONAL TO MASS OF THE BUILDING

TIME PERIOD IS INVERSELY PROPORTINAL TO STIFFNESS OF THE BUILDING.

$$T_n = 2\pi\sqrt{\frac{m}{k}};$$

HEAVY AND FLEXIBLE BUILDINGS HAVE LARGER NATURAL PERIOD THAN LIGHTER AND STIFFER BUILDINGS.

WHAT IS THE FREQUENCY OF THE BUILDING ?

FREQUENCY IS THE RECIPROCAL OF THE TIME PERIOD

$$f = \frac{1}{T}$$

UNIT OF FREQUENCY IS HERTZ (Hz)

THE BUILIDING OFFERS LEAST RESISTANCE WHEN SHAKEN AT ITS NATURAL FREQUENCY.

STRUCTURAL ENGINEERS WORK WITH TIME PERIOD RATHER THAN FREQUENCY,ALTHOUGH BOTH ARE VERY IMPORTANT.

CAN BUILDINGS SHOW RESONANCE ?

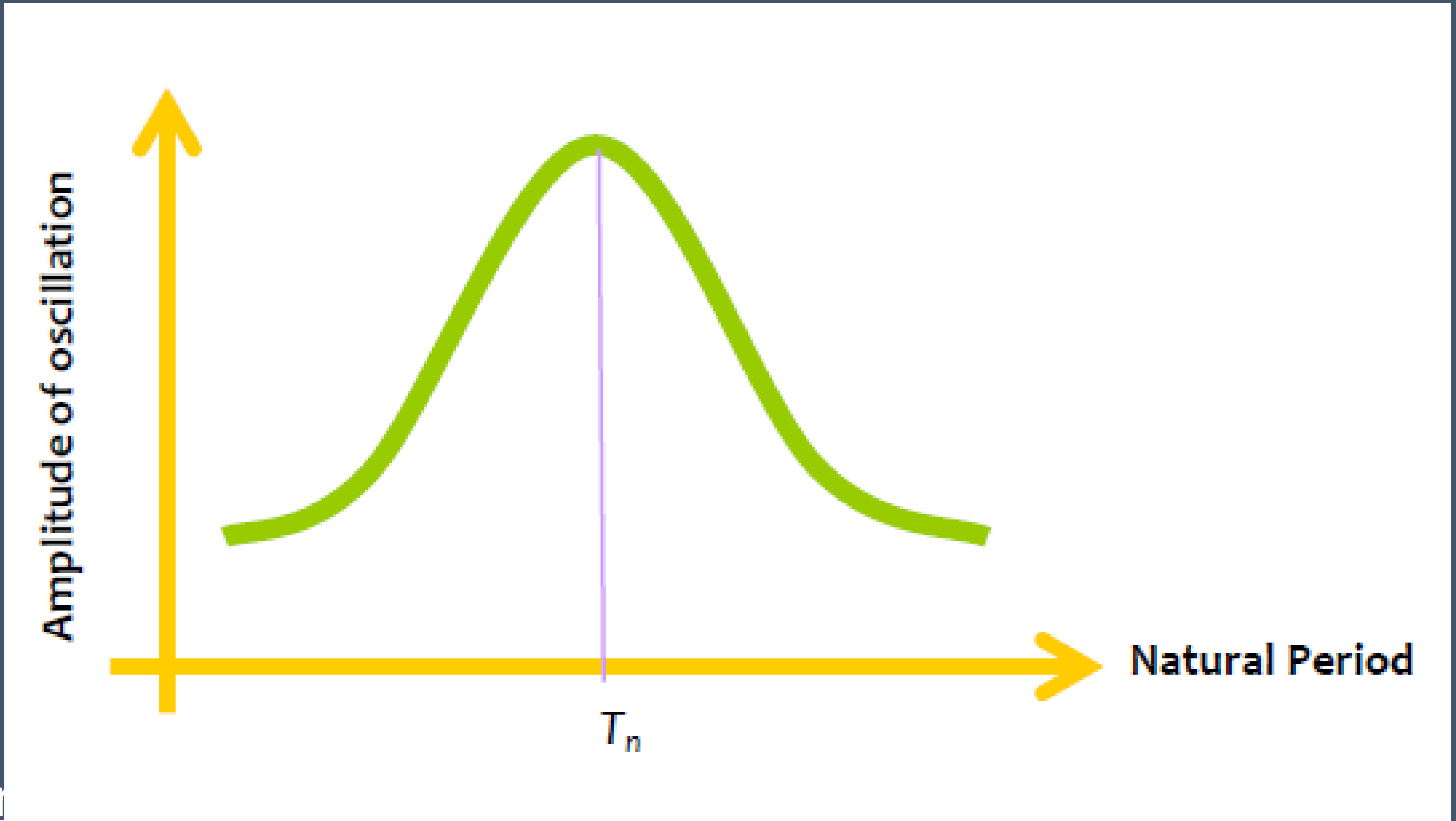
- THE ANSWER IS **YES !**, BUT VERY RARELY.
- RESONANCE WILL OCCUR IN A BUILDING, ONLY IF FREQUENCY AT WHICH GROUND SHAKES IS STEADY AT OR NEAR ANY OF THE NATURAL FREQUENCIES OF BUILDING AND APPLIED OVER AN EXTENDED PERIOD OF TIME.
- **THEN WHY RARELY ??**

1. THE GROUND MOTION CONTAINS A SET OF FREQUENCIES THAT ARE CONTINUALLY AND RANDOMLY CHANGING VERY FAST. THERE IS NO GUARANTEE THAT THE GROUND SHAKING CONTAINS THE SAME FREQUENCY (AND THAT TOO CLOSE TO *NATURAL FREQUENCY* OF THE BUILDING) THROUGHOUT OR EVEN FOR A SUSTAINED DURATION.

2. SECOND, THE SMALL DURATION FOR WHICH THE GROUND SHAKING OCCURS AT FREQUENCIES CLOSE TO *FN* OF THE BUILDING, IS INSUFFICIENT TO BUILD RESONANT CONDITIONS IN MOST CASES OF THE USUAL GROUND MOTIONS

ONE OF FEW CASES OF *RESONANCE* DURING EARTHQUAKE SHAKING WAS NOTICED DURING THE

- 1985 MEXICO CITY EARTHQUAKE – THE BUILDINGS HAVING NATURAL PERIODS IN A SMALL RANGE ALONE COLLAPSED, WHILE THOSE WITH NATURAL PERIODS OUTSIDE THE RANGE PERFORMED NORMALLY.

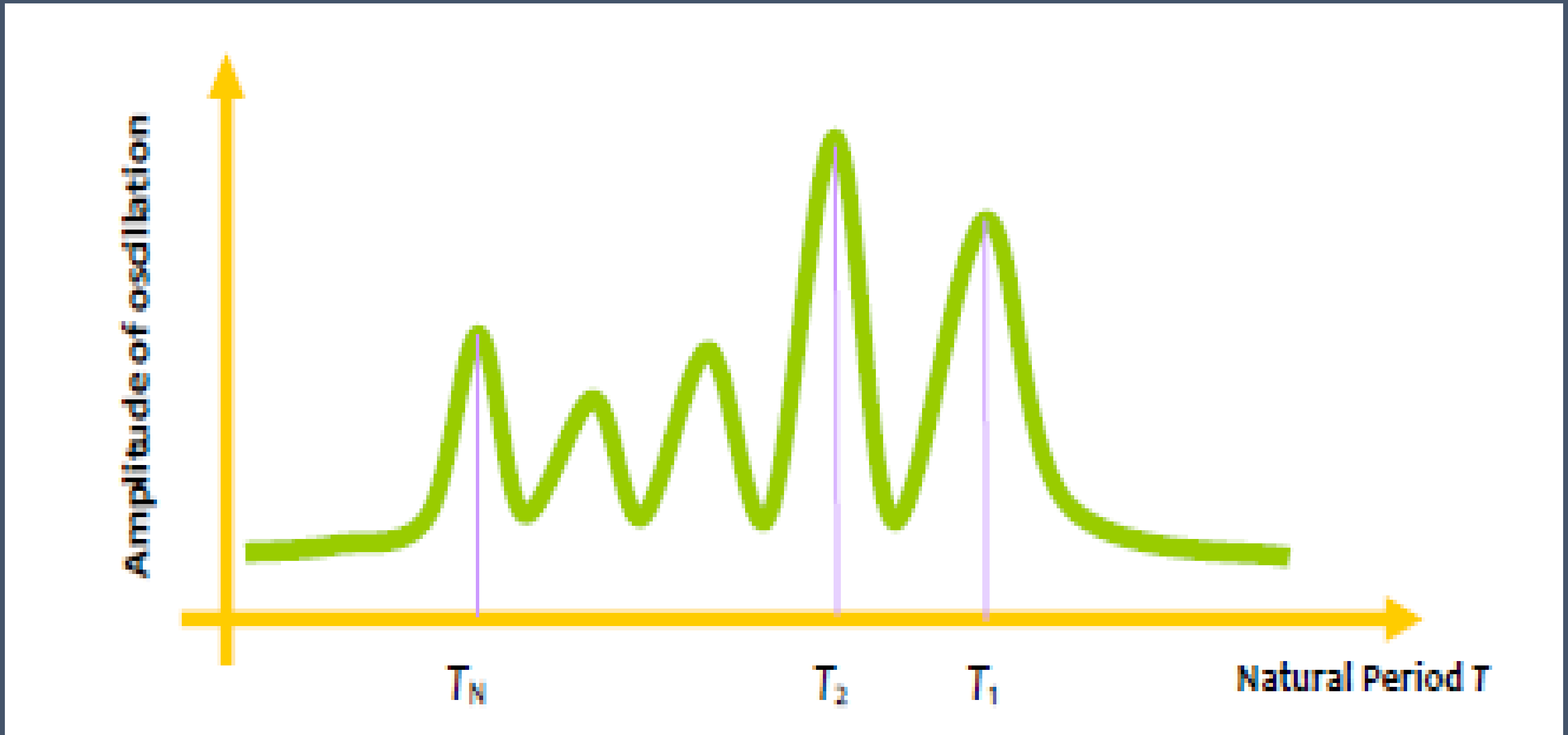


Images Proper

https://www.udemy.com/etabscourse/

FUNDAMENTAL NATURAL PERIOD OF BUILDING

- EVERY BUILDING HAS NUMBER OF NATURAL FREQUENCIES AT WHICH IT OFFERS MINIMUM RESISTANCE OT SHAKING
- EACH OF THESE NATURAL FREQUENCIES AND THE ASSOCIATED DEFORMATION SHAPE OF A BUILDING CONSTITUTE A *NATURAL MODE OF OSCILLATION*.
- EACH OF THESE MODE OF OSCILLATION WITH THE SMALLEST NATURAL FREQUENCY AND LARGEST TIME PERIOD IS CALLED FUNDAMENTAL MODE.
- T1 = FUNDAMENTAL NATURAL PERIOD
- F1 = 1/T1 = FUNDAMENTAL NATURAL FREQUENCY



Images Property of GSDMA

FUNDAMENTAL NATURAL PERIOD OF BUILDING

FURTHER, REGULAR BUILDINGS HELD AT THEIR BASE FROM TRANSLATION IN THE THREE DIRECTIONS, HAVE

(1) THREE FUNDAMENTAL TRANSLATIONAL NATURAL PERIODS,

TX1 = ASSOCIATED WITH ITS HORIZONTAL TRANSLATIONAL OSCILLATION ALONG X

TY1 = ASSOCIATED WITH ITS HORIZONTAL TRANSLATIONAL OSCILLATION ALONG Y

TZ1 = ASSOCIATED WITH ITS HORIZONTAL TRANSLATIONAL OSCILLATION ALONG Z

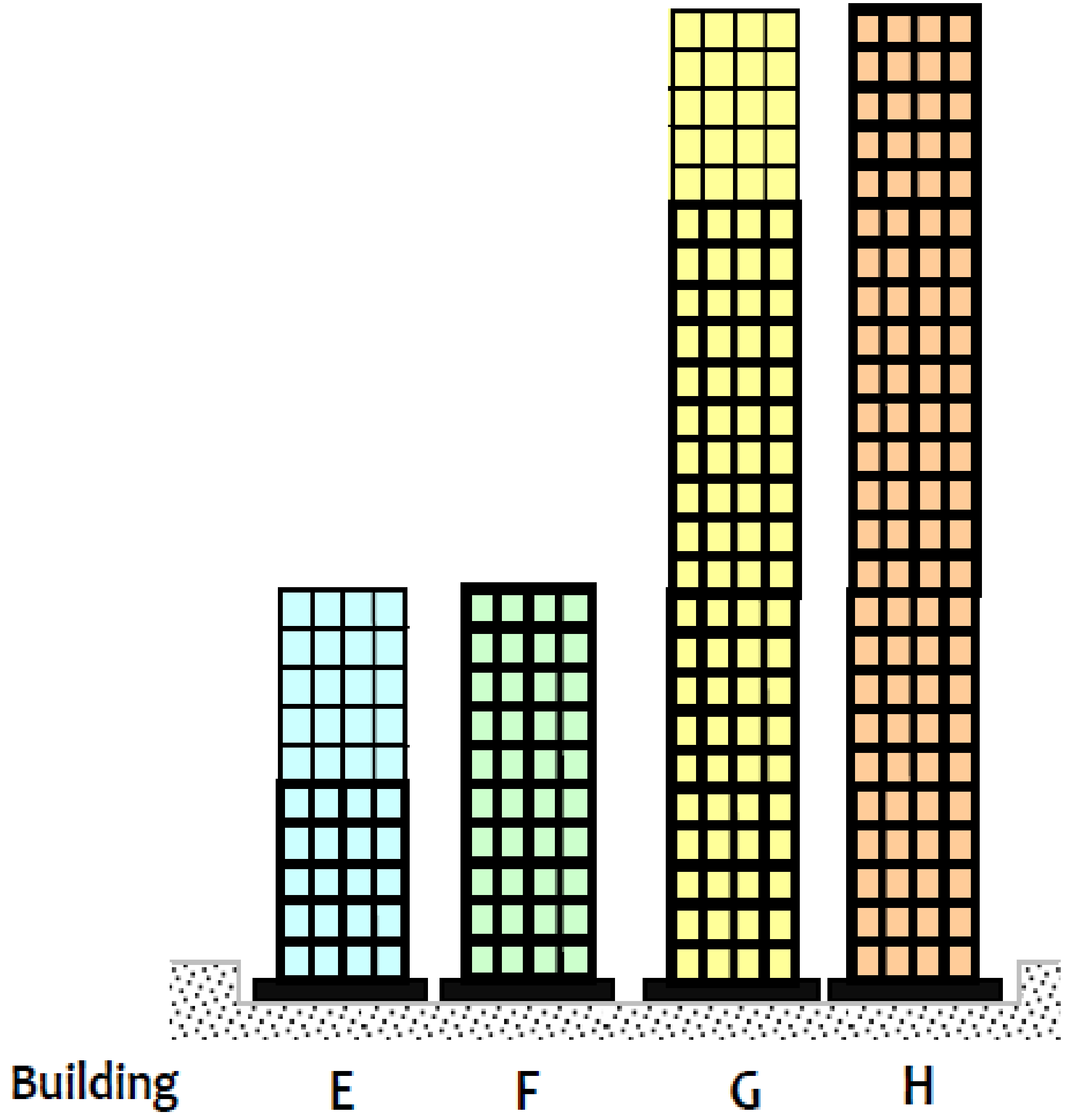
(2) ONE FUNDAMENTAL ROTATIONAL NATURAL PERIOD $T_{\vartheta 1}$ ASSOCIATED WITH ITS ROTATION ABOUT AN AXIS PARALLEL TO Z AXIS.

CASE STUDY OF 10 DIFFERENT BUILDINGS FOR TIME PERIOD AND FREQUENCY

Building	Description	Number of Storeys	Number of Bays		Column Dimension (mm × mm)
			X-DIRECTION	Y-DIRECTION	
A	2 STOREY BUILDING	2	4	3	400X400
B	BENCHMARK 5 STOREY BUILDING	5	4	3	400X400
C	BENCHMARK BUILDING WITH RECTANGULAR COLUMNS ORIENTED ALONG X DIRECTION	5	4	3	550X300
D	BENCHMARK BUILDING WITH RECTANGULAR COLUMNS ORIENTED ALONG Y DIRECTION	5	4	3	300X550
E	10-STOREY BUILDING WITH VARYING COLUMN SIZE ALONG BUILDING HEIGHT	10	4	3	UPPER 5 STOREYS 400X400 BOTTOM 5 STOREYS 600X600
F	10-STOREY BUILDING	10	4	3	600X600
G	25-STOREY BUILDING WITH VARYING COLUMN SIZE ALONG BUILDING HEIGHT	25	4	3	Upper 5 storey: 400 × 400 Middle 10 storey: 600 × 600 Bottom 10 storey: 800 × 800

Building	Description	Number of Storeys	Number of Bays		Column Dimension (mm × mm)
			X-DIRECTION	Y-DIRECTION	
H	25 storey building	25	4	3	800x800
j	25-STOREY BUILDING WITH IMPOSED MASS 10% LARGER THAN BUILDING H	25	4	3	800x800
K	25-STOREY BUILDING WITH IMPOSED MASS 20% LARGER THAN BUILDING H	25	4	3	800X800
NOTE:					
1. BAY LENGTH IN EACH PLAN DIRECTION IS 4M(CENTER TO CENTER)					
2. ALL COLUMNS AT EACH STOREY ARE OF THE SAME SIZE.					
3. ALL BEAMS IN THE BUILDINGS ARE OF THE SAME SIZE (300MMX400MM)					

STIFFNESS CASE STUDY

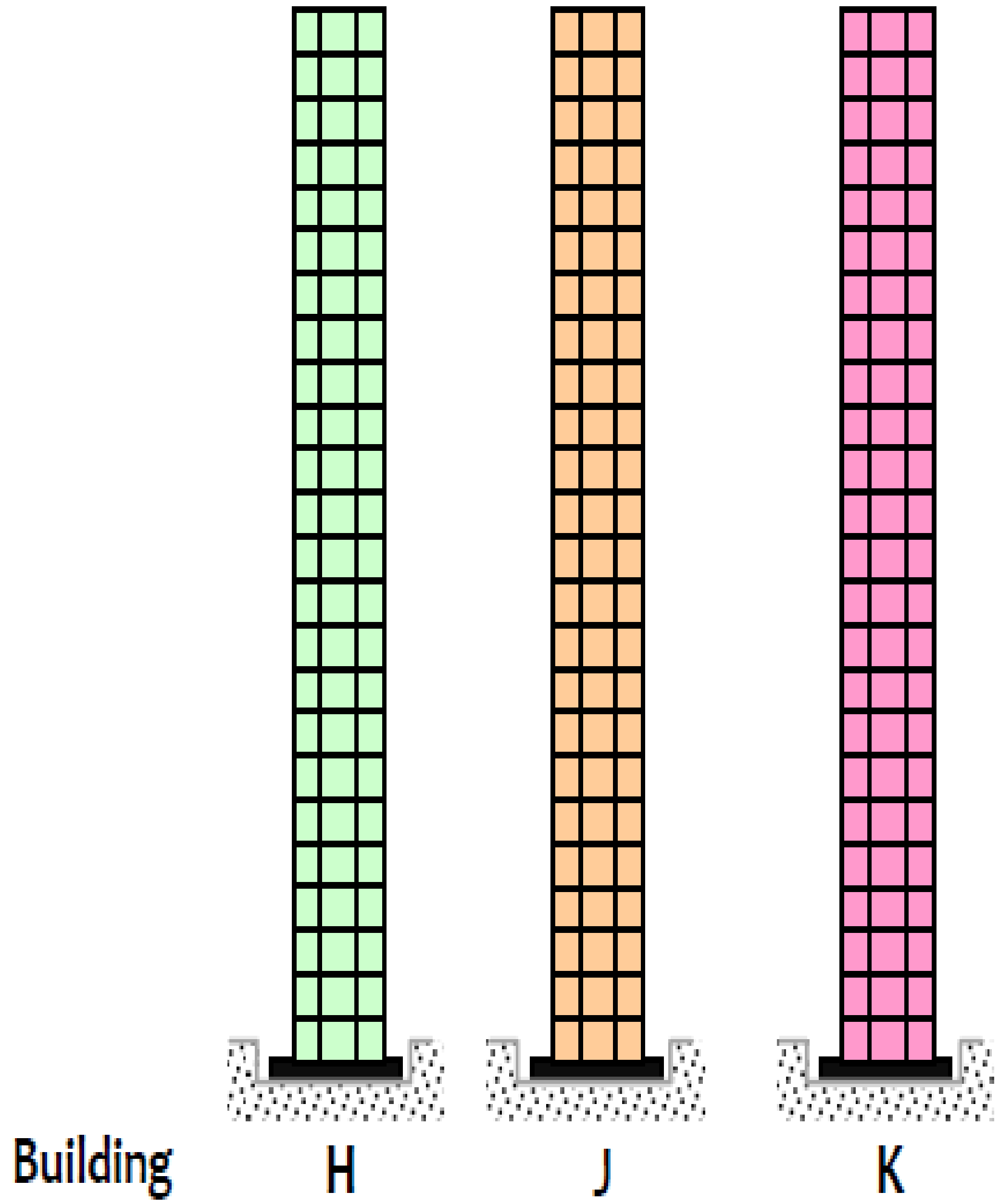


Building E	Building F
$T_{X_1} = 1.32$ s $T_{Y_1} = 1.36$ s	$T_{X_1} = 1.31$ s $T_{Y_1} = 1.35$ s
Building G	**Building H**
$T_{X_1} = 2.89$ s $T_{Y_1} = 3.04$ s	$T_{X_1} = 2.98$ s $T_{Y_1} = 3.14$ s

EFFECT OF STIFFNESS

- INCREASING THE COLUMN SIZE INCREASES BOTH STIFFNESS AND MASS OF BUILDINGS. BUT, WHEN THE PERCENTAGE INCREASE IN STIFFNESS AS A RESULT OF INCREASE IN COLUMN SIZE IS LARGER THAN THE PERCENTAGE INCREASE IN MASS, THE NATURAL PERIOD REDUCES.
- THUS, BUILDING F (WITH 600×600 COLUMN THROUGHOUT) IS RELATIVELY STIFFER THAN BUILDING E AND THE FUNDAMENTAL PERIOD OF THE STIFFER BUILDING F (1.35 *S*) IS ONLY MARGINALLY SMALLER THAN THAT OF THE BUILDING E (1.36 *S*).
- BETWEEN BUILDINGS G AND H, THE LATTER IS MUCH STIFFER. BUT, WHILE INCREASING STIFFNESS, THE MASS IS ALSO INCREASED.HENCE TIME PERIOD INCREASES.

EFFECT OF MASS OF THE BUILDING ON TIME PERIOD

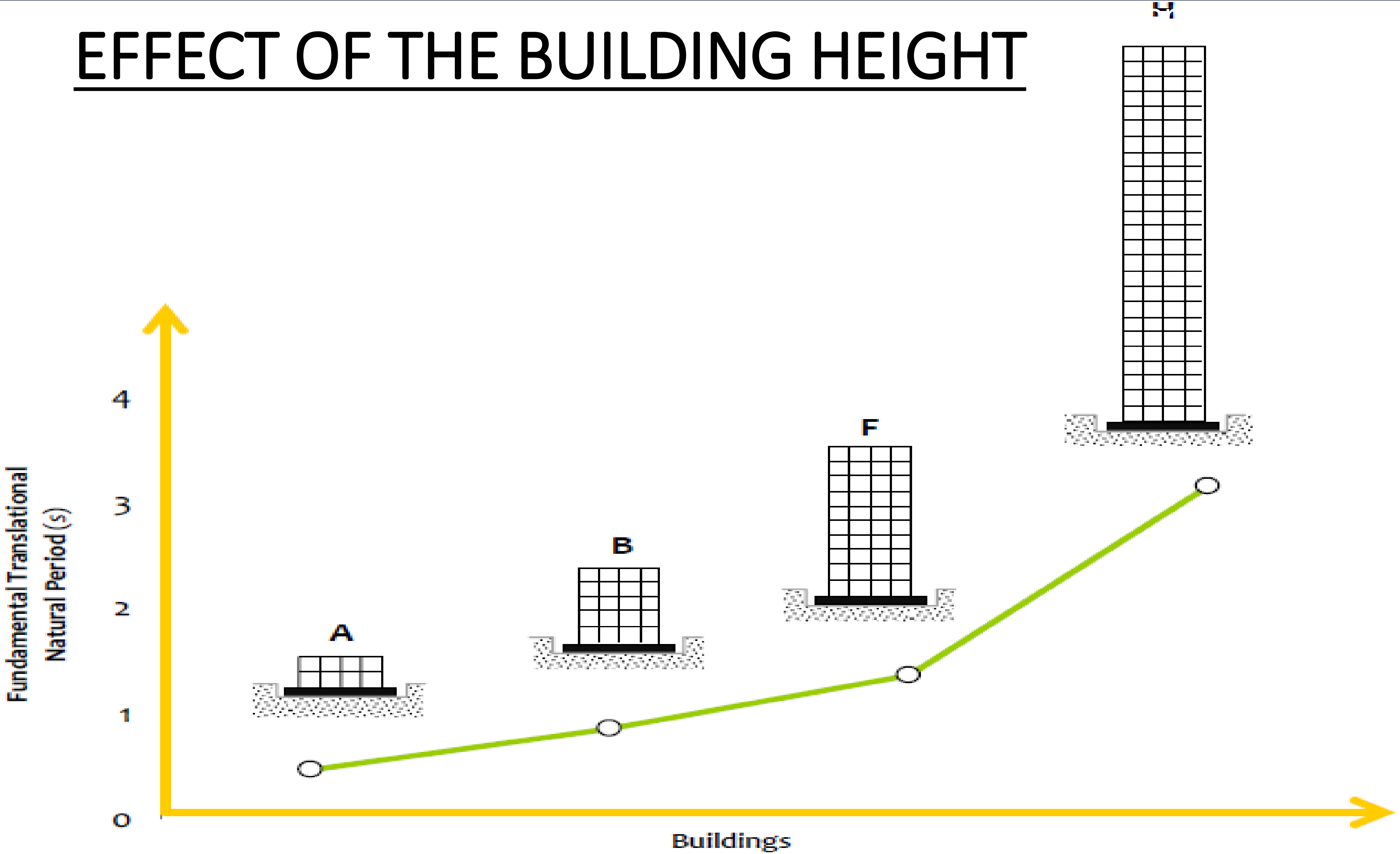


Building H	Building J	Building K
Mass m $T_{X1} = 2.98$ s $T_{Y1} = 3.14$ s	Mass 1.1m $T_{X1} = 3.12$ s $T_{Y1} = 3.29$ s	Mass 1.2m $T_{X1} = 3.25$ s $T_{Y1} = 3.43$ s

EFFECT OF MASS OF THE BUILDING ON TIME PERIOD

- *SEISMIC MASS OF THE BUILDING IS THE* MASS OF A BUILDING THAT IS *EFFECTIVE* IN LATERAL OSCILLATION DURING EARTHQUAKE SHAKING . IT IS THE SUM OF ITS SEISMIC MASSES AT DIFFERENT FLOOR LEVELS.
- SEISMIC MASS AT EACH FLOOR LEVEL IS EQUAL TO FULL DEAD LOAD PLUS APPROPRIATE FRACTION OF LIVE LOAD.
- AN INCREASE IN MASS OF A BUILDING INCREASES ITS NATURAL PERIOD

EFFECT OF THE BUILDING HEIGHT

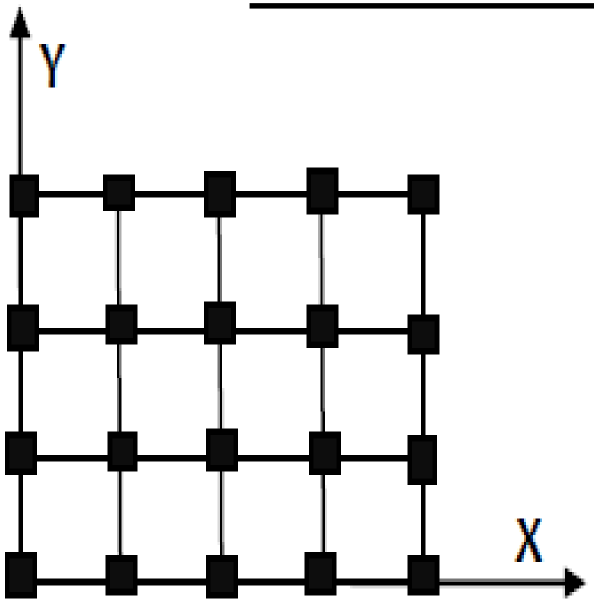


EFFECT OF THE BUILDING HEIGHT ON TIME PERIOD

- As the height of building increases, its mass increases but its overall stiffness decreases.

- HENCE, THE NATURAL PERIOD OF A BUILDING INCREASES WITH INCREASE IN HEIGHT

EFFECT OF COLUMN ORIENTATION ON TIME PERIOD

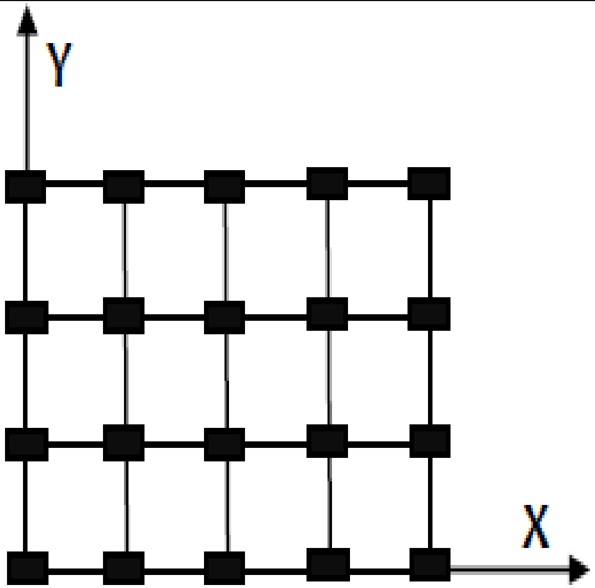


Building B

Column size : 400 × 400

T_{X_1} = 0.88 s

T_{Y_1} = **0.89** s

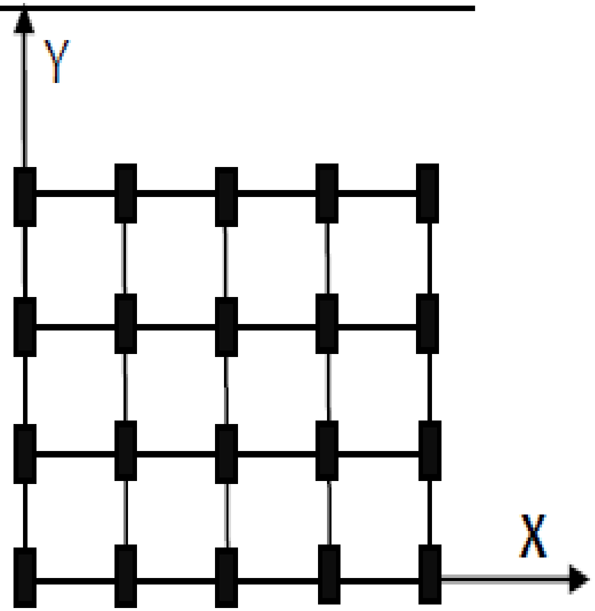


Building C

Column size : 550 × 300

T_{X_1} = 0.77 s

T_{Y_1} = **1.1** s



Building D

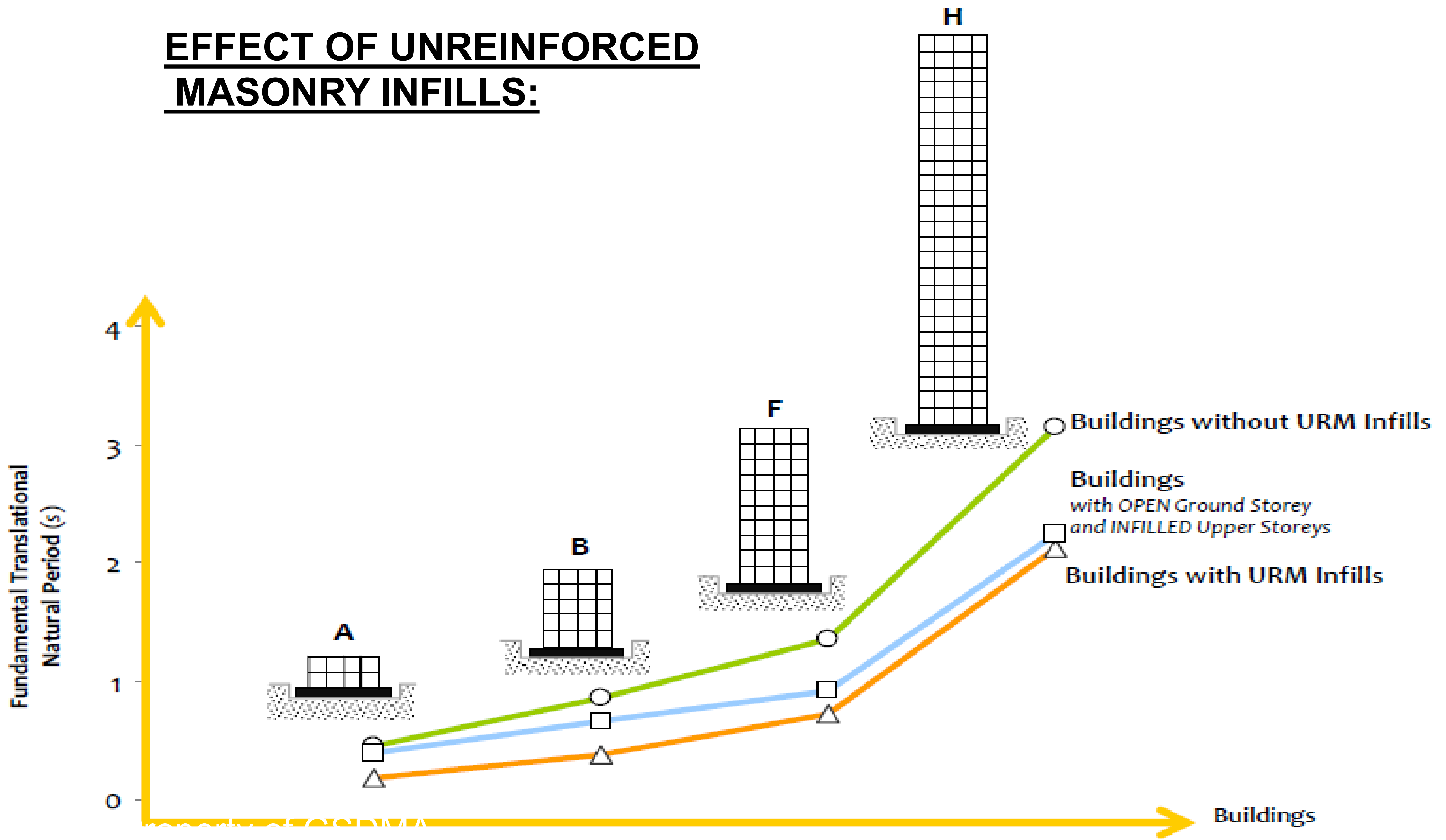
Column size : 300 × 550

T_{X_1} = **0.93** s

T_{Y_1} = 0.74 s

NATURAL PERIOD OF BUILDINGS ALONG THE LONGER DIRECTION OF COLUMN CROSS-SECTION IS SMALLER THAN THAT ALONG THE SHORTER DIRECTION

EFFECT OF UNREINFORCED MASONRY INFILLS:



EFFECT OF UNREINFORCED MASONRY INFILL WALLS IN RC FRAMES

- THE SPACE BETWEEN THE BEAMS AND COLUMNS OF BUILDING ARE SOMETIMES FILLED WITH UNREINFORCED MASONRY (URM) INFILLS.
- THESE INFILLS PARTICIPATE IN THE LATERAL RESPONSE OF BUILDINGS AND AS A CONSEQUENCE ALTER THE LATERAL STIFFNESS OF BUILDINGS. HENCE, NATURAL PERIODS (AND MODES OF OSCILLATION) OF THE BUILDING ARE AFFECTED IN THE PRESENCE OF URM.
- SEISMIC BEHAVIOUR OF SHORTER BUILDINGS IS AFFECTED SIGNIFICANTLY AS COMPARED TO THAT OF TALLER BUILDINGS, WHEN STIFFNESS ENHANCEMENT DUE TO URM IS CONSIDERED

TWO TYPES OF CROSS SECTIONAL PROPERTIES (EFFECTIVE STIFFNESS)

GROSS SECTION PROPERTIES

1. GROSS CROSS-SECTIONAL PROPERTIES ARE COMPUTED USING GROSS SECTIONAL AREA **WITHOUT CONSIDERING THE STIFFNESS ENHANCEMENT** DUE TO THE PRESENCE OF LONGITUDINAL REINFORCEMENT

2. THE **EXTENT OF CRACKING** OF THE MEMBER IS ASSUMED TO BE **MINIMUM**

3. THEY ARE USED FOR ESTIMATING FORCE AND DEFORMATION DEMANDS ON MEMBERS SUBJECTED TO **GRAVITY LOADING BASED ON LINEAR ANALYSIS**.

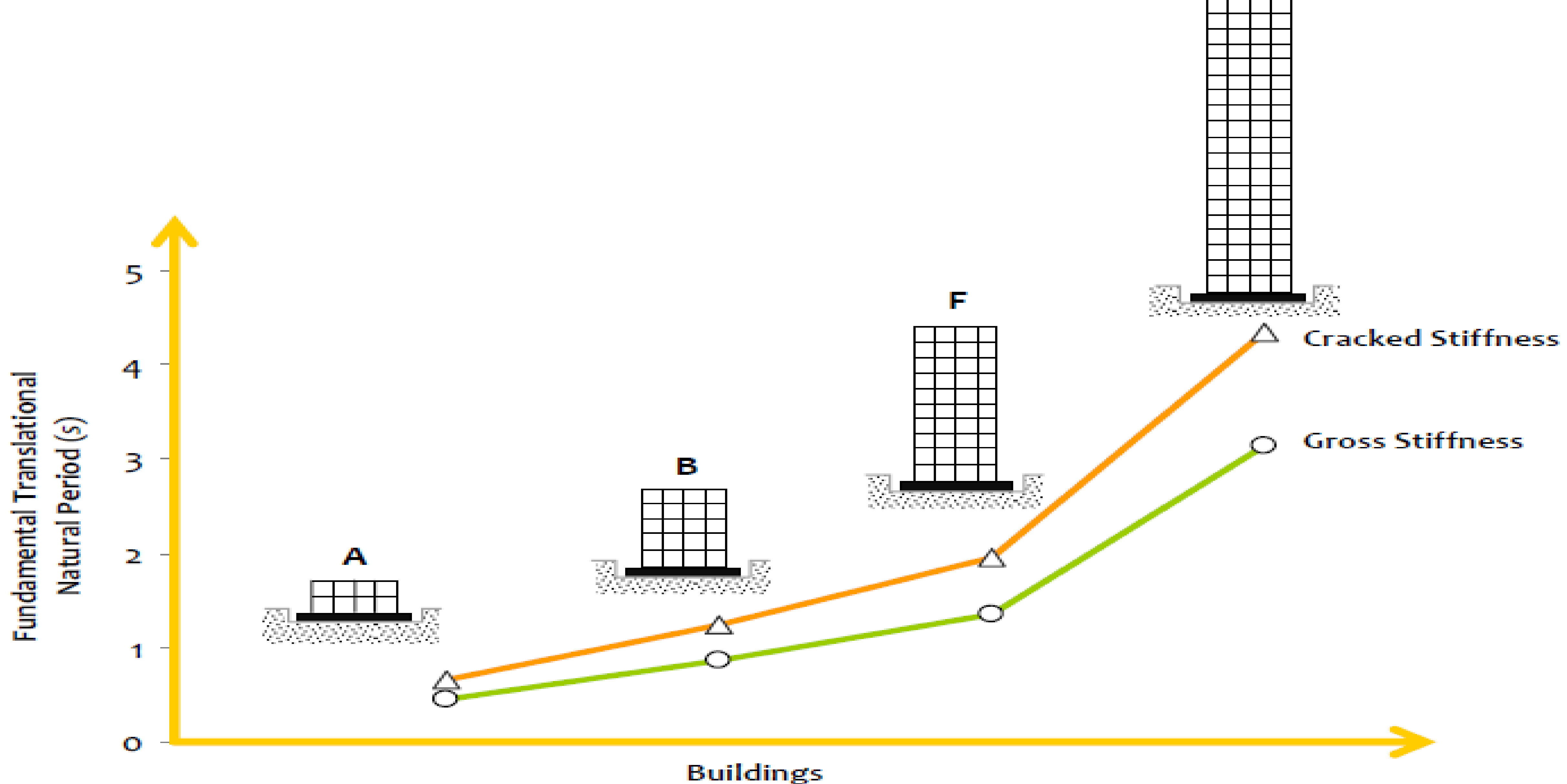
CRACKED SECTION PROPERTIES

1. EFFECTIVE PROPERTIES REPRESENT **REDUCED STIFFNESS** OF MEMBERS IN THEIR DAMAGED STATE. WHEN SECTIONS UNDERGO **EXTENSIVE CRACKING DURING EARTHQUAKE SHAKING.**

2. EFFECTIVE PROPERTIES REPRESENT REDUCED STIFFNESS OF MEMBERS IN THEIR DAMAGED STATE AND ARE **EXPRESSED AS A FRACTION OF GROSS STIFFNESS**

Type of Member	*Range*	*Recommended Value*
Rectangular Beams	$0.30I_g$ - $0.50I_g$	$0.40I_g$
T and L Beam	$0.25I_g$ - $0.45I_g$	$0.35I_g$
Columns ($P> 0.5f_cA_g$)	$0.70I_g$ - $0.90I_g$	$0.80I_g$
Columns ($P> 0.2f_cA_g$)	$0.50I_g$ - $0.70I_g$	$0.60I_g$
Columns ($P>-0.05f_cA_g$)	$0.30I_g$ - $0.50I_g$	$0.40I_g$

NATURAL PERIOD OF BUILDING ESTIMATED USING GROSS STIFFNESS IS LOWER THAN NATURAL PERIOD OF BUILDING ESTIMATED USING EFFECTIVE STIFFNESS.



SUMMARY OF WHAT WE HAVE LEARNED TILL NOW

THE NATURAL PERIODS OF BUILDINGS DEPEND ON THE DISTRIBUTION OF MASS AND STIFFNESS ALONG THE BUILDING (IN ALL DIRECTIONS).

1. NATURAL PERIODS OF BUILDINGS REDUCE WITH INCREASE IN STIFFNESS.

2. NATURAL PERIODS OF BUILDINGS INCREASE WITH INCREASE IN MASS.

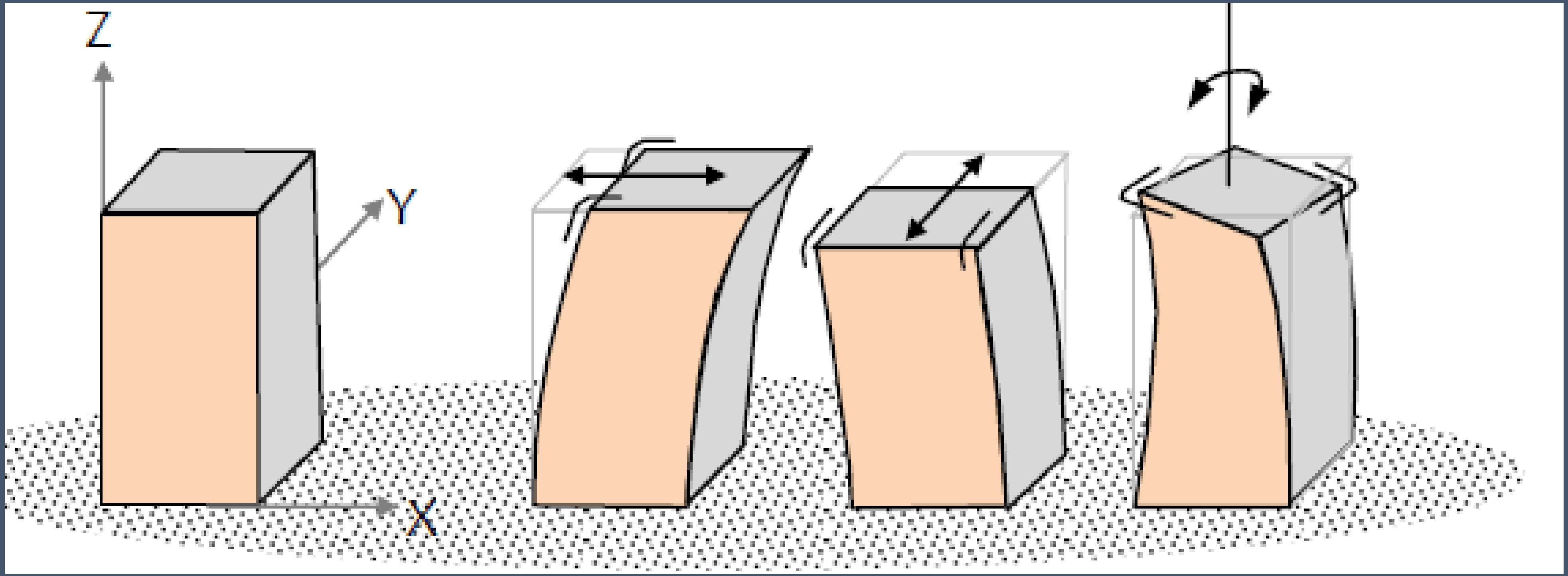
3. TALLER BUILDINGS HAVE LARGER FUNDAMENTAL TRANSLATIONAL NATURAL PERIODS.

4. BUILDINGS TEND TO OSCILLATE IN THE DIRECTIONS IN WHICH THEY ARE MOST FLEXIBLE AND HAVE LARGER TRANSLATIONAL NATURAL PERIODS.

5. NATURAL PERIODS OF BUILDINGS DEPEND ON AMOUNT AND EXTENT OF SPATIAL DISTRIBUTION OF UNREINFORCED MASONRY INFILL WALLS.

MODE SHAPE OF THE BUILDING

- MODE SHAPE OF OSCILLATION ASSOCIATED WITH A NATURAL PERIOD OF A BUILDING IS THE DEFORMED SHAPE OF THE BUILDING WHEN SHAKEN AT THE NATURAL PERIOD. HENCE, A BUILDING HAS AS MANY MODE SHAPES AS THE NUMBER OF NATURAL PERIODS.
- FOR A BUILDING, THERE ARE INFINITE NUMBERS OF NATURAL PERIOD.



MODE SHAPES

- THE DEFORMED SHAPE OF THE BUILDING ASSOCIATED WITH OSCILLATION AT FUNDAMENTAL NATURAL PERIOD IS TERMED ITS FIRST MODE SHAPE.
- SIMILARLY, THE DEFORMED SHAPES ASSOCIATED WITH OSCILLATIONS AT SECOND, THIRD, AND OTHER HIGHER NATURAL PERIODS ARE CALLED SECOND MODE SHAPE, THIRD MODE SHAPE, AND SO ON, RESPECTIVELY.
- THERE ARE THREE BASIC MODES OF OSCILLATION,

1. PURE TRANSLATIONAL ALONG X-DIRECTION
2. PURE TRANSLATIONAL ALONG Y-DIRECTION AND
3. PURE ROTATION ABOUT Z-AXIS.

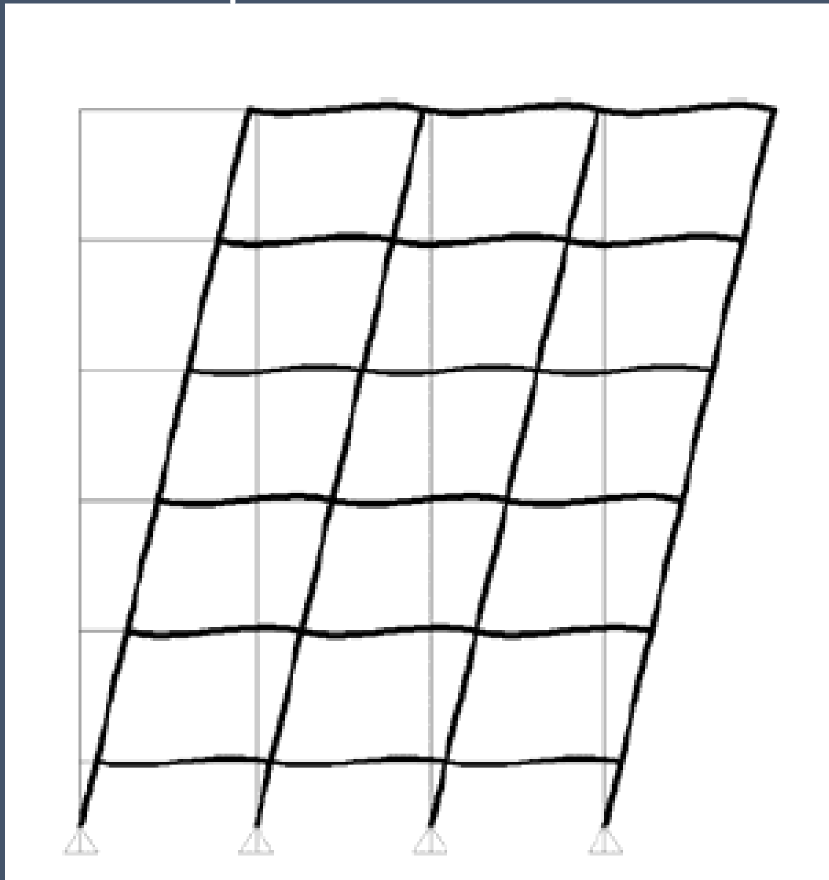
I AM GETTING CONFUSED ABOUT MODE SHAPES ! PLEASE HELP !

- THE OVERALL RESPONSE OF A BUILDING IS THE SUM OF THE RESPONSES OF ALL OF ITS MODES.
- IN REGULAR BUILDINGS TOO, LOCATION AND SIZE OF THE STRUCTURAL ELEMENTS SHOULD BE SUCH THAT *TORSIONAL* AND *MIXED* MODES OF OSCILLATION DO NOT PARTICIPATE MUCH IN THE OVERALL OSCILLATORY MOTION OF THE BUILDING.
- ONE WAY OF AVOIDING TORSIONAL MODES TO BE THE EARLY MODES OF OSCILLATION IN BUILDINGS IS INCREASING THE TORSIONAL STIFFNESS OF BUILDING.
- ADDING BRACES OR INTRODUCING STRUCTURAL WALLS IN SELECT BAYS INCREASES THE TORSIONAL STIFFNESS OF THE BUILDING AND TORSIONAL AND MIXED MODES DO NOT PARTICIPATE MUCH IN THE OSCILLATORY MOTION OF THE BUILDING.

THREE FACTORS INFLUENCING MODE SHAPES

(1) EFFECT OF FLEXURAL STIFFNESS OF STRUCTURAL ELEMENTS

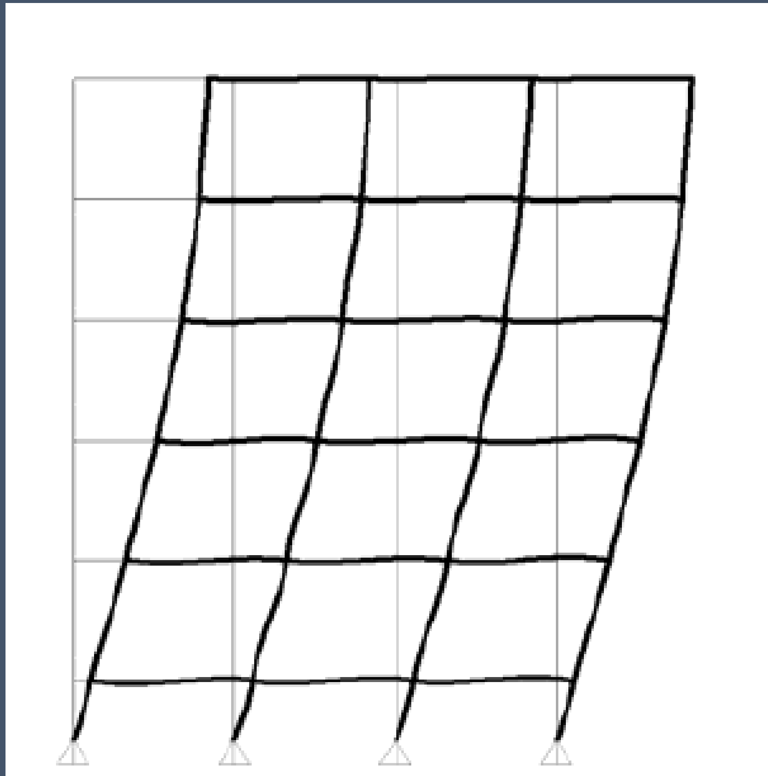
- The overall lateral translational mode shapes depend on *flexural stiffness* of beams relative to that of adjoining columns. The fundamental mode shape of buildings changes from *flexural-type* to *shear-type* as beam flexural stiffness increases relative to that of column
- In pure flexural response (when flexural stiffness of beams is small compared to that of the adjoining columns), column deformation is predominantly in single curvature bending leading to overall flexure-type deformation behavior of (The cantilever) building



FOUR FACTORS INFLUENCING MODE SHAPES

(1) EFFECT OF FLEXURAL STIFFNESS OF STRUCTURAL ELEMENTS

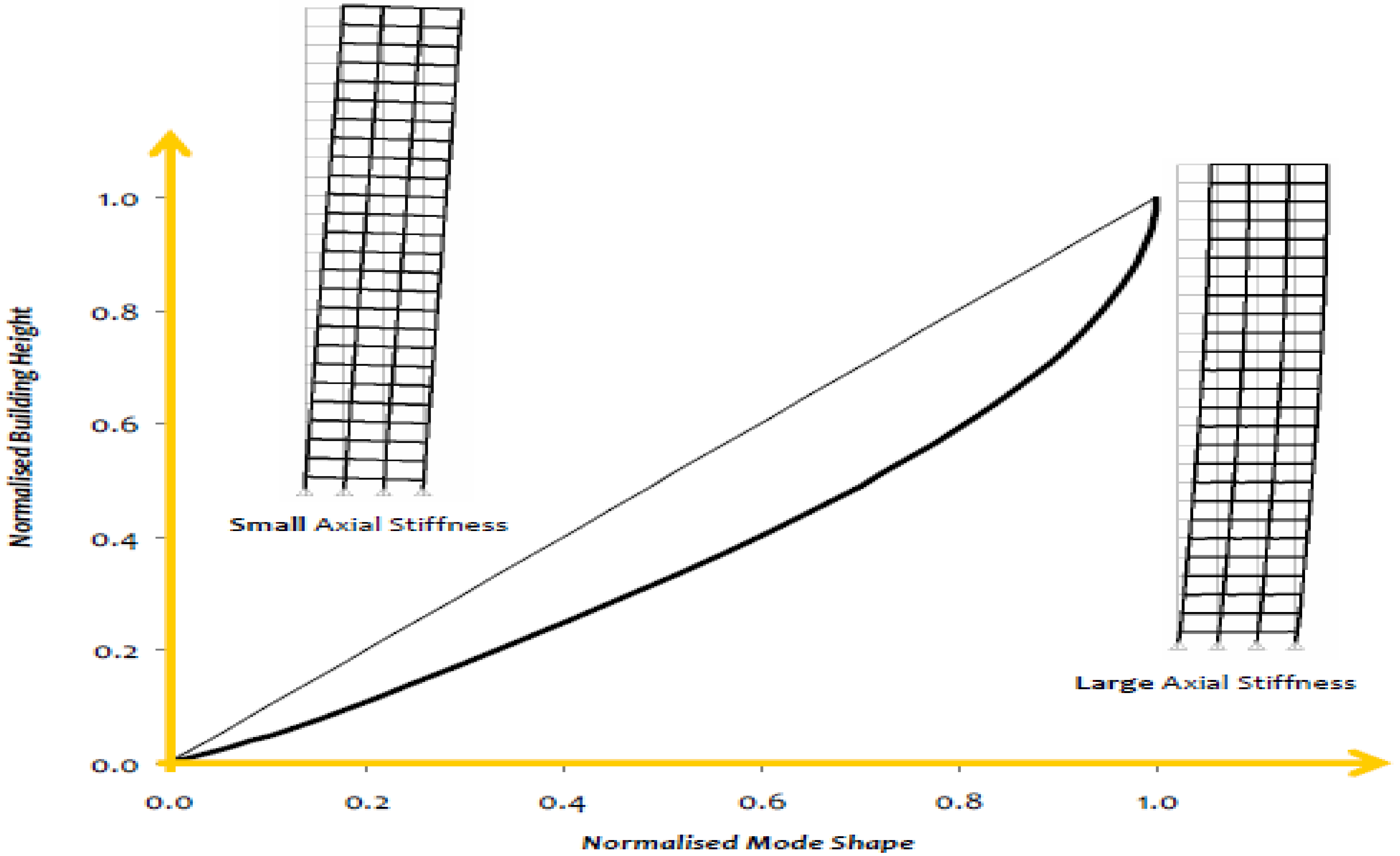
- In *pure shear-type* deformation behavior (when flexural stiffness of beams is large compared to that of the adjoining columns), column deformation is predominantly in double curvature bending within in each storey leading to overall shear-type deformation behavior of building.
- Often in low-rise and mid-rise buildings that are designed as per codes, the relative stiffness of frame members lies in between the above two extreme cases.



FOUR FACTORS INFLUENCING MODE SHAPES

2. EFFECT OF AXIAL STIFFNESS OF VERTICAL MEMBERS

- Mode shapes depend on axial stiffness of vertical members in a building (*i.e.,* of columns or structural walls).
- Small axial stiffness causes significant axial compressive and tensile deformation in columns in addition to single or double curvature flexural deformations.
- Additional axial deformation changes the fundamental mode shape from shear type to flexural type, particularly in tall buildings.
- Pure flexural response is not desirable because of large lateral sway, particularly at higher floors.
- Hence, designers ensure that the axial areas are large of building columns and structural walls.

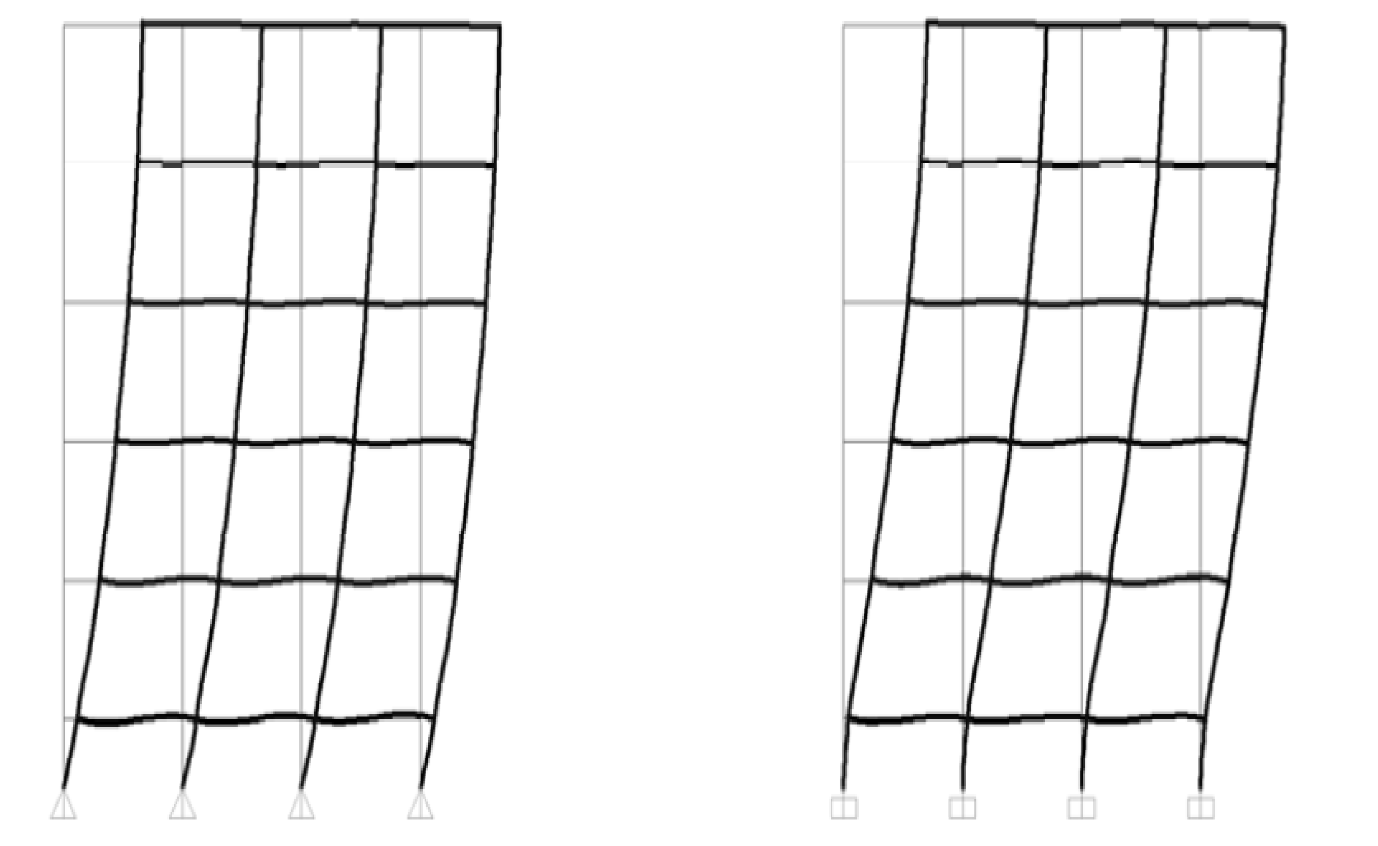


Small Axial Stiffness
Large Axial Stiffness
Normalised Building Height
Normalised Mode Shape
0.0
0.2
0.4
0.6
0.8
1.0

FOUR FACTORS INFLUENCING MODE SHAPES

3. EFFECT OF DEGREE OF FIXITY AT MEMBER ENDS

- TWO CONDITIONS DETERMINE THE ROTATIONAL FLEXIBILITY OF COLUMNS AT THE BASE OF THE BUILDING.
- THE FIRST CONDITION IS WHEN THE STRUCTURAL DESIGN AND DETAILING DELIBERATELY CREATES ROTATIONAL FLEXIBILITY AT THOSE LOCATIONS.
- AND, THE SECOND IS WHEN THE FLEXIBILITY OF SOIL UNDERNEATH THE FOOTINGS OF COLUMNS ALLOWS ROTATION OF THE COLUMNS; THIS HAPPENS WHEN INDIVIDUAL FOOTINGS ARE USED.



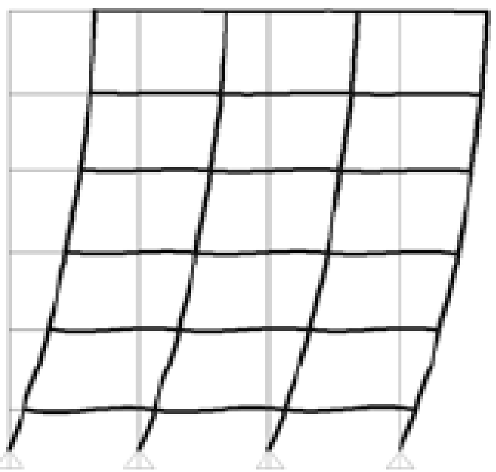
Images Property of GSDMA

FOUR FACTORS INFLUENCING MODE SHAPES

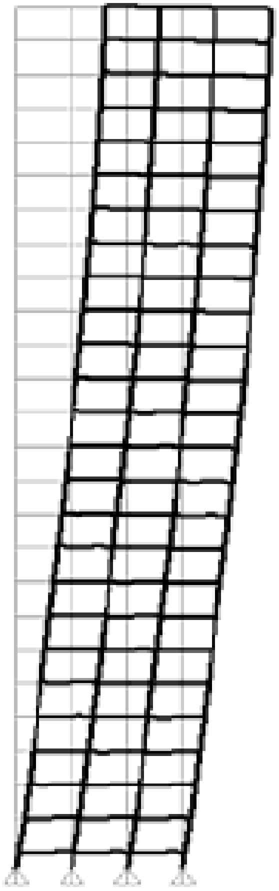
3. EFFECT OF DEGREE OF FIXITY AT MEMBER ENDS

- HIGHLY FLEXIBLE SOILS MAKE COLUMN BASES AS GOOD AS HINGED, AND ROCKY LAYERS BELOW AS GOOD AS FIXED.
- LACK OF ROTATIONAL FIXITY AT COLUMN BASE (HINGED CONDITION) INCREASES THE LATERAL SWAY IN THE LOWER STOREY THAN IN HIGHER STOREY, AND THE OVERALL RESPONSE OF THE BUILDING IS MORE OF SHEAR-TYPE.
- ON THE OTHER HAND, FULL ROTATIONAL FIXITY AT COLUMN BASE RESTRICTS THE LATERAL SWAY AT THE FIRST STOREY AND THUS, INDUCES INITIAL FLEXURAL BEHAVIOR NEAR THE BASE .
- THE OVERALL RESPONSE OF THE BUILDING IS STILL OF SHEAR-TYPE DUE TO FLEXURAL STIFFNESS OF BEAMS

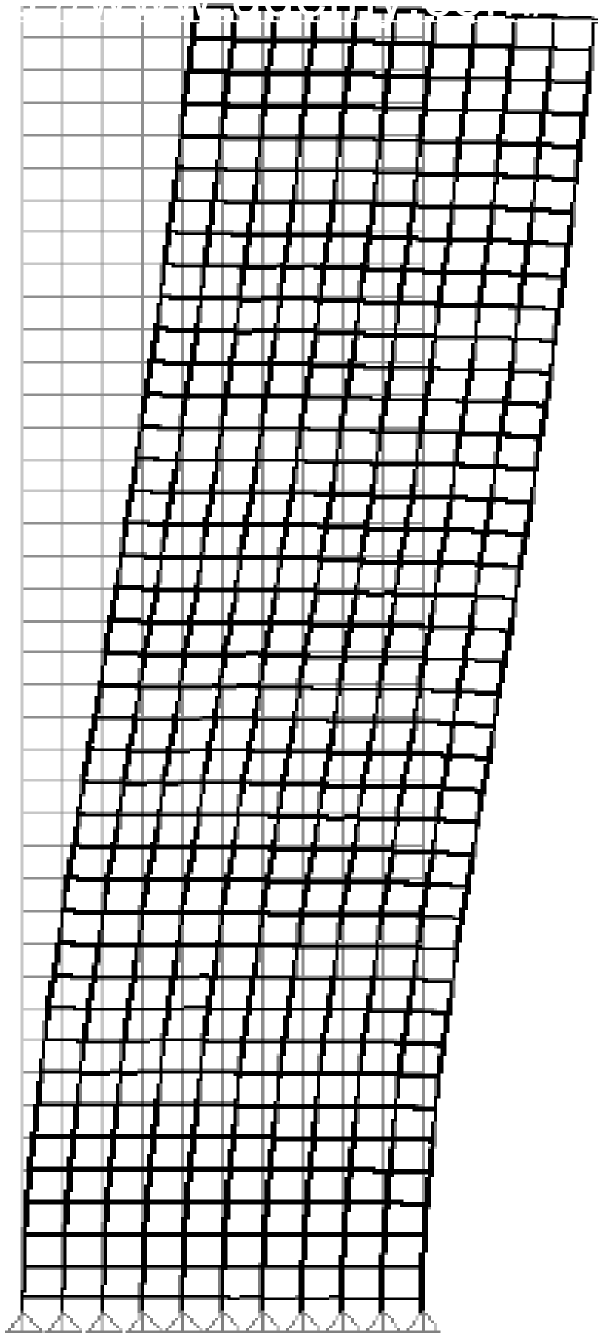
FOUR FACTORS INFLUENCING MODE SHAPES
4. EFFECT OF BUILDING HEIGHT



5 – STOREY BUILDING



25 – STOREY BUILDING



40 – STOREY BUILDING

FOUR FACTORS INFLUENCING MODE SHAPES
4. EFFECT OF BUILDING HEIGHT

- IN WELL-DESIGNED LOW HEIGHT MOMENT FRAME BUILDINGS, THE FUNDAMENTAL TRANSLATIONAL MODE OF OSCILLATION IS OF SHEAR-TYPE.

- BUILDINGS BECOME LATERALLY FLEXIBLE AS THEIR HEIGHT INCREASES.

- AS A RESULT, THE NATURAL PERIOD OF BUILDINGS INCREASE WITH INCREASE IN HEIGHT.

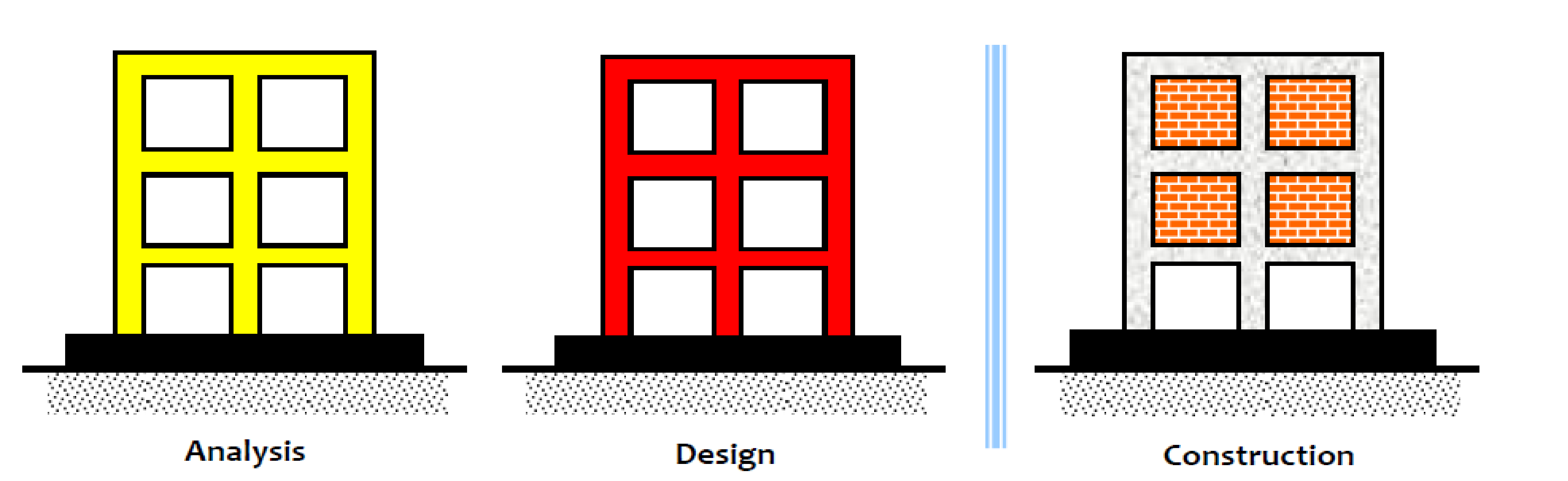
- HOWEVER, THE FUNDAMENTAL MODE SHAPE DOES NOT CHANGE SIGNIFICANTLY (FROM SHEAR TYPE TO FLEXURE TYPE).

- FLEXURAL TYPE BEHAVIOR IS EXHIBITED ONLY NEAR THE LOWER STOREYS WHERE THE AXIAL DEFORMATION IN THE COLUMNS COULD BE SIGNIFICANT, PARTICULARLY IN TALL BUILDINGS.

- HOWEVER AT HIGHER FLOOR LEVELS, THE RESPONSE CHANGES TO SHEAR TYPE AS THE AXIAL LOAD LEVEL LOWERS.

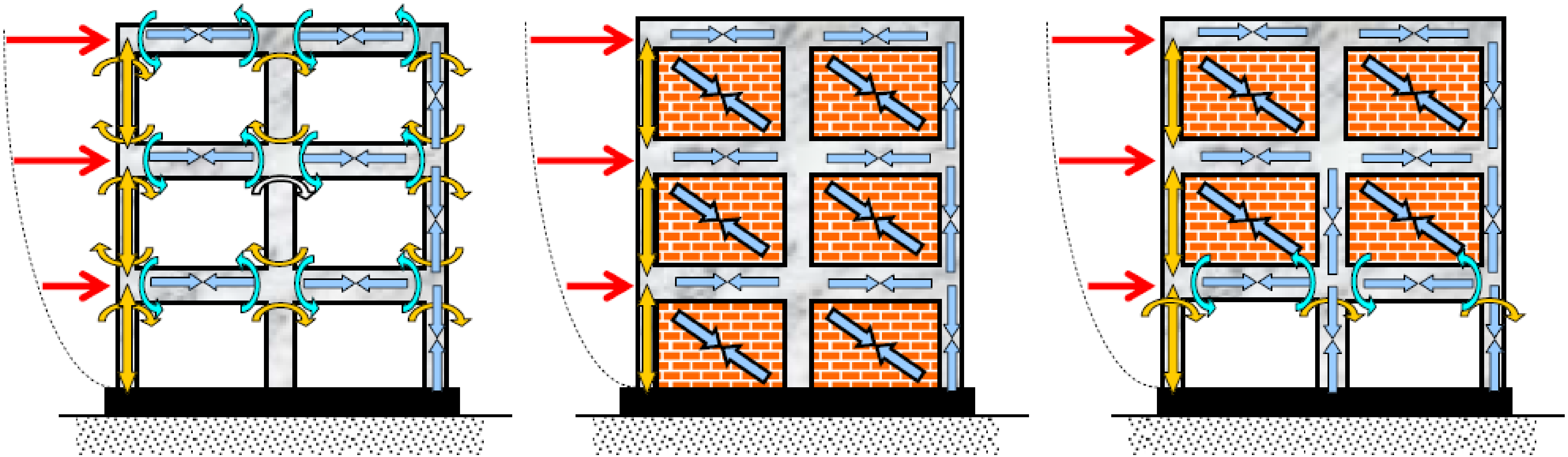
WHAT IS THE PURPOSE OF THE MASONRY WALL ?

- URM infill walls are assumed to not carry any vertical or lateral forces, and hence, *declared* as *non-structural elements* insofar as transfer of forces is concerned between structural elements (*e.g.,* beams and columns) that are generated in the building during earthquake shaking.
- This assumption causes a large gap between the building that is considered in *analysis* and *design*, and that finally *constructed.*



WHAT IS THE PURPOSE OF THE MASONRY WALL ?

- This is attributed to the fact that URM infills participate in lateral force transfer.



Bare Frame

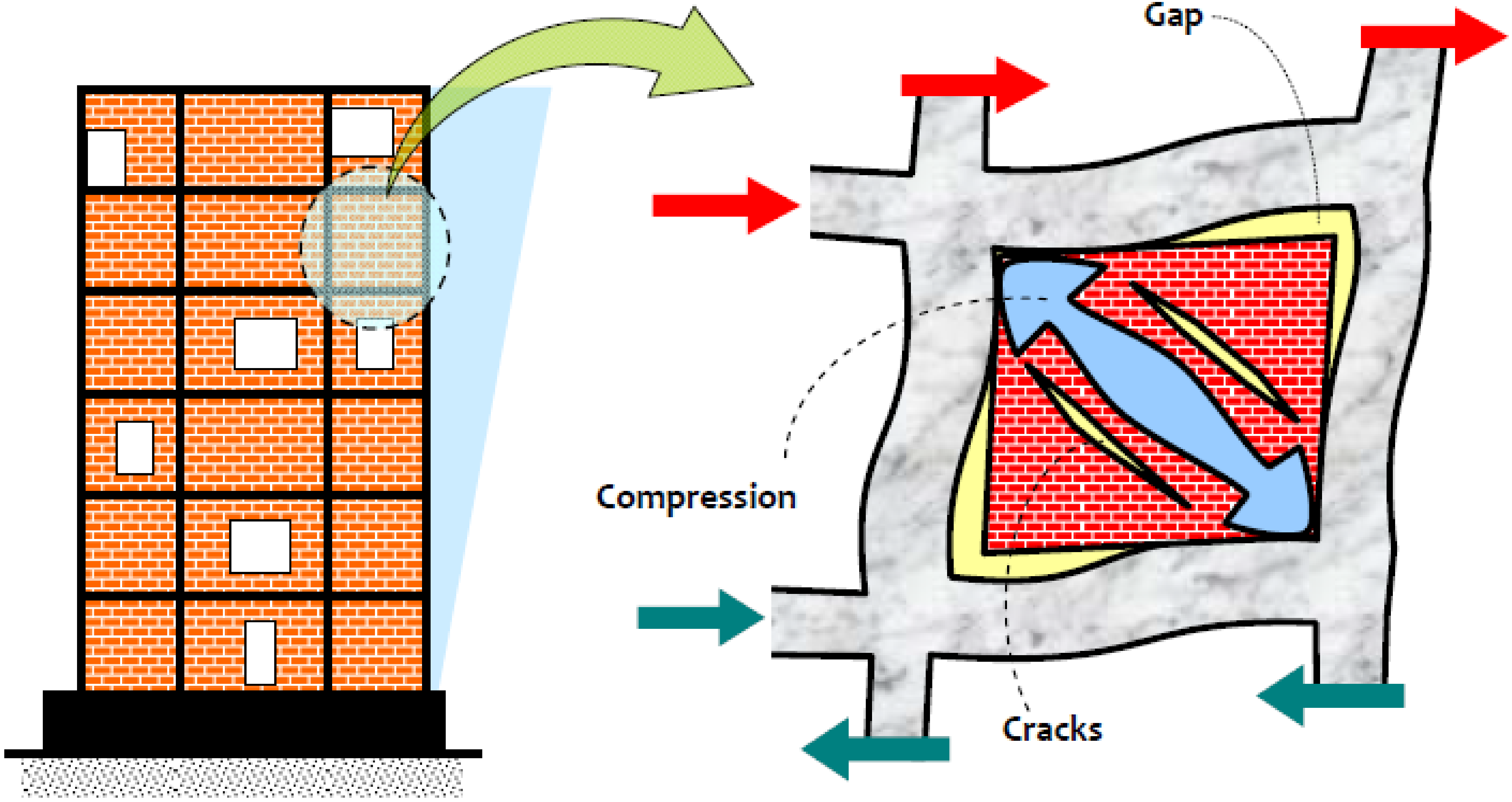
Predominant frame action

Infilled Frame

Predominant truss action

Hybrid Frame

Mixed Action


Gap
Compression
Cracks

https://www.udemy.com/etabscourse/

Images Property of GSDMA

TIPS FOR STRUCTURAL DESIGNERS

Design engineers need to control both the mass and stiffness of buildings.

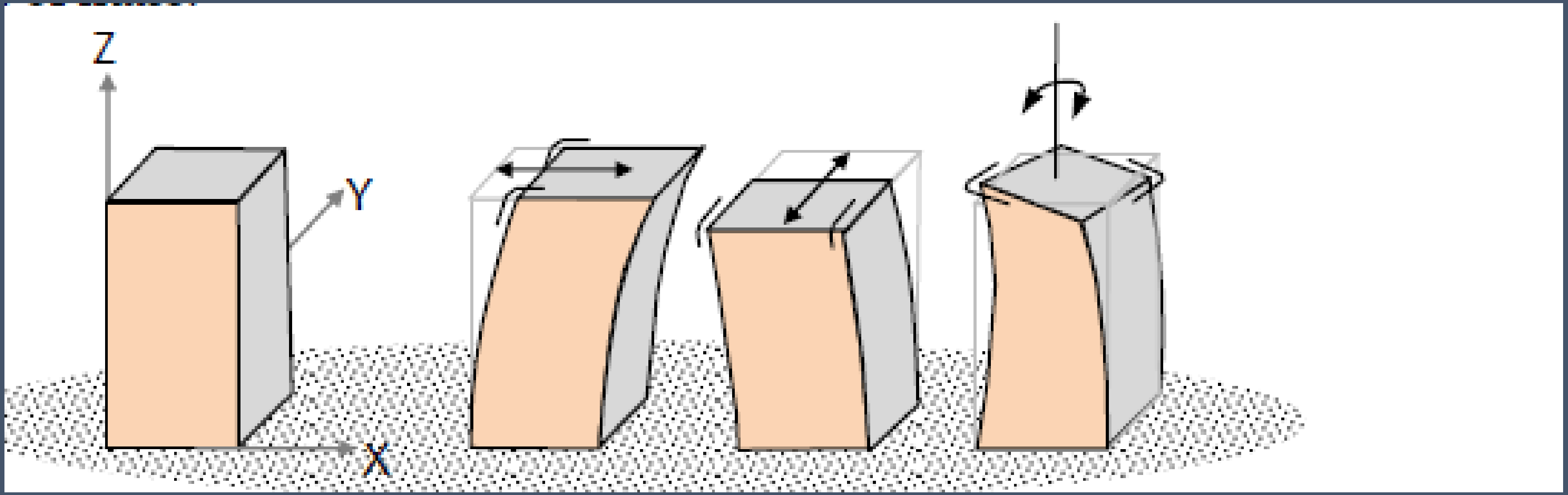
OK, BUT HOW ????????????

TIPS FOR STRUCTURAL DESIGNERS
POINT NO. 1

1) THE FUNDAMENTAL MODES OF OSCILLATION SHOULD BE THE TRANSLATIONAL NATURAL MODES OF OSCILLATION, AND THAT TOO ARE THE PURE TRANSLATIONAL MODE SHAPES AND NOT DIAGONAL OR TORSIONAL OSCILLATIONS.

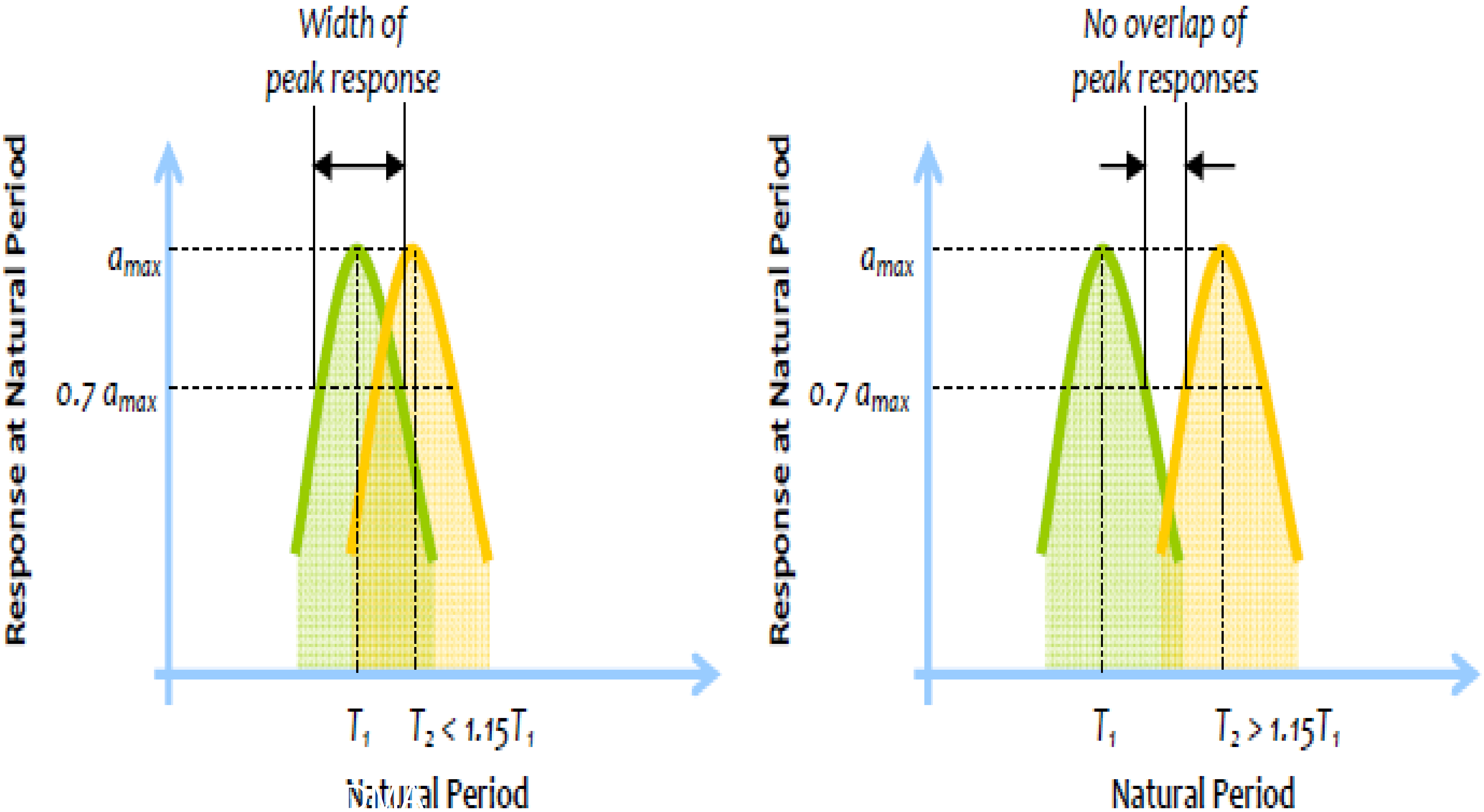
TIPS FOR STRUCTURAL DESIGNERS
POINT NO. 2

(2) ALL TORSIONAL MODES OF OSCILLATION AND MIXED (TORSIONAL-CUM-TRANSLATIONAL) MODES OF OSCILLATION, IF ANY, SHOULD PUSHED TO POSSESS NATURAL PERIODS OUTSIDE THE RANGE 0.04-2.00S, BY INCREASING THE TORSIONAL STIFFNESS OF THE BUILDING THROUGH THE INTRODUCTION OF STRUCTURAL WALLS ALONG THE PERIMETER OF THE BUILDING.



TIPS FOR STRUCTURAL DESIGNERS POINT NO. 3

- (3) BUILDINGS SHOULD NOT BE MADE STRUCTURALLY BI-SYMMETRIC IN THE TWO PLAN DIRECTIONS RESULTING IN THE SAME NATURAL PERIOD FOR THE TWO PURE HORIZONTAL TRANSLATIONAL MODES OF OSCILLATION.
- NO TWO NATURAL PERIODS OF PURE TRANSLATIONAL MODES OF VIBRATION SHOULD BE WITHIN 15% OF THE LARGER NATURAL PERIOD. THIS 15% LIMIT IS ARRIVED AT TO ENSURE THAT THE WIDTH OF THE PEAK RESPONSE (TAKEN AS THAT CORRESPONDING TO 70% OF PEAK RESPONSE AS DEFINED BY *HALF POWER METHOD* FOR ESTIMATING DAMPING) AT A CERTAIN NATURAL PERIOD DOES NOT OVERLAP WITH THAT AT THE ADJACENT NATURAL PERIOD


Width of
peak response
a_{max}
$0.7\ a_{max}$
Response at Natural Period
T_1
$T_2 < 1.15T_1$
Natural Period
No overlap of
peak responses
a_{max}
$0.7\ a_{max}$
Response at Natural Period
T_1
$T_2 > 1.15T_1$
Natural Period

TIPS FOR STRUCTURAL DESIGNERS

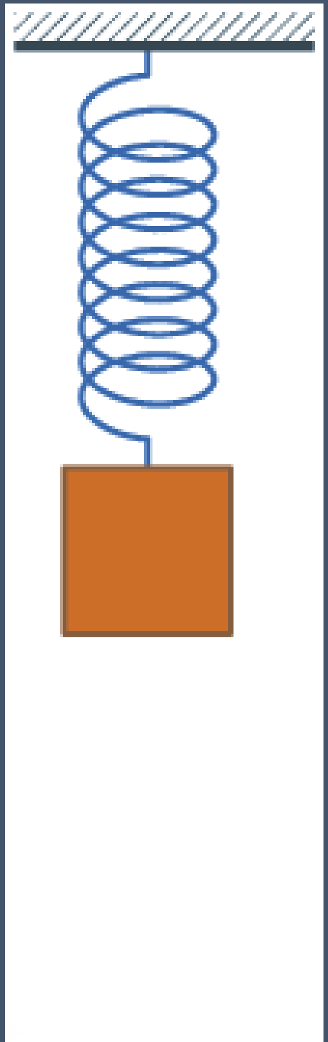
POINT NO. 4

(4) THE AXIAL STIFFNESS OF THE VERTICAL ELEMENTS SHOULD BE HIGH, TO ENSURE SHEAR-TYPE LATERAL TRANSLATIONAL MODE SHAPE OF OSCILLATION. THIS WILL RESULT IN REDUCED OVERALL LATERAL DEFORMATION OF THE BUILDING.

LET'S LEARN ABOUT DAMPING !!!!!

DAMPING IN SIMPLE WORDS !!!

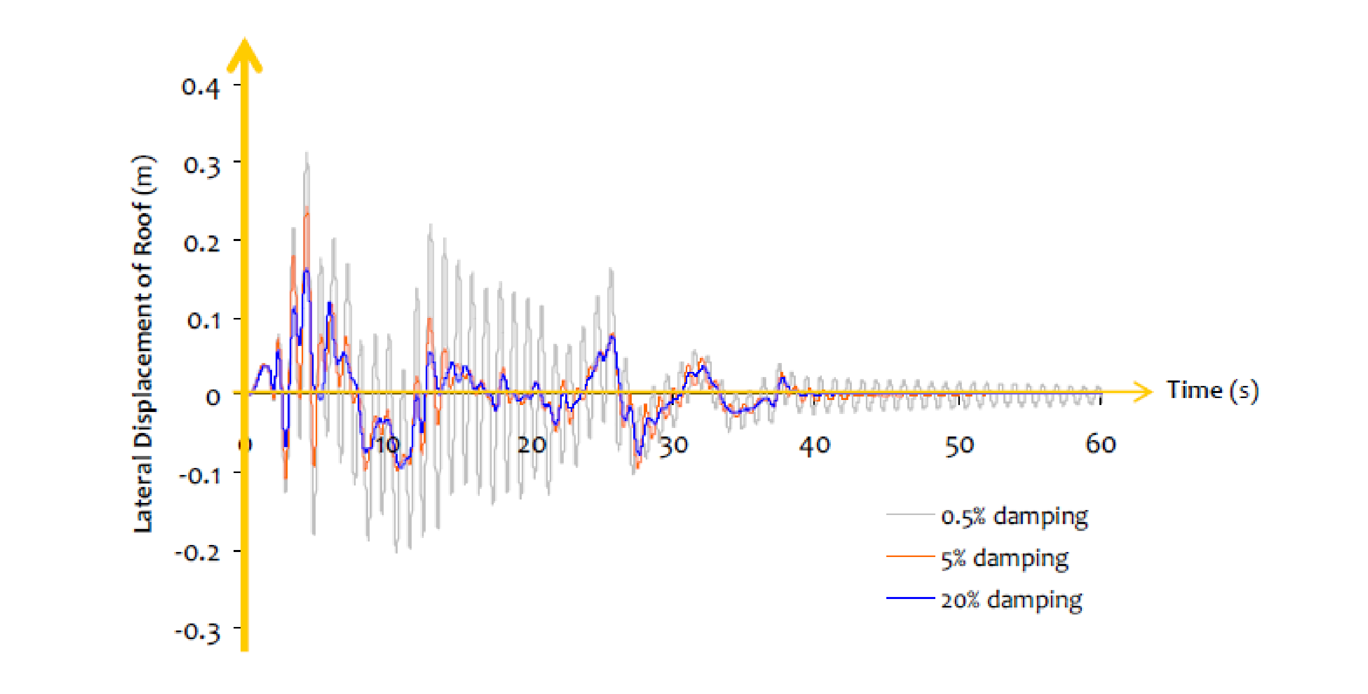
- BUILDINGS SET TO OSCILLATION BY EARTHQUAKE SHAKING EVENTUALLY COME BACK TO REST WITH TIME. THIS IS DUE TO DISSIPATION OF THE OSCILLATORY ENERGY THROUGH CONVERSION TO OTHER FORMS OF ENERGY, LIKE HEAT AND SOUND.
- IT IS A PHENOMENON THAT MAKES ANY VIBRATING BODY/STRUCTURE TO DECAY IN AMPLITUDE OF MOTION GRADUALLY BY MEANS OF ENERGY DISSIPATION THROUGH VARIOUS MECHANISMS.



THE MECHANISM OF THIS CONVERSION IS CALLED DAMPING.

https://www.udemy.com/etabscourse/

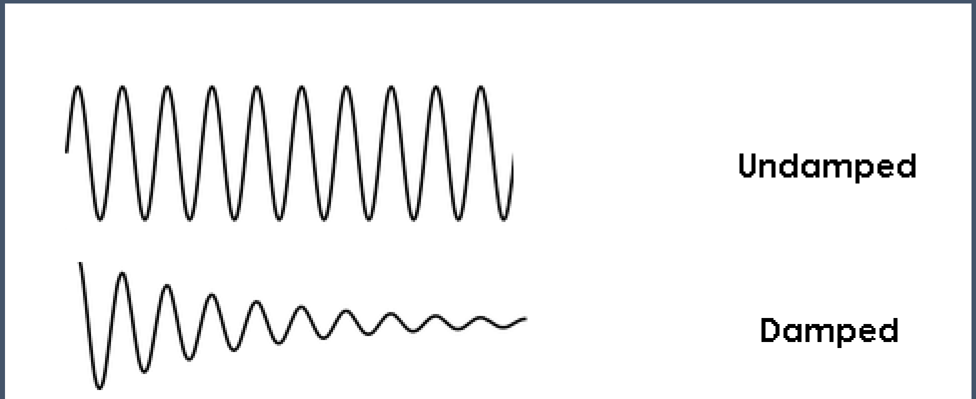
- Damping is expressed as a fraction of the critical damping (which is the minimum value of damping at which the building gradually comes to rest from any one side of its neutral position without undergoing any oscillation).
- EXAMPLE , Indian seismic codes recommends the use of 5% damping for all natural modes of oscillation of reinforced concrete buildings, and 2% for steel structures.



Images Property of GSDMA

THREE TYPES OF DAMPING
1. STRUCTURAL DAMPING

- IN NORMAL AMBIENT SHAKING OF BUILDING, MANY FACTORS IMPEDE ITS MOTION, *E.G.*, DRAG FROM AIR RESISTANCE AROUND THE BUILDING, MICRO CRACKING OF CONCRETE IN THE STRUCTURAL MEMBERS, AND FRICTION BETWEEN VARIOUS INTERFACES IN THE BUILDING (LIKE MASONRY INFILL WALLS AND RC BEAMS AND COLUMNS). THIS DAMPING IS CALLED *STRUCTURAL DAMPING*.



Images Property of GSDMA

THREE TYPES OF DAMPING
2. HYSTERETIC DAMPING

- UNDER STRONG EARTHQUAKE SHAKING, BUILDINGS ARE DAMAGED.
- REINFORCEMENT BARS AND CONCRETE OF THE RC BUILDINGS ENTER NONLINEAR RANGE OF MATERIAL BEHAVIOR.
- THE DAMPING THAT ARISES FROM THESE INELASTIC ACTIONS IS CALLED *HYSTERETIC DAMPING*; THIS FURTHER DAMPENS OSCILLATIONS OF THE BUILDING.

THREE TYPES OF DAMPING
3. RADIATION DAMPING

- ANOTHER FORM OF DAMPING IS ASSOCIATED WITH SOIL. THIS DAMPING OCCURS WHEN THE SOIL STRATA UNDERNEATH THE BUILDING IS FLEXIBLE AND ABSORBS ENERGY INPUT TO THE BUILDING DURING EARTHQUAKE SHAKING, AND SENDS IT TO FAR OFF DISTANCES IN THE SOIL MEDIUM. THIS IS CALLED *RADIATION DAMPING*.

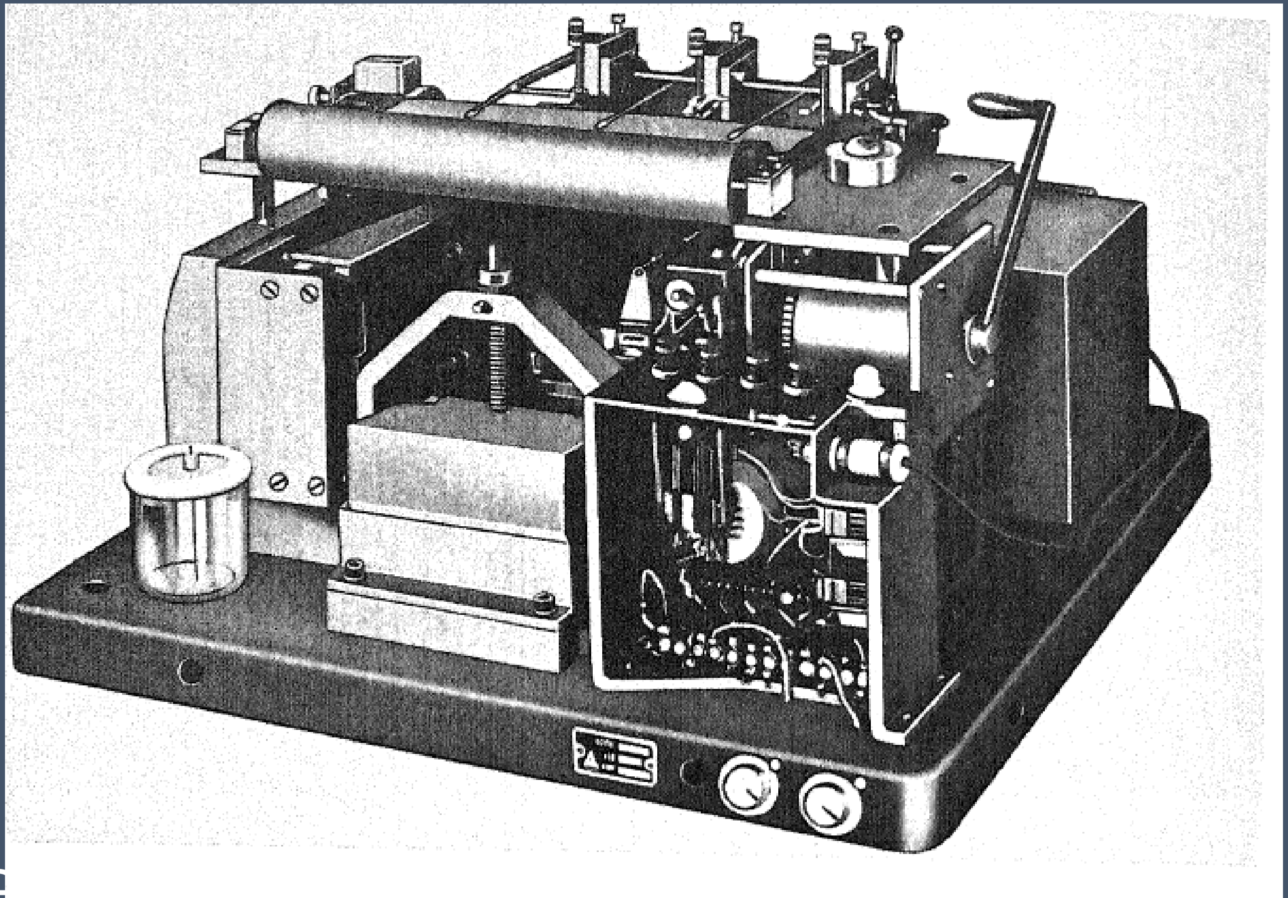
EXPLAIN ABOUT EARTHQUAKE !!

- **EARTHQUAKE ORIGINATES BELOW THE SURFACE OF THE EARTH DUE TO RUPTURE OF BED-ROCK. THIS IS ASSOCIATED WITH RELEASE OF STORED STRAIN ENERGY THAT SPREADS OUT IN ALL DIRECTIONS FROM THE FAULT REGION IN THE FORM OF SEISMIC WAVES THAT TRAVEL THROUGH THE BODY AND ALONG THE SURFACE OF THE EARTH.**
- **THESE SEISMIC WAVES, PRIMARILY OF TWO TYPES CALLED THE *BODY WAVES* AND *SURFACE WAVES*, TOGETHER CAUSE SHAKING OF THE GROUND (SURFACE OF THE EARTH) ON WHICH THE BUILDINGS ARE FOUNDED. THE CHARACTERISTICS OF THE GROUND SHAKING CONTROL EARTHQUAKE RESPONSE OF BUILDINGS, IN ADDITION TO THE BUILDING CHARACTERISTICS.**

https://www.udemy.com/etabscourse/

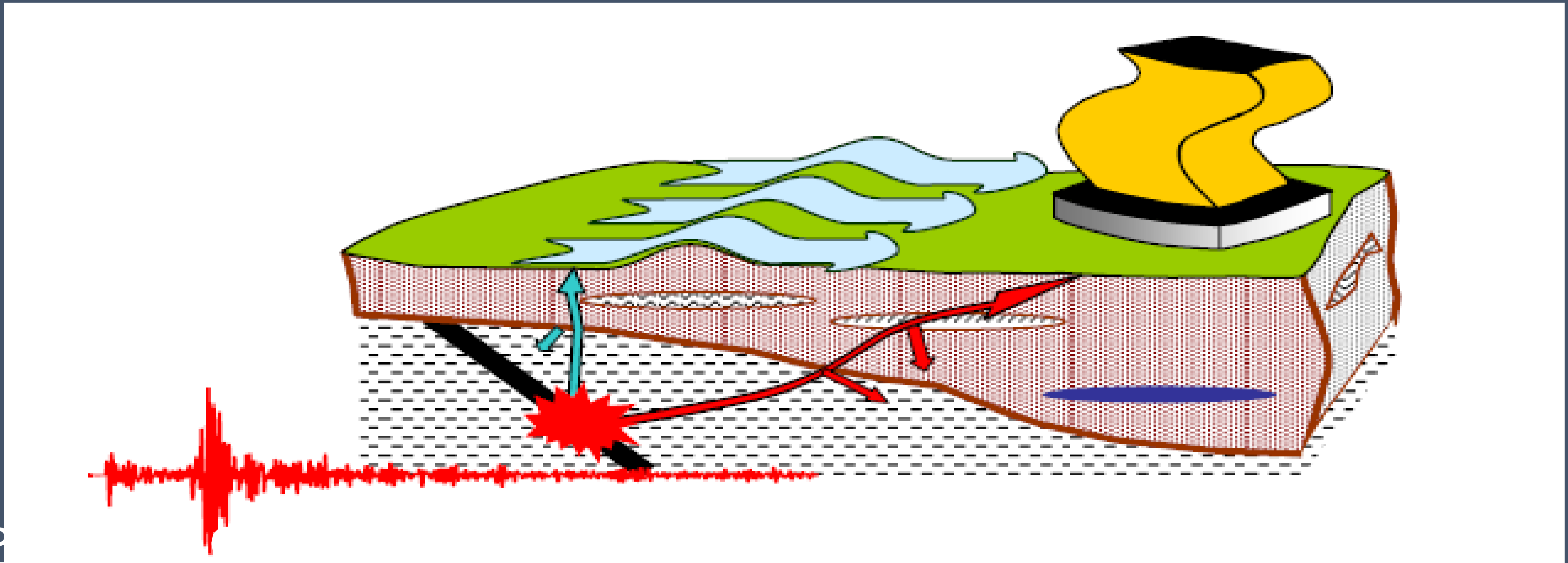
WHAT ARE WAVES IN EARTHQUAKE !!

- THE GROUND MOTION CAN BE MEASURES IN THE FORM OF ACCELERATION, VELOCITY OR DISPLACEMENT.
- ACCELEROGRAPH SUCCESSFULLY CAPTURE THE GROUND SHAKING EVEN IN THE NEAR FIELD OF THE EARTHQUAKE FAULTS, WHERE THE SHAKING IS VIOLENT.



Images Property of GSDMA

- THE RECORD OBTAINED FROM AN ACCELEROGRAPH, *I.E.*, THE VARIATION OF GROUND ACCELERATION WITH TIME RECORDED AT A POINT ON GROUND DURING AN EARTHQUAKE, IS CALLED AN *ACCELEROGRAM*.
- THREE ACCELEROGRAMS ARE RECORDED SIMULTANEOUSLY ALONG THREE MUTUALLY PERPENDICULAR DIRECTIONS TO CAPTURE THE COMPLETE OSCILLATION OF THE GROUND AT A LOCATION (CALLED A *STATION*).
- THESE THREE RECORDS OF THREE MUTUALLY PERPENDICULAR CORRESPOND TO TWO ALONG THE HORIZONTAL DIRECTIONS AND ONE ALONG THE VERTICAL DIRECTION.



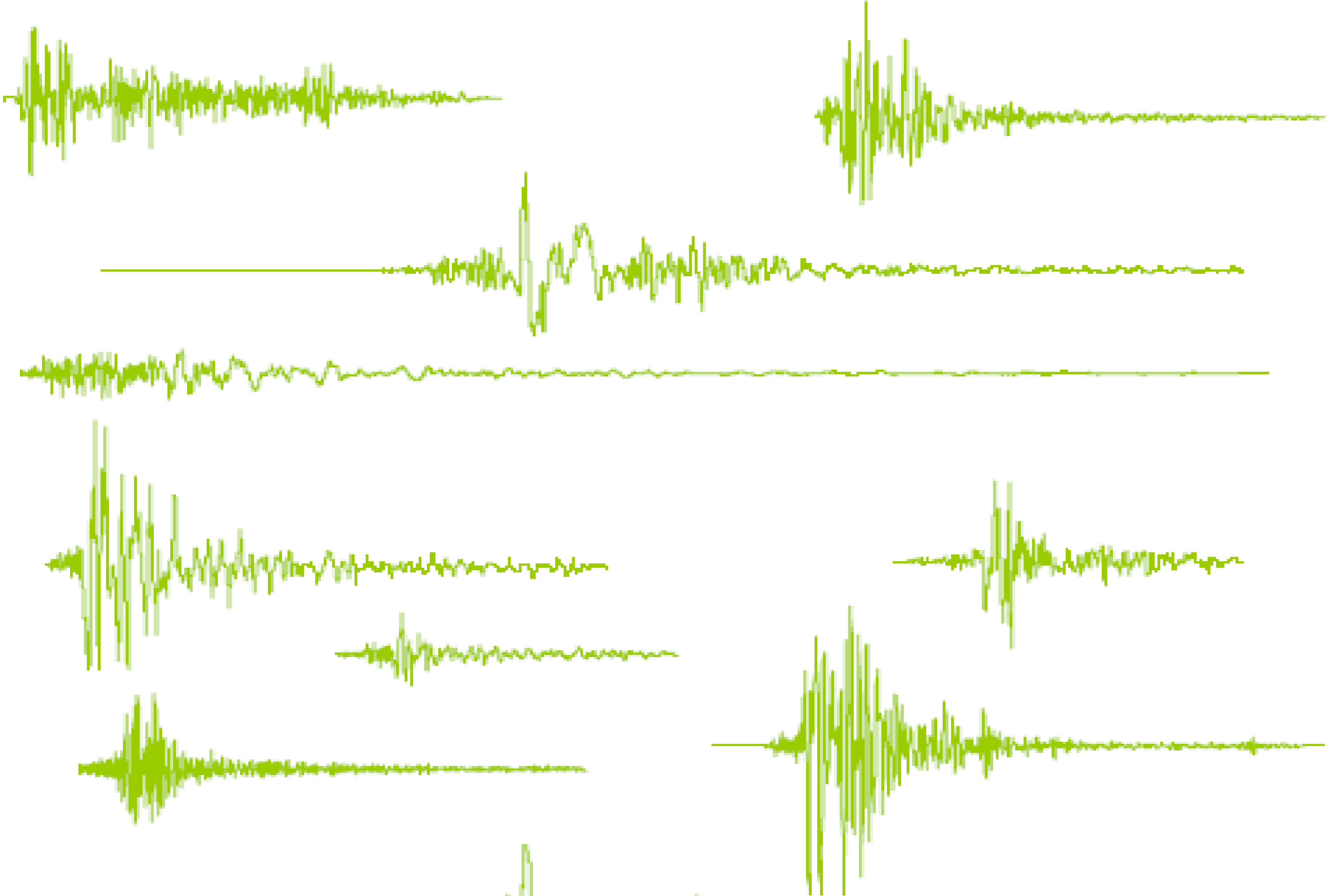
Images P

WHAT IS PEAK GROUND ACCELERATION !

- Accelerograms Carry distinct information regarding ground shaking, namely *peak amplitude*, *duration of strong shaking*, *frequency content* .
- Peak amplitude, representing the *peak ground acceleration* (PGA), is an important design parameter.
- For instance, a horizontal PGA value of 0.6g (*i.e.,* a peak ground acceleration of 0.6 times the acceleration due to gravity *g*) suggests that the shaking of the ground can cause a rigid building to sustain a maximum horizontal inertia force of 60% of its weight.

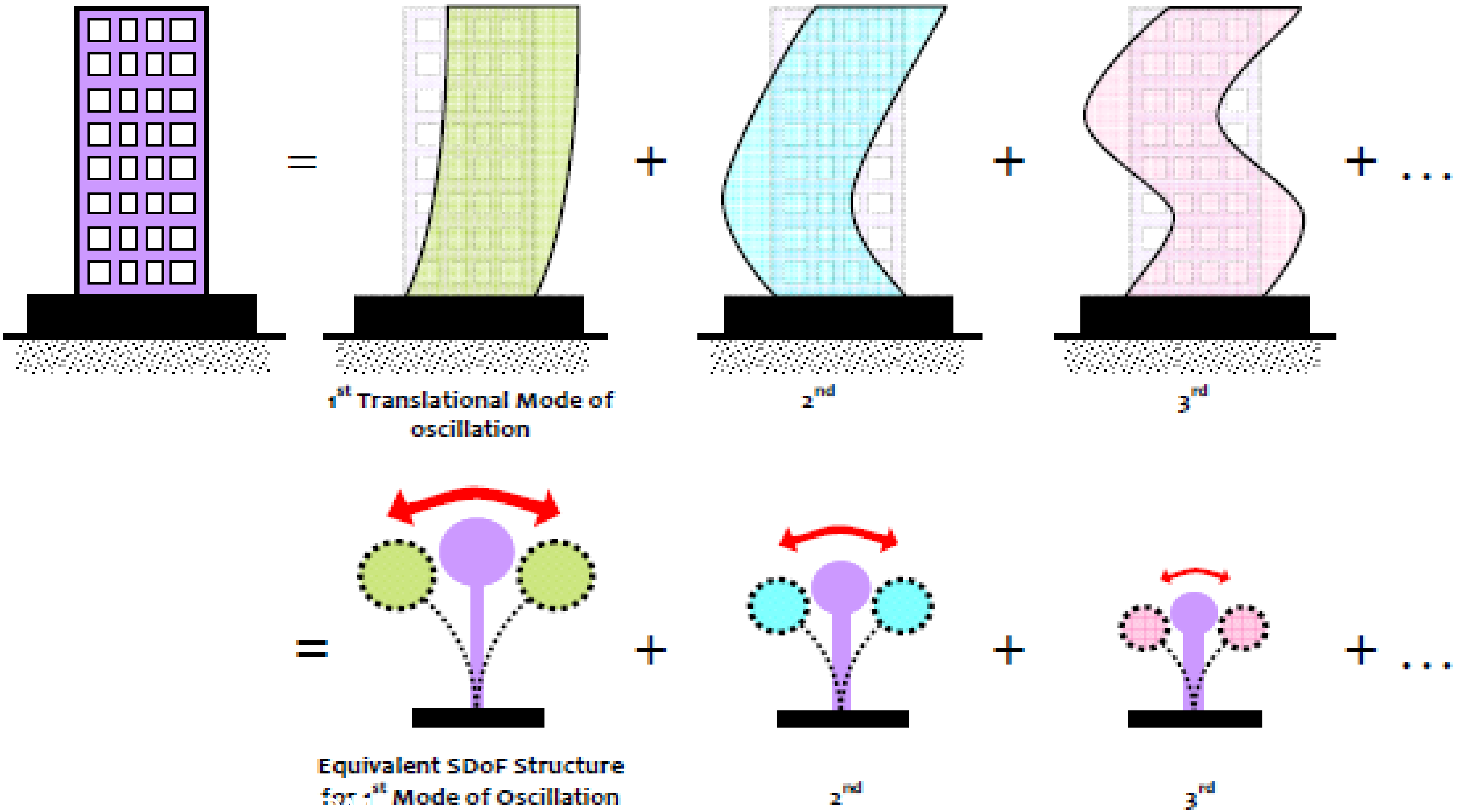
Notable earthquakes [edit]

PGA single direction (max recorded)	PGA vector sum (H1, H2, V) (max recorded)	Mag	Depth	Fatalities	Earthquake
3g[11]		7.8	15 km	2	2016 Kaikoura earthquake
2.7g[12]	2.99 g[13][14]	9.0	30 km[15]	>15,000[16]	2011 Tōhoku earthquake and tsunami
2.2g[17][18]		6.3[19]	5 km	185	February 2011 Christchurch earthquake
2.13g[20][21]		6.4	6 km	1	June 2011 Christchurch earthquake
	4.36g[22]	6.9/7.2	8 km	12	2008 Iwate–Miyagi Nairiku earthquake
1.7g[23]		6.7	19 km	57	1994 Los Angeles earthquake
	1.47g[24]	7.1	42 km[15]	4	April 2011 Miyagi earthquake
1.26g[25][26]		7.1	10 km	0	2010 Canterbury earthquake
1.01g[27]		6.6	10 km	11	2007 Chūetsu offshore earthquake
1.01g[28]		7.3	8 km	2,415	1999 Jiji earthquake
1.0g[29]		6.0	8 km	0	December 2011 Christchurch earthquake
0.8g		6.8	16 km	6,434	1995 Kobe earthquake
0.78g[30]		8.8	23 km[31]	521	2010 Chile earthquake
0.6g[32]		6.0	10 km	143	1999 Athens earthquake
0.51g[33]		6.4		612	2005 Zarand earthquake



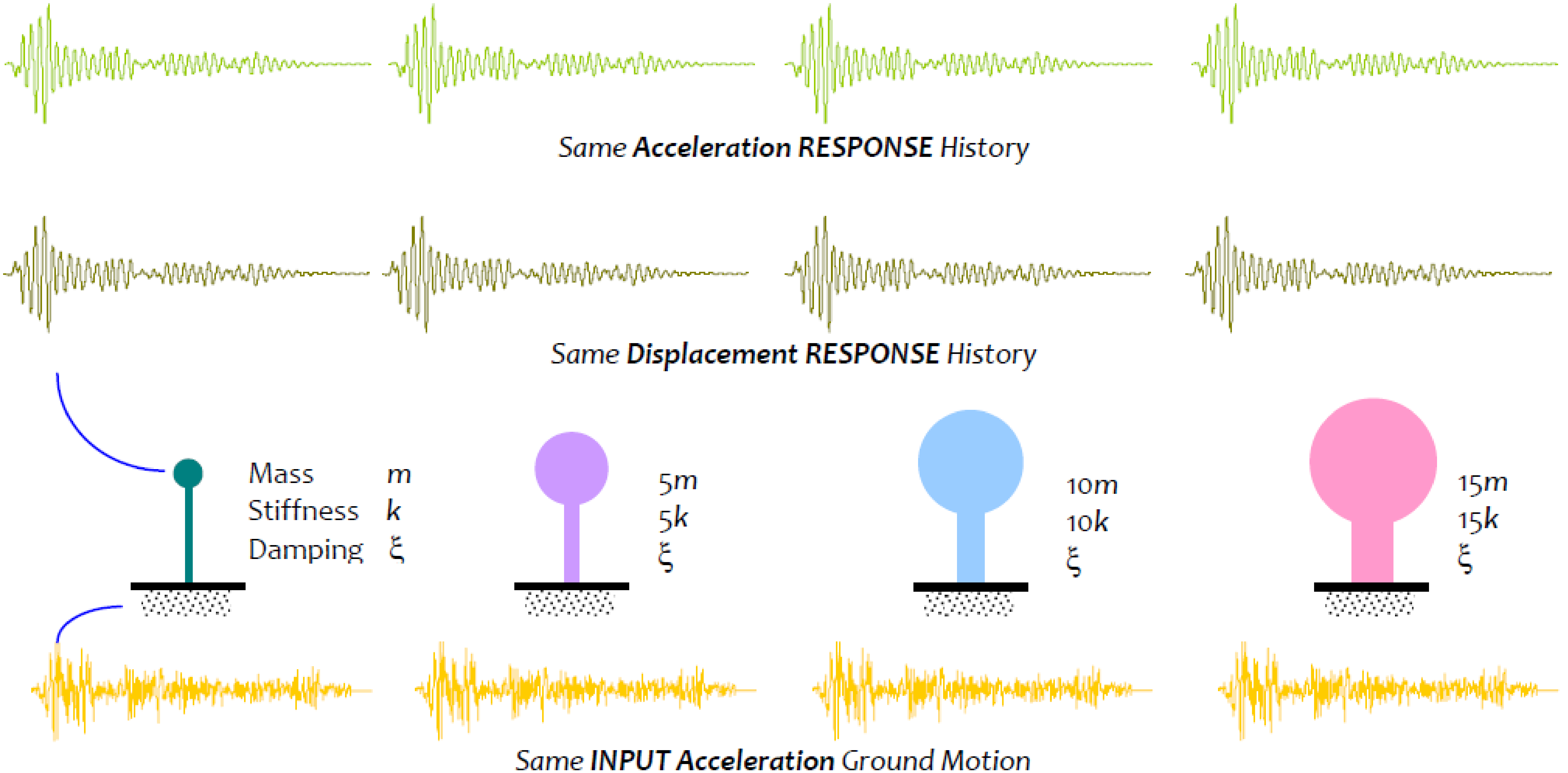
RESPONSE SPECTRUM OF GROUND MOTION – BASICS

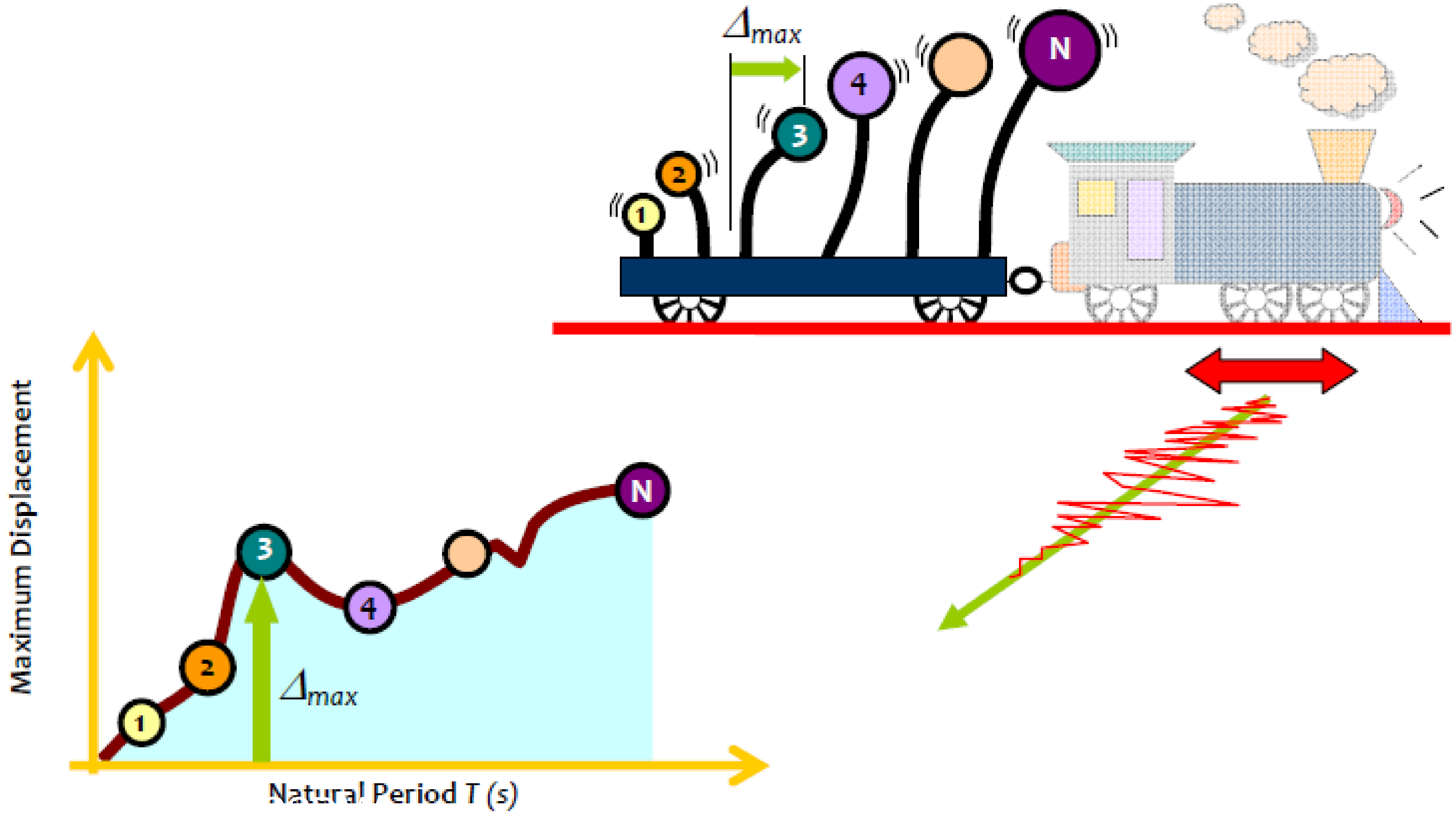
- A BUILDING CAN BE MATHEMATICALLY CONCEIVED TO BE A COLLECTION OF EQUIVALENT SIMPLE STRUCTURES EACH HAVING ONLY ONE NATURAL PERIOD OF OSCILLATION, CORRESPONDING TO ONE OF THE MODES OF OSCILLATION OF THE BUILDING. THESE ARE CALLED THE EQUIVALENT SINGLE-DEGREE-OF-FREEDOM (SDOF) STRUCTURES CORRESPONDING TO EACH MODE OF OSCILLATION OF THE ORIGINAL BUILDING


=
+
+
+ ...
1st Translational Mode of oscillation
2nd
3rd
=
+
+
+ ...
Equivalent SDoF Structure for 1st Mode of Oscillation
2nd
3rd

- A single-degree-of-freedom structure has mass *m*, stiffness *k* and associated structural damping ξ.
- Thus, all the single-degree-of-freedom structures with same proportion of mass and stiffness have the same natural period.
- Such a set of structures with same natural period (or frequency) of oscillation and same structural damping ξ exhibit same time history of response (*i.e.,* acceleration, velocity and displacement), when subjected to the same earthquake ground shaking.

$$T_n = 2\pi\sqrt{\frac{m}{k}};$$


Same **Acceleration RESPONSE** History
Same **Displacement RESPONSE** History
Mass m
Stiffness k
Damping ξ
$5m$
$5k$
ξ
$10m$
$10k$
ξ
$15m$
$15k$
ξ
Same **INPUT Acceleration** Ground Motion



Δmax
1
2
3
4
N
Maximum Displacement
Natural Period T (s)

ACCELERATION RESPONSE SPECTRUM OF A GROUND MOTION

Usual seismic design of structures is performed using the *maximum force induced* in the structure due to earthquake shaking.

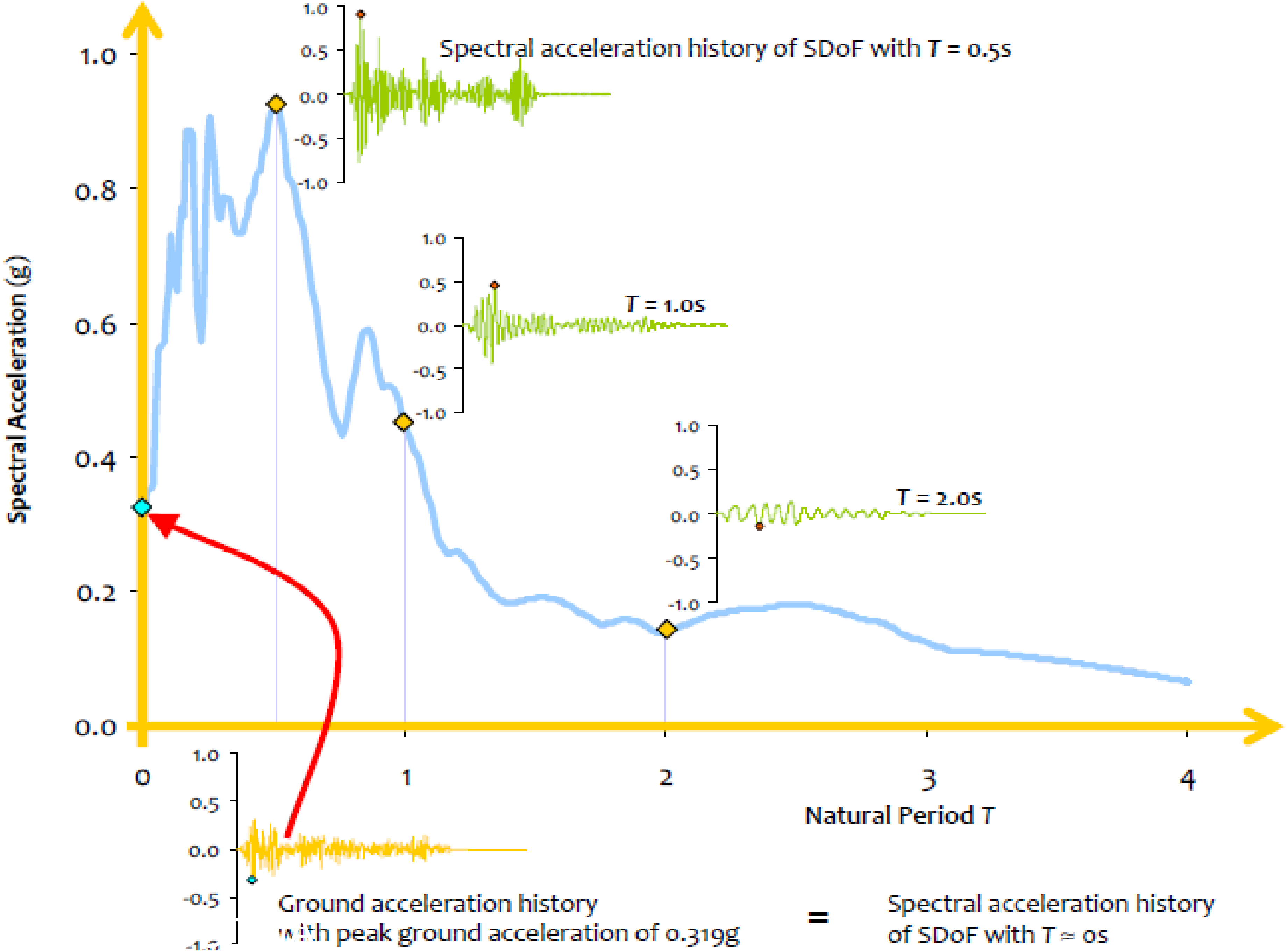
Force can be defined in two ways:

- (i) mass *m* times acceleration *a*, representing *inertia force*, or
- (ii) stiffness *k* times displacement *x* representing *elastic force*, *i.e.*,

$$F = ma \text{ or } F = kx$$

As the absolute maximum of such response is useful in design, a graph of the maximum response is generated for a spectrum of SDoF structures with different natural periods *T* and the same damping under the same earthquake ground motion. This graph is called the *Response Spectrum* of the particular earthquake ground motion.

One such response spectrum corresponding to the acceleration of the building, called the *acceleration response spectrum* for 5% damping under the action of 1940 Imperial Valley earthquake ground motion.



Spectral Acceleration (g)
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
Natural Period T
Spectral acceleration history of SDoF with T = 0.5s
T = 1.0s
T = 2.0s
Ground acceleration history
with peak ground acceleration of 0.319g
=
Spectral acceleration history
of SDoF with T = 0s

- In real buildings, it is easier to compute the mass of the building that is effective during earthquake shaking, called *seismic mass* (equal to seismic weight divided by acceleration due to gravity *g*), than to evaluate overall stiffness.
- Thus, once the natural period associated with each mode of oscillation is estimated, the corresponding seismic lateral force is obtained by multiplying the acceleration response spectrum value (from the acceleration response spectrum) with the mass associated to each mode of oscillation.
- In the design of buildings, seismic design codes provide a *design* response spectrum and the corresponding force obtained is called the *design* seismic lateral force of the building or the design *seismic base shear* of the building.

Elastic earthquake behavior of buildings is primarily controlled by four virtues of

CONFIGURATION,
STIFFNESS,
STRENGTH AND
DUCTILITY.

CONFIGURATION

- Configuration is critical to good seismic performance of buildings. The important aspects affecting seismic configuration of buildings are

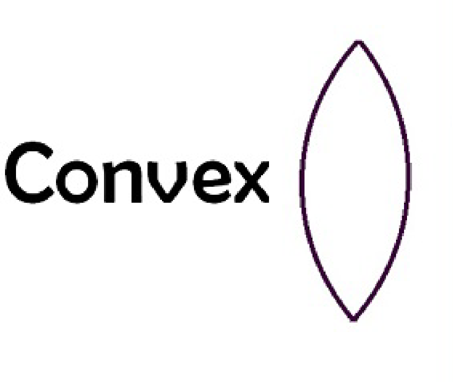
OVERALL GEOMETRY, STRUCTURAL SYSTEMS, AND LOAD PATHS

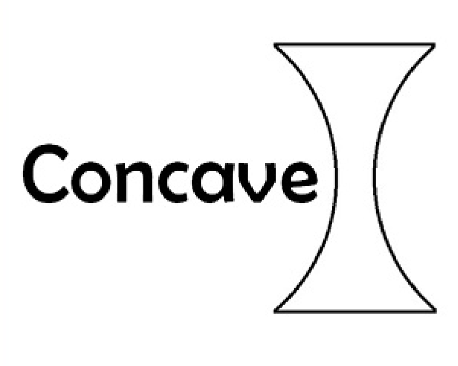
OVERALL GEOMETRY

1. AVOID COMPLEX PLAN SHAPES

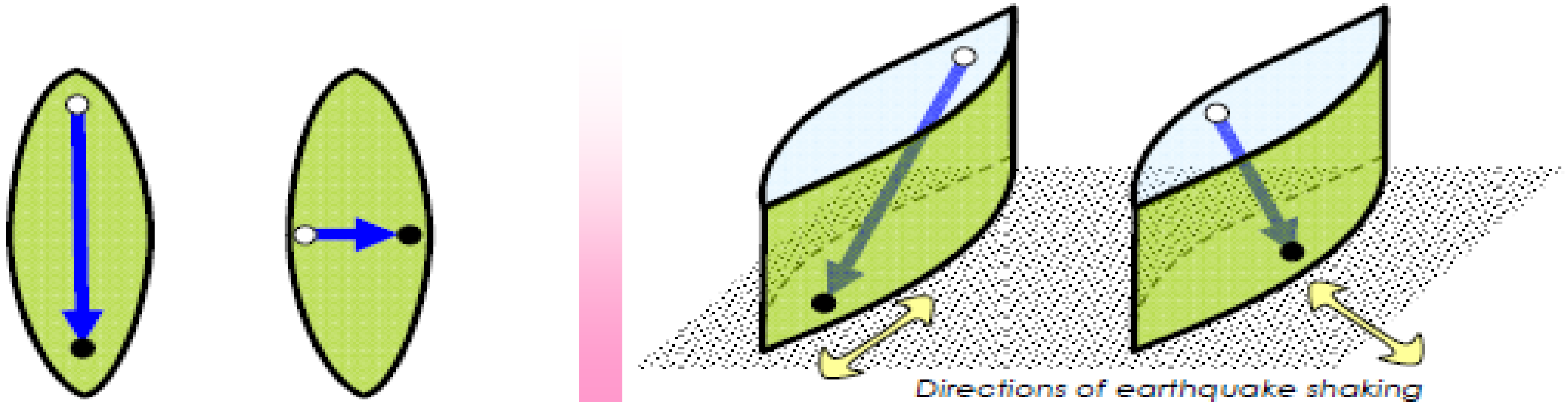
- The influence of plan geometry of the building on its seismic performance is best understood from the basic geometries of *convex*- and *concave*-type lenses

CONVEX GEOMETRY	CONCAVE GEOMETRY
Buildings with convex plan shape have direct load paths for transferring seismic inertia forces to its base,	Buildings with concave plan shape necessitate indirect load paths that result in stress concentrations at points where load paths bend.

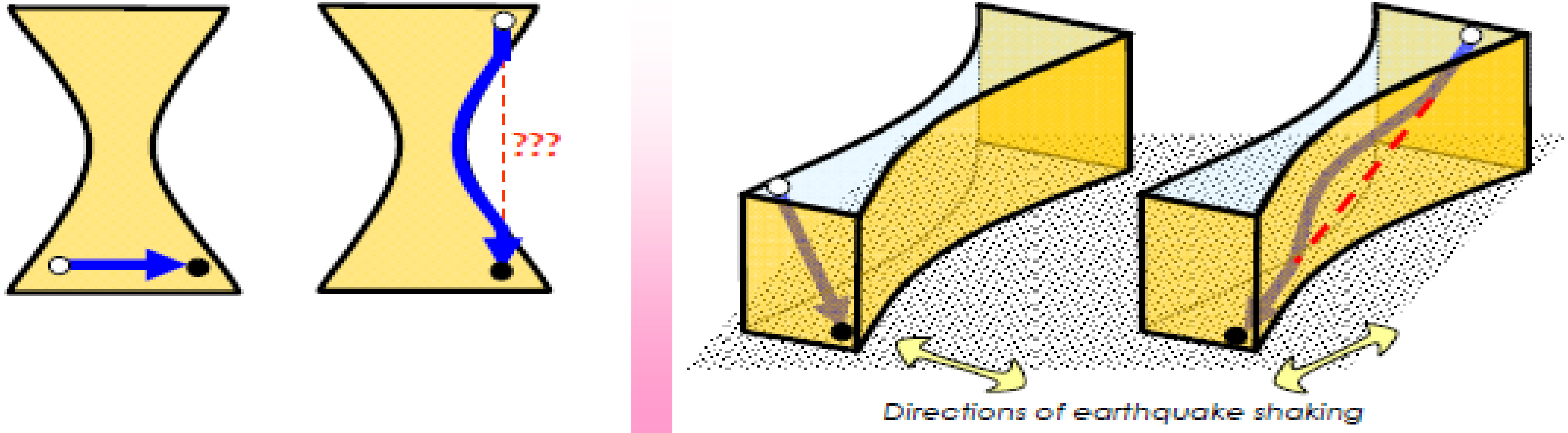


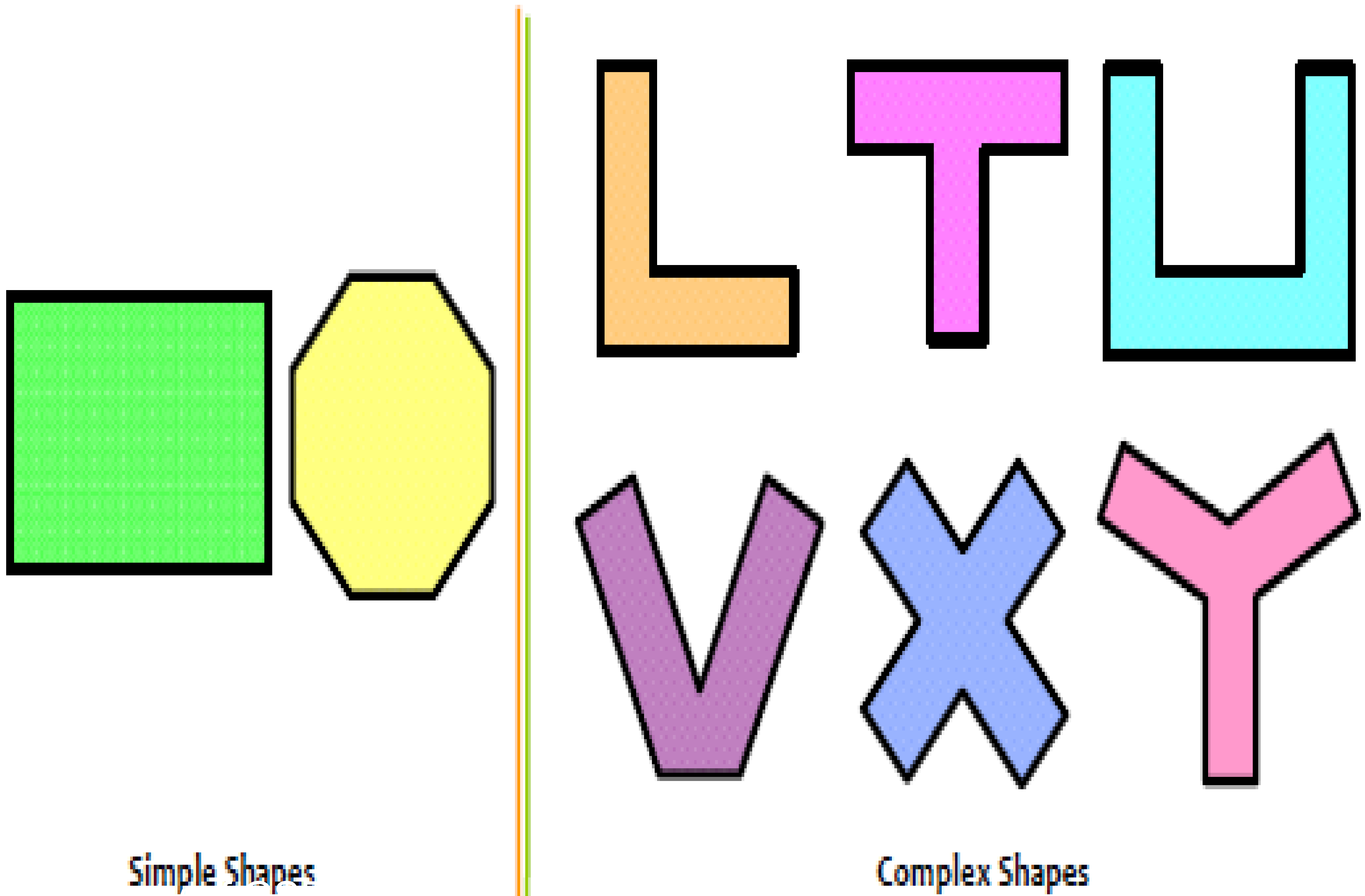


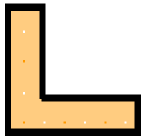
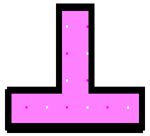
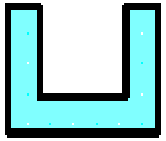
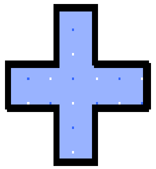
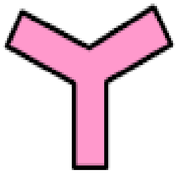
Images Property of GSDMA


Directions of earthquake shaking

(a)

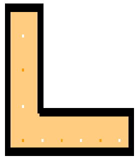

???
Directions of earthquake shaking

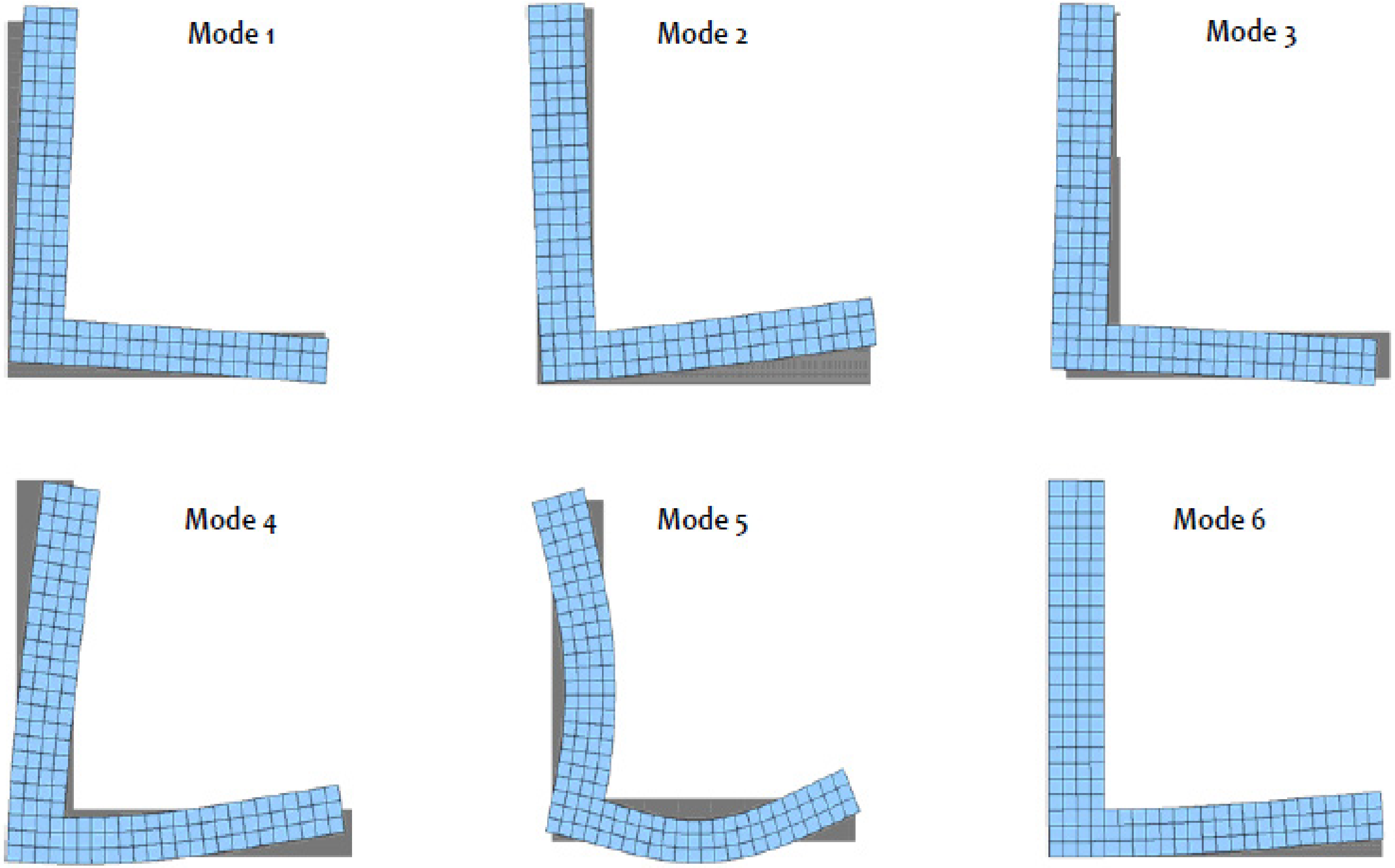

Simple Shapes
Complex Shapes

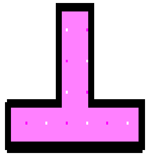
Mode	*Type of oscillation in first six modes in buildings with different plan shapes*					
						
1	Y-translation	Y-translation with torsion	X-translation	*Torsion*	X-translation with torsion	*Torsion*
2	X-translation	X-translation with torsion	Y-translation	Y-translation	Y-translation with torsion	X-translation
3	*Torsion*	*Torsion*	*Torsion*	X-translation	Torsional	Y-translation
4	Opening-closing	Opening-closing	Opening-closing	Opening-closing	Opening-closing	Dog tail wagging
5	Mixed	Dog tail wagging	Mixed	Mixed	Dog tail wagging	Opening-closing
6	Mixed	Mixed	2nd X-translation	Mixed	Mixed	Mixed

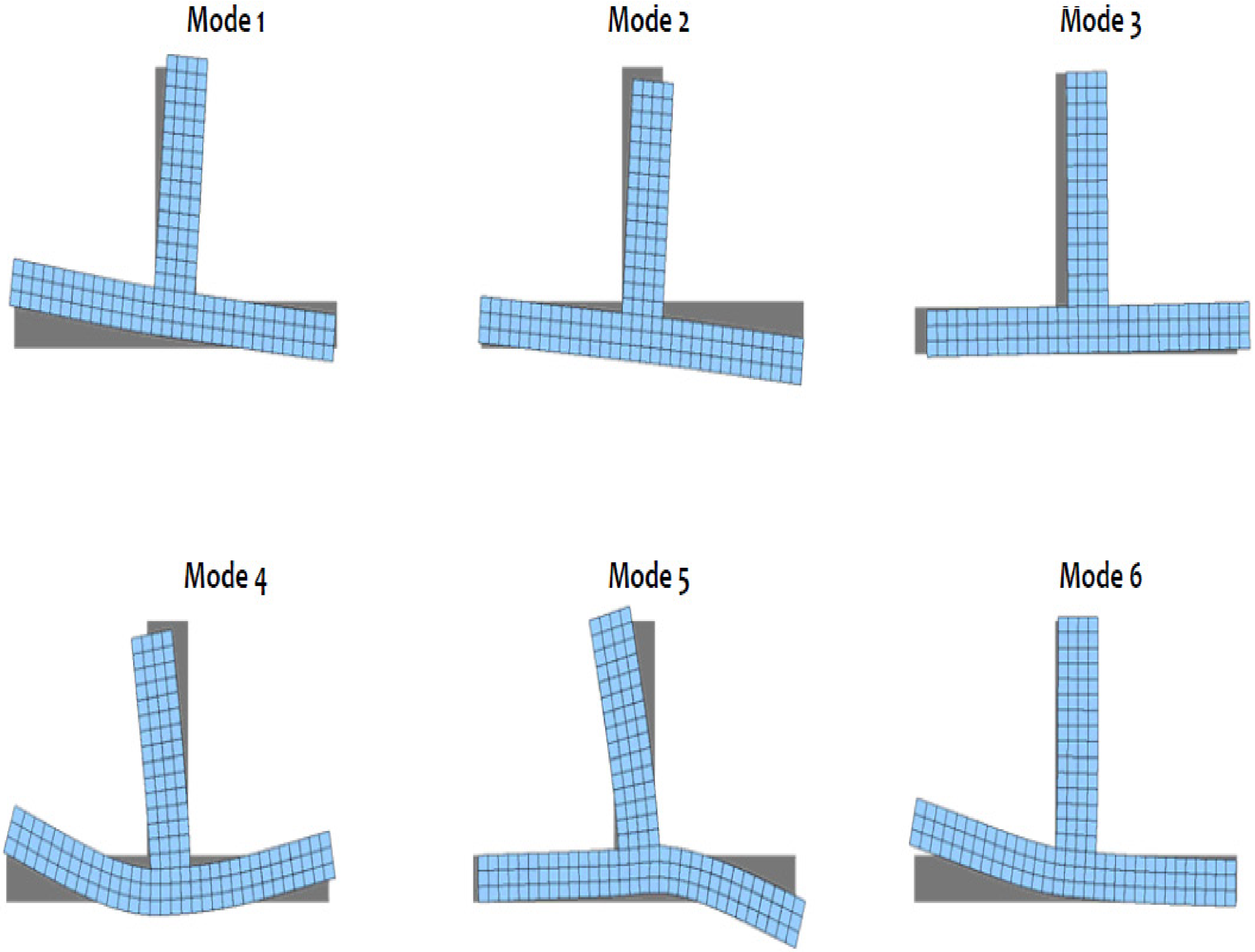
Note:

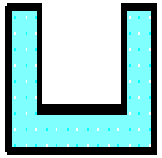
Diagonal translation, torsion, opening-closing, and dog-tail-wagging are not acceptable as initial modes of oscillation in buildings

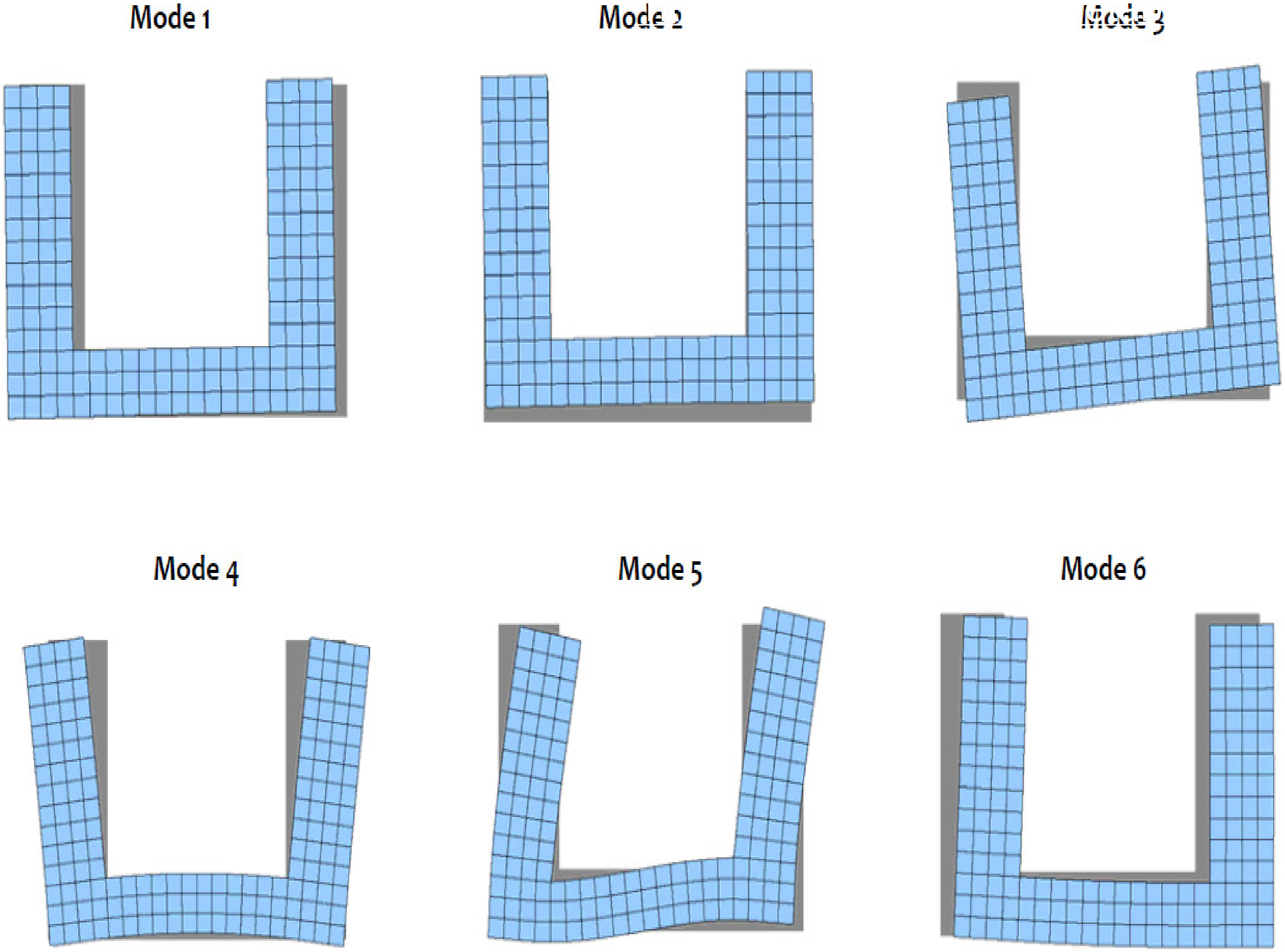
Mode	
1	Y-translation
2	X-translation
3	*Torsion*
4	Opening-closing
5	Mixed
6	Mixed

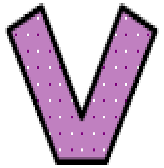


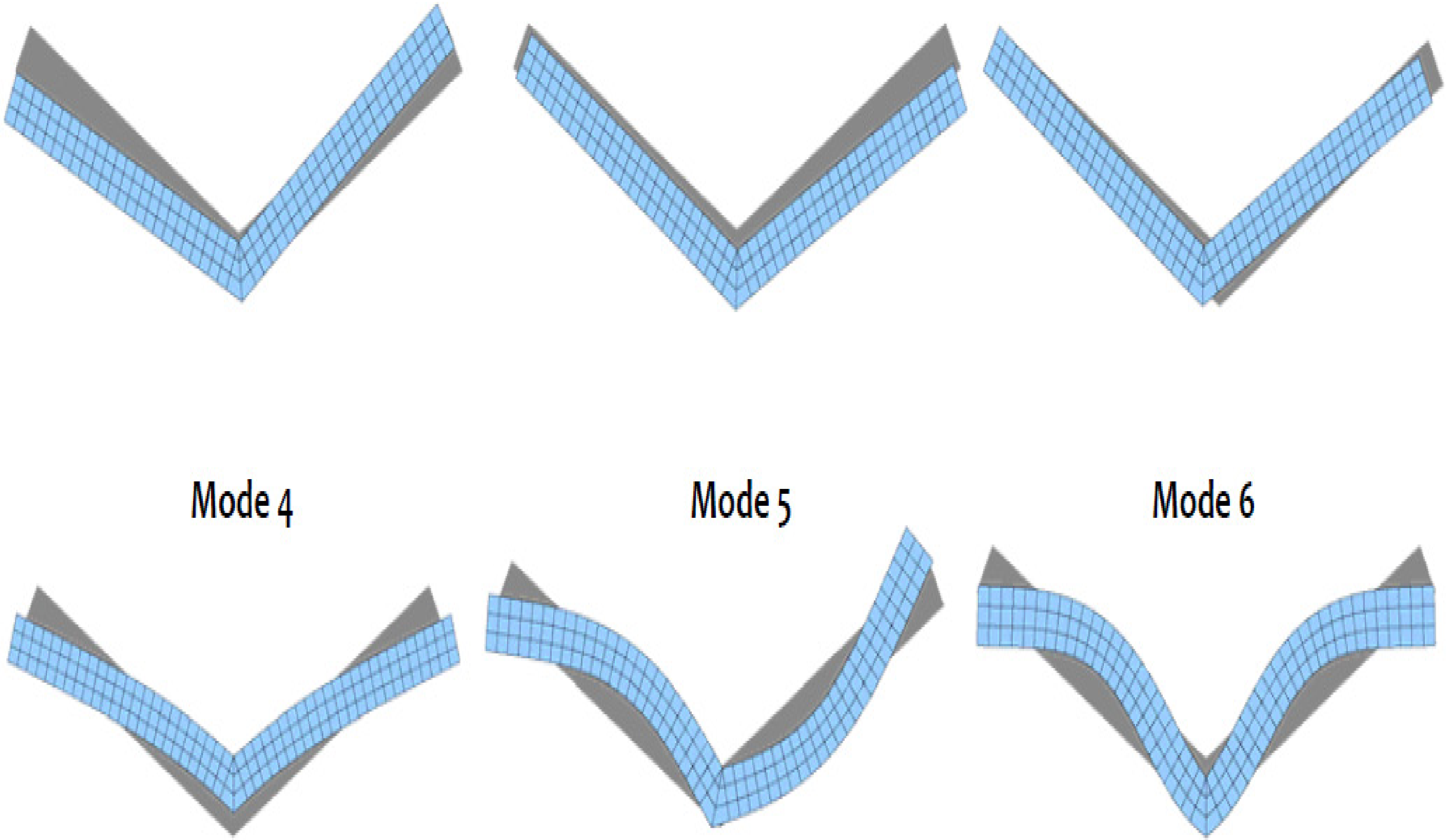
Mode	
1	Y-translation with torsion
2	X-translation with torsion
3	*Torsion*
4	Opening-closing
5	Dog tail wagging
6	Mixed

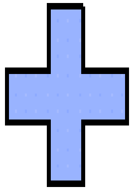


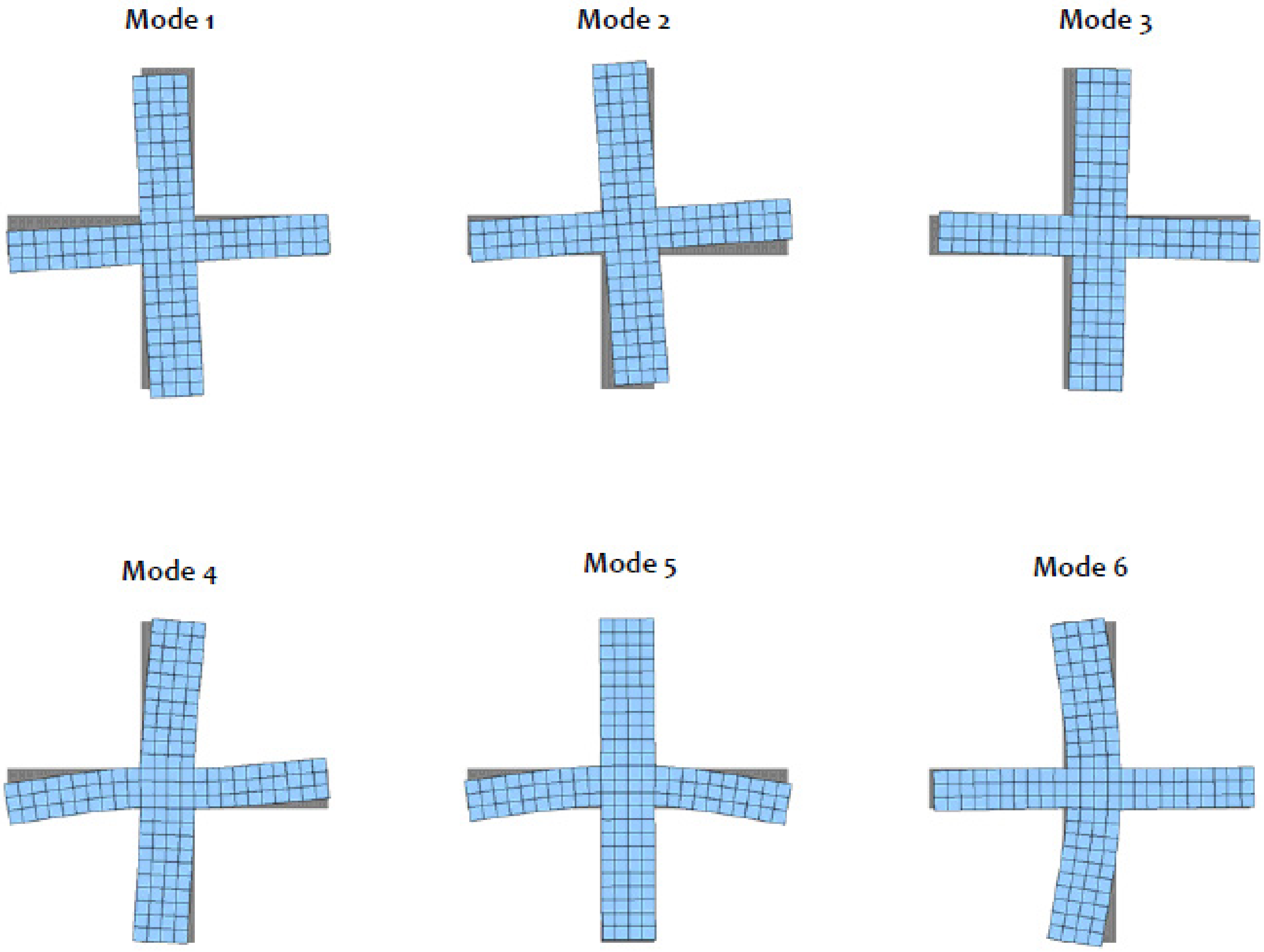
Mode	[redacted] 
1	X-translation
2	Y-translation
3	*Torsion*
4	Opening-closing
5	Mixed
6	2nd X-translation

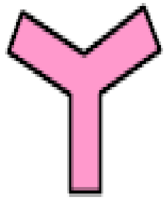


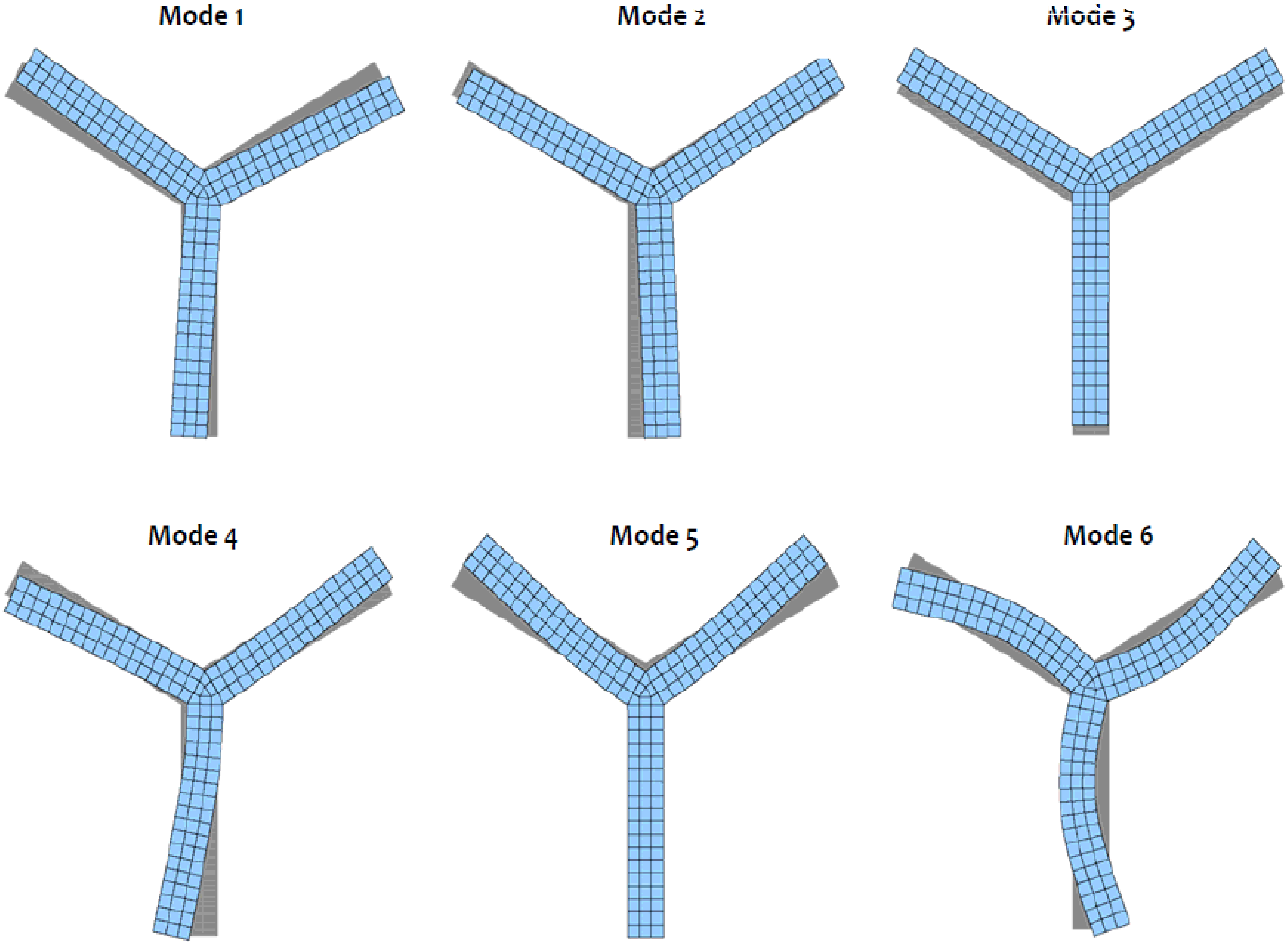
Mode	
1	*Torsion*
2	Y-translation
3	X-translation
4	Opening-closing
5	Mixed
6	Mixed



Mode	
1	X-translation with torsion
2	Y-translation with torsion
3	Torsional
4	Opening-closing
5	Dog tail wagging
6	Mixed



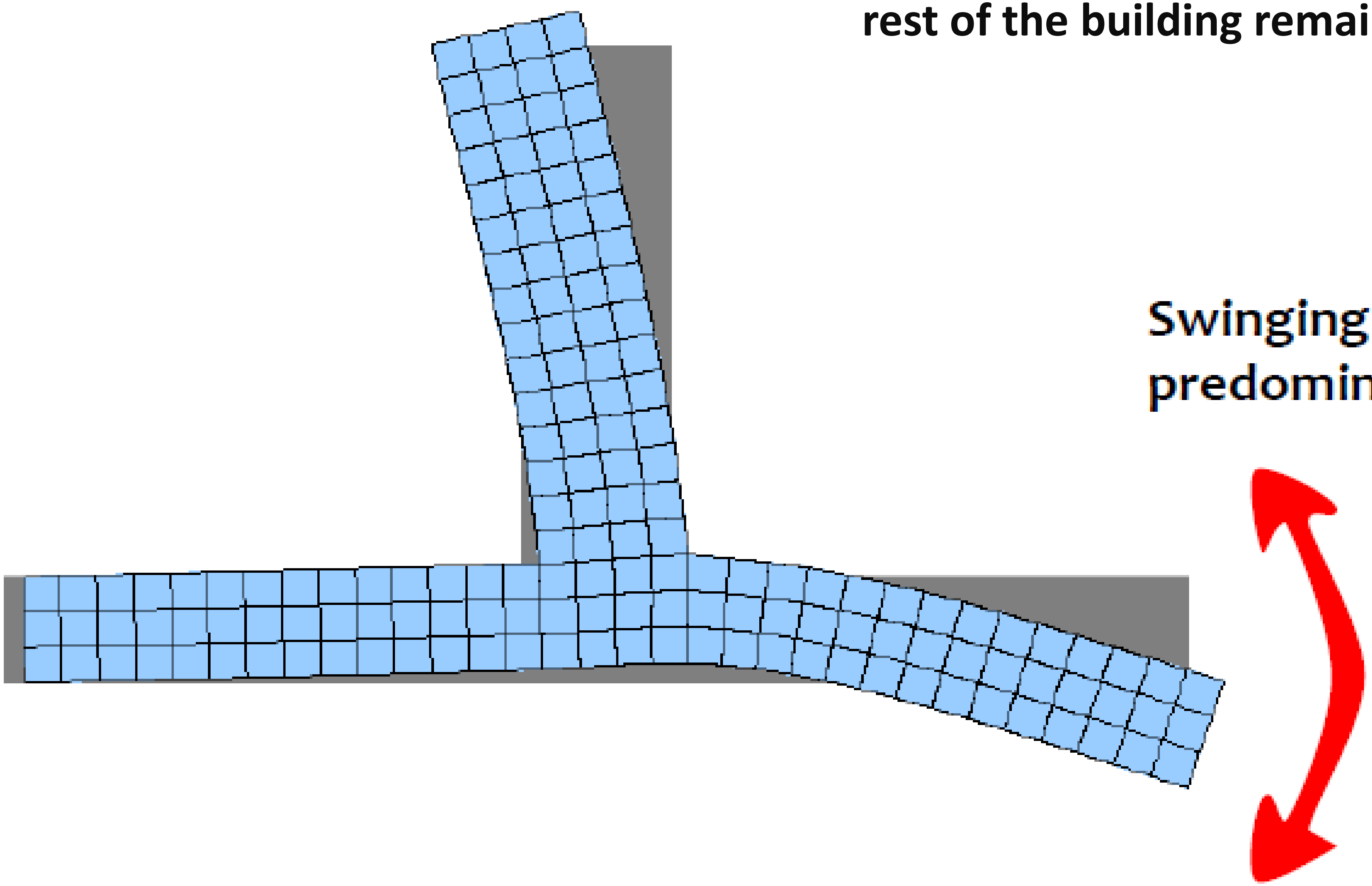
Mode	
1	*Torsion*
2	X-translation
3	Y-translation
4	Dog tail wagging
5	Opening-closing
6	Mixed



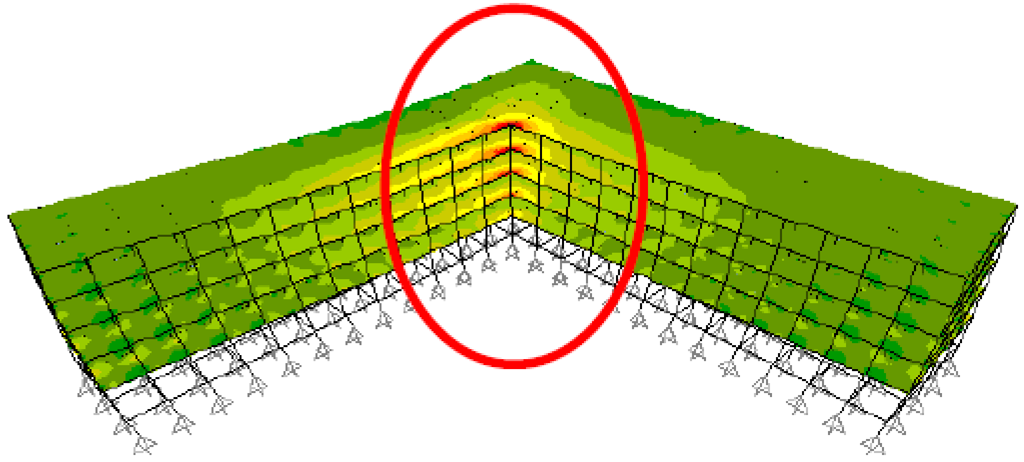
WHAT IS THIS DOG TAIL WAGGING MODE !!

- Buildings with complex shapes, particularly with projections or re-entrant corners, exhibit special modes of oscillation, in addition to translatory (pure or diagonal) or torsional modes.
- These include an opening-closing mode, and the unique local-high-frequency oscillatory mode like, that of the wagging of a dog’s tail.
- *Dog tail wagging* mode of oscillation is interesting because in this mode, only a slender or long projection oscillates and the remaining part of the building almost remains still, just like the dog’s body remains still when its tail wags
- The effect of these special modes of oscillation is to induce high stress concentration at the re-entrant corners that may cause significant structural damage

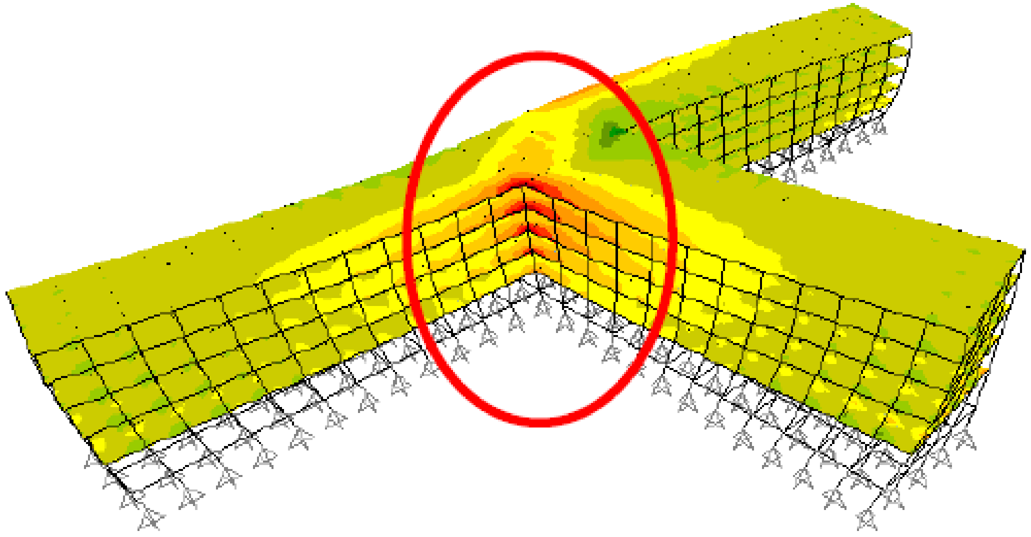
Only a projection oscillates significantly, while the rest of the building remains almost still



STRESS CONCENTRATION AT RE-ENTRANT CORNERS



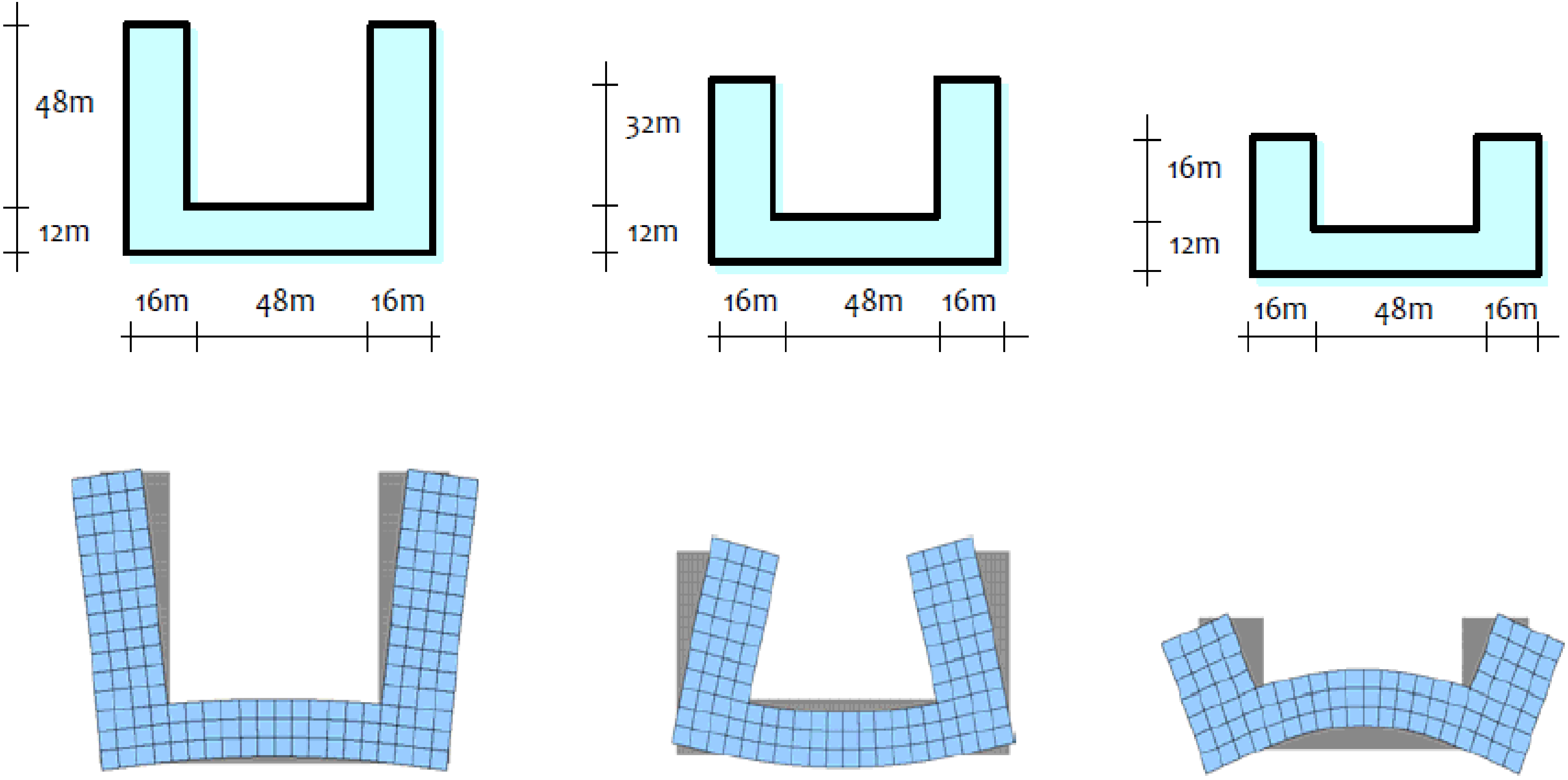
Opening closing mode of oscillation



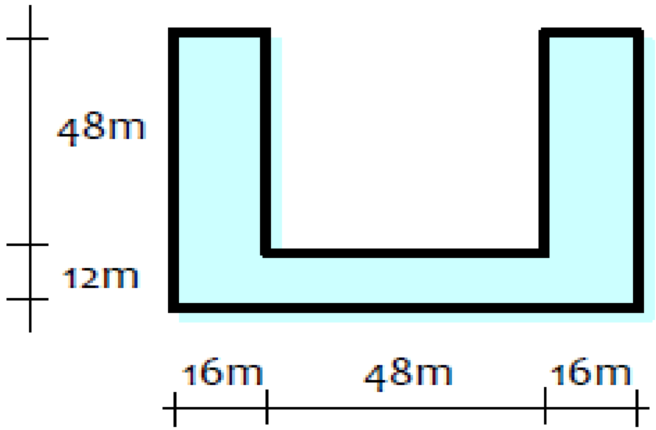
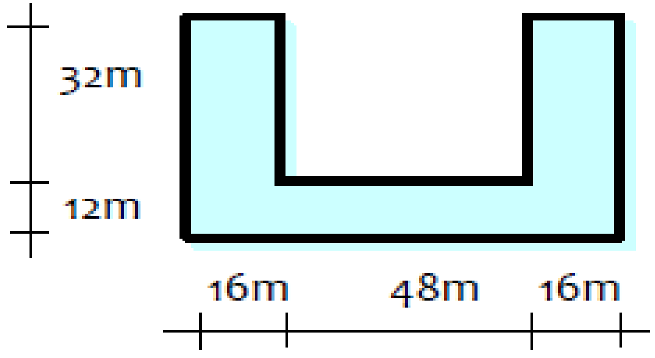
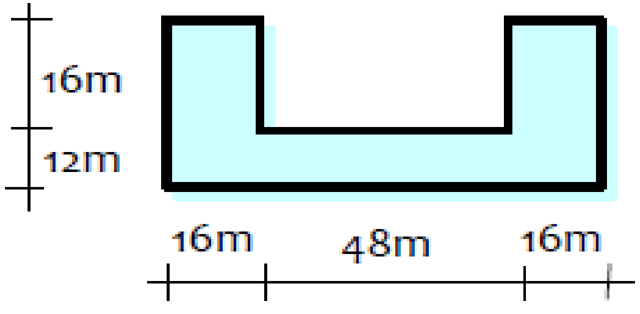
Dog-tail wagging mode of oscillation

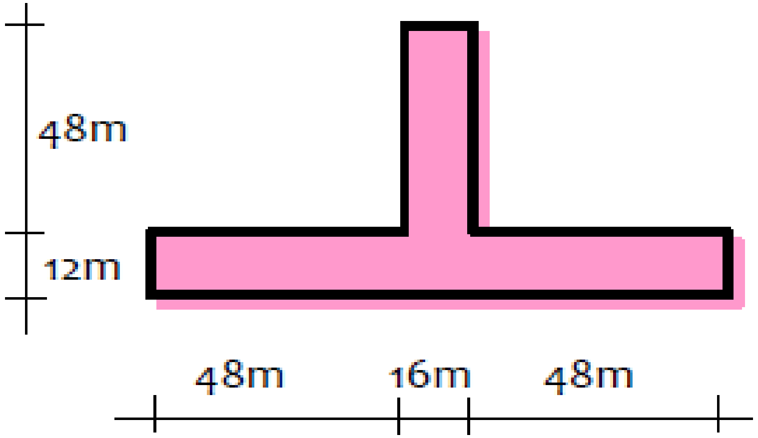
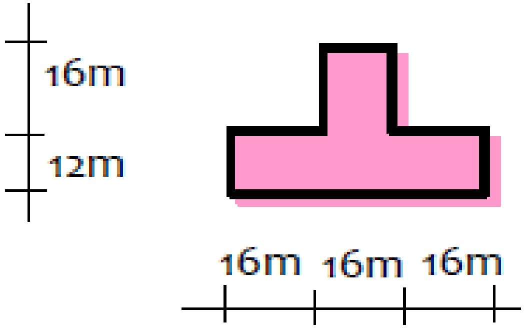
AVOID LONG PROJECTIONS !!

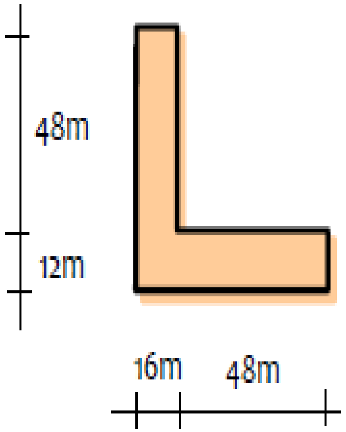
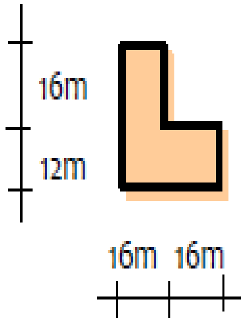
- Projections, if required, must be short, although they still offer stress concentration at their re-entrant corners. Consider buildings with U-plan shape, but with different length of projections
- The first three modes of oscillation in all the three buildings are same – two lateral translations and torsion, with similar natural periods (between 0.92s to 0.89s).
- However, the periods of oscillation of the fourth mode, that of opening-closing one, are significantly different – 0.77s, 0.63s, and 0.42s in the buildings with 48m, 32m and 16m projections, respectively.
- This signifies that the contribution of the opening-closing mode of oscillation in the overall response of the building with 16m projecting arms is least and will ensure better seismic behavior of the building than buildings with 32m and 48m projecting arms.

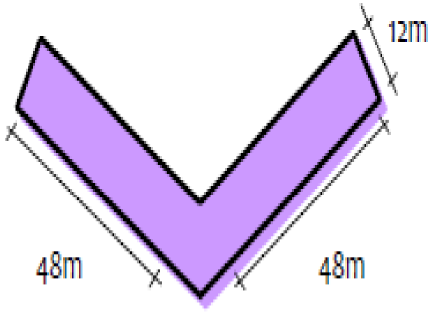
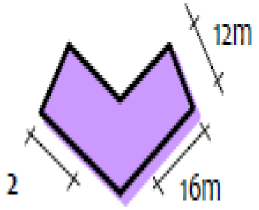


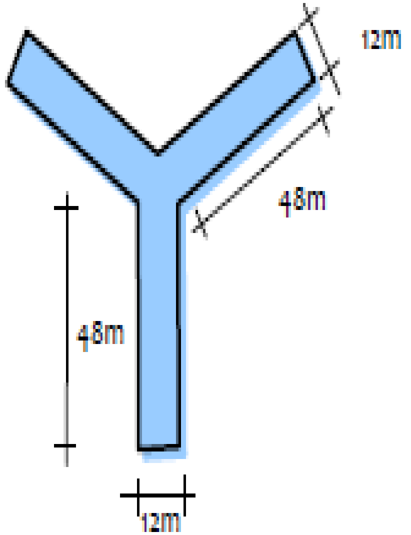
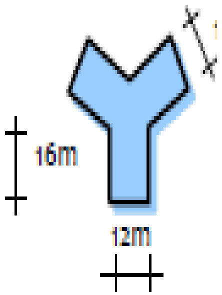
$T_{n4} = 0.77s$ $T_{n4} = 0.63s$ $T_{n4} = 0.42s$

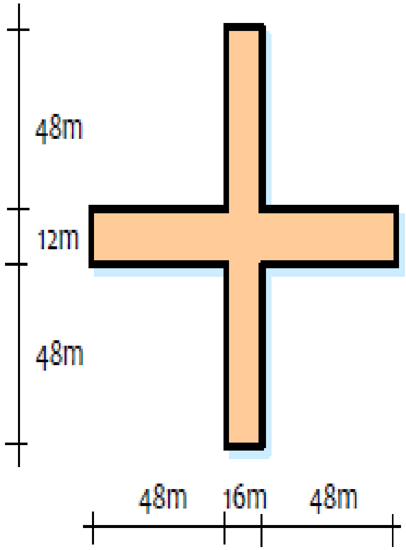
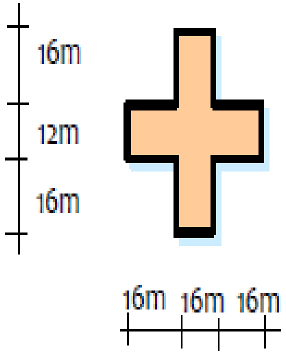
Mode	*Type of oscillation in first ten modes in buildings with U-plan shape and different lengths of projecting arm*		
			
1	X translation (0.92s)	Y translation *(0.92s)*	Y translation *(0.94s)*
2	Y translation *(0.91s)*	X translation (0.92s)	X translation (0.91s)
3	Torsional (0.89s)	Torsional (0.89s)	Torsional (0.90s)
4	*Opening-closing (0.77s)*	*Opening-closing (0.63s)*	*Opening-closing (0.42s)*
5	Opening-closing (0.48s)	Opening-closing (0.34s)	2nd Y translation (0.29s)
6	2nd X translation (0.28s)	2nd Y translation (0.29s)	2nd X translation (0.28s)
7	2nd Y translation (0.28s)	2nd X translation (0.28s)	2nd torsion (0.26s)
8	Opening-closing (0.27s)	2nd torsion (0.26s)	Opening-closing (0.25s)
9	2nd torsion (0.27s)	Opening-closing (0.26s)	Opening-closing (0.19s)
10	Opening-closing (0.25s)	Opening-closing (0.23s)	Opening-closing (0.17s)

Mode	*Type of oscillation in first ten modes in buildings with T-plan shape and different lengths of projecting arm*	
		
1	Y translation (0.92s)	Y translation (0.91s)
2	*Torsional (0.92s)*	X translation (0.89s)
3	X translation (0.90s)	*Torsional (0.87s)*
4	*Opening-closing (0.49s)*	2^{nd} Y translation (0.28s)
5	Opening-closing (0.48s)	2^{nd} X translation (0.27s)
6	2^{nd} Y translation (0.26s)	2^{nd} torsion (0.27s)
7	2^{nd} Torsional (0.26s)	3^{rd} Y translation (0.15s)
8	2^{nd} X translation (0.25s)	3^{rd} X translation (0.15s)
9	2^{nd} opening-closing (0.24s)	3^{rd} torsion (0.14s)
10	2^{nd} opening-closing (0.23s)	*Opening-closing (0.11s)*

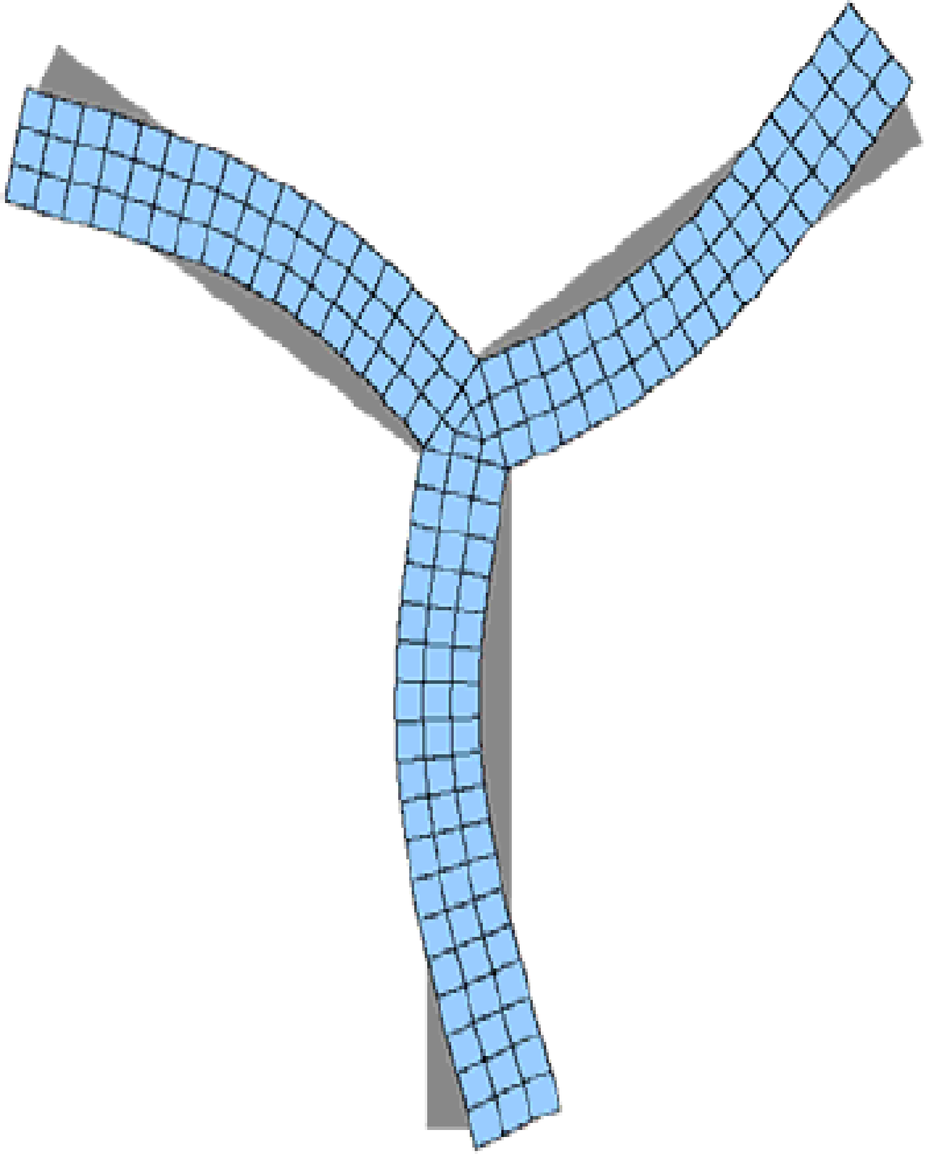
Mode	*Type of oscillation in first ten modes in buildings with L-plan shape and different lengths of projecting arm*	
		
1	*Diagonal translation (0.92s)*	Y translation (0.91s)
2	*Diagonal translation (0.91s)*	X translation (0.90s)
3	*Torsional (0.88s)*	*Torsional (0.85s)*
4	*Opening-closing (0.47s)*	2nd Y translation (0.28s)
5	2nd diagonal translation (0.28s)	2nd X translation (0.28s)
6	2nd diagonal translation (0.27s)	2nd torsion (0.26s)
7	2nd torsion (0.27s)	3rd Y translation (0.15s)
8	2nd opening-closing (0.25s)	3rd X translation (0.15s)
9	Mixed (0.16s)	3rd torsional (0.14s)
10	3rd diagonal translation (0.15s)	*Opening-closing (0.10s)*

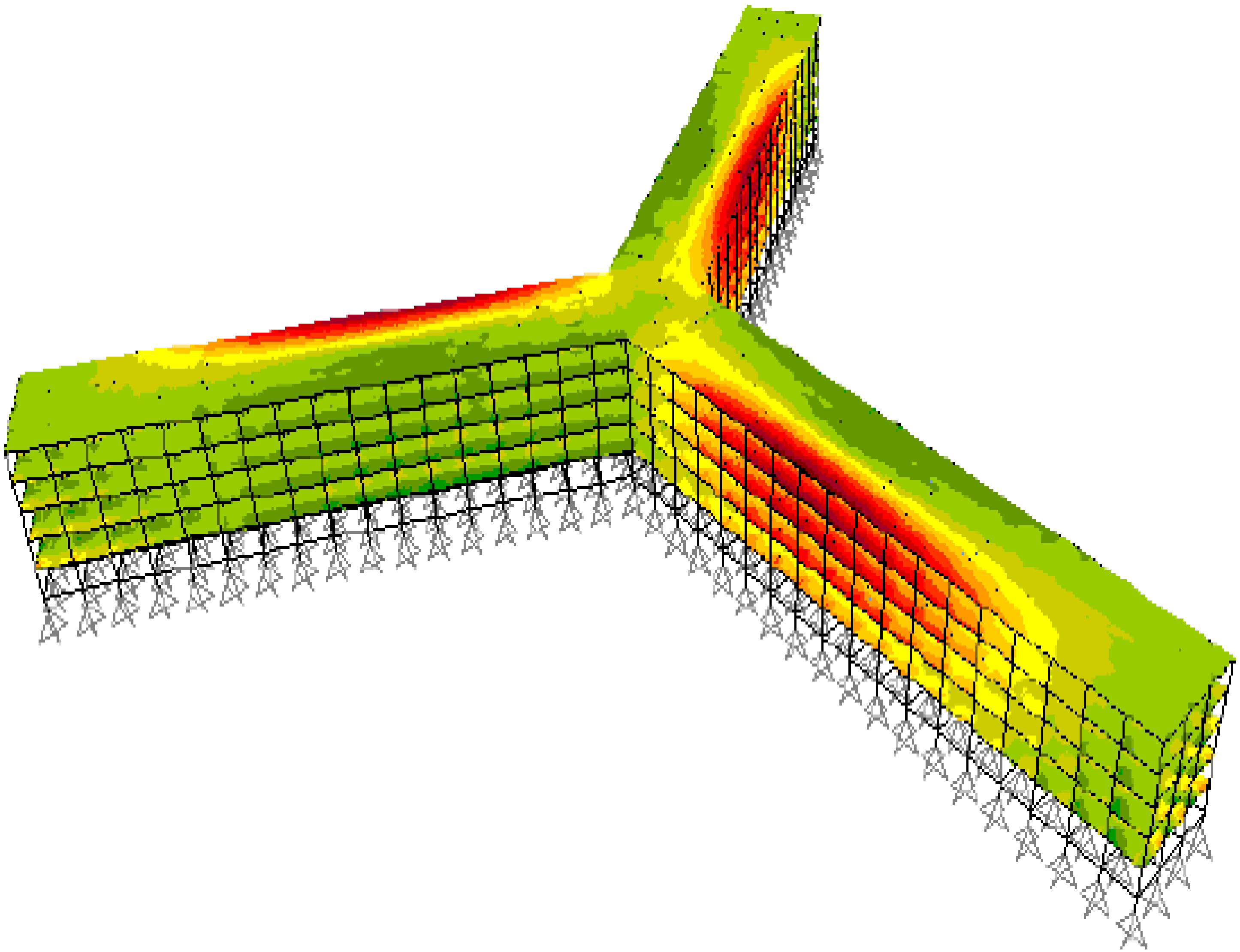
Mode	*Type of oscillation in first ten modes in buildings with V-plan shape and different lengths of projecting arm*	
		
1	Y translation (0.87s)	Y translation (0.86s)
2	X translation (0.87s)	X translation (0.85s)
3	*Torsional (0.81s)*	*Torsional (0.78s)*
4	*Opening-closing (0.43s)*	2nd Y translation (0.27s)
5	2nd Y translation (0.27s)	2nd X translation (0.27s)
6	2nd X translation (0.27s)	2nd torsion (0.26s)
7	2nd torsion (0.26s)	3rd Y translation (0.15s)
8	Opening-closing (0.24s)	3rd X translation (0.15s)
9	Mixed(0.16s)	3rd torsional (0.14s)
10	Mixed (0.15s)	4th Y translation (0.10s)

Mode	*Type of oscillation in first ten modes in buildings with Y-plan sh* *and different lengths of projecting arm*	
		
1	*Torsional (0.87s)*	Y translation (0.87s)
2	Y translation (0.85s)	X translation (0.85s)
3	X translation (0.84s)	*Torsional (0.81s)*
4	*Opening-closing (0.47s)*	2nd Y translation (0.26s)
5	*Dog Tail wagging (0.47s)*	2nd X translation (0.26s)
6	2nd torsional (0.27s)	2nd torsion (0.26s)
7	2nd Y translation (0.27s)	3rd Y translation (0.16s)
8	2nd X translation (0.27s)	3rd X translation (0.15s)
9	2nd dog tail wagging (0.24s)	3rd torsional (0.14s)
10	2nd opening-closing (0.24s)	4th Y translation (0.10s)

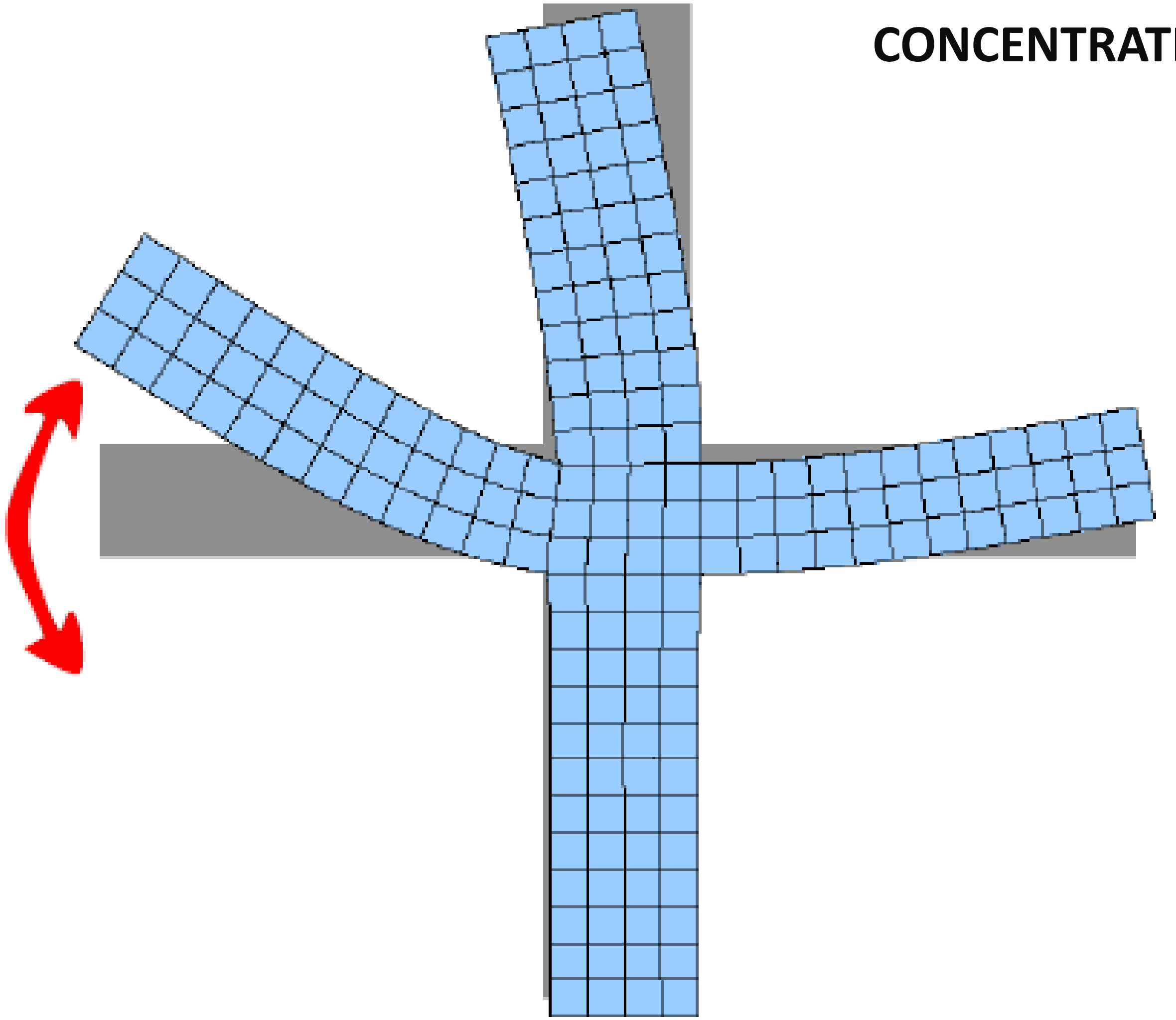
Mode	*Type of oscillation in first ten modes in buildings with X-plan shape and different lengths of projecting arm*	
		
1	X translation (0.89s)	Y translation (0.83s)
2	Y translation (0.85s)	X translation (0.82s)
3	*Torsional (0.75s)*	*Torsional (0.81s)*
4	*Dog tail wagging (0.49s)*	2nd Y translation (0.26s)
5	*2nd Dog Tail wagging(0.40s)*	2nd X translation (0.26s)
6	*Opening-closing (0.37s)*	2nd torsion (0.26s)
7	2nd torsional (0.28s)	3rd Y translation (0.16s)
8	2nd X translation (0.27s)	3rd X translation (0.15s)
9	2nd Y translation (0.26s)	3rd torsional (0.14s)
10	3rd torsion (0.24s)	4th Y translation (0.10s)

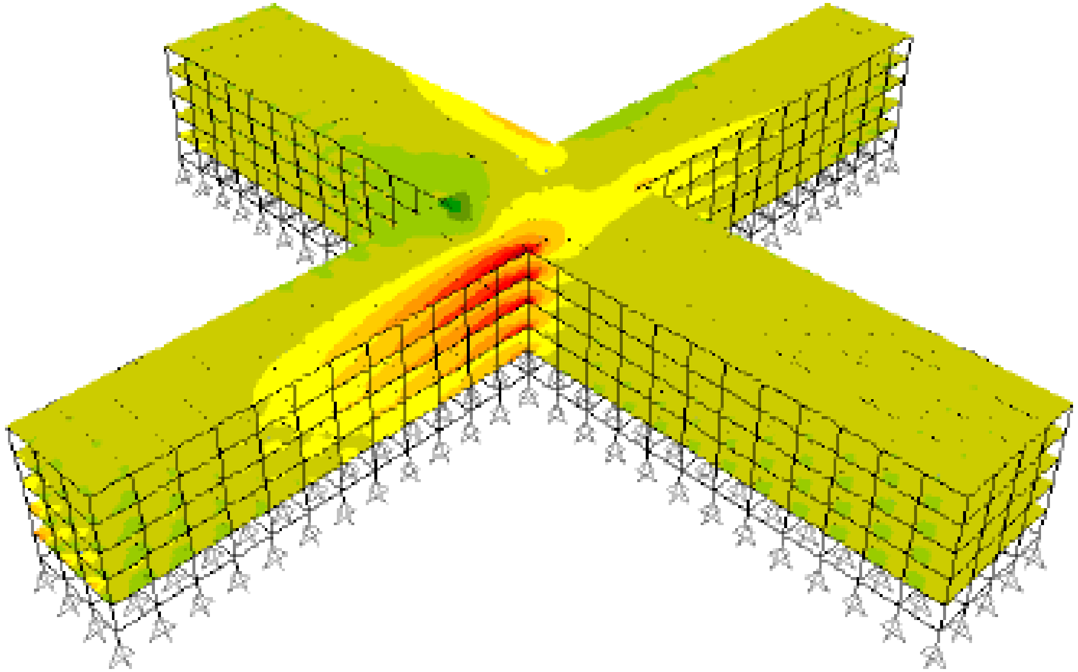
Torsional mode of oscillation in buildings with complex shape contribute significantly to overall building response if it has large natural period





DOG-TAIL-WAGGING MODE OF OSCILLATION IN BUILDING WITH X-PLAN SHAPE CAUSE SIGNIFICANT STRESS CONCENTRATION AT RE-ENTRANT CORNERS





SUMMARY OF WHAT WE JUST LEARNED ABOUT BUILDING PLAN SHAPES

- In summary, the important observations are

(1) Torsional modes of oscillations are predominant in buildings with L-, X- and Y-plan shapes, which should be avoided with suitable choice of structural configuration;

(2) Diagonal translation modes of oscillations are predominant in buildings with L- and X-plan shapes, which should be avoided with suitable changes in structural configuration;

(3) Opening-closing and dog-tail-wagging modes of oscillation are predominant in buildings with

large projecting arms;

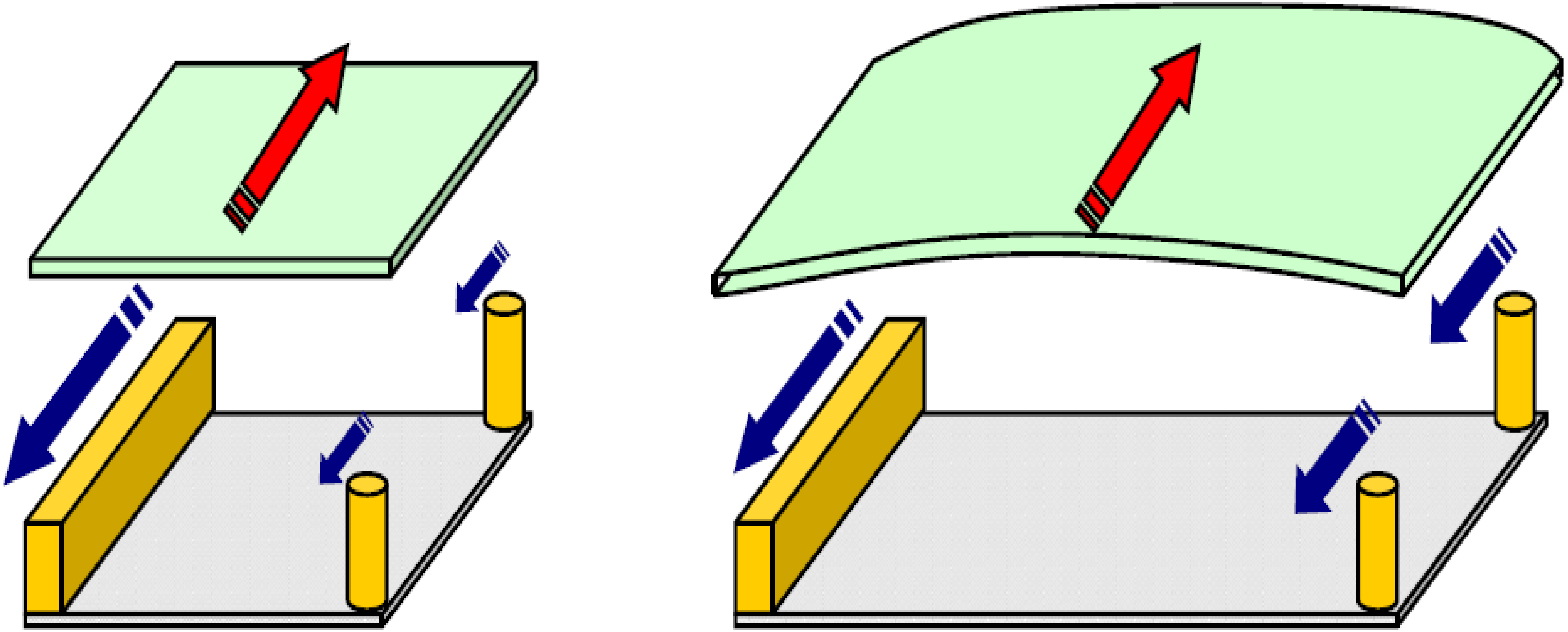
(4) Opening-closing and dog-tail-wagging modes of oscillation cause significant stress

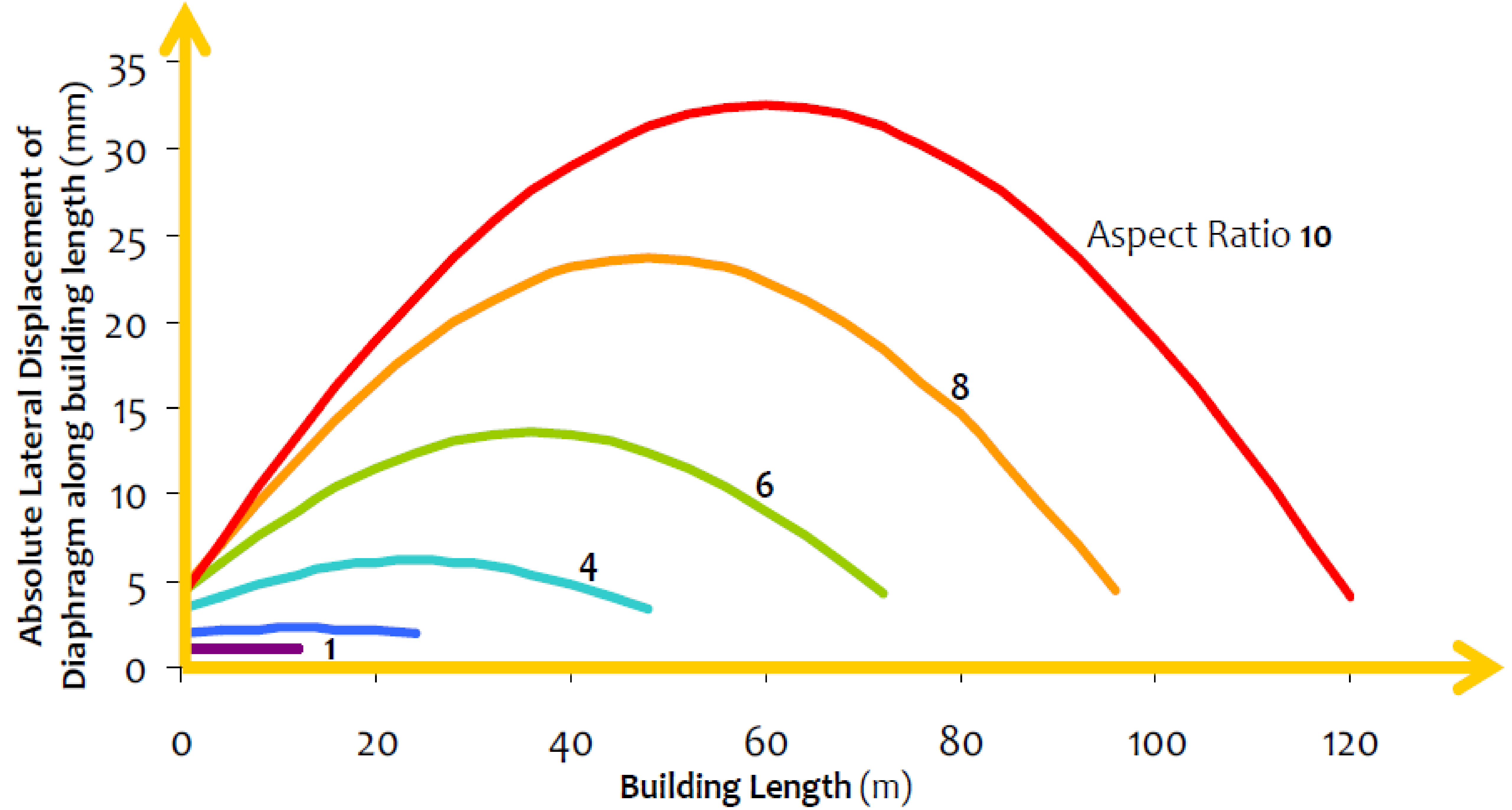
concentrations at re-entrant corners and can cause structural damage; and

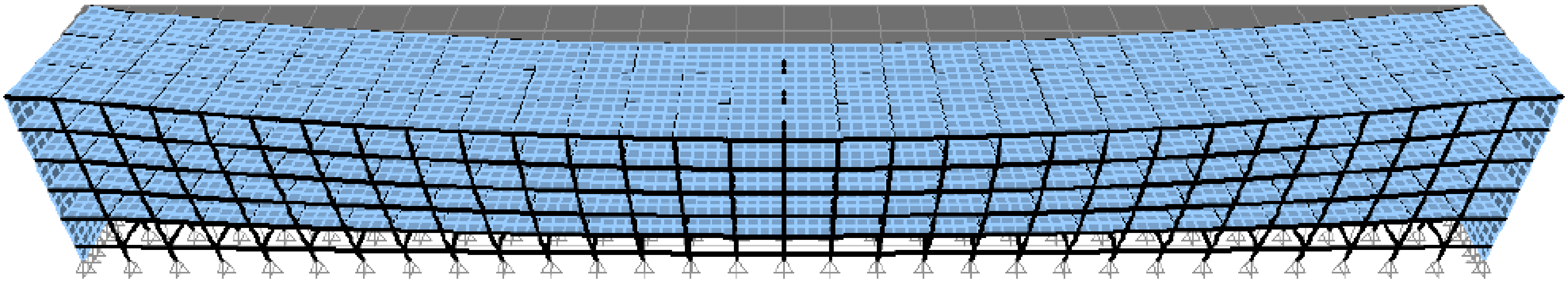
(5) It is prudent to not use buildings with complex plan shapes, or if compelled, ensure that their natural periods are small (outside the range of natural periods with significant earthquake energy).

OVERALL GEOMETRY
2. AVOID LARGE PLAN ASPECT RATIO

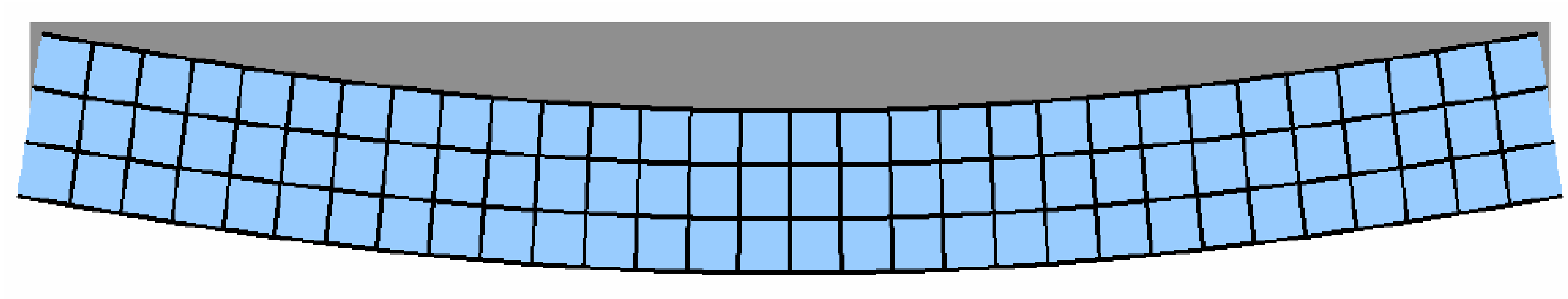
- It is not good to have buildings with large plan aspect ratio, just like it is not good to have buildings with large projections.
- During earthquake shaking, inertia force is mobilized in the building, usually at the floor levels where the mass is large. The inertia force then is distributed to different lateral load resisting systems (columns and/or structural walls). It is preferred to distribute this lateral inertia force to various lateral load resisting systems in proportion to their lateral load resisting capacities
- This is achieved when the floor slabs do not deform too much in their own (horizontal) plane. This condition, when floor slab helps in distributing the inertia force to different lateral load resisting systems in proportion to their stiffness, is known as *rigid diaphragm action*.
- However, the inertia force is distributed based on tributary area when floor slabs deform in their plane. This leads to overloading of members with less capacity and thus causing undue damage to buildings. Floor slabs in buildings with large plan aspect ratio (>4) may not provide rigid diaphragm action.




Absolute Lateral Displacement of Diaphragm along building length (mm)
35
30
25
20
15
10
5
0
Aspect Ratio 10
8
6
4
1
0
20
40
60
80
100
120
Building Length (m)



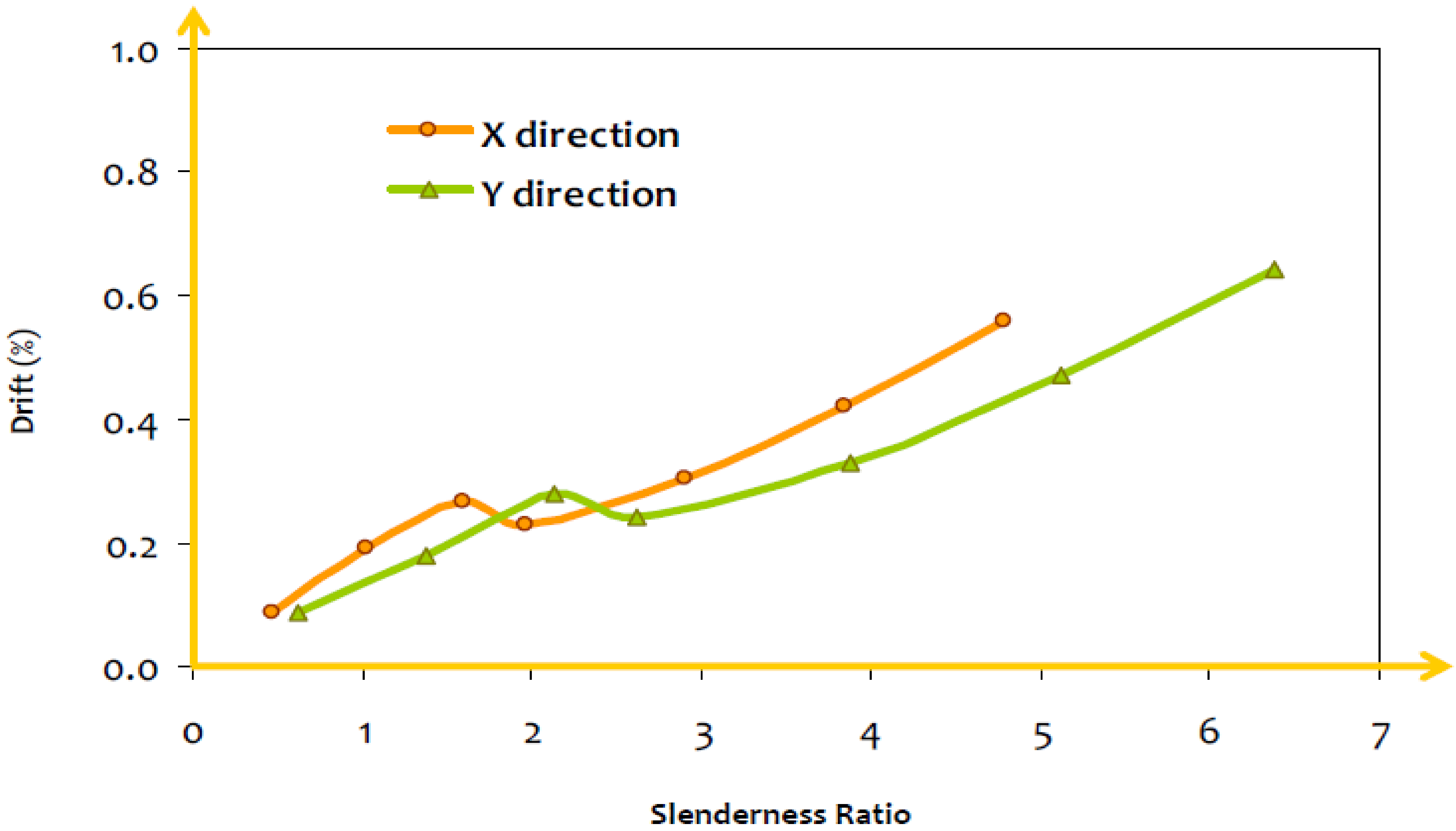
3D View



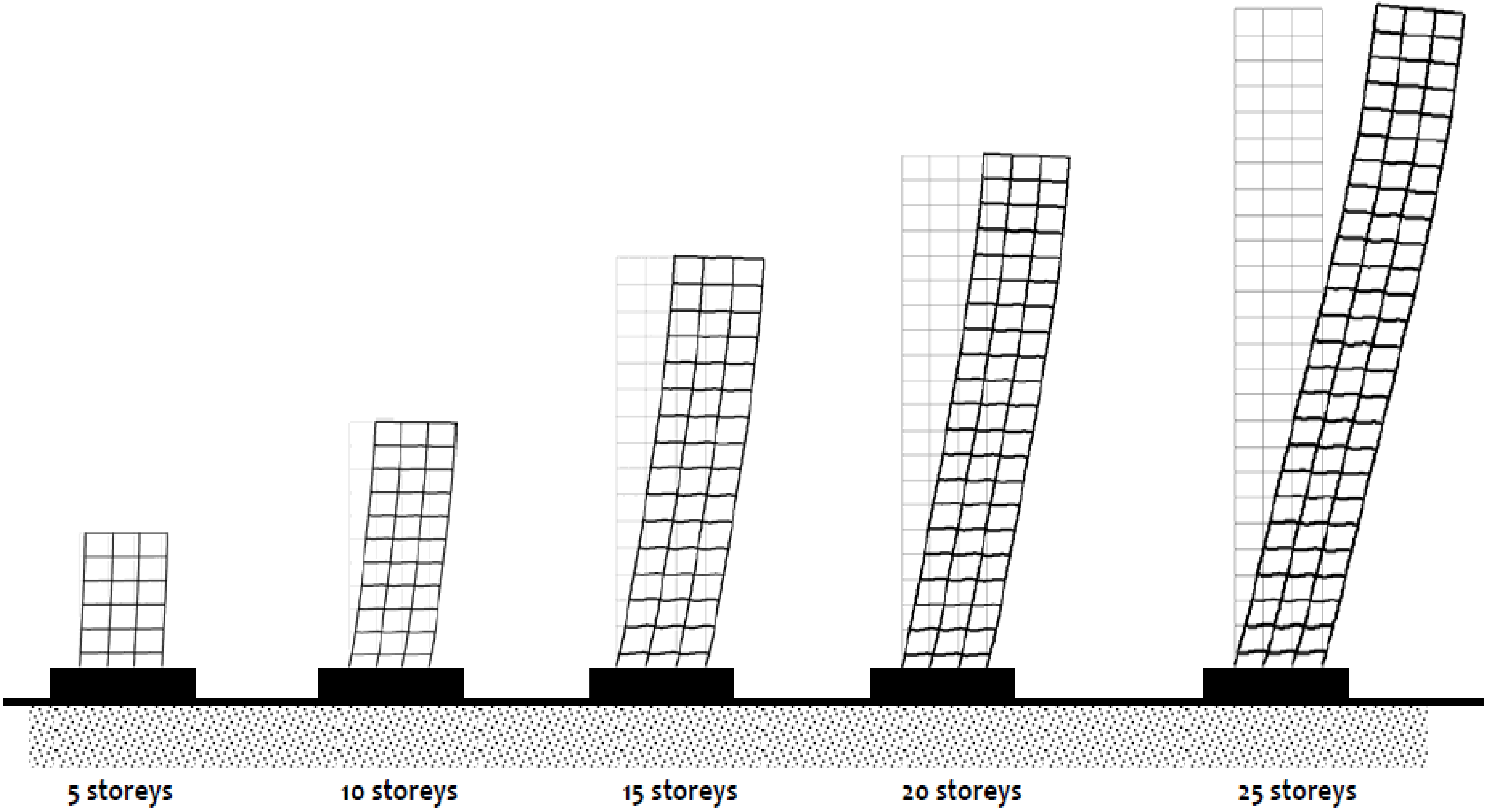
Plan View

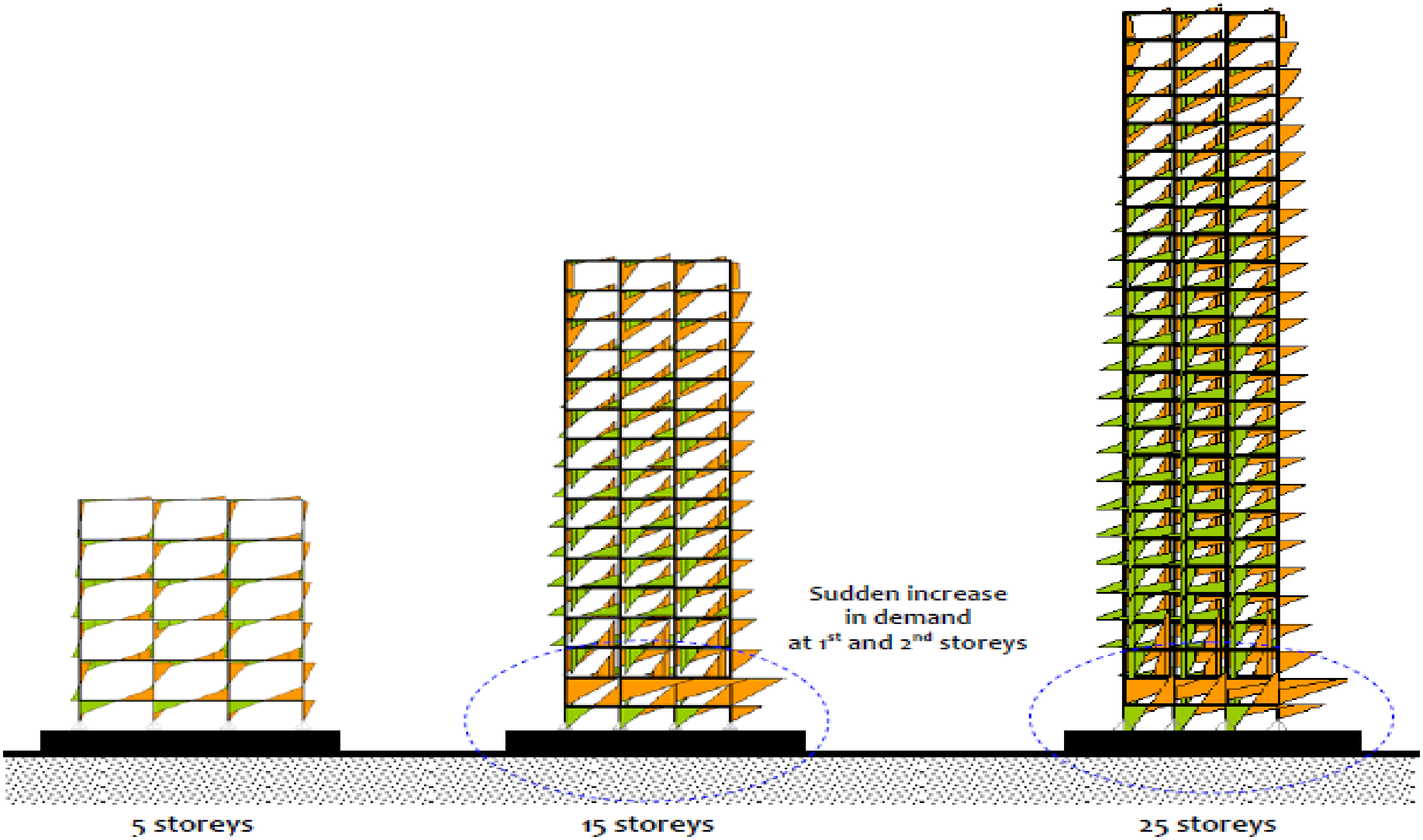
OVERALL GEOMETRY
3. AVOID LARGE SLENDERNESS RATIO

- It is not desirable to have buildings with large slenderness ratio, just like it is not good to have buildings with large projecting arms and large plan aspect ratio.
- During earthquake shaking, buildings ,ay sway laterally and excessive lateral displacement is not desirable.
- Large lateral displacements cause significant non-structural damage, structural damage and even second order *P*-Δ effects that lead to collapse of buildings.
- Design codes recommend that inter-storey drift under design earthquake forces be restricted to 0.4 percent of storey height.(As per Indian Codes)



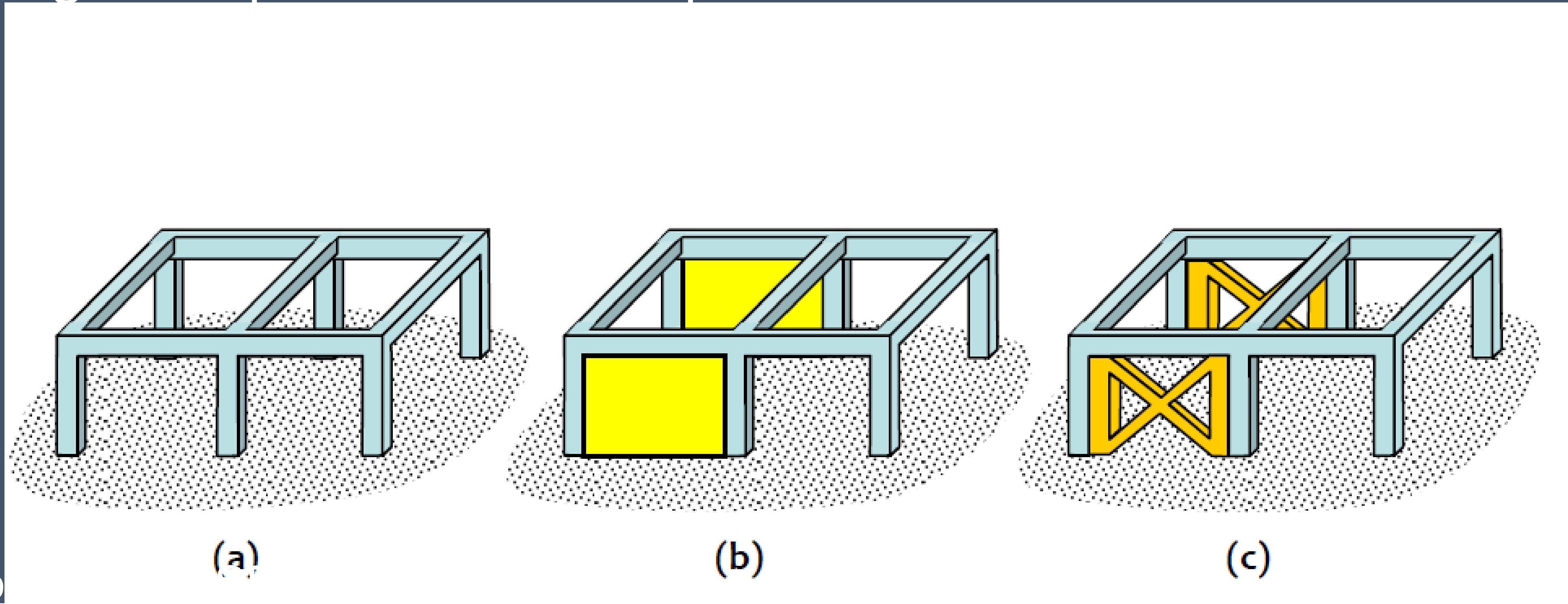
1.0
0.8
0.6
0.4
0.2
0.0
X direction
Y direction
Drift (%)
0
1
2
3
4
5
6
7
Slenderness Ratio


5 storeys
10 storeys
15 storeys
20 storeys
25 storeys


Sudden increase
in demand
at 1st and 2nd storeys
5 storeys
15 storeys
25 storeys

TYPES OF STRUCTURAL SYSTEMS

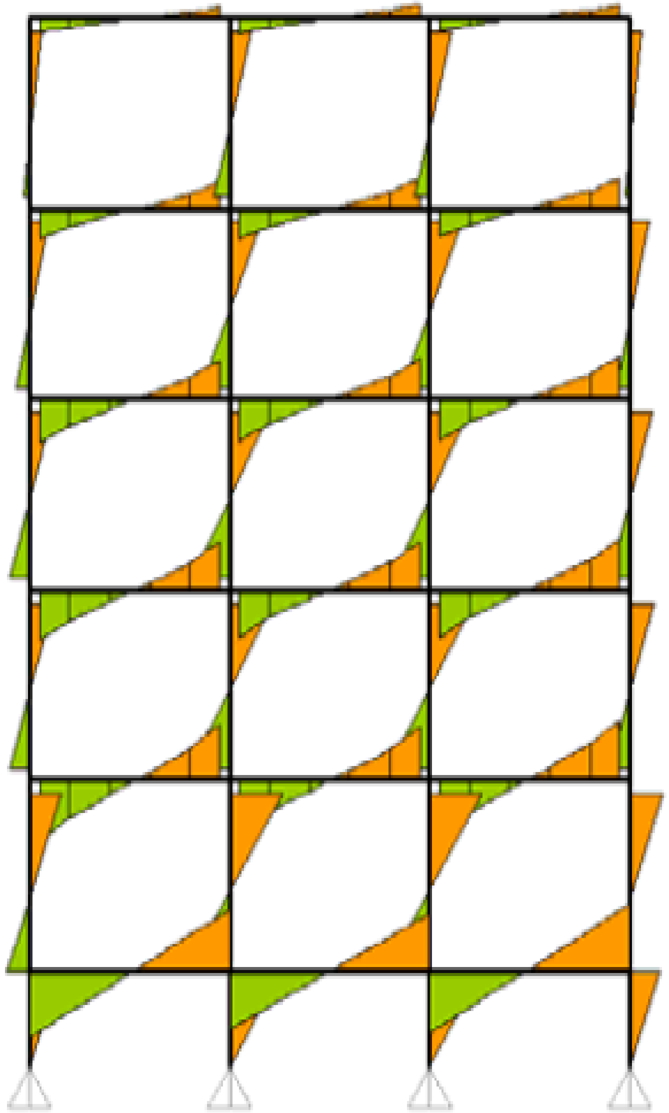
- Using an appropriate structural system is critical to good seismic performance of buildings. While *moment-frame* is the most commonly used lateral load resisting structural system, other structural systems also are commonly used like *structural walls*, *frame-wall system*, and *braced-frame system*. Sometimes, even more redundant structural systems are necessary, *e.g.*, *Tube*, *Tube-in-Tube* and *Bundled Tube systems* are required in many buildings to improve their earthquake behavior.



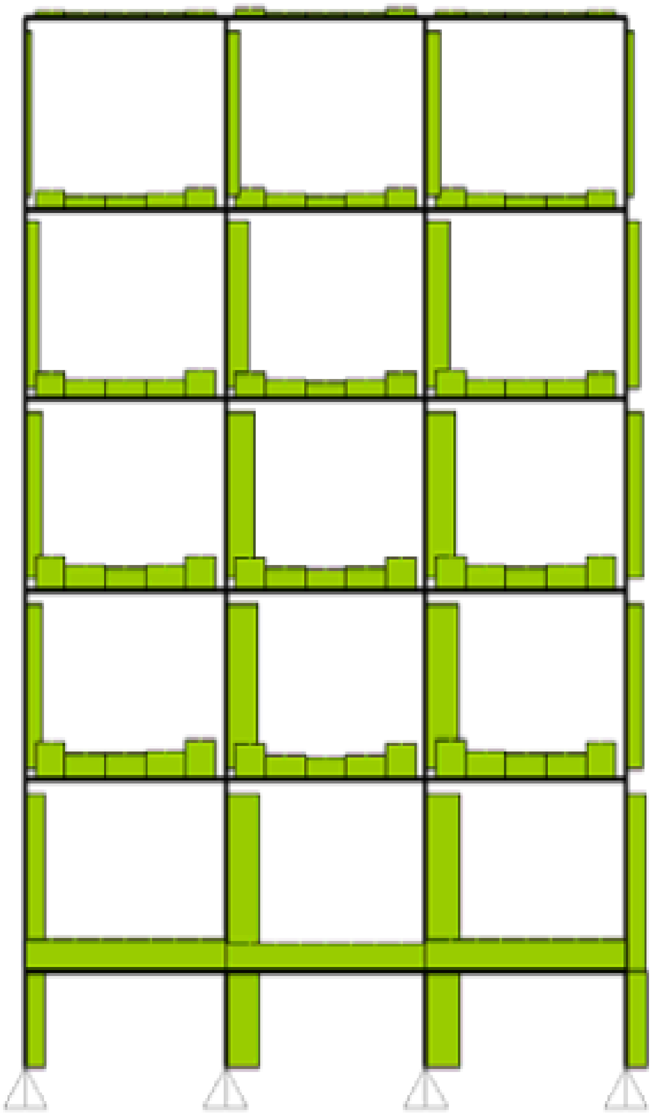
Images Pro

WHAT ARE MOMENT FRAMES BUILDING SYSTEMS ?

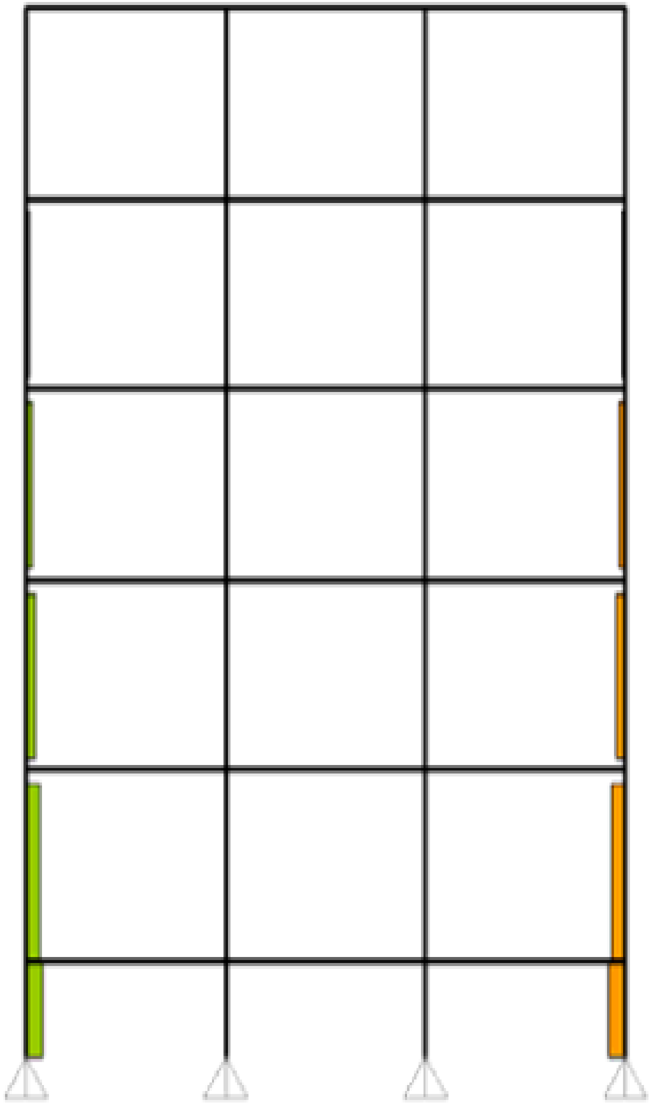
- Moment frames consist of a grid of vertical (*i.e.,* columns) and horizontal (*i.e.,* beams) members
- They resist lateral loads through axial forces, bending moment and shear force generated in both beams and columns .
- Beam and column sections should be designed as under-reinforced sections, and thereby, can be expected to undergo ductile behavior; brittle shear failure must be prevented through capacity design procedures.
- While deciding the structural configuration of the building, predominant flexural behavior in beams and columns should be facilitated.
- This can be achieved by using relatively long frame members; short beams and columns attract large forces and are susceptible to fail in a brittle manner.



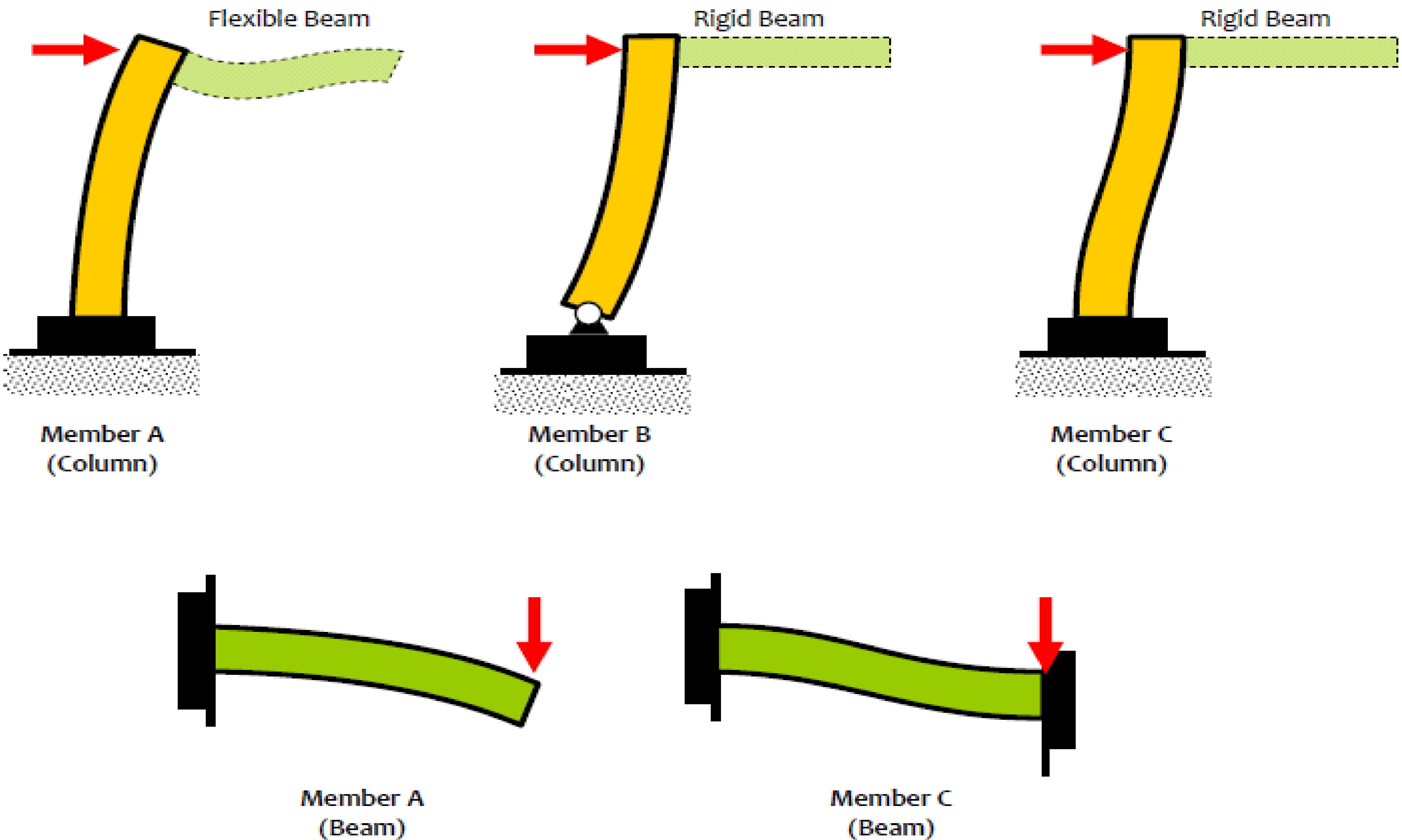
Bending Moment



Shear Force



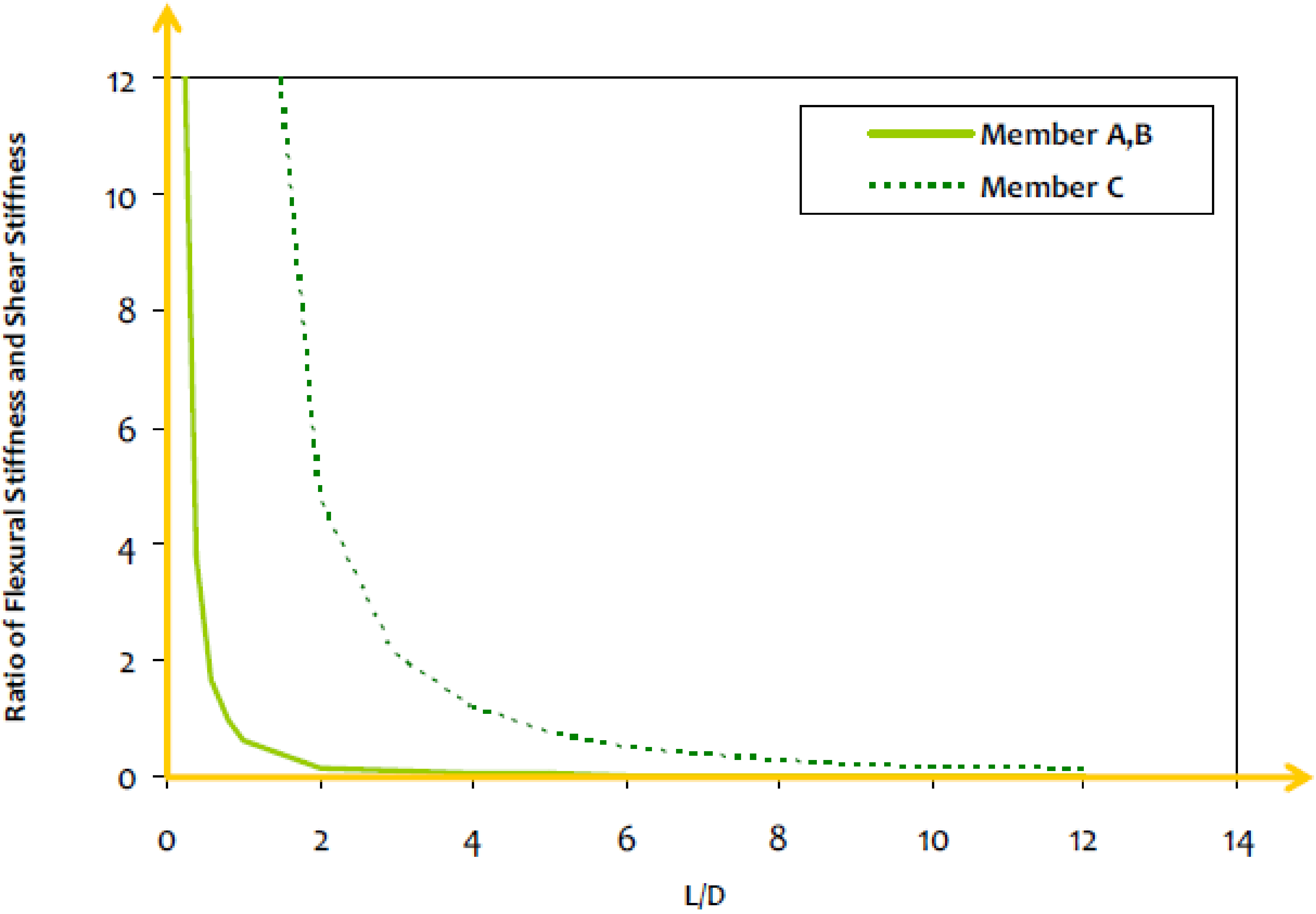
Axial Force



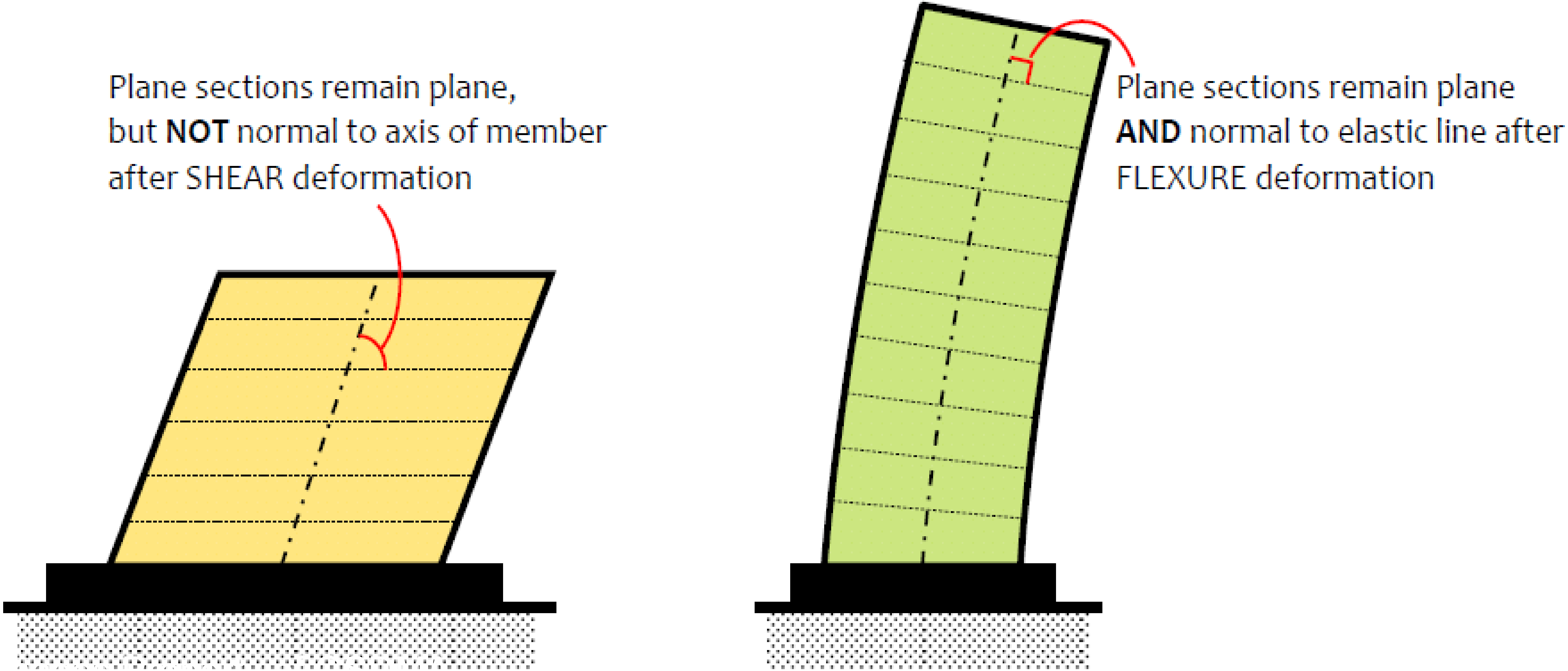
Flexible Beam
Rigid Beam
Rigid Beam
Member A
(Column)
Member B
(Column)
Member C
(Column)
Member A
(Beam)
Member C
(Beam)

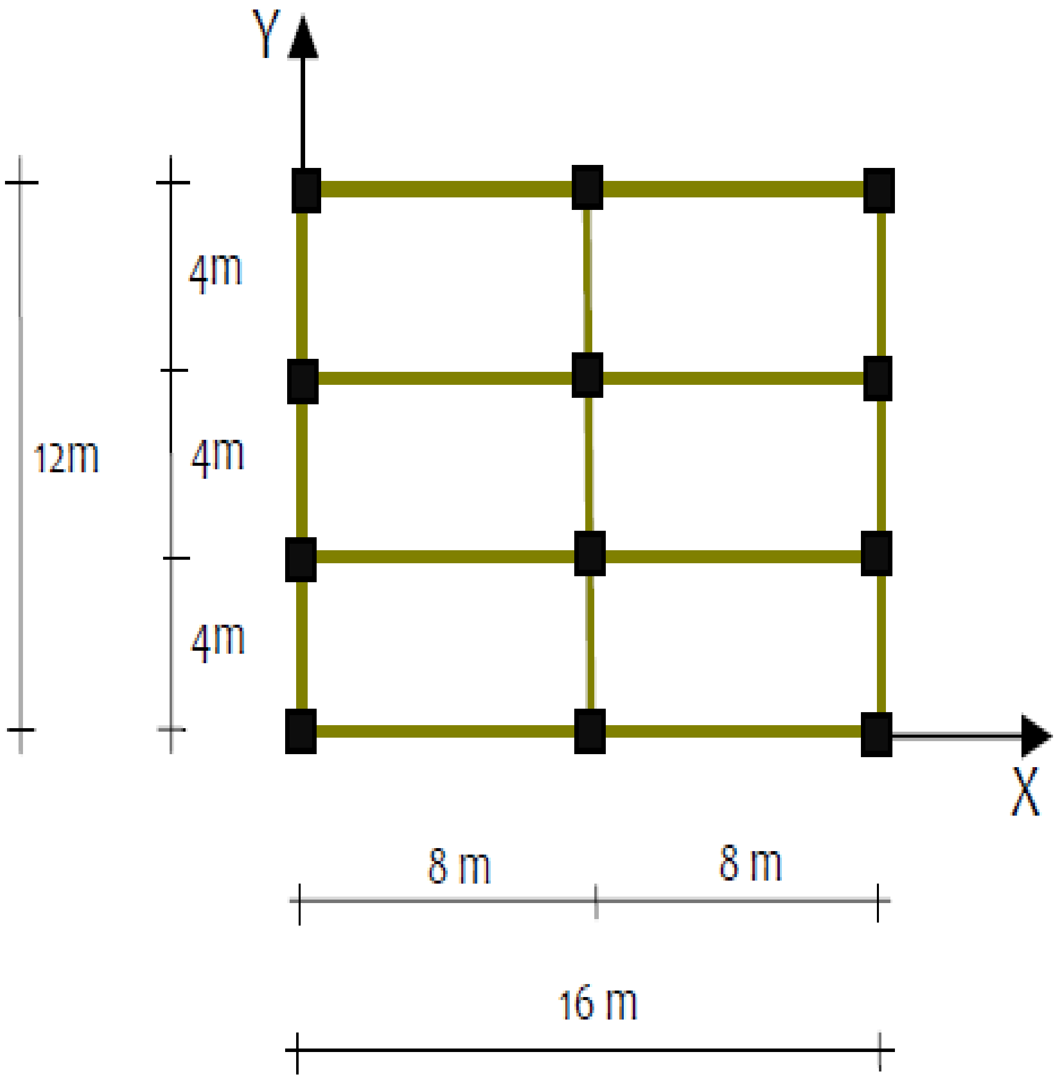
Distance between Beta and L/D ratio

- The ratio β is the ratio of pure *flexural translational stiffness* to *pure shear translational stiffness*
- With increase in *L/D* ratio, flexural stiffness of the member decreases and hence β decreases. Thus, the deformation is primarily dominated by flexural action in members with large *L/D* ratios.
- On the contrary, flexural stiffness of a member increases significantly, and hence β increases rapidly, with decrease in *L/D* ratio *below 1.0*.
- In this range (*L/D* < 1.0) the deformation is governed by shear action . Thus, load transfer mechanism changes from flexure-type (*Bernoulli's Beam type)* to shear-type (*strut and tie type)* with decrease in *L/D* ratio.

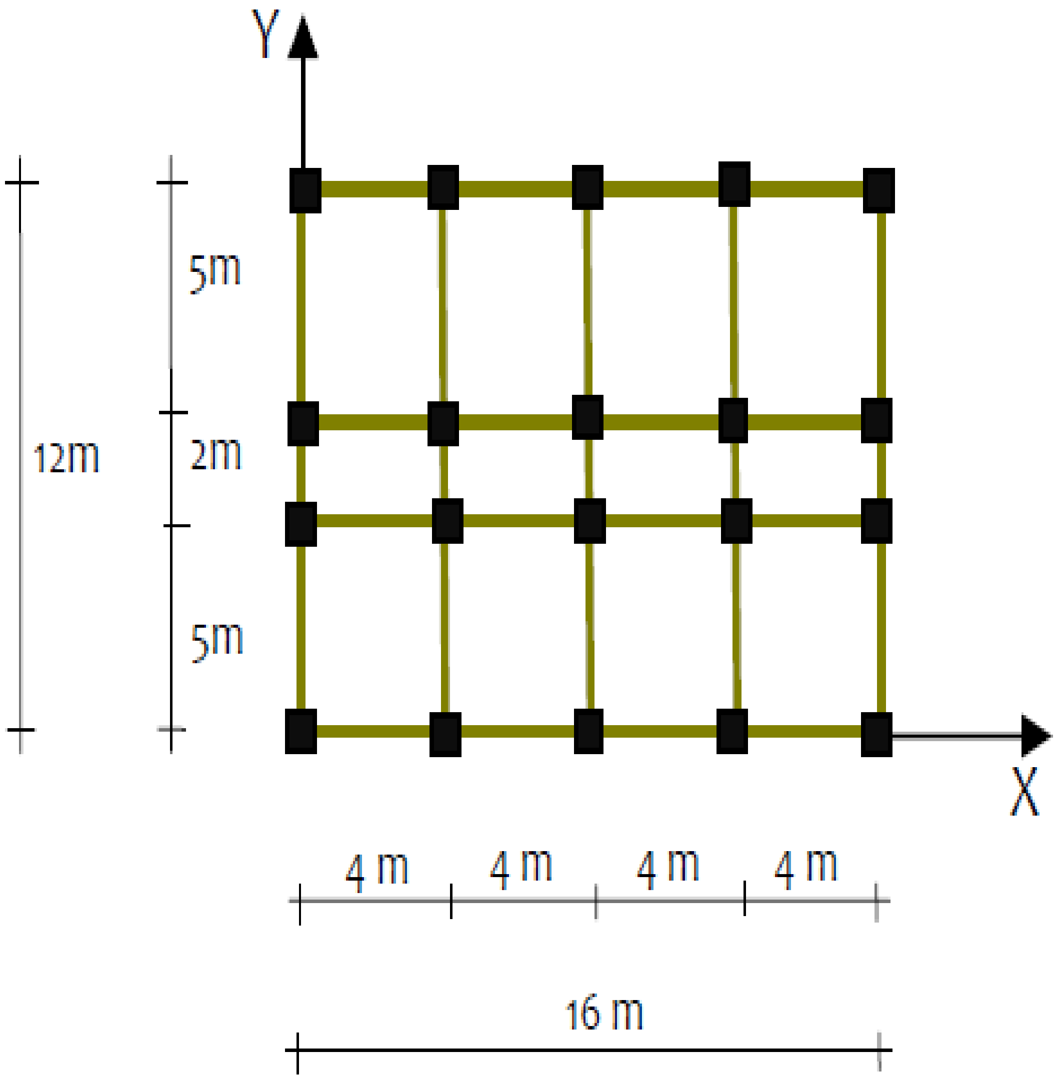


Member A,B
Member C
Ratio of Flexural Stiffness and Shear Stiffness
12
10
8
6
4
2
0
0
2
4
6
8
10
12
14
L/D

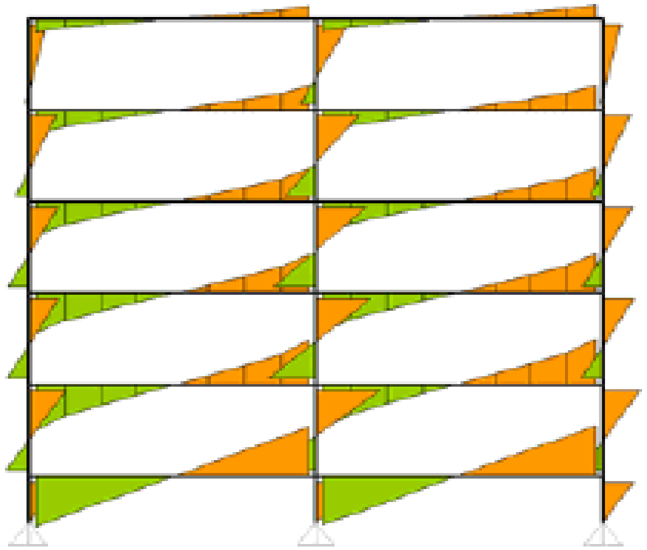

Plane sections remain plane,
but **NOT** normal to axis of member
after SHEAR deformation
Plane sections remain plane
AND normal to elastic line after
FLEXURE deformation



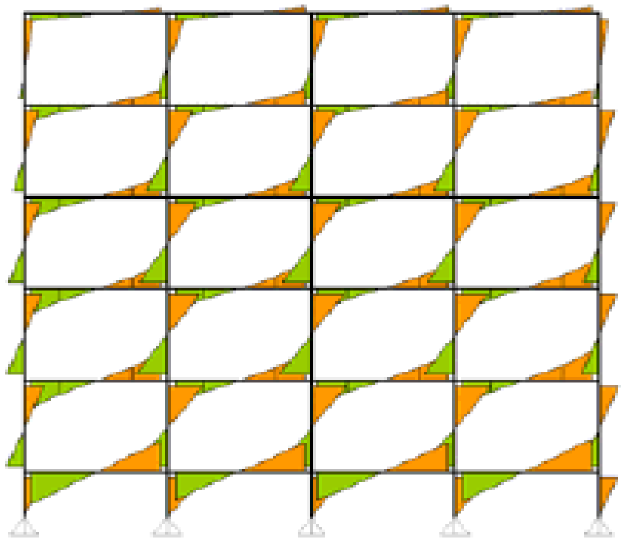
Flexural (Long) Beams in Building A

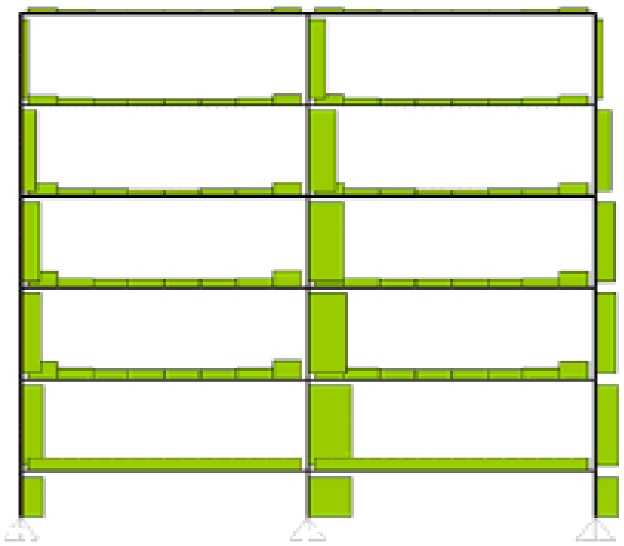


Shear (Short) Beams in Building B

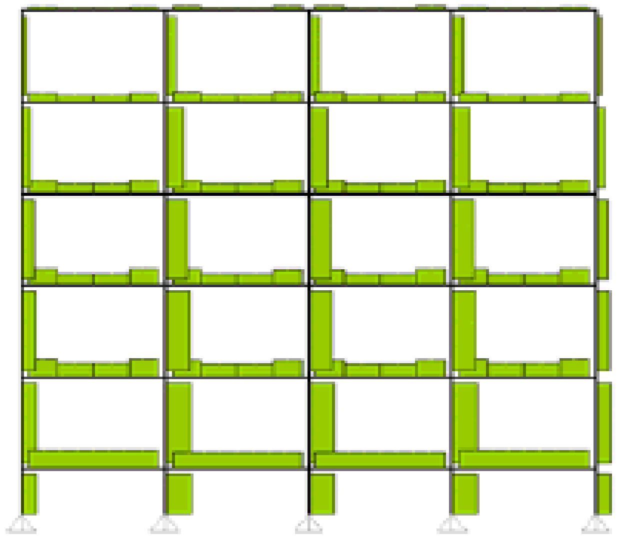


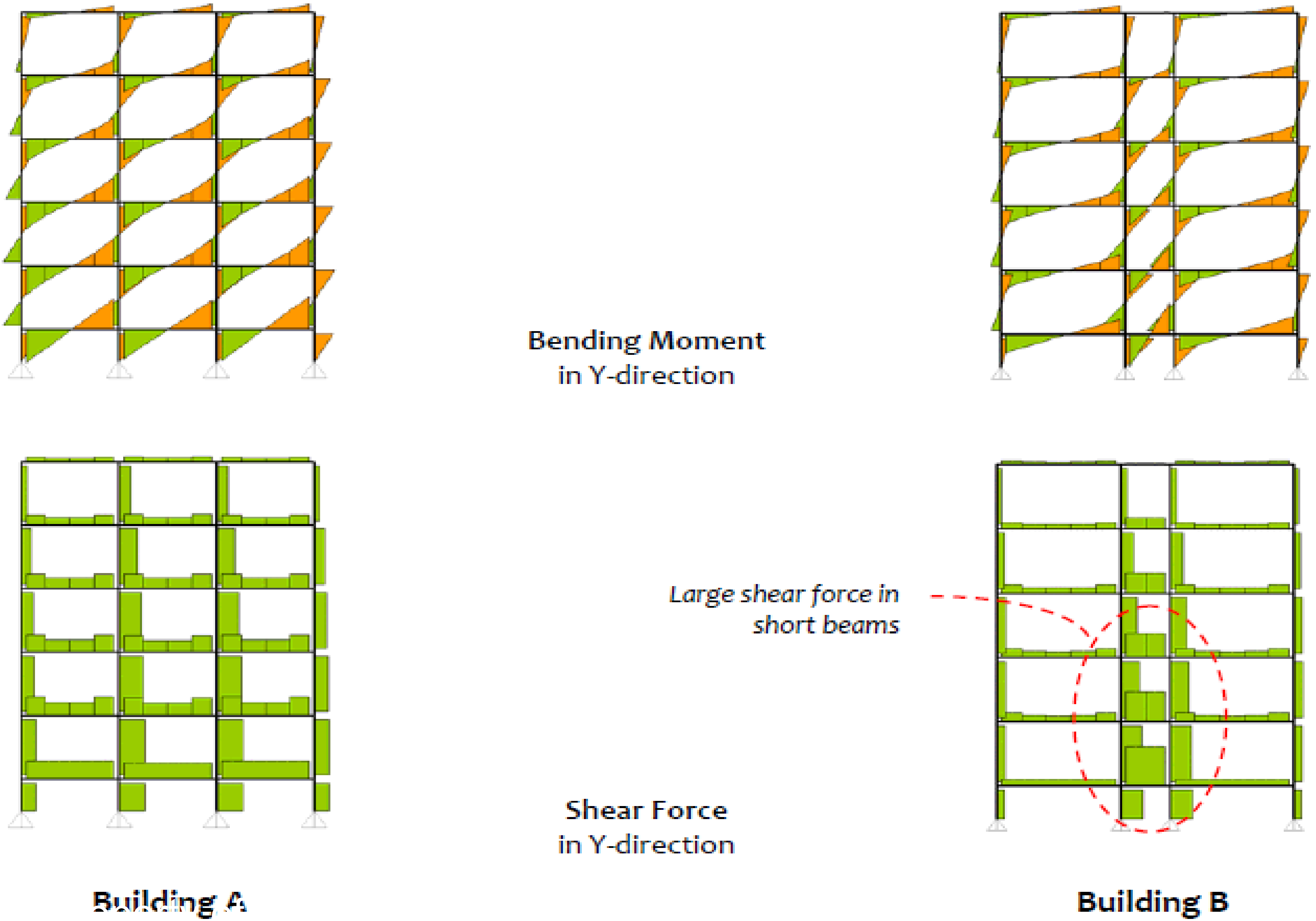
Bending Moment
in X-direction





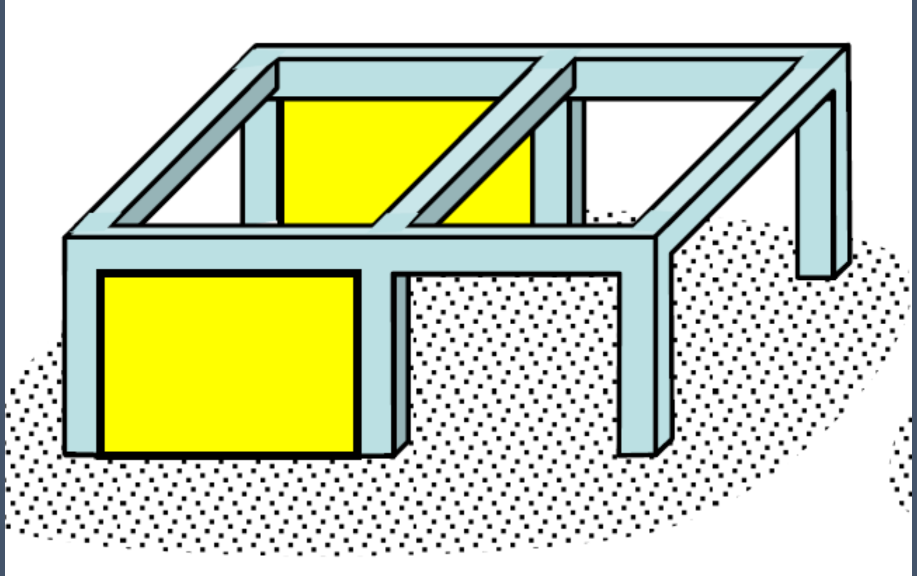
Shear Force
in X-direction




Bending Moment
in Y-direction
Large shear force in
short beams
Shear Force
in Y-direction
Building A
Building B

WHAT ARE STRUCTURAL WALL-FRAME SYSTEMS

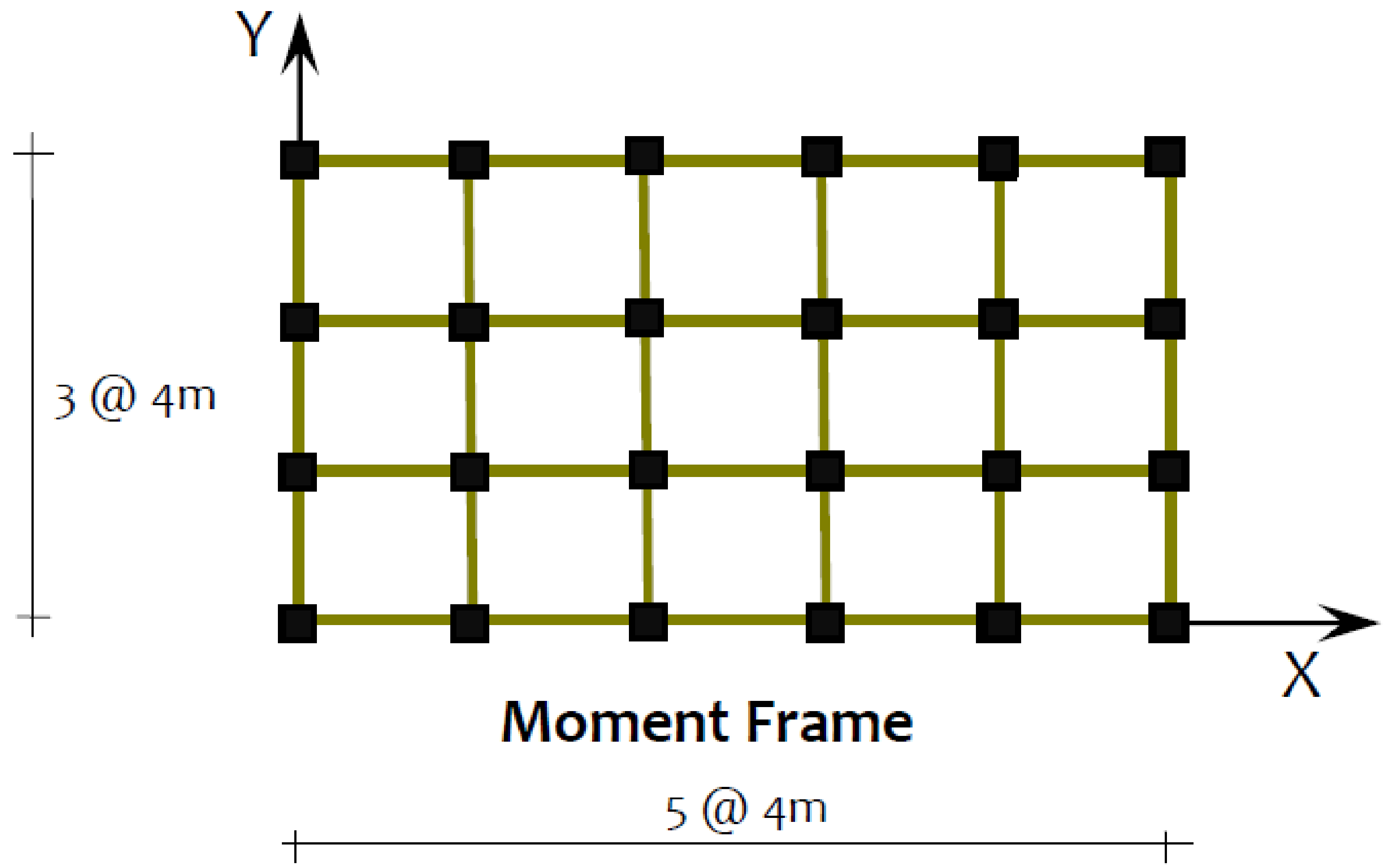
- Earthquake resistant buildings should possess, at least a minimum lateral stiffness, so that they do no swing too much during small levels of shaking.
- Moment frame buildings may not be able to offer this always. When lateral displacement is large in a building with moment frames only, *structural walls*, often commonly called *shear walls*, can be introduced to help reduce overall displacement of buildings, because these vertical plate-like structural elements have large in-plane stiffness and strength. Therefore, the structural system of the building consists of moment frames with specific bays in each direction having structural walls



WHAT ARE STRUCTURAL WALL-FRAME SYSTEMS

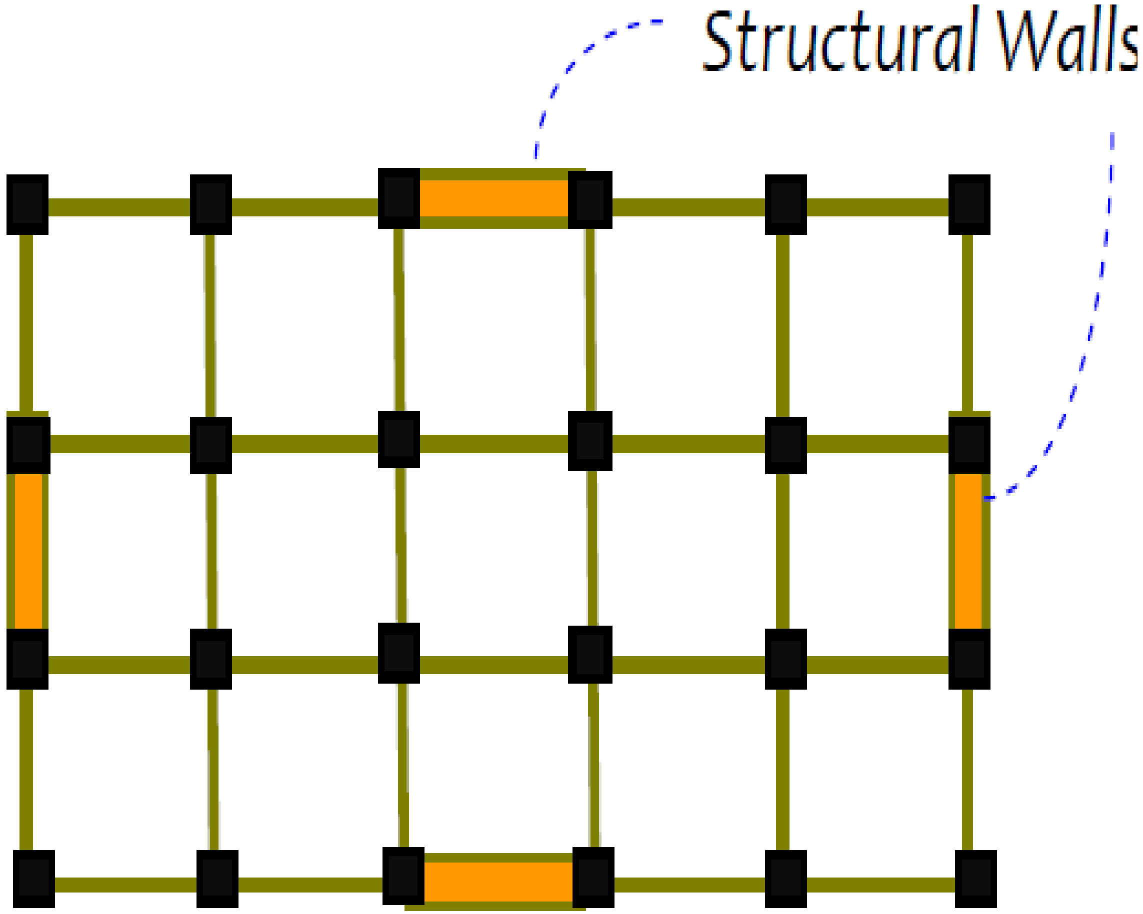
- Structural walls resist lateral forces through combined axial-flexure-shear action.
- Structural walls help reduce shear and moment demands on beams and columns in the moment frames of the building, when provided along with moment frames as lateral load resisting system.
- Structural walls should be provided throughout the height of buildings for best earthquake performance.
- Structural walls offer best performance when rested on hard soil strata.

WHAT SHOULD BE THEIR LOCATION IN A BUILDING ?

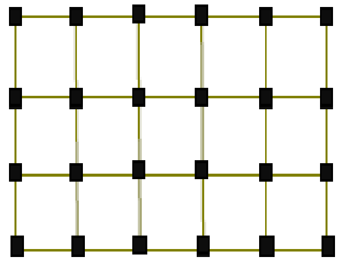
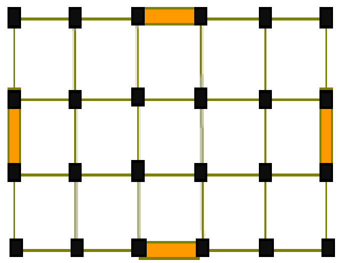


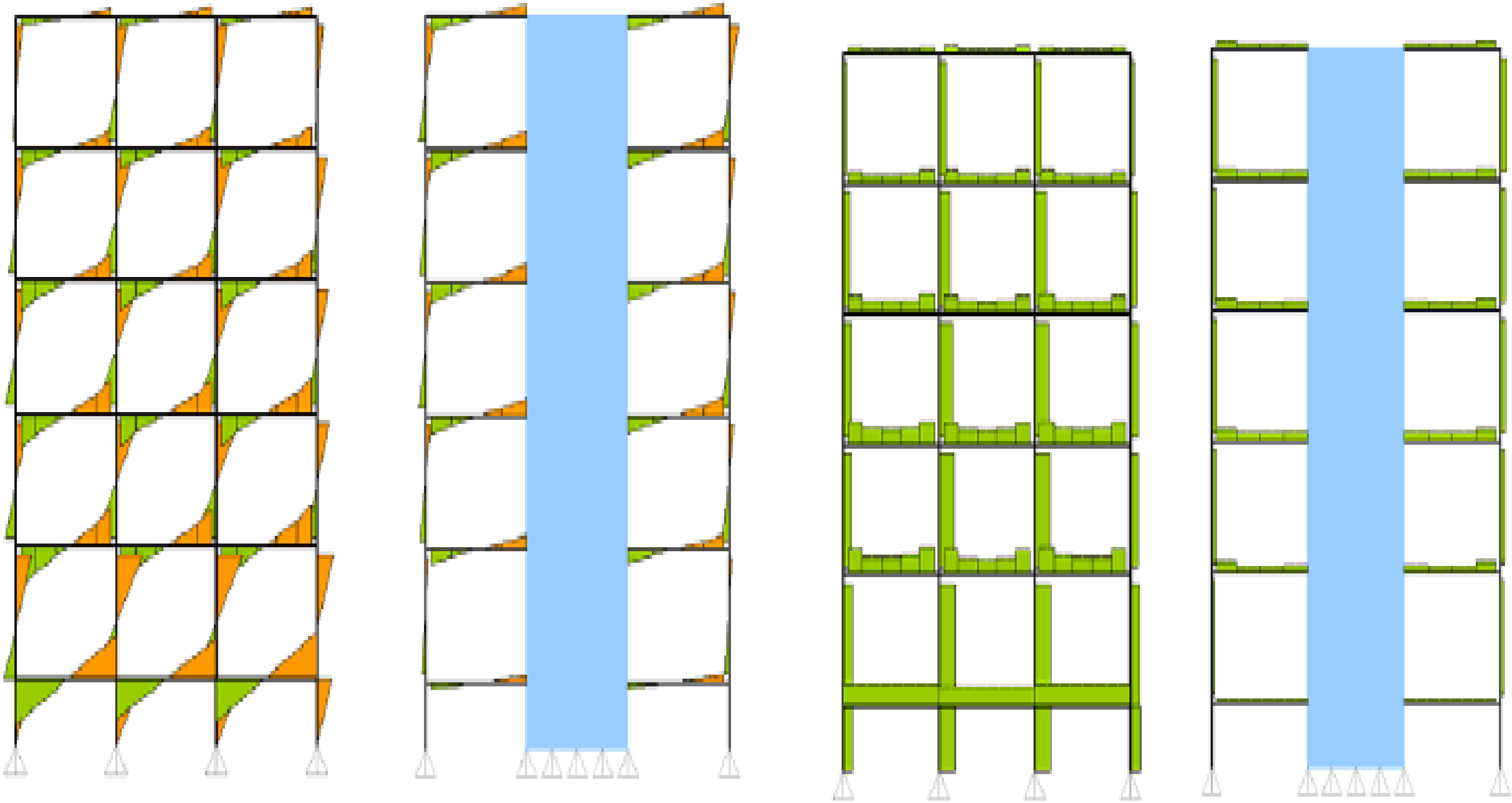
Moment Frame

OPTION 1-STRUCTURAL WALLS AT PERIPHERY



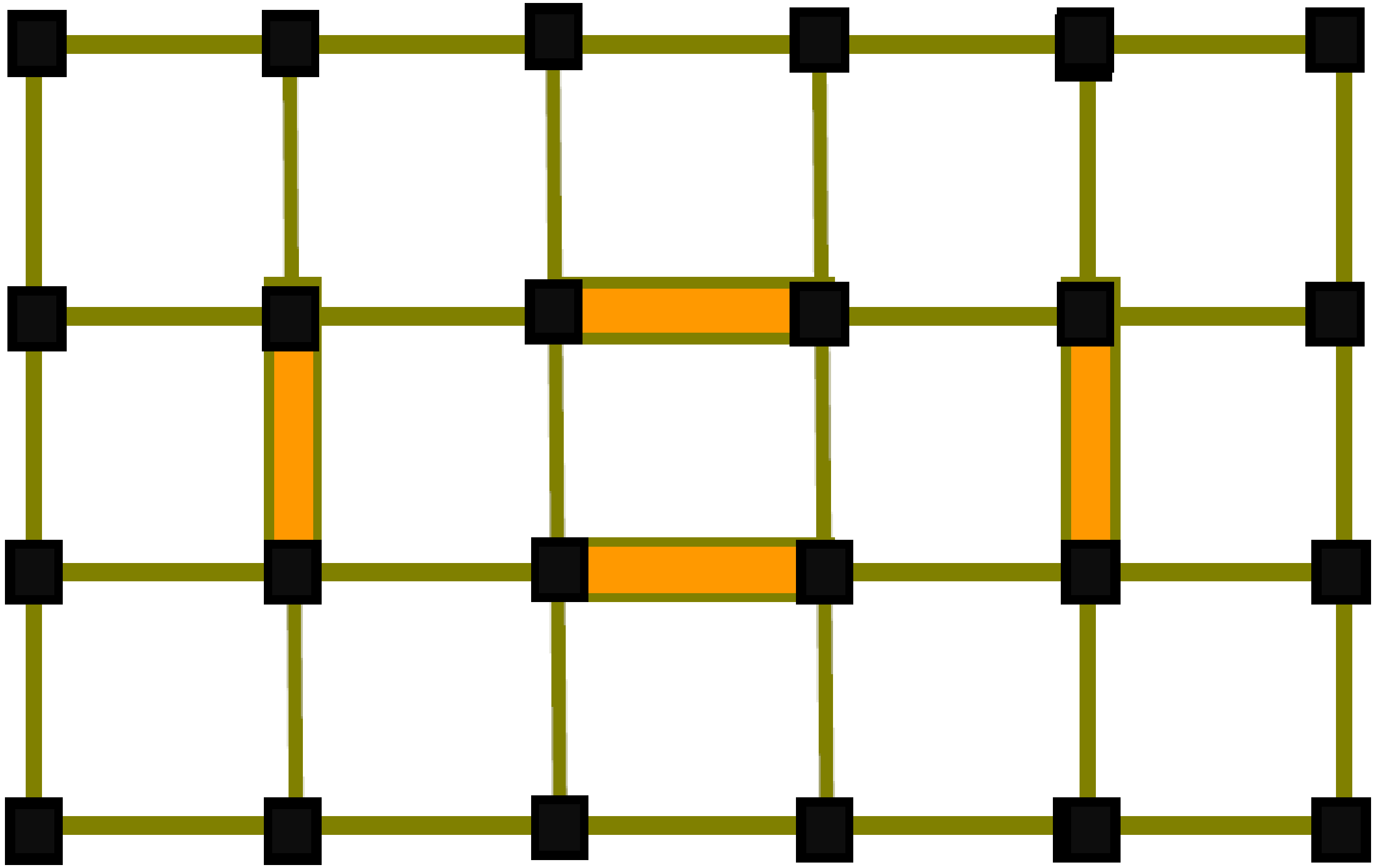
Structural Wall at Periphery

Case		
Mode 1	Y translation (0.74s)	Y translation (0.48s)
Mode 2	X translation (0.72s)	X translation (0.47s)
Mode 3	*Torsion* (0.65s)	*Torsion* (0.33s)
Roof displacement in X direction	21.6 mm	11.9 mm
Roof displacement in Y direction	23.4 mm	12.4 mm

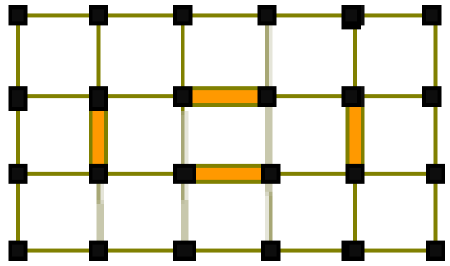


Bending Moment Shear Force

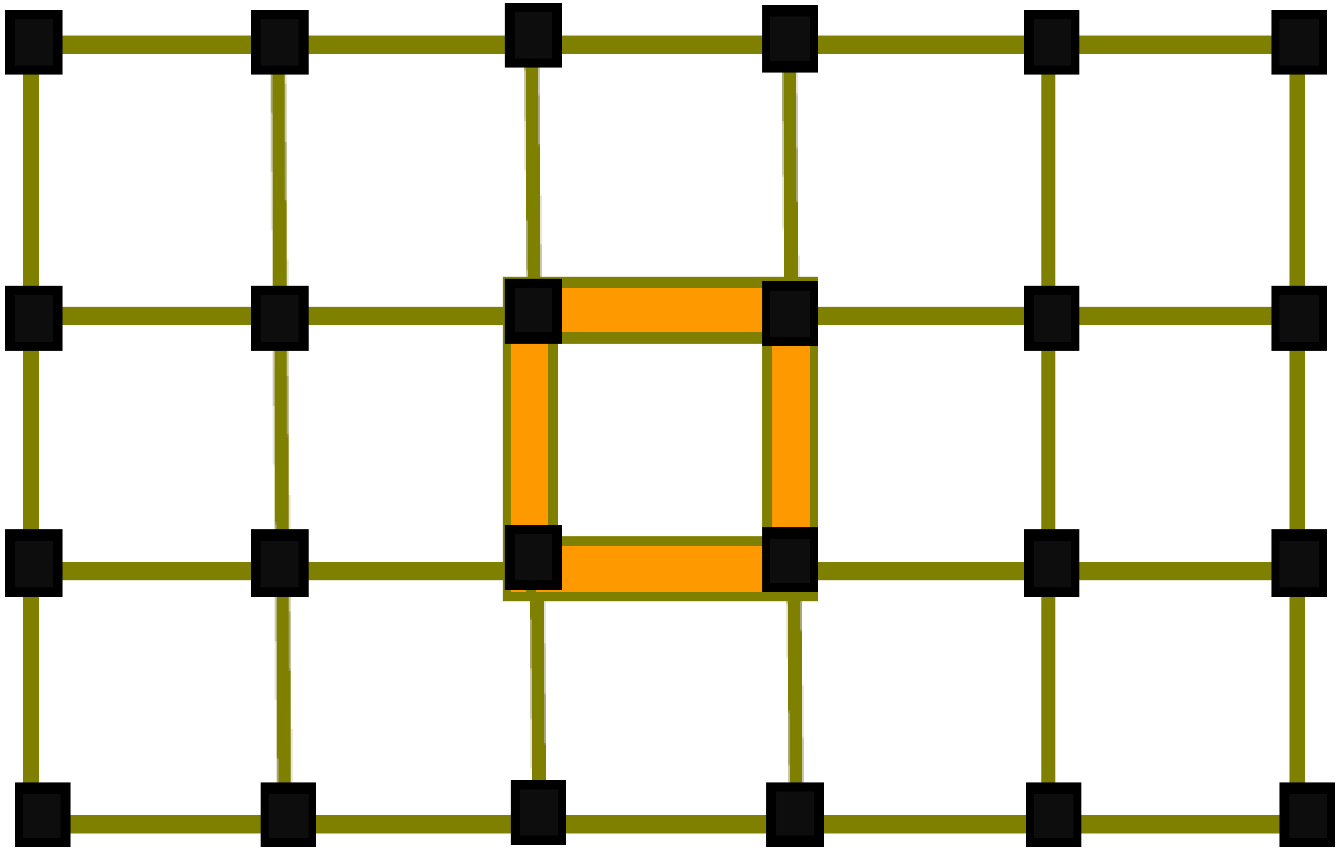
OPTION – 2 STRUCTURAL WALLS IN INNER BAYS



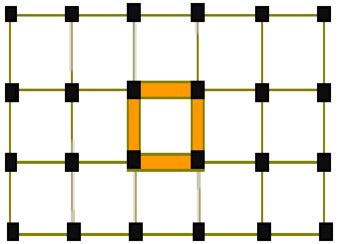
Structural Wall in Inner Bays

Case	
Mode 1	X translation (0.48s)
Mode 2	Y translation (0.47s)
Mode 3	*Torsion* (0.47s)
Roof displacement in X direction	11.5 mm
Roof displacement in Y direction	10.9 mm

OPTION – 3 STRUCTURAL WALLS IN CORE

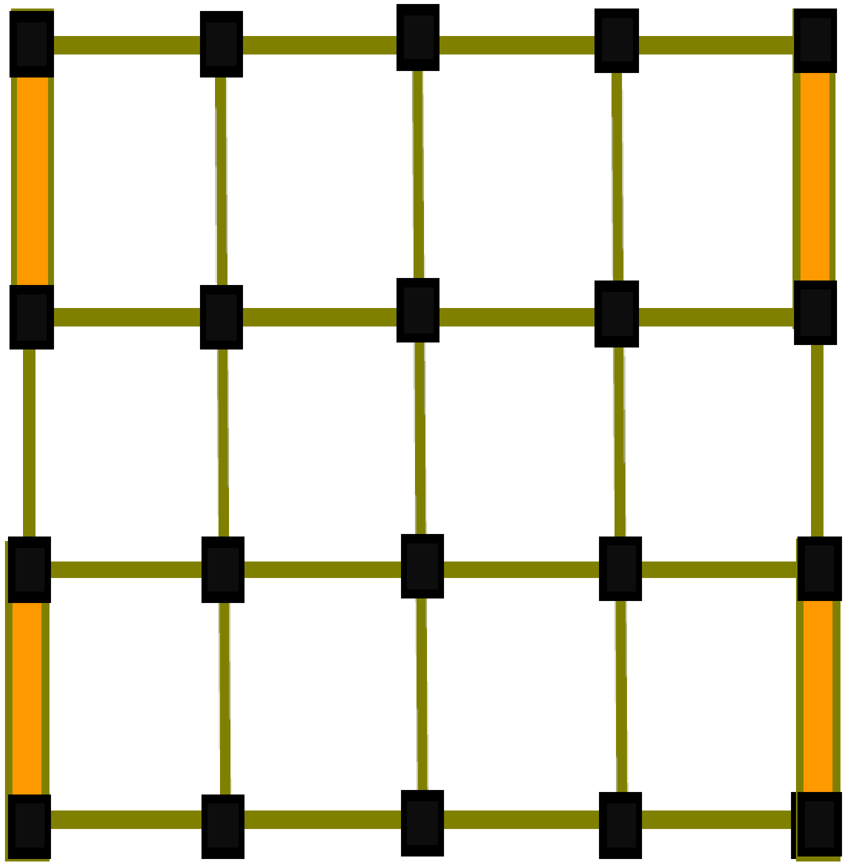


Structural Wall Core at Center

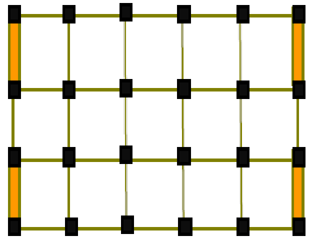
Case	
Mode 1	Torsion (0.37s)
Mode 2	Y translation (0.34s)
Mode 3	X translation (0.33s)
Roof displacement in X direction	5.9 mm
Roof displacement in Y direction	6.0 mm

OPTION -4 TWO SEPARATE STRUCTURAL WALLS

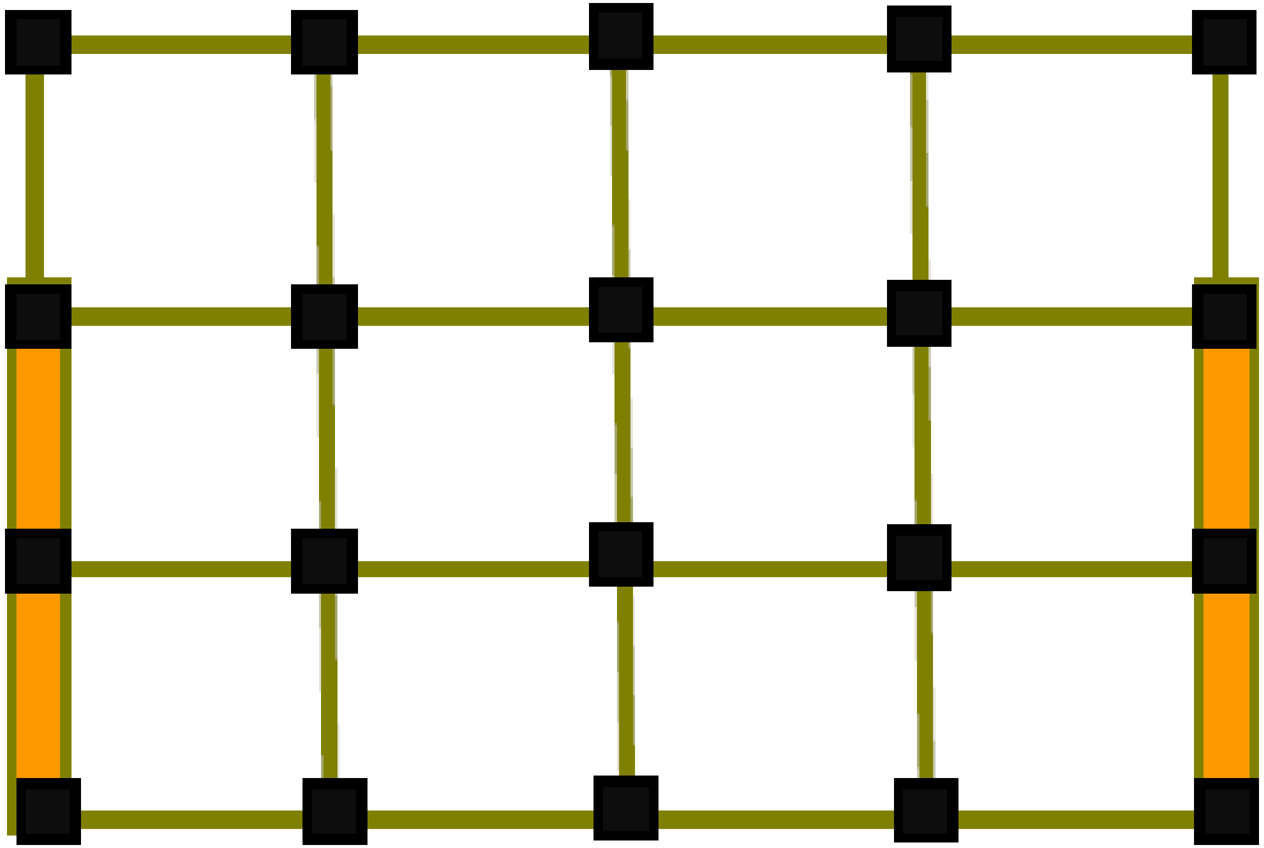
https://www.udemy.com/etabscourse/

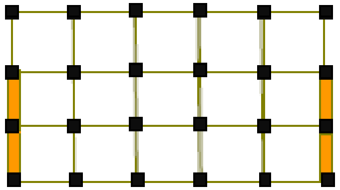


Two Separate Structural Walls

	
Mode 1	X translation (0.91s)
Mode 2	Y translation (0.38s)
Mode 3	Torsion (0.30s)
Roof displacement in Y direction	8.1 mm
Base Shear	759 kN

OPTION – 5 COMBINED LONG STRUCTURAL WALLS

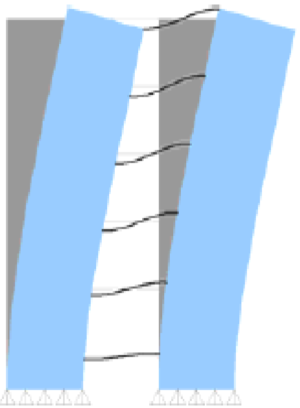


	
Mode 1	X translation (0.89s)
Mode 2	Y translation (0.27s)
Mode 3	Torsion (0.25s)
Roof displacement in Y directio	3.4 mm
Base Shear	784 kN

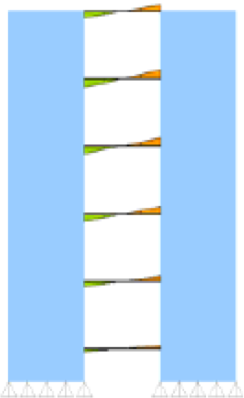
Combined Structural Walls

https://www.udemy.com/etabscourse/

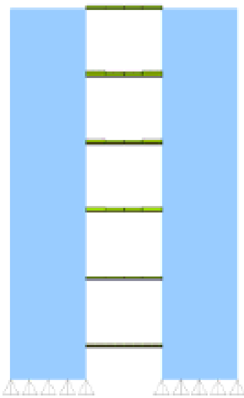
CONCLUSION -LONG STRUCTURAL WALLS ARE MORE EFFICIENT THAN A NUMBER OF SHORT ONES



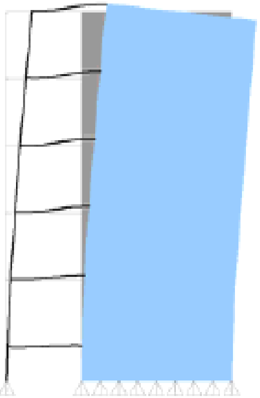
Deformation Profile



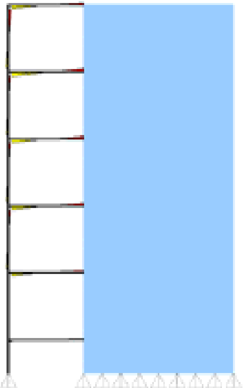
Bending Moment



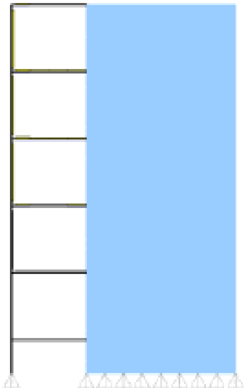
Shear Force



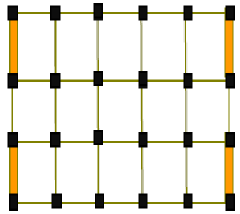
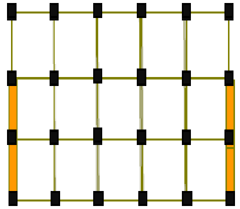
Deformation Profile



Bending Moment

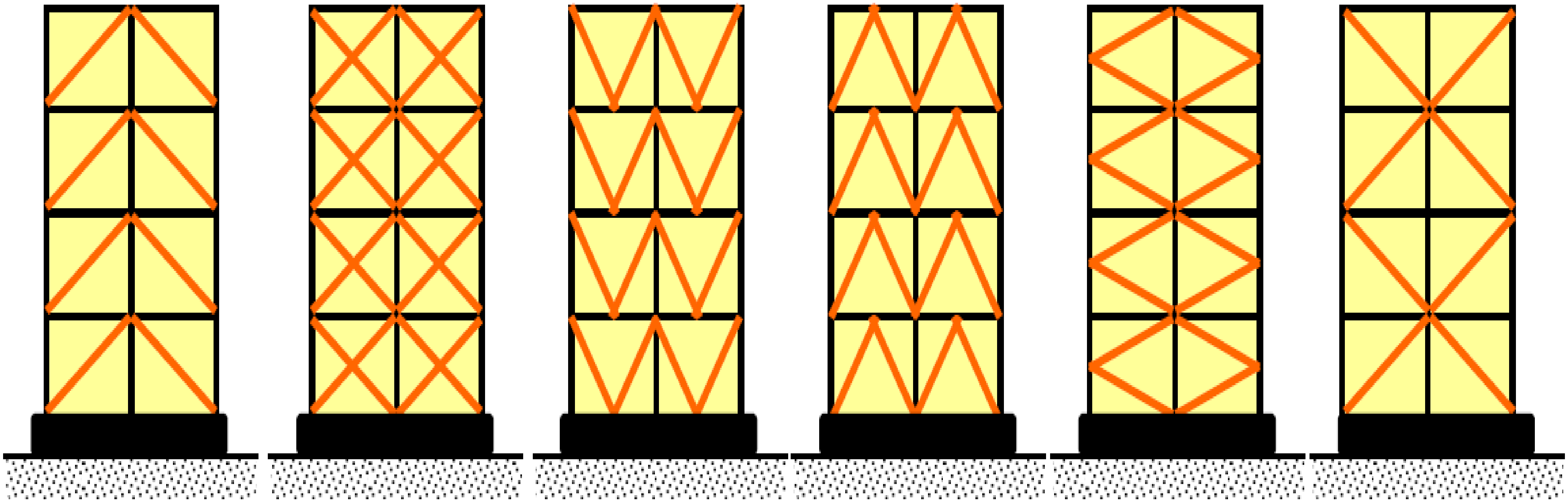


Shear Force

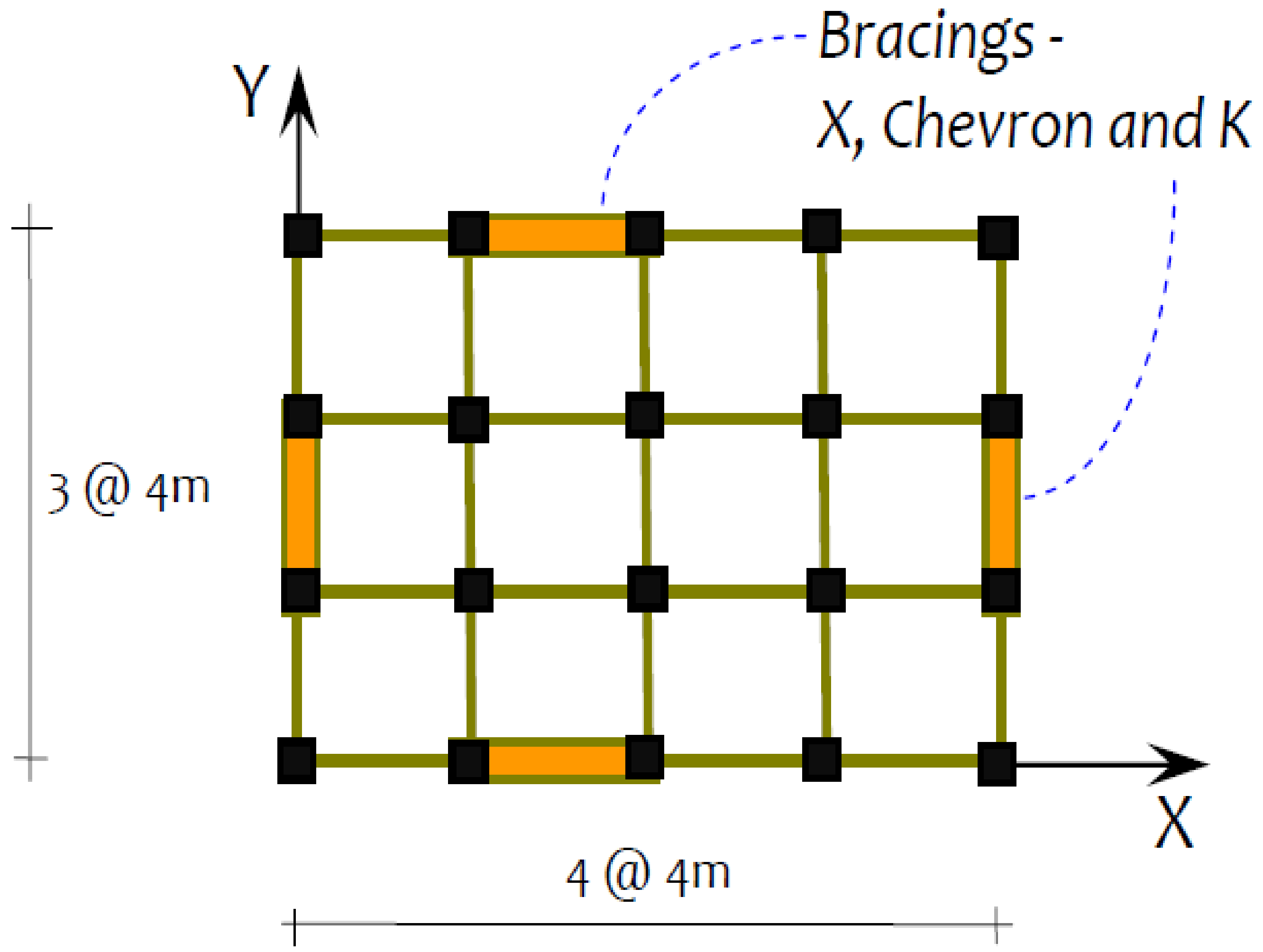
		
Mode 1	X translation (0.91s)	X translation (0.89s)
Mode 2	Y translation (0.38s)	Y translation (0.27s)
Mode 3	Torsion (0.30s)	Torsion (0.25s)
Roof displacement in Y direction	8.1 mm	3.4 mm
Base Shear	759 kN	784 kN

WHAT ARE BRACED FRAME SYSTEMS

- This structural system consists of moment frames with specific bays provided with braces throughout the height of the building.
- Braces are provided in both plan directions such that no twisting is induced in the building owing to unsymmetrical stiffness in plan.
- Braces help in reducing overall lateral displacement of buildings, and in reducing bending moment and shear force demands on beams and columns in buildings.
- The earthquake force is transferred as axial tensile and compressive force in the brace members.
- Various types of bracings can be used including global bracing along the building height.
- Consider the five-storey benchmark building with three types of local bracing systems namely, *X-*, *Chevron* and *K-bracing* systems. X- and Chevron braces effectively reduce bending moment, shear force and axial force demands on the beams and columns of the original frame and are commonly used.
- But, K-braces increases shear demand on columns and can cause brittle shear failure. Thus, some design codes prohibit use of K-braces in earthquake resistant design.

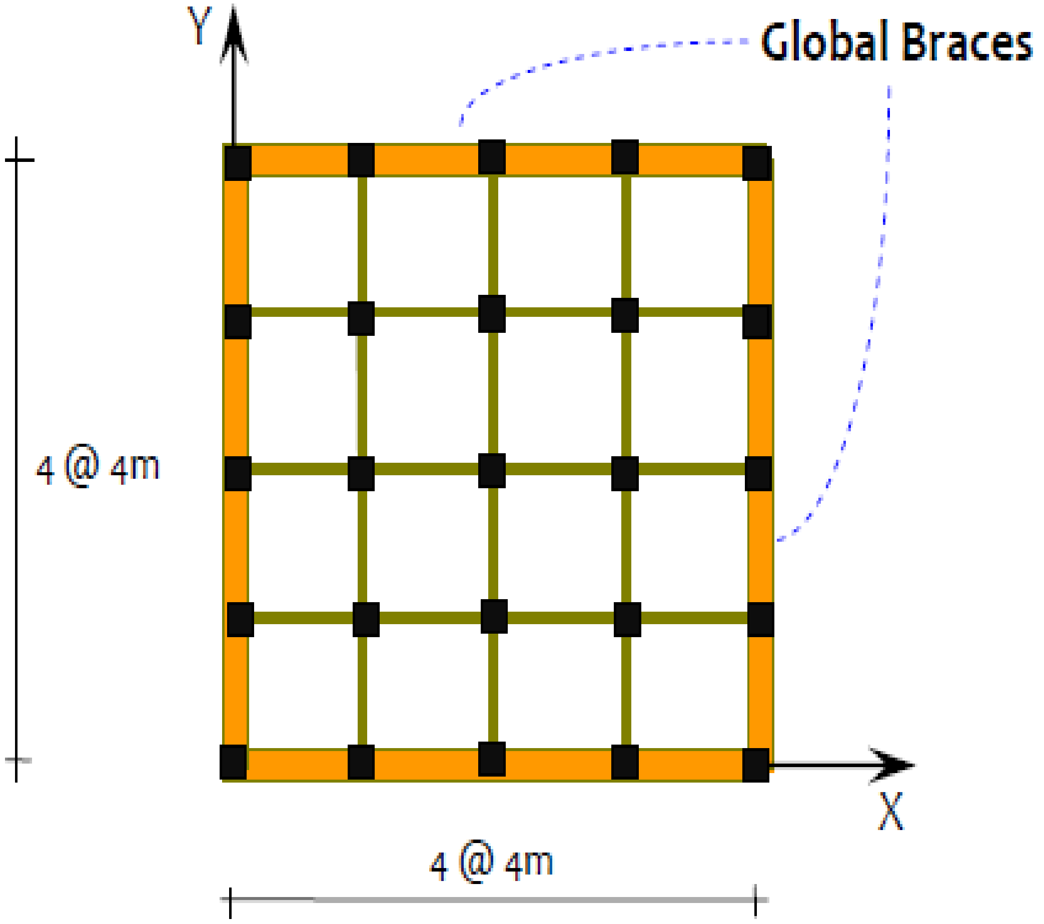


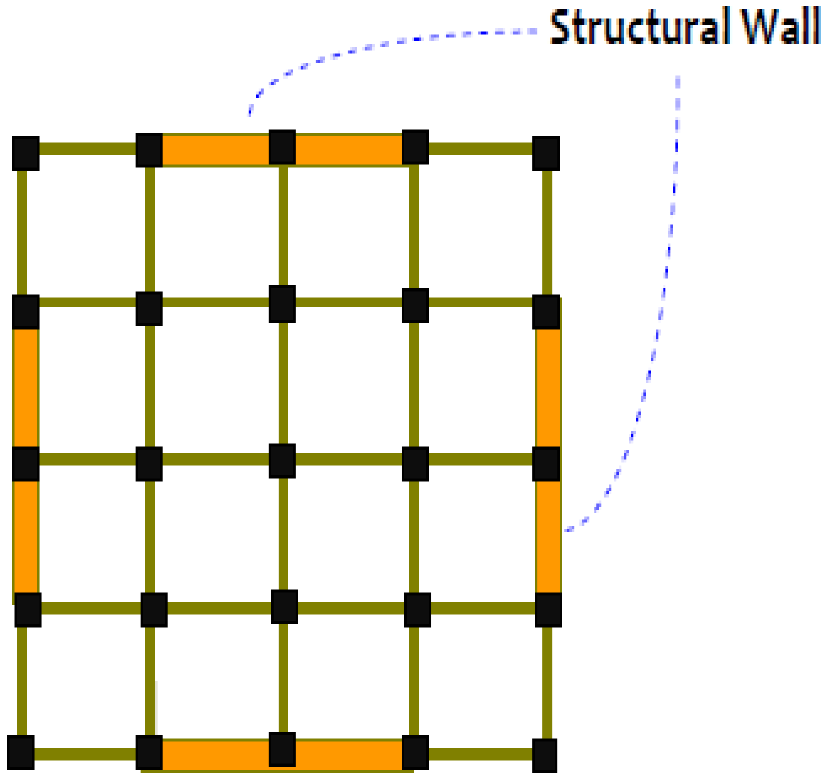
Diagonal Bracing
X Bracing
V Bracing
Chevron Bracing
K Bracing
Global Bracing



Bracings -
X, Chevron and K
Y
X
3 @ 4m
4 @ 4m

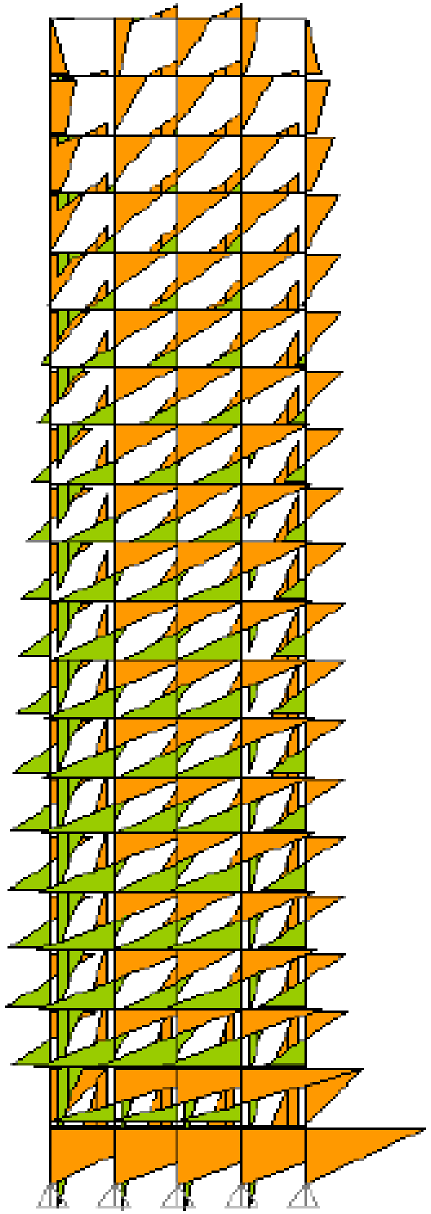
WHY BRACINGS ARE USED AND WHAT IS THEIR IMPACT ON STRUCTURAL FORCES ?



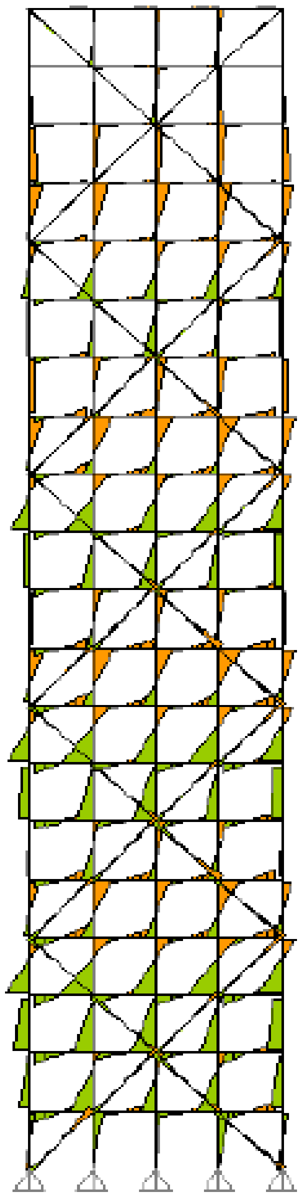


Images Property of GSDMA

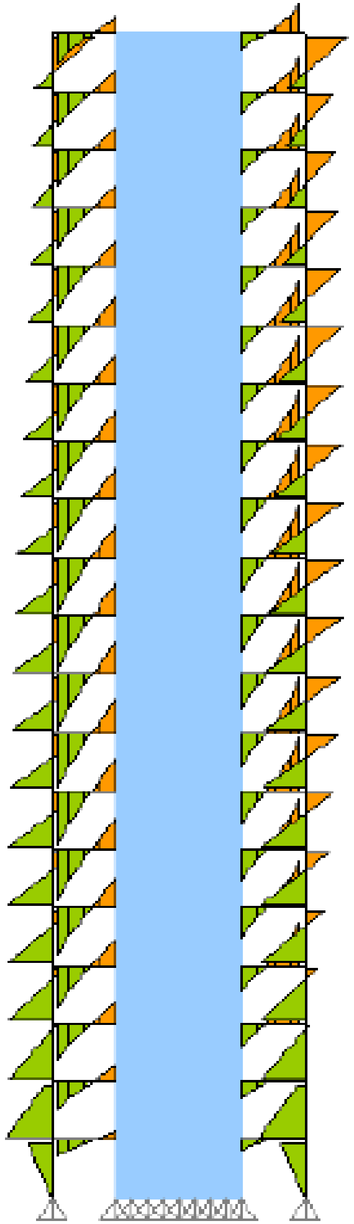
BENDING MOMENTS PROFILE IN VARIOUS STRUCTURAL SYSTEMS



Moment Frame Only

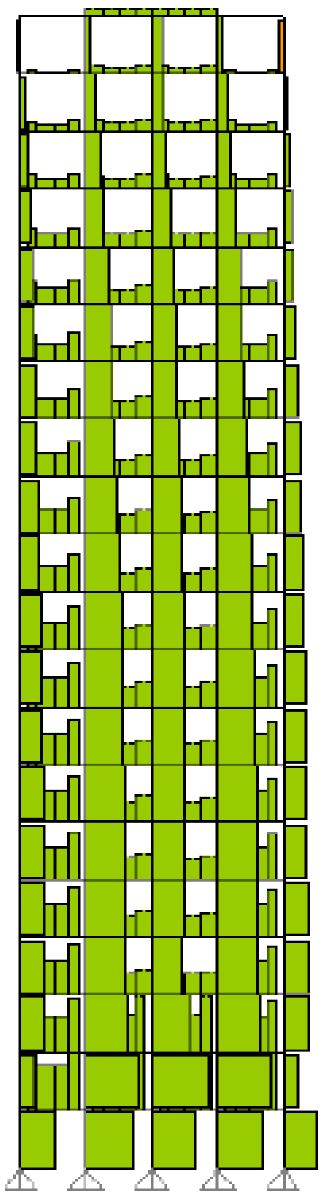


Global Brace

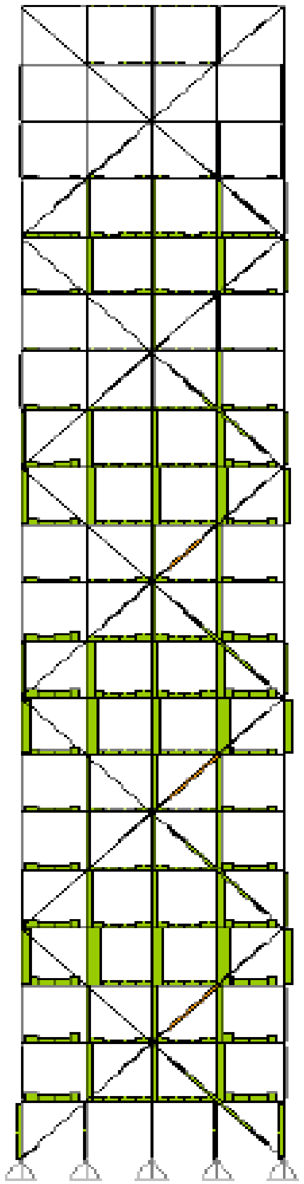


Structural Wall

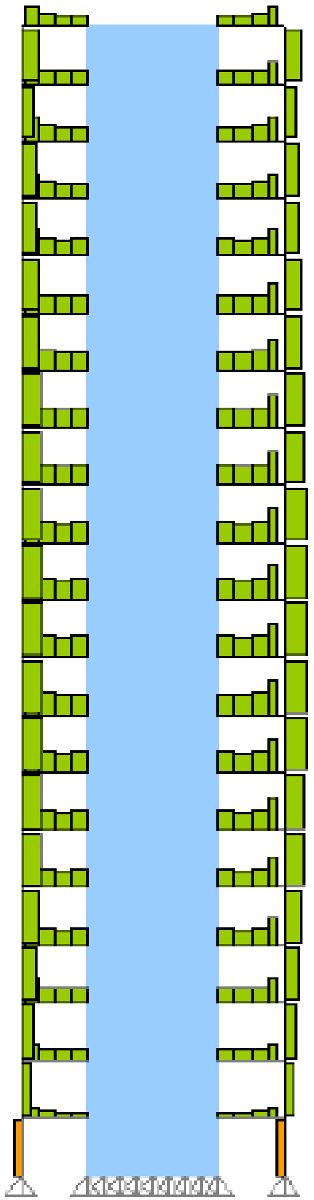
SHEAR FORCE PROFILE IN VARIOUS STRUCTURAL SYSTEMS



Moment Frame Only

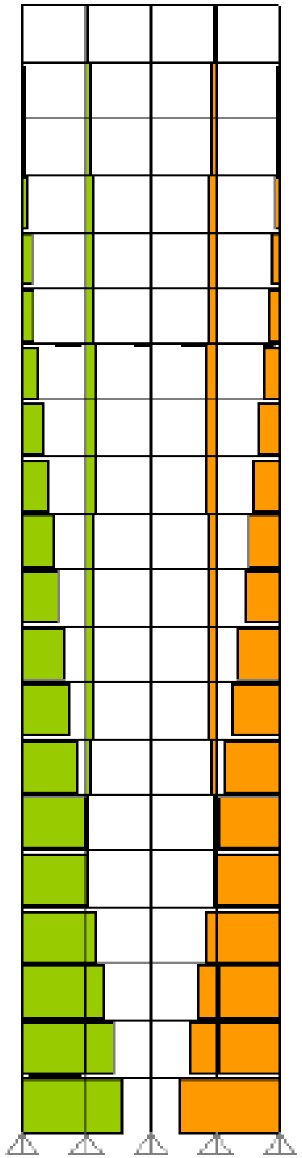


Global Brace

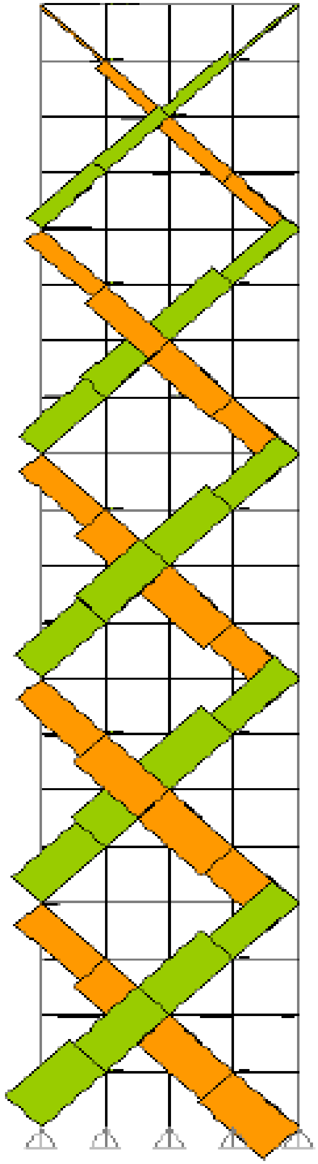


Structural Wall

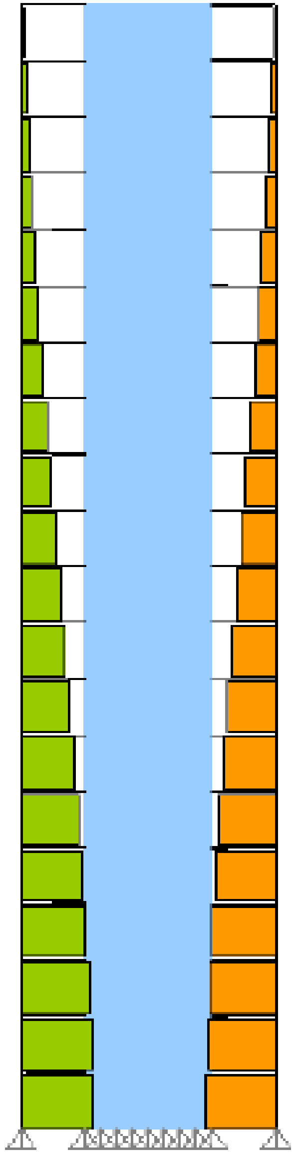
AXIAL FORCE PROFILE IN VARIOUS STRUCTURAL SYSTEMS



Moment Frame Only

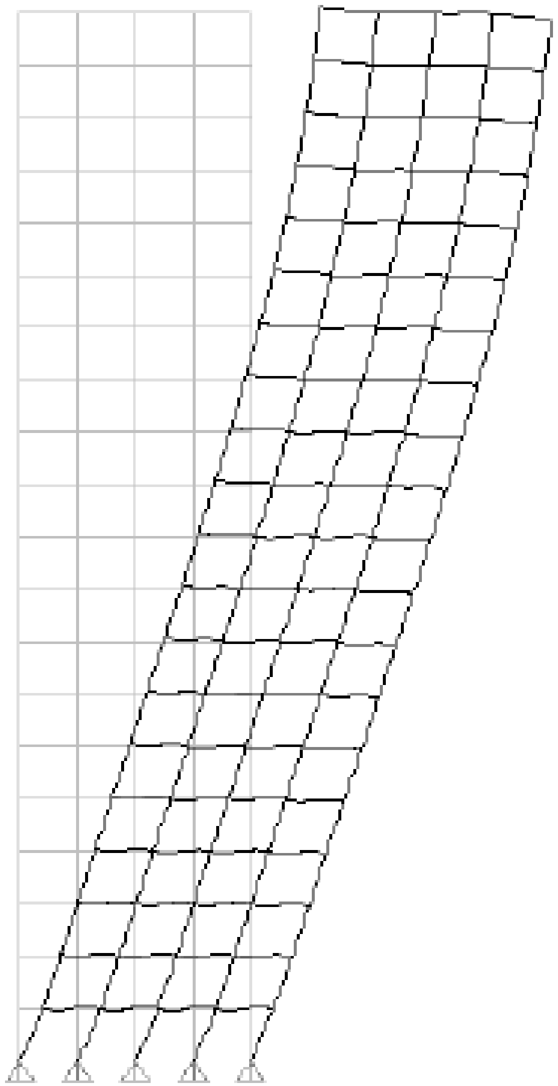


Global Brace

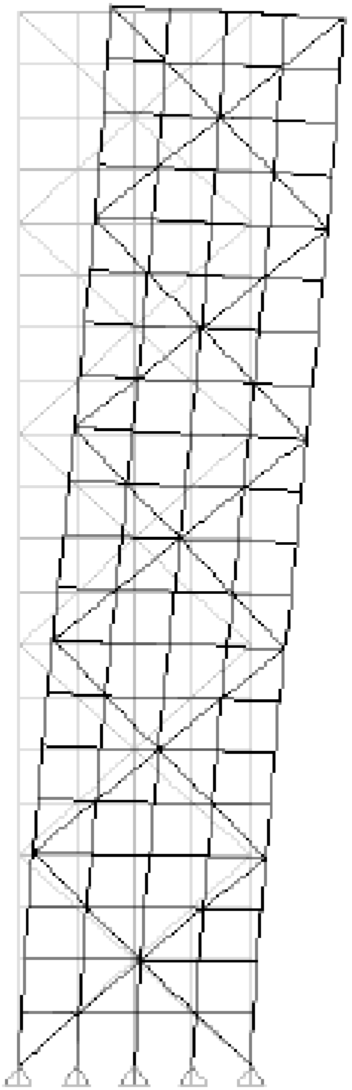


Structural Wall

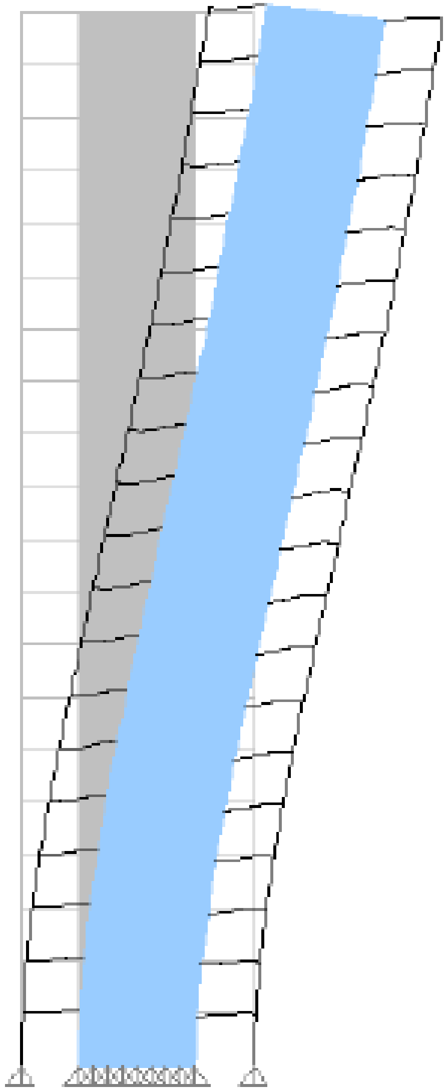
DISPLACEMENT PROFILE IN VARIOUS STRUCTURAL SYSTEMS



Moment Frame Only



Global Brace

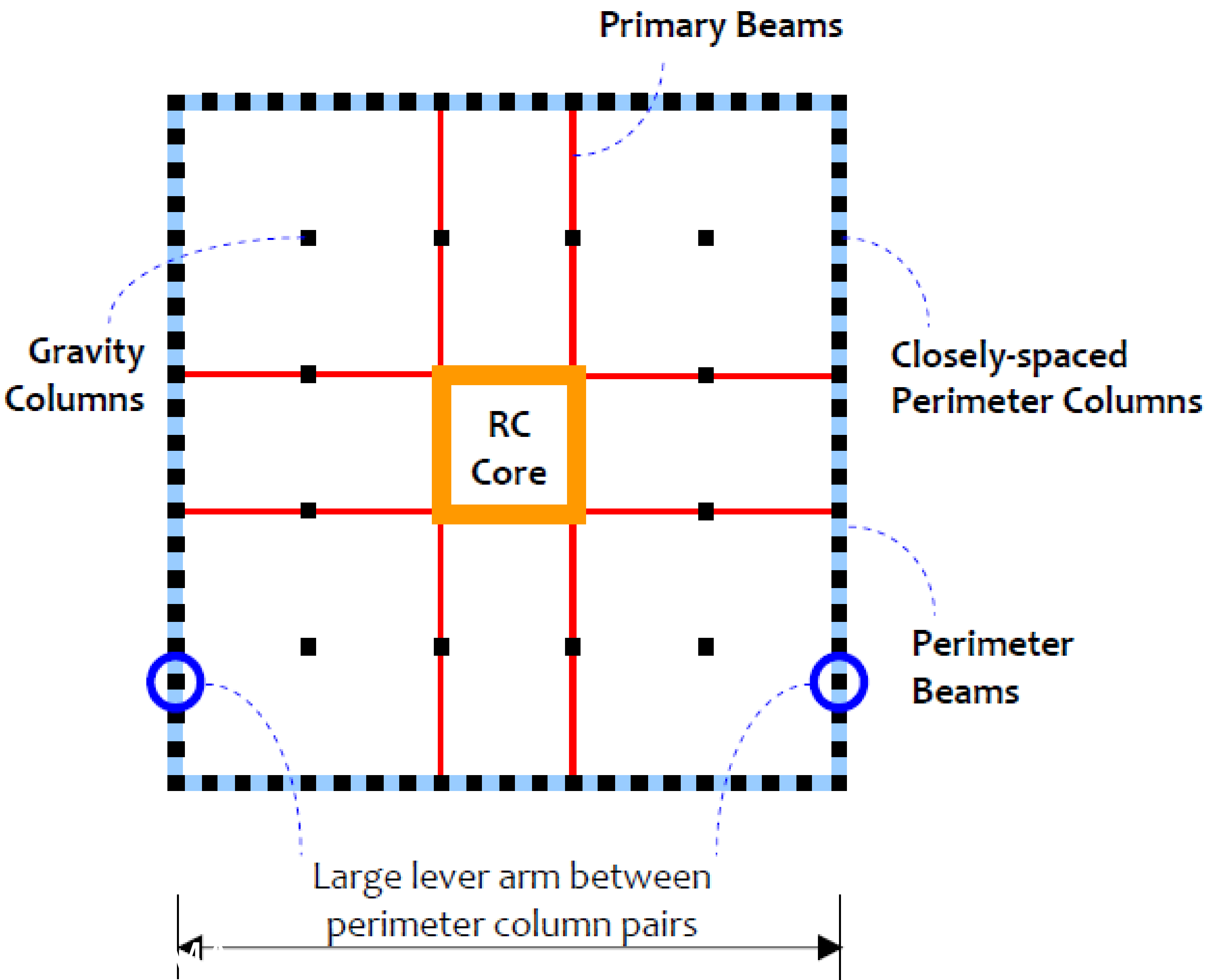


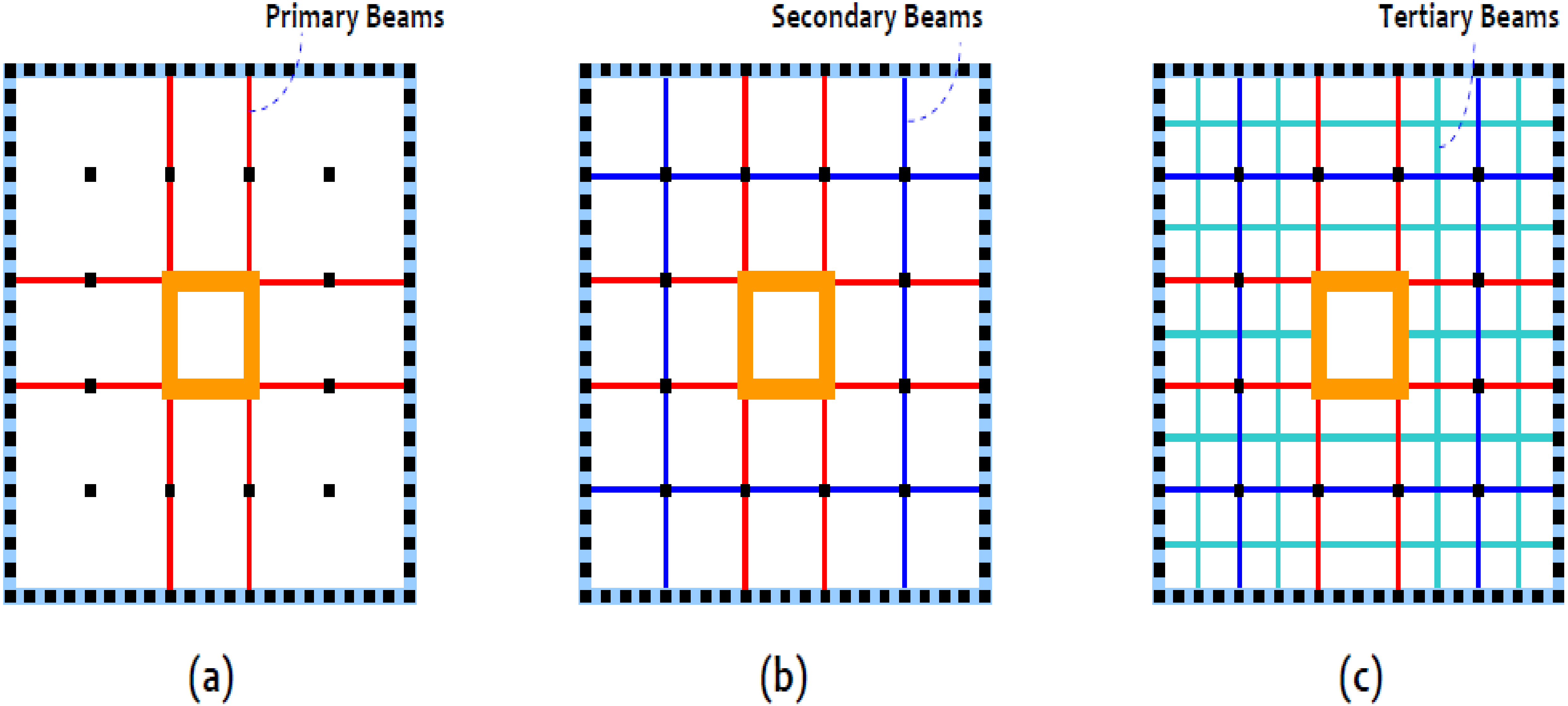
Structural Wall

WHAT ARE TUBE SYSTEMS

- For tall buildings, use of braced frames and structural walls alone (even though of reasonably sized members) may be insufficient to control their overall lateral displacement as well as the force demands on various structural members.
- In such cases, more rigid structural systems are required, like *Tube*, *Tube-in-Tube* and *Bundled Tube systems*, depending on the size and loads on the building are suggested.

- Closely-spaced heavy columns forming a closed loop inter-connected with beams, together called the *tube*, forms the first part of the lateral load resisting system.
- Heavy reinforced concrete structural walls together creating a closed shaft, called as the *core*, form the other part.
- The *Tube System* consists of *one* perimeter tube with a central core.
- The inter-connection is important between the perimeter tube and the central core.
- A system of grid beams is used for this purpose, consisting of *primary beams* (those running between the perimeter columns and central core), *secondary beams* (those running between columns such that no column is left without being connected to the rest of the system), and *tertiary beams* (those running between beams and not connected to any column)


Primary Beams
Gravity Columns
Closely-spaced Perimeter Columns
RC Core
Perimeter Beams
Large lever arm between perimeter column pairs

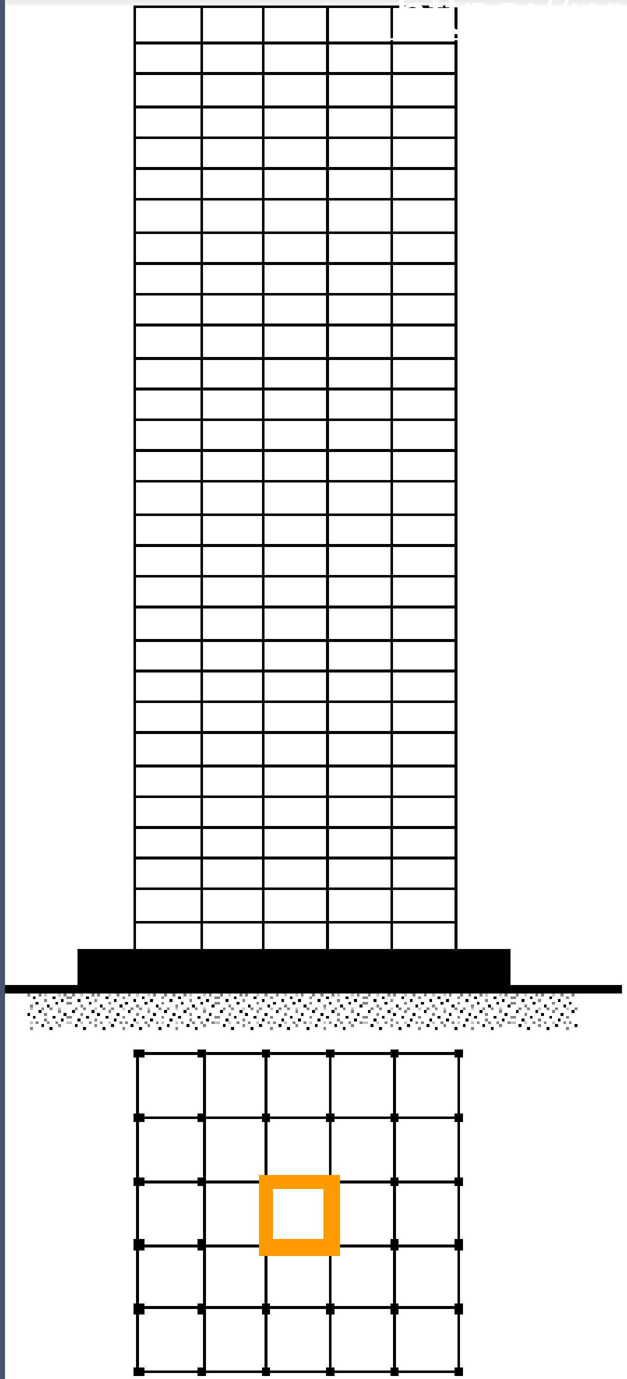

Primary Beams
Secondary Beams
Tertiary Beams
(a)
(b)
(c)

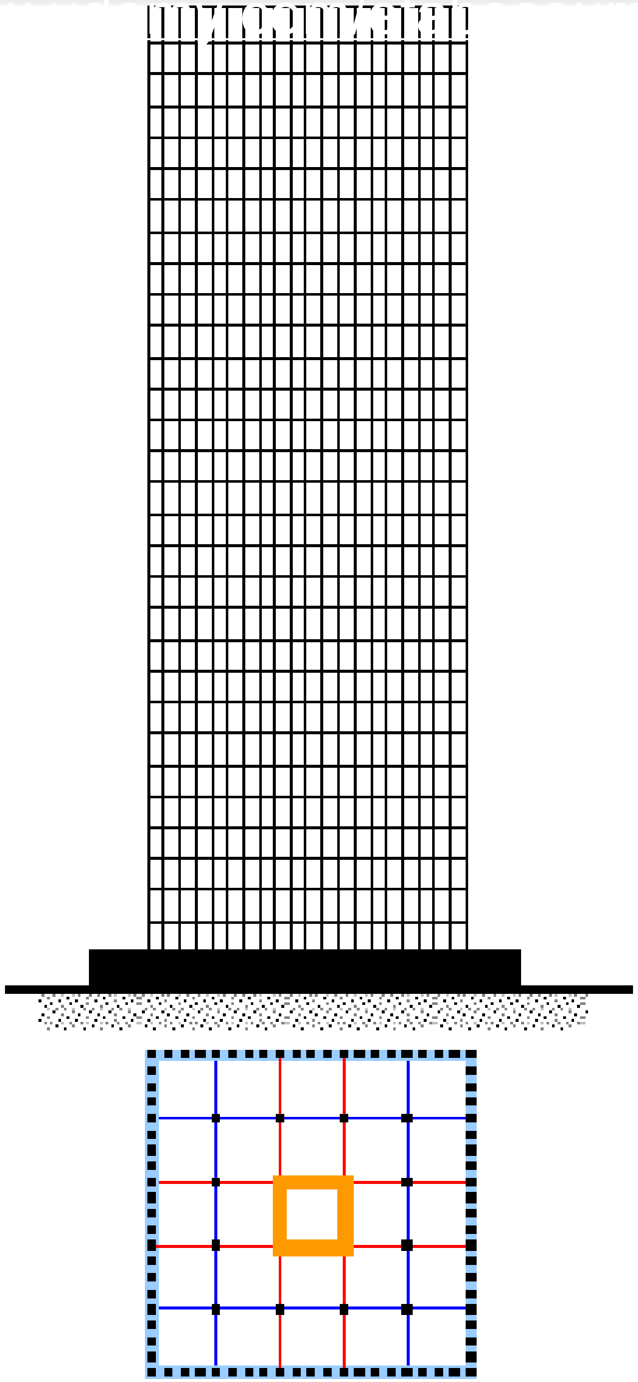
- This aspect of the Tube System that the perimeter draws most of the lateral force induced in the building during earthquake shaking, is in contrast to the normal building frame with a central core, In the traditional frame building with the central core, most of the lateral forces are carried by the central reinforced concrete core.
- The load transfer path carries the forces to the concrete core. As the lateral force travels down towards the base of the building, the force flows towards the more stiffened corners of the core in the form of axial tension and compression.
- Thus, the corners of the core at the base of the building carry larger axial force than the mid sides of the core.
- By introducing a perimeter tube consisting of closely spaced columns interconnected with beams, this concentration of the force in the core is relieved but the same behavior is shifted to the perimeter tube.
- Since the lever arm between the perimeter column pairs (located on two parallel faces of the tube) is large, the axial stresses induced in the columns are smaller than those induced in the core of the traditional frame building.

- By introducing a perimeter tube consisting of closely spaced columns interconnected with beams, this concentration of the force in the core is relieved but the same behavior is shifted to the perimeter tube.

Since the lever arm between the perimeter column pairs (located on two parallel faces of the tube) is large, the axial stresses induced in the columns are smaller than those induced in the core of the traditional frame building.

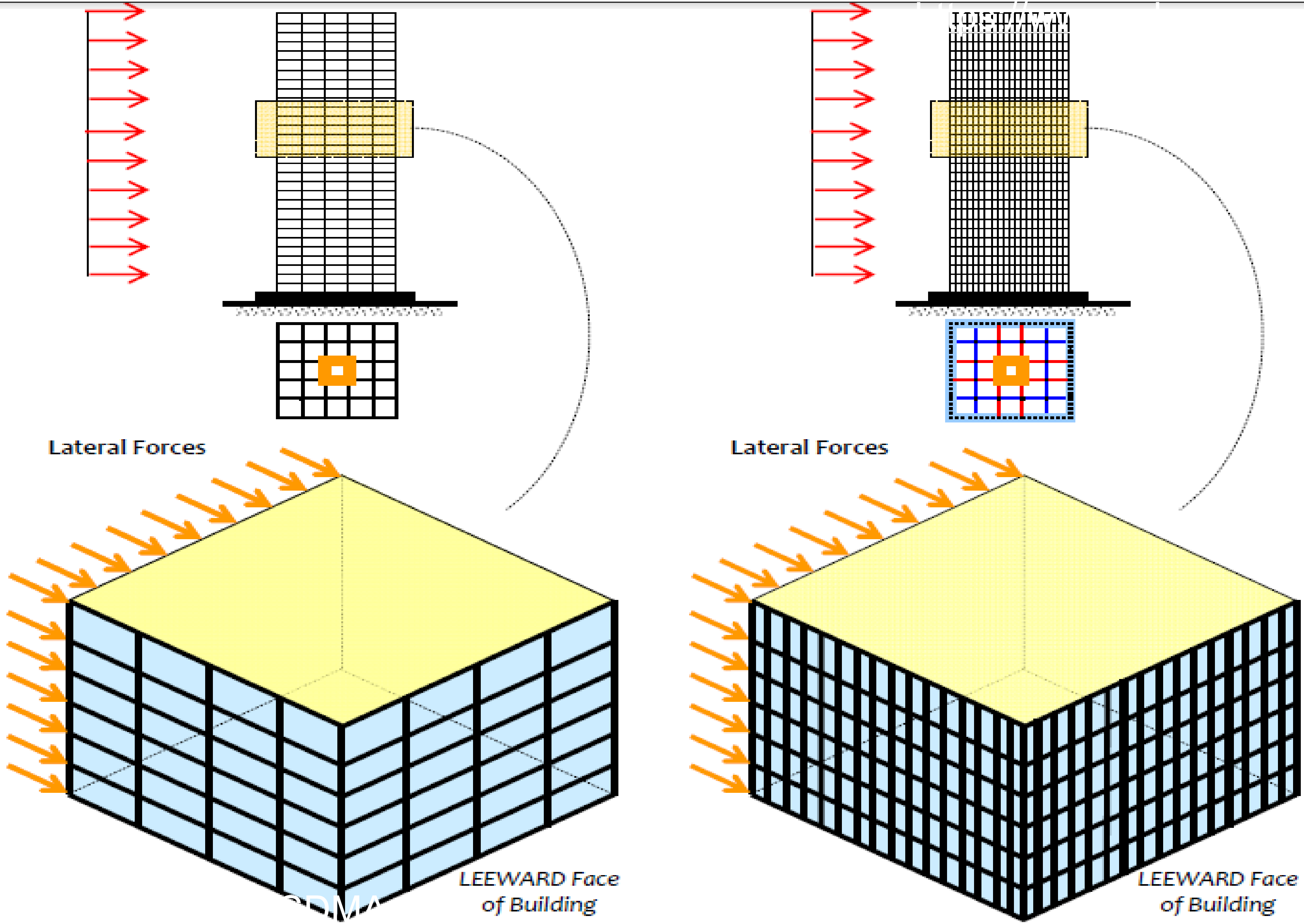
Images Property of GSDMA

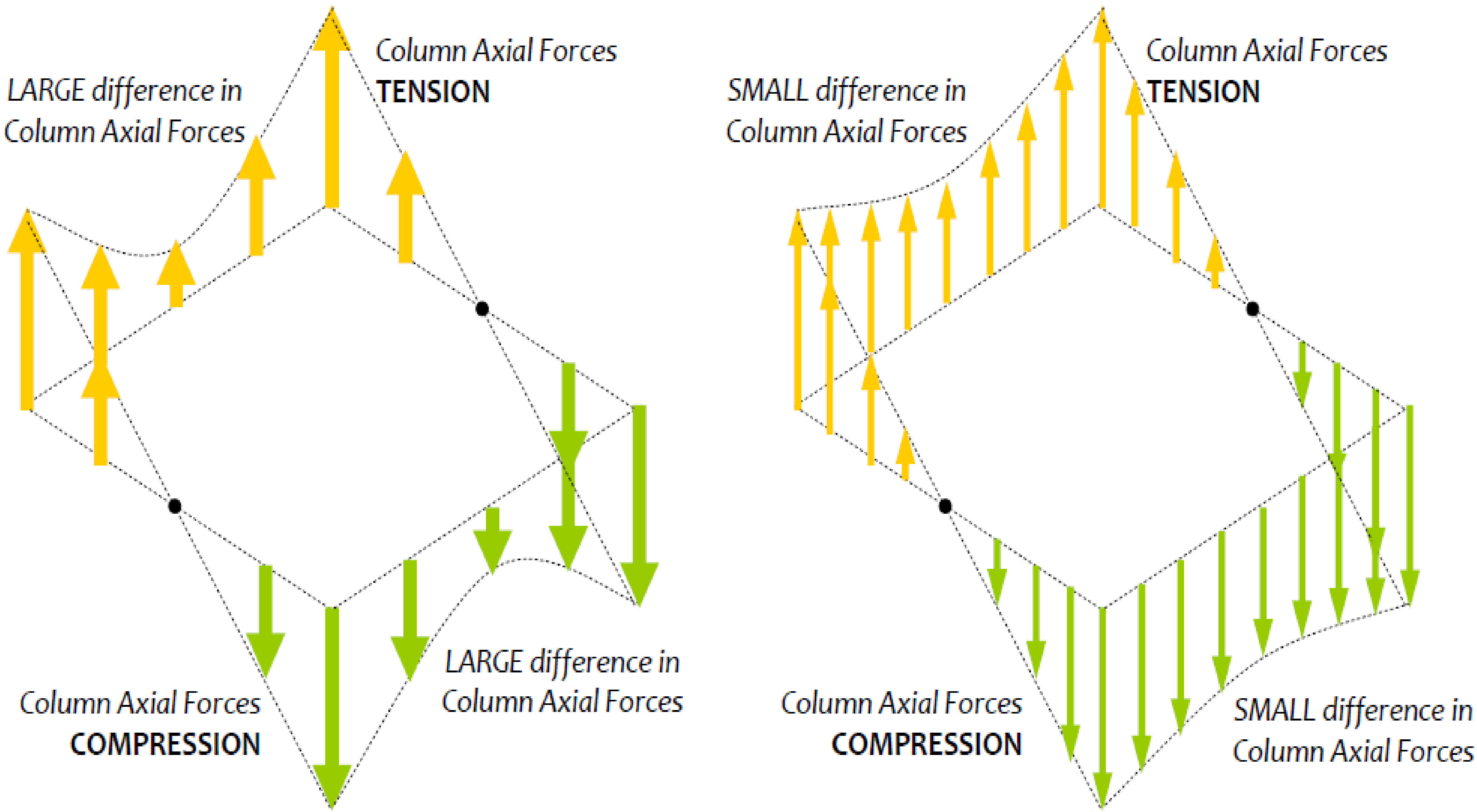




WHAT IS SHEAR LAG EFFECT IN HIGH RISE BUILDINGS ?

- Under the earthquake induced lateral inertia forces, there is difference in axial forces amongst columns on the leeward and on the windward faces; the corner columns have larger axial force than the interior columns.
- In addition, farther the spacing of columns, the larger is the difference in column axial forces.
- Thus, buildings with *traditional frame structural system* have larger shear lag effect than buildings with *tube structural system*.
- The earthquake induced lateral inertia force is carried most by the stiffer frames. In a tube system, the closely spaced columns makes the two perimeter planes of the tube stiffer in the direction of inertia force.
- Hence, the less stiff frames move more than these and thereby induce deformation in beams.

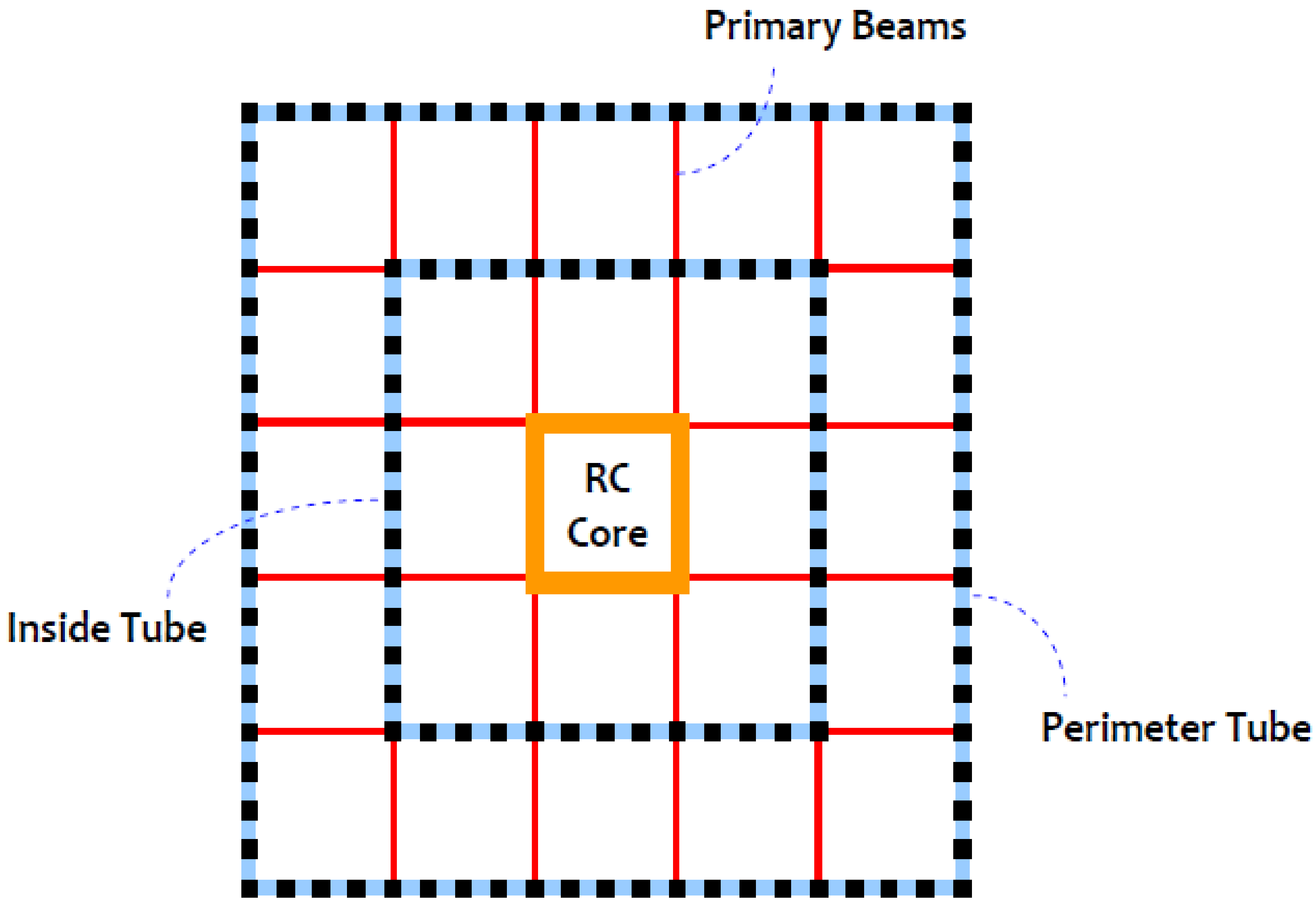

Lateral Forces
LEEWARD Face
of Building
Lateral Forces
LEEWARD Face
of Building



Column Axial Forces
TENSION
LARGE difference in
Column Axial Forces
Column Axial Forces
COMPRESSION
LARGE difference in
Column Axial Forces
Column Axial Forces
TENSION
SMALL difference in
Column Axial Forces
Column Axial Forces
COMPRESSION
SMALL difference in
Column Axial Forces

WHAT IS TUBE-IN-TUBE AND BUNDLED TUBE SYSTEMS

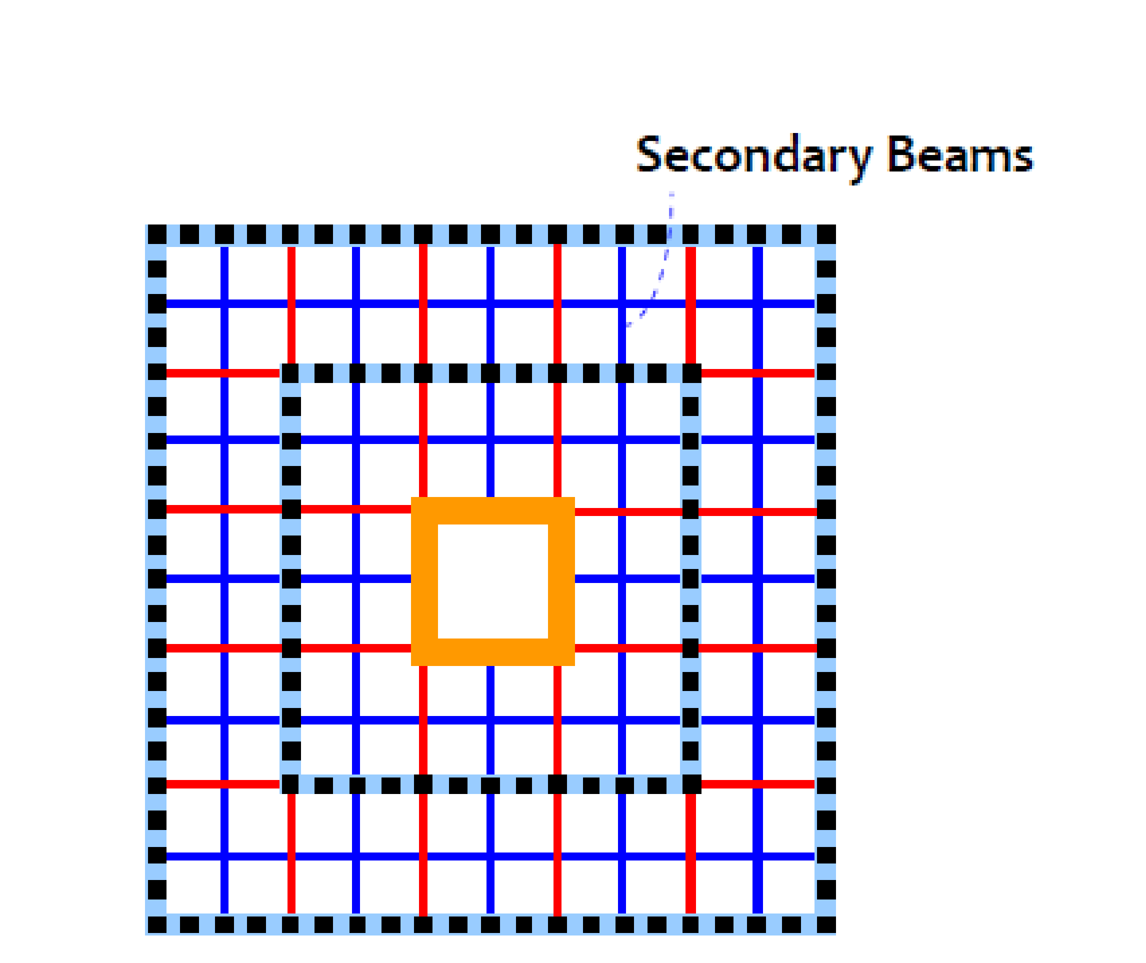
- When the plan size of the building increases, additional columns may be required to support the gravity loads between the outer tube and inner core, and prevent the slab from bending too much.
- These columns are not part of the *main* lateral load resisting system, and therefore are not intended to carry any lateral loads; they are called *gravity columns*.
- When the building plan is large, sometimes, many columns may be required to support the gravity loads.
- Then, it may be beneficial to create *a second* tube of columns interconnected with beams *inside* the perimeter tube of columns interconnected with beams. This system is called the *Tube-in-Tube System*



Primary Beams
RC
Core
Inside Tube
Perimeter Tube

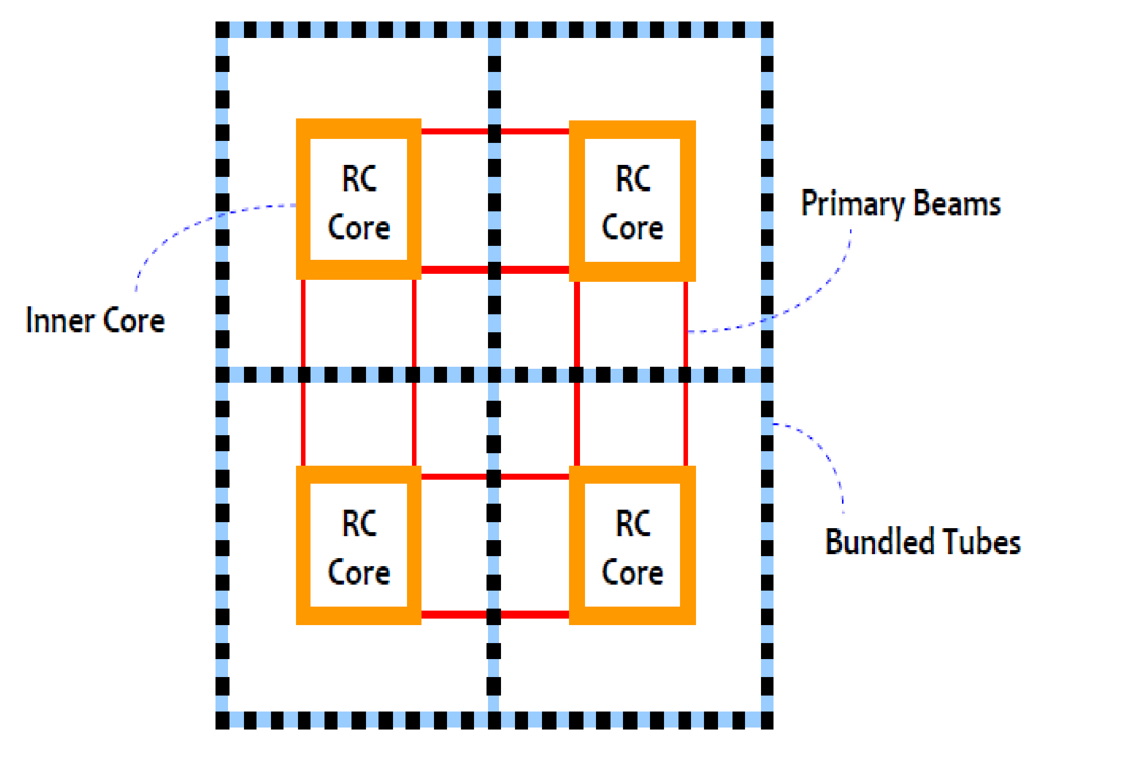
HOW TUBE IN TUBE SYSTEM WORKS ?

- In the *Tube-in-Tube system*, the tubes should be tied together with a stiff and strong grid of beams.
- This also helps in uniform distribution of forces to the perimeter tube columns.
- If the distance between the two tubes is large, intermediate *secondary* beams, along with additional gravity columns, may become necessary for effectively transferring lateral forces to the tubes
- The additional gravity columns keep the intermediate beams from deflecting too much and thereby make them capable of transferring axial compression without much out-of-plane deformation.
- More uniform distribution of gravity forces is achieved with closely spaced beam grids between the tubes.



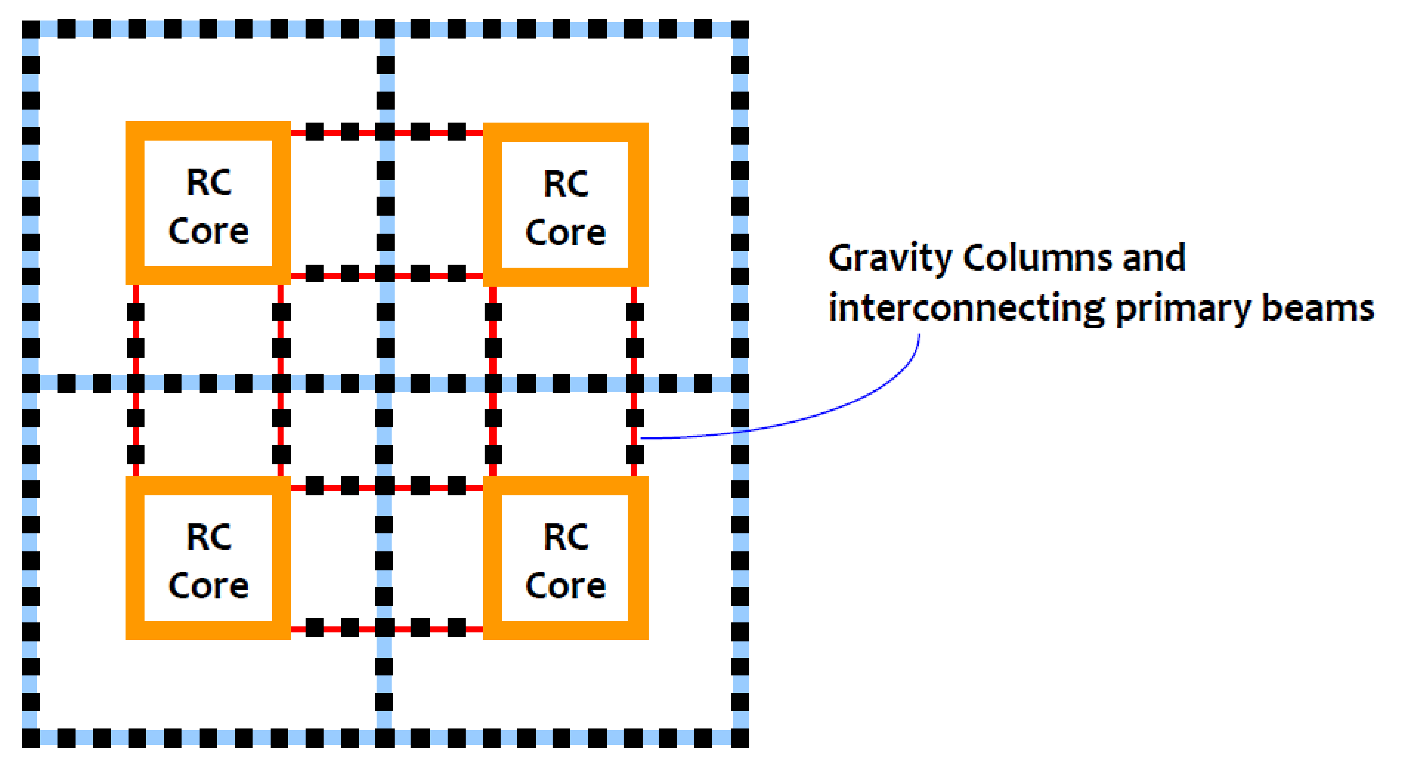
WHAT IF TUBE IN TUBE SYSTEM ALSO FAILS TO WORK ?

- In large plan area buildings, when even the *Tube-in-Tube system* fails to control the lateral deformation of the building, an even *stiffer* lateral force resisting system is required.
- One system that can offer this is the *Bundled-Tubes System*; as the name goes, here a set of *Tube Systems* are stacked together to form the overall lateral load resisting system. The closely-spaced columns of the different tubes are placed in line to form an overall tube system.



STRENGTHEN THE BUNDLED TUBE SYSTEM

- The RC cores of the tubes are connected to each other with beams that span directly between these stiff vertical elements; these beams are called *primary* beams. As in *Tube* and *Tube-in-Tube Systems*, additional gravity columns, secondary beams and tertiary beams may be employed when the span between the tubes and the cores are large, to improve the distribution of gravity loads to the tubes.

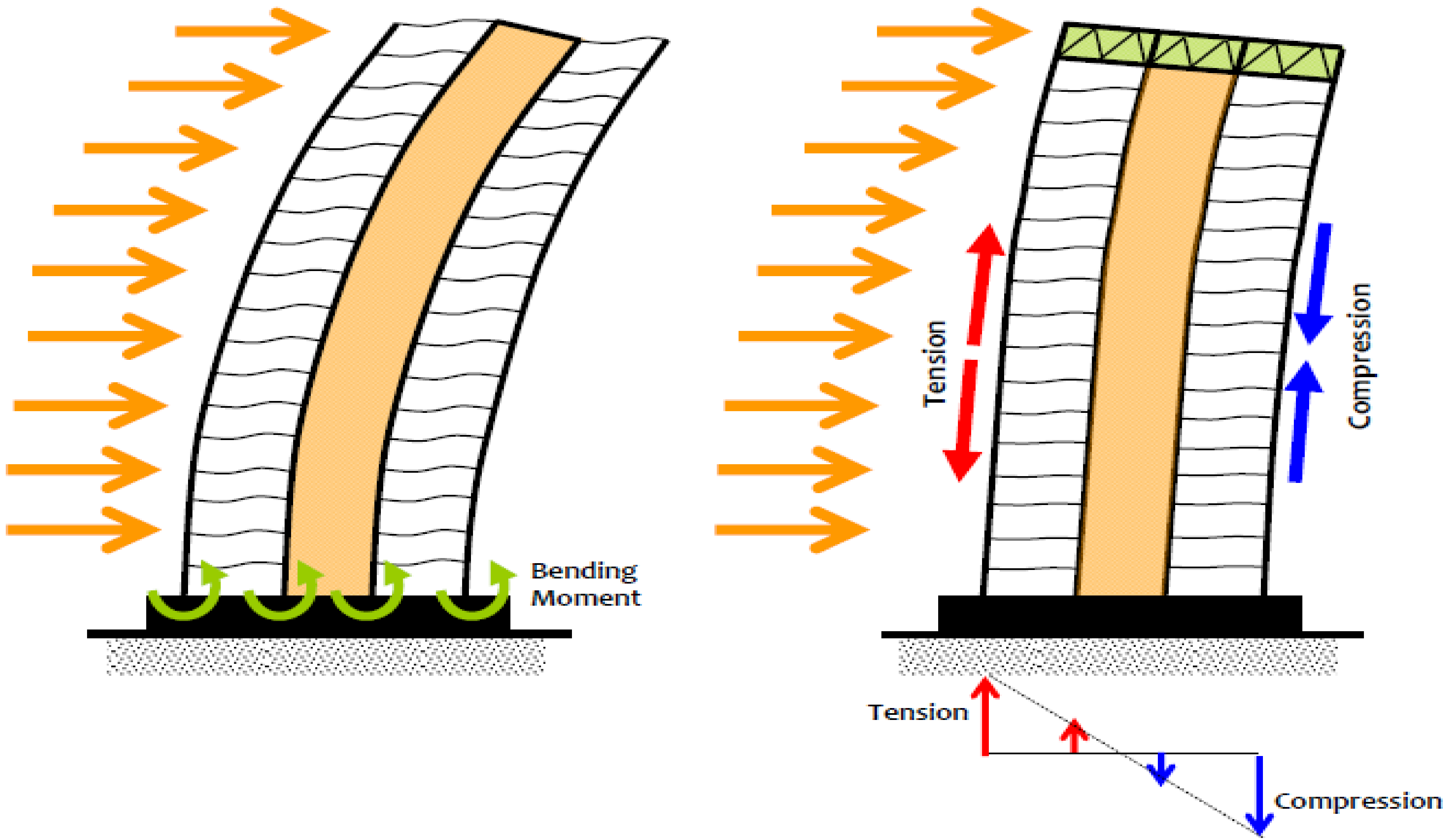


Images Property of GSDMA

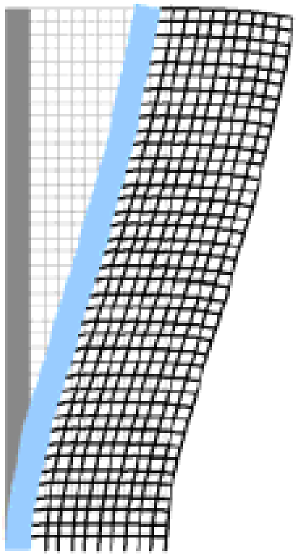
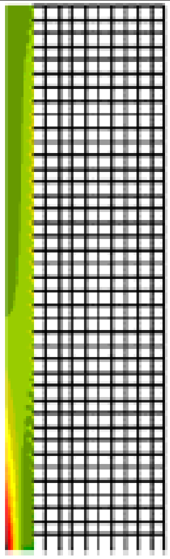
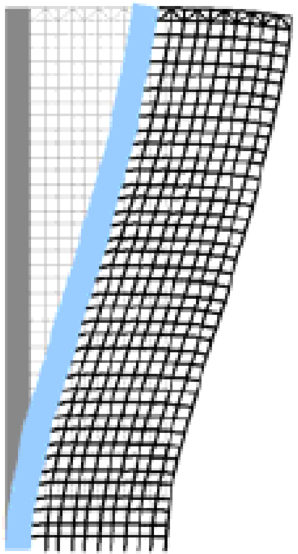
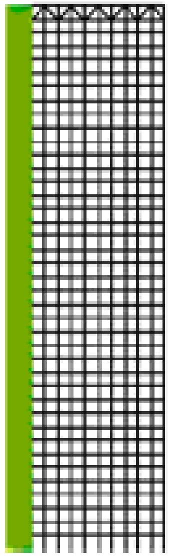
THE TESSERACT OF STRUCTURAL ENGINEERS FOR TALL BUILDINGS

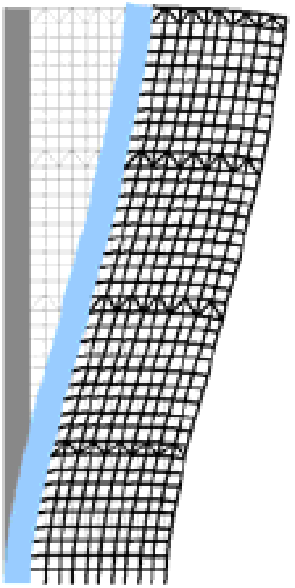
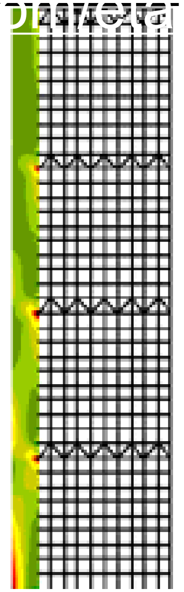
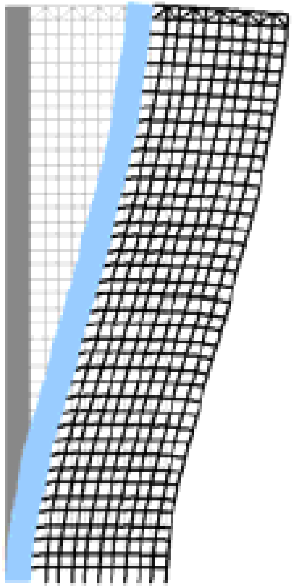
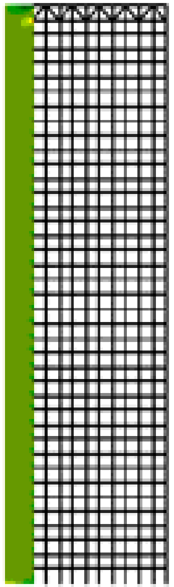
- The *outrigger truss* is a simple trusses spanning over the full height of that storey and across the full width of building.
- The role of the outrigger trusses is to make the columns act together in resisting overturning moments acting on the building.
- The pairs of columns generate couples of axial tension and axial compression to counter the overturning moments; this reduces the overall bending effects in columns.

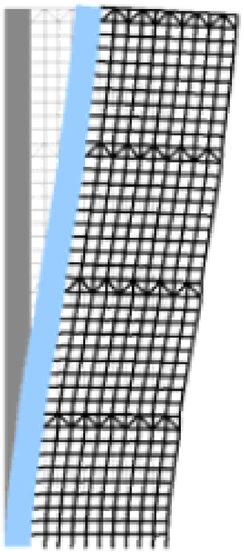
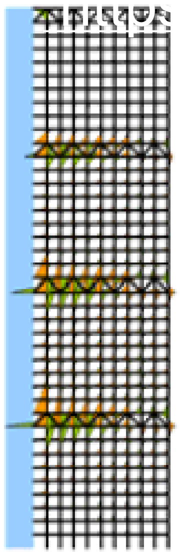
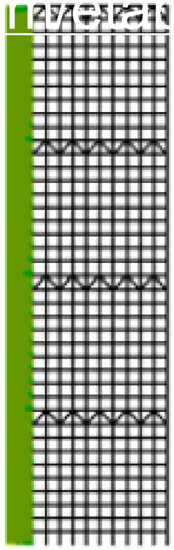
Images Property of GSDMA



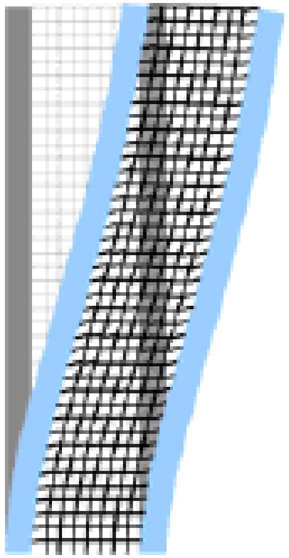
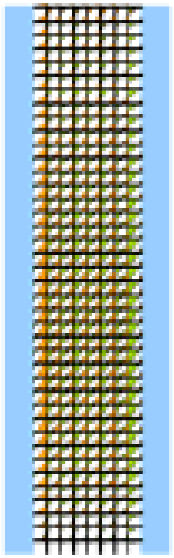
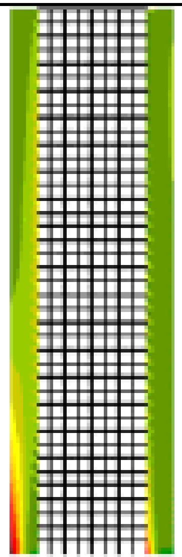
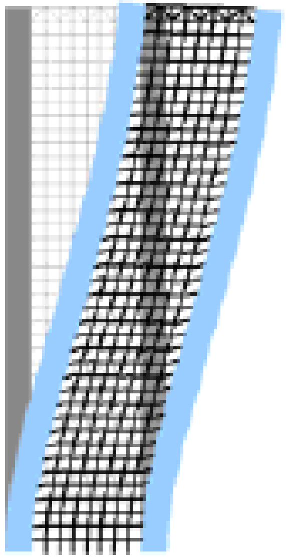
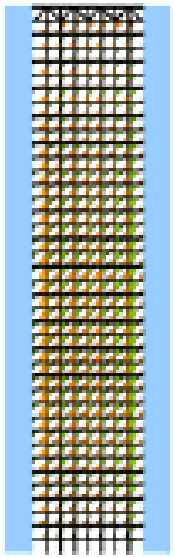
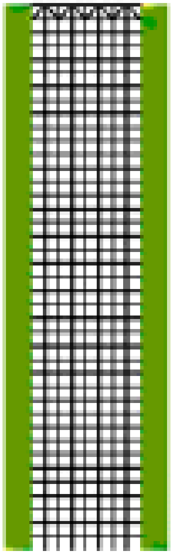
Bending Moment
Tension
Compression
Tension
Compression

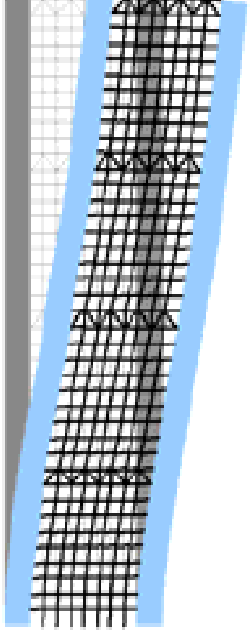
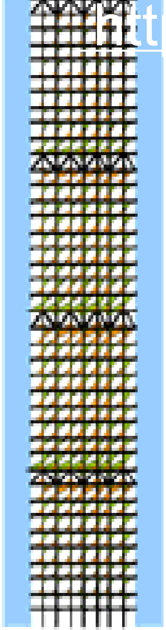
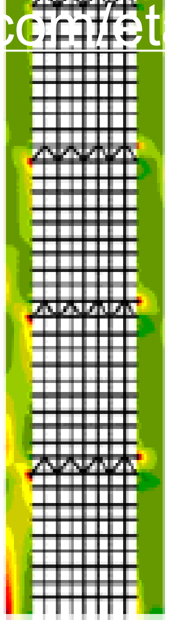
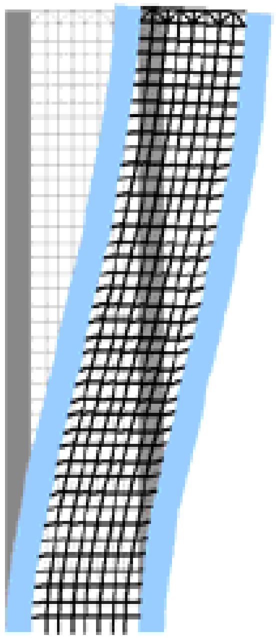
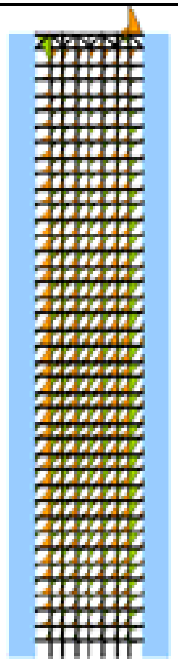
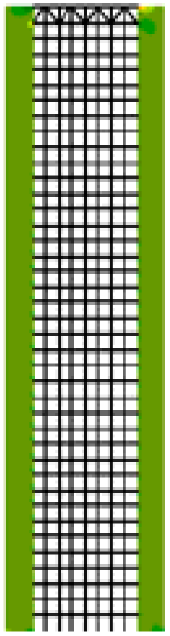
Regular frame with	*Deformed Shape*	*Bending Moment in Frame Members*	*Principal Stresses in Wall*
1. Stiff core on left side 2. Perimeter tube on right side	 39 mm		
1. Stiff core on left side 2. Perimeter tube on right side 3. Outrigger truss connecting core and flexible direction of perimeter tube on right side ONLY at the top	 38 mm		

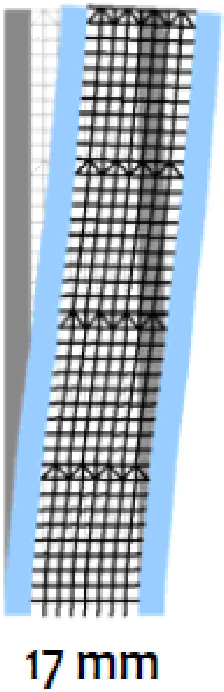
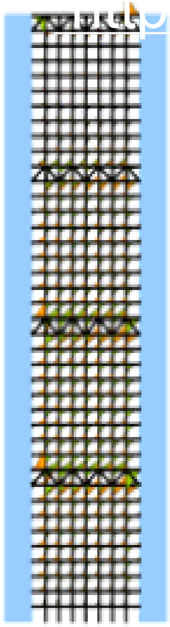
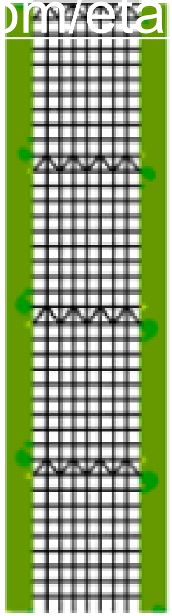
1. Stiff core on left side 2. Perimeter tube on right side 3. Outrigger truss connecting core and flexible direction of perimeter tube on right side at FOUR levels	 36 mm		
1. Stiff core on left side 2. Perimeter tube on right side 3. Extremely stiff outrigger truss connecting core and flexible direction of perimeter tube on right side ONLY at the top	 36 mm		

1. Stiff core on left side 2. Perimeter tube on right side 3. Extremely stiff outrigger truss connecting core and flexible direction of perimeter tube on right side at FOUR levels	 21 mm		

- The presence of a stiff wall *on one side alone* does not help, even if the axial and flexural stiffness of the outrigger truss members are large.
- This confirms that using outrigger trusses in Tube and Tube-in-Tube Systems is not beneficial.

Regular frame with	*Deformed Shape*	*Bending Moment in Frame Members*	*Principal Stresses in Wall*
1. Stiff core on both sides	 35 mm		
1. Stiff core on both sides 2. Outrigger truss connecting core and flexible direction of perimeter tube on right side ONLY at the top	 34 mm		

1. Stiff core on both sides 2. Outrigger truss connecting core and flexible direction of perimeter tube on right side at FOUR levels	 24 mm		
1. Stiff core on both sides 2. Extremely stiff outrigger truss connecting core and flexible direction of perimeter tube on right side ONLY at the top	 33 mm		

1. Stiff core on both sides 2. Extremely stiff outrigger truss connecting core and flexible direction of perimeter tube on right side at FOUR levels			

- The presence of a stiff wall *on either side* helps immensely, especially when the axial and flexural stiffness of the outrigger truss members are large.
- **THIS SUGGESTS THAT USING OUTRIGGER TRUSSES IS BENEFICIAL IN BUNDLED-TUBE SYSTEM.**

WHAT IS FLAT SLAB STRUCTURAL SYSTEM ?

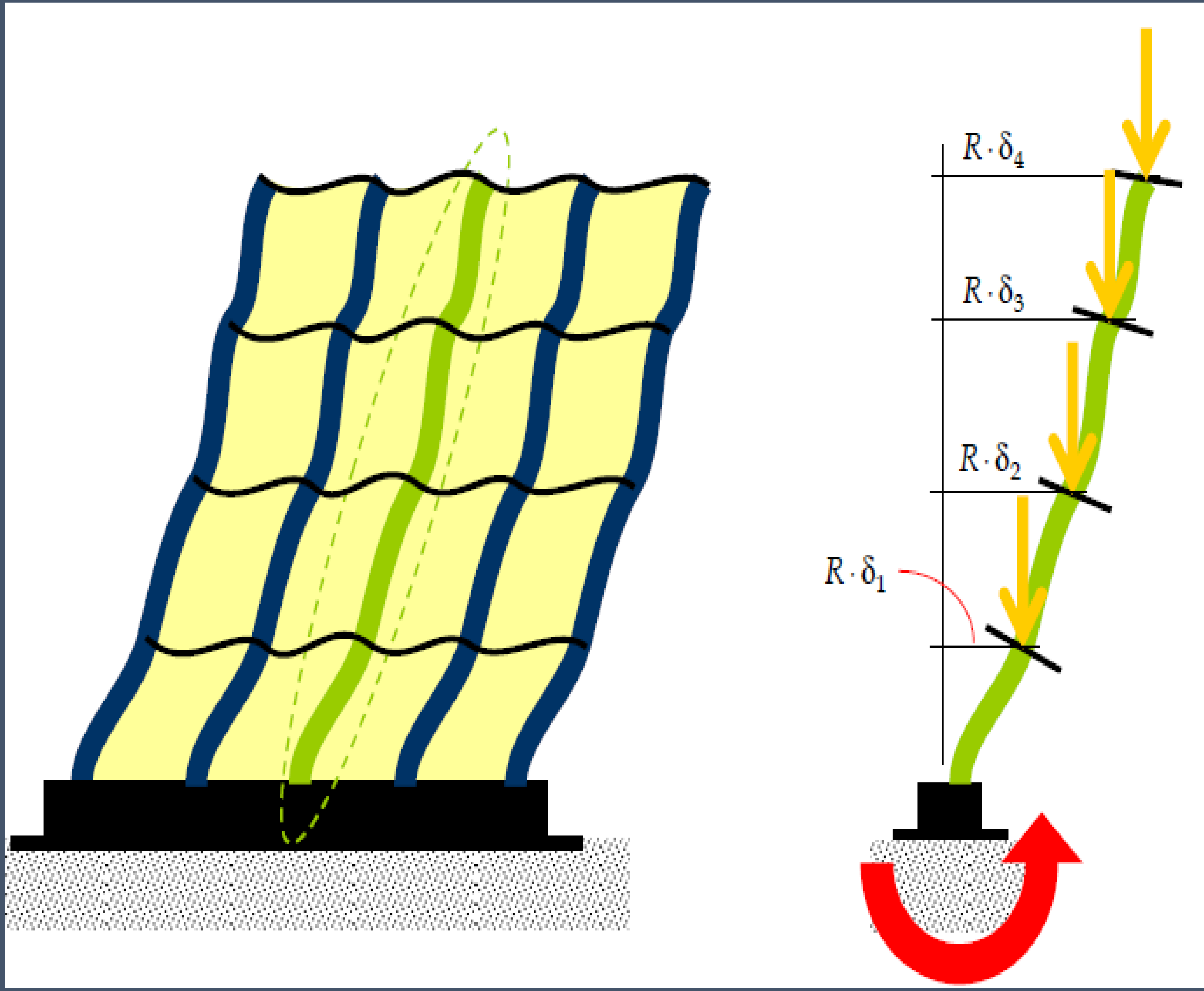
- When the slabs rest directly on columns or walls (with or without drop panels) without employing any beams. This system is called *flat slab* construction.
- Flat slab building has a *column-slab system*, which is expected to resist both *gravity loads* and *earthquake-induced lateral inertia loads*.

Images Property of GSDMA

https://www.udemy.com/etabscourse/

IS FLAT SLAB STRUCTURAL SYSTEM SAFE FOR EARTHQUAKES ?

- Flat slab buildings have low lateral stiffness, and hence swing by large amounts elastically even during low level earthquake shaking owing to little/no rotational flexibility offered by the thin slabs inter-connecting the columns.
- Since the column-slab system has small lateral stiffness and lateral load resistance, this large overall lateral drift of the flat slab building makes the columns incapable of accommodating the additional secondary moments generated by the lateral deformations. Thus, there are serious concerns on the use of flat slab buildings in seismic regions.



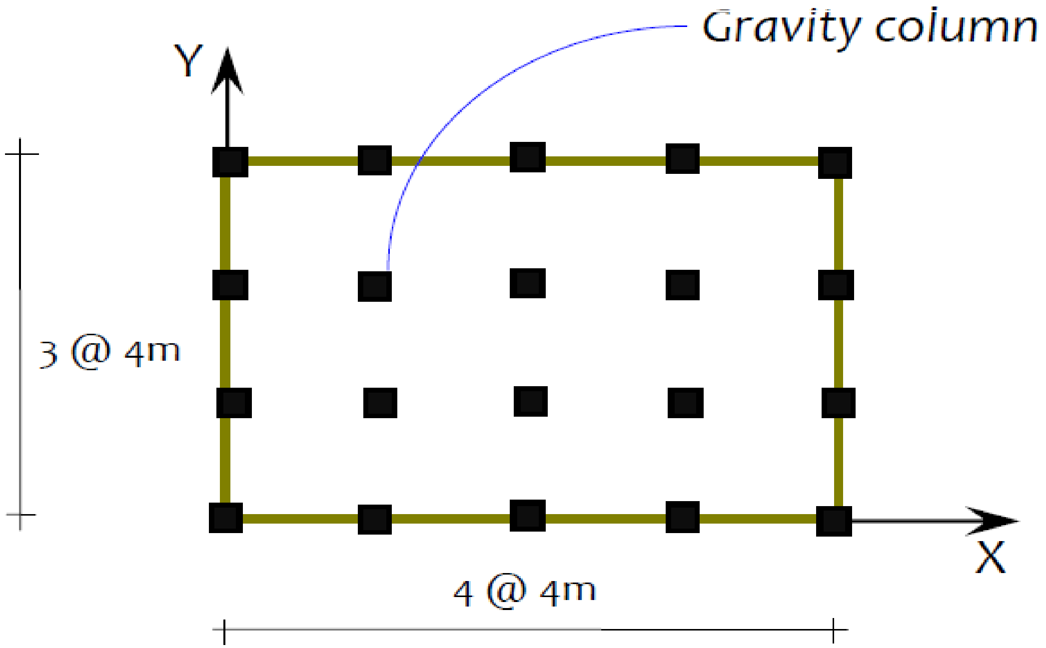
Images Property of GSDMA

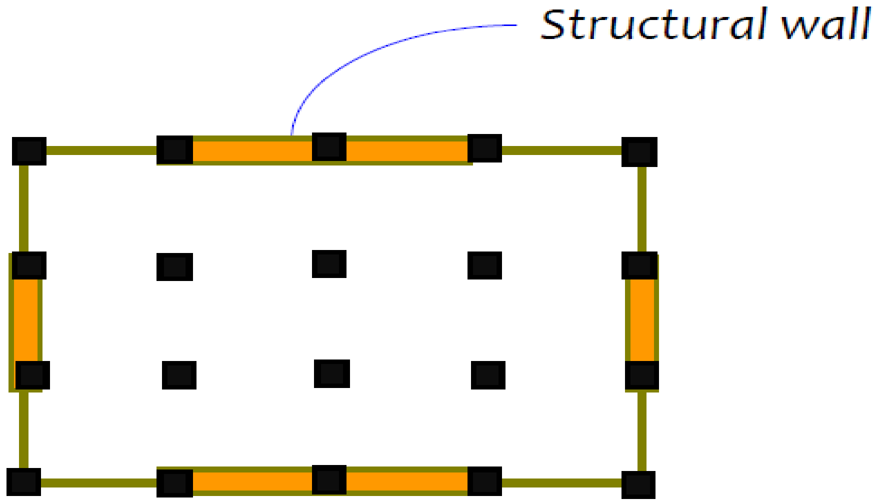
IS FLAT SLAB STRUCTURAL SYSTEM SAFE FOR EARTHQUAKES ?

YES, BUT IF DESIGNED PROPERLY AND ONLY FOR LOW SEISMIC REGIONS .

HOW FLAT SLAB STRUCTURAL SYSTEM IS SAFE FOR EARTHQUAKES ?

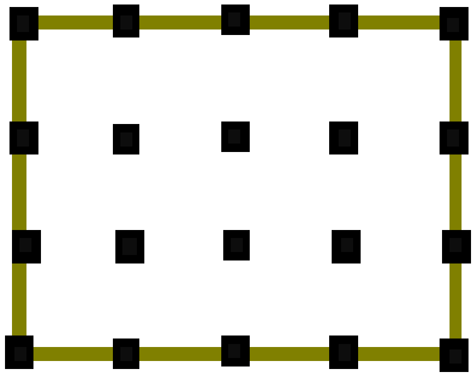
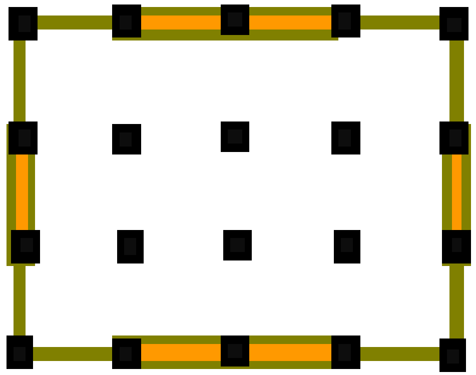
- Flat Slab Structural System can be provided by reducing overall lateral deformation and thereby to improve their overall lateral resistance by adding a supplemental *lateral load resisting system* (LLRS) in the form of structural walls.
- Lateral drift is minimized by adding structural walls to flat slab buildings.





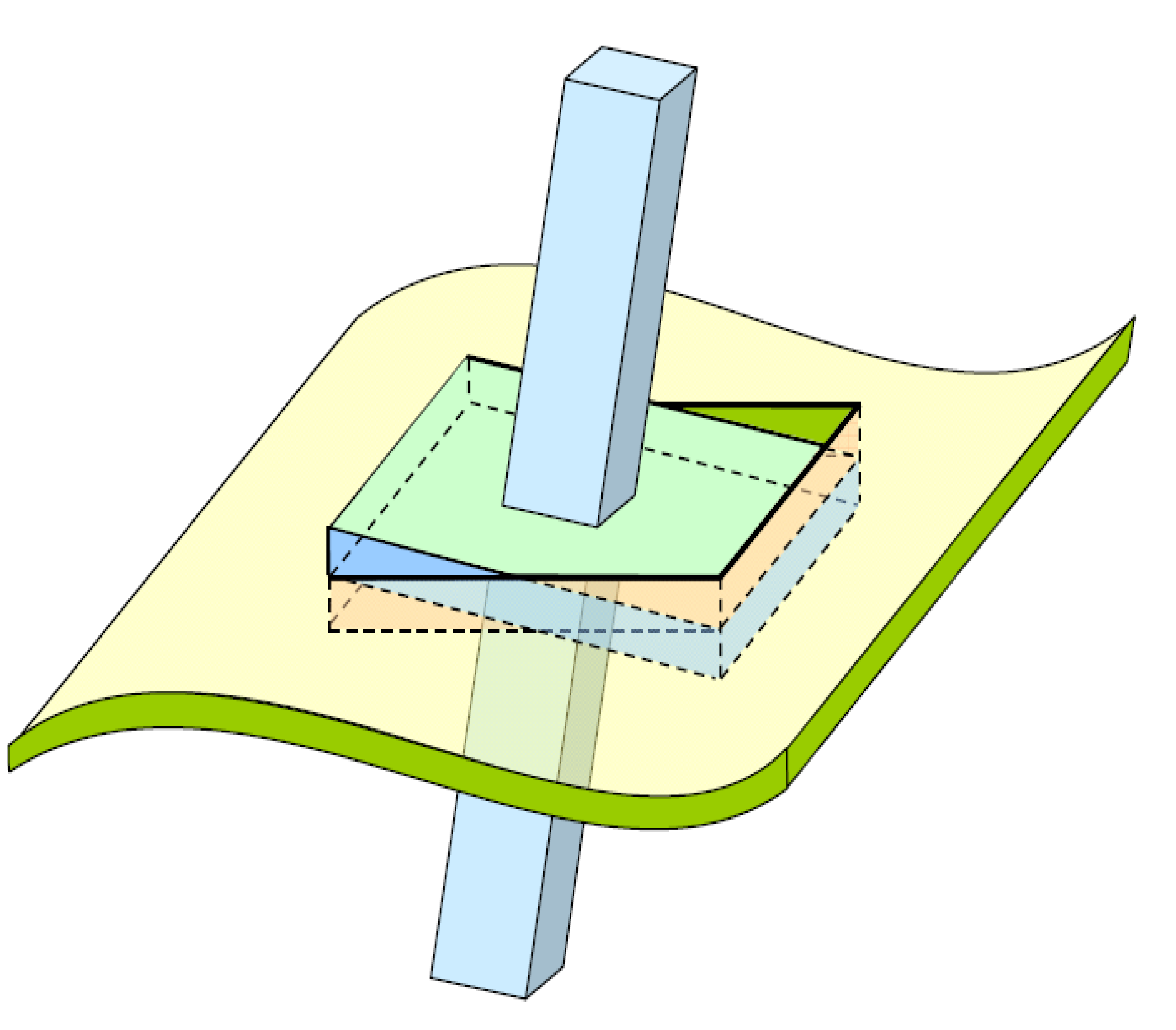
Flat slab supported on walls at edges

Images Property of GSDMA

		
Mode 1	Y translation (1.07s)	X translation (0.42s)
Mode 2	X translation (0.97s)	Y translation (0.20s)
Mode 3	Torsion (0.76s)	Torsion (0.20s)
Roof displacement in Y direction	116 mm	24 mm
Roof displacement in X direction	96 mm	5 mm

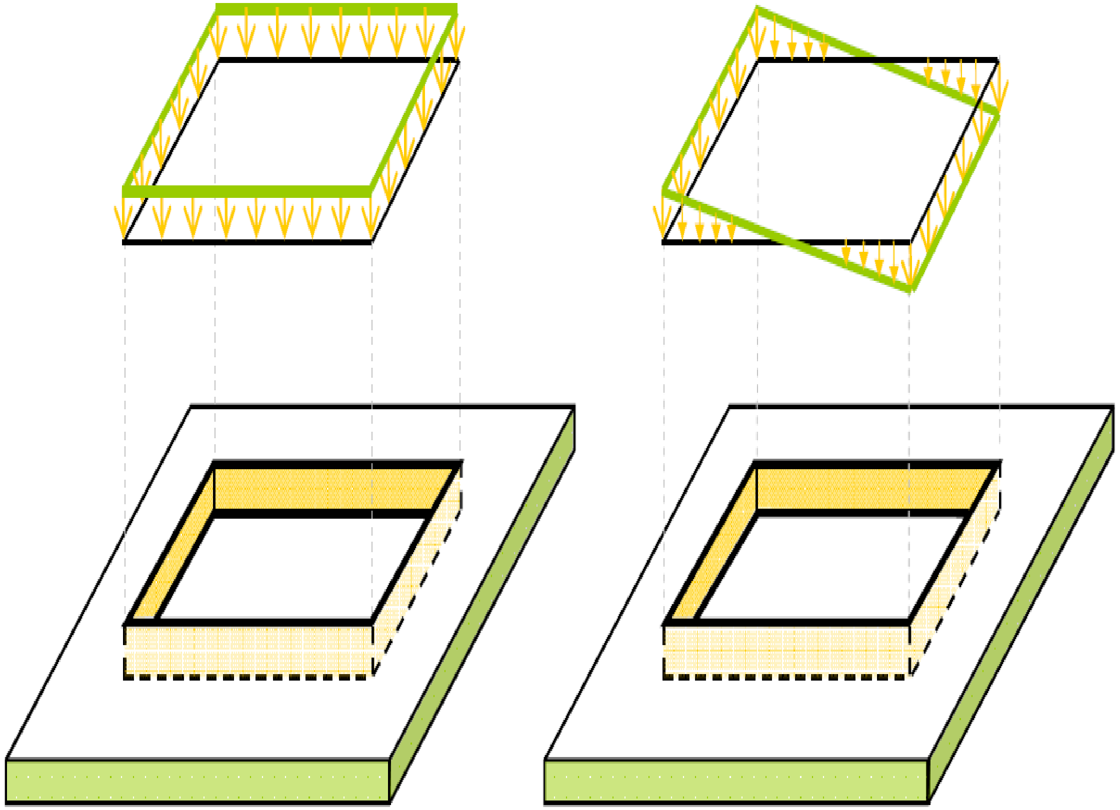
WHAT MAY EXACTLY HAPPEN IN EARTHQUAKES IN FLAT SLAB SYSTEM

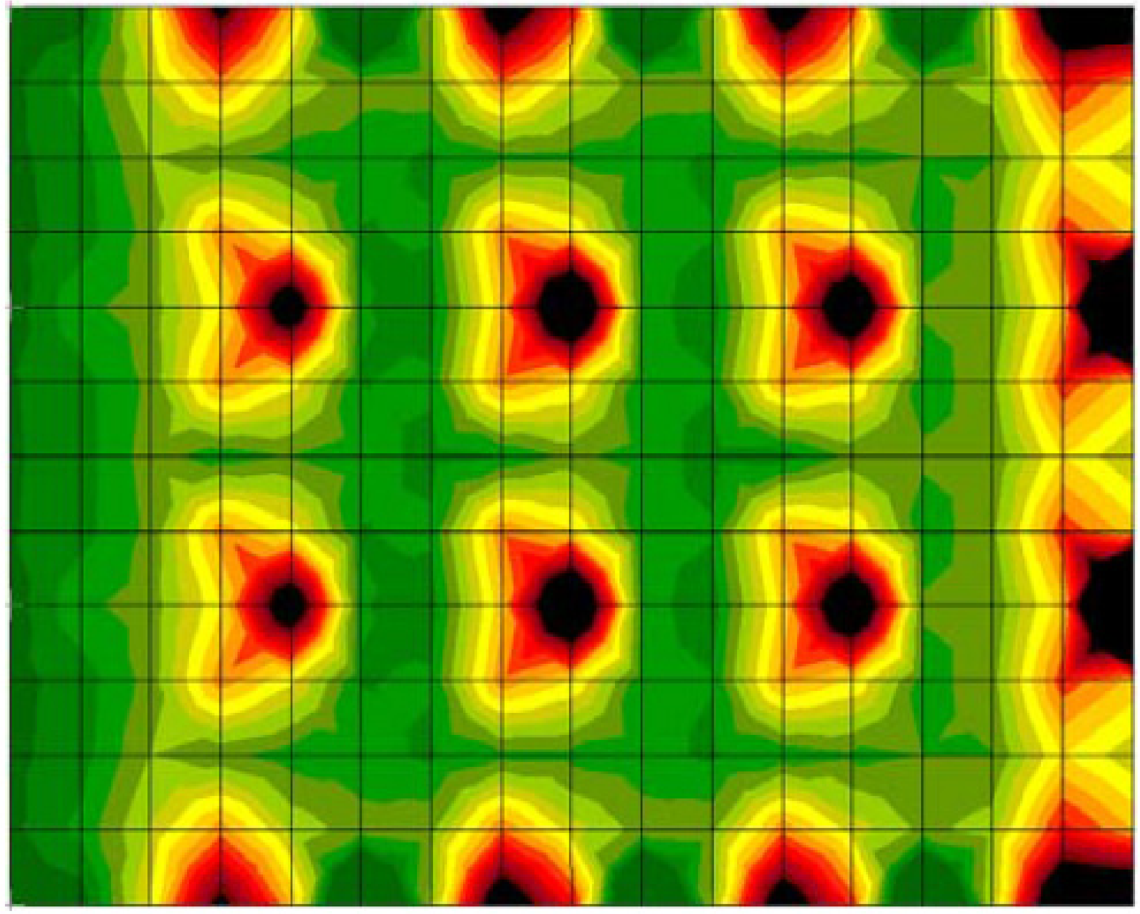
- Under increasing levels of overall lateral drift on the building during seismic action, shear stresses in the flat slab increase.
- Even with the large lateral stiffness provided with supplemental lateral load resisting system (*i.e.,* structural wall) and the overall lateral drift of the building controlled, this unsymmetrical shear stress cannot be prevented from being generated owing to the displacement compatibility between structural wall and *flat slab – column system*.
- Hence, flat slab building with structural walls are at best suitable ONLY for *low seismic regions*.



Images Property of GSDMA

UNSYMMETRICAL FLEXURAL SHEAR STRESSES IN FLAT SLAB OF RC FLAT SLAB BUILDING UNDER LATERAL DRIFT





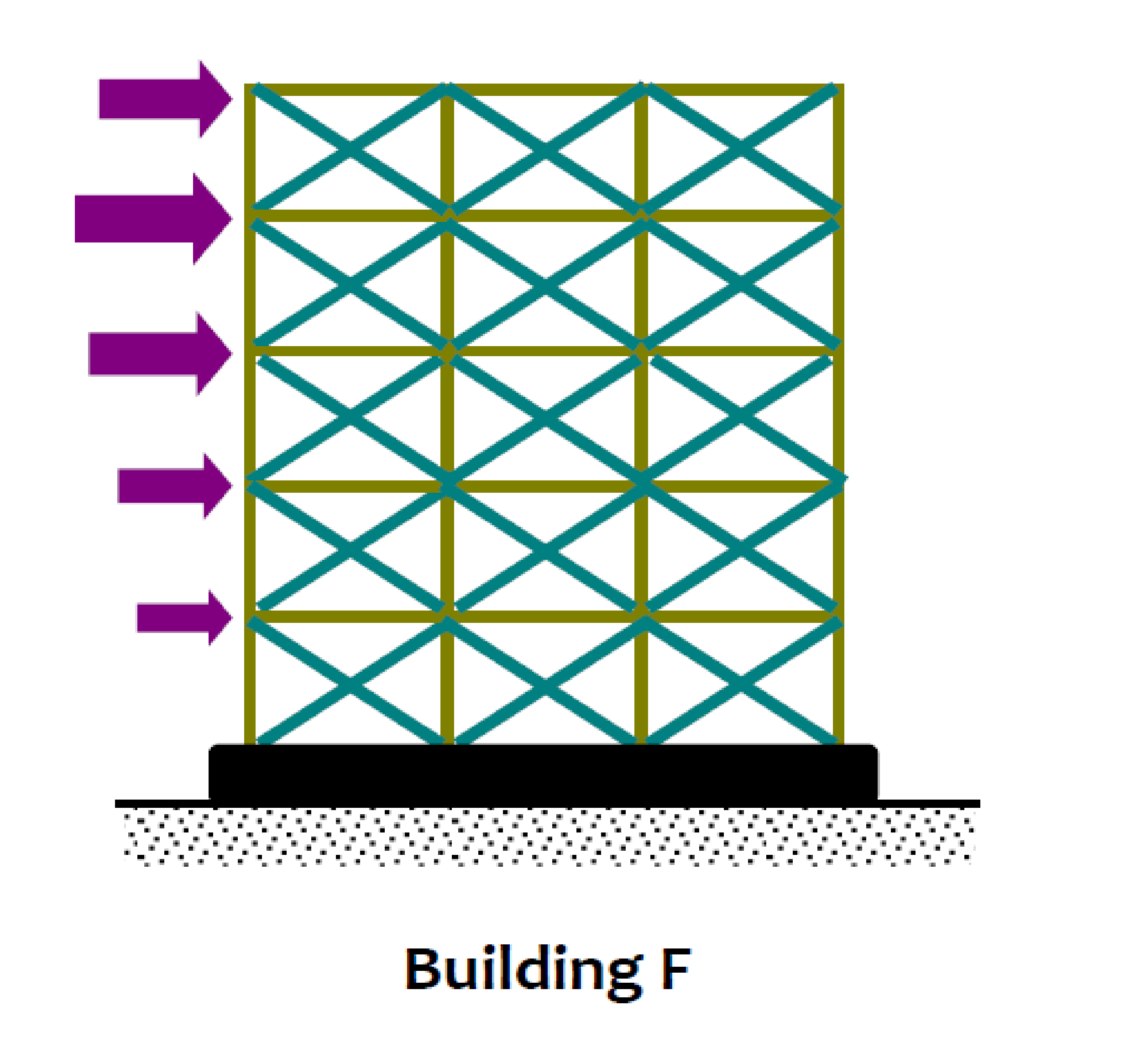
Images Property of GSDMA

WHY GOOD LOAD PATH IS IMPORTANT ?

- Inertia forces mobilized in buildings during earthquake shaking travel towards the foundations.
- These forces travel through structural members, and thus, the choice and location of structural members greatly affect the seismic performance of buildings.
- A smooth path of least resistance needs to be provided for efficient transfer of forces up to the foundation.

BRACES OFFER DIRECT LOAD PATHS

- Inertia forces mobilized in buildings during earthquake shaking travel towards the foundations.
- These forces travel through structural members, and thus, the choice and location of structural members greatly affect the seismic performance of buildings.
- A smooth path of least resistance needs to be provided for efficient transfer of forces up to the foundation.

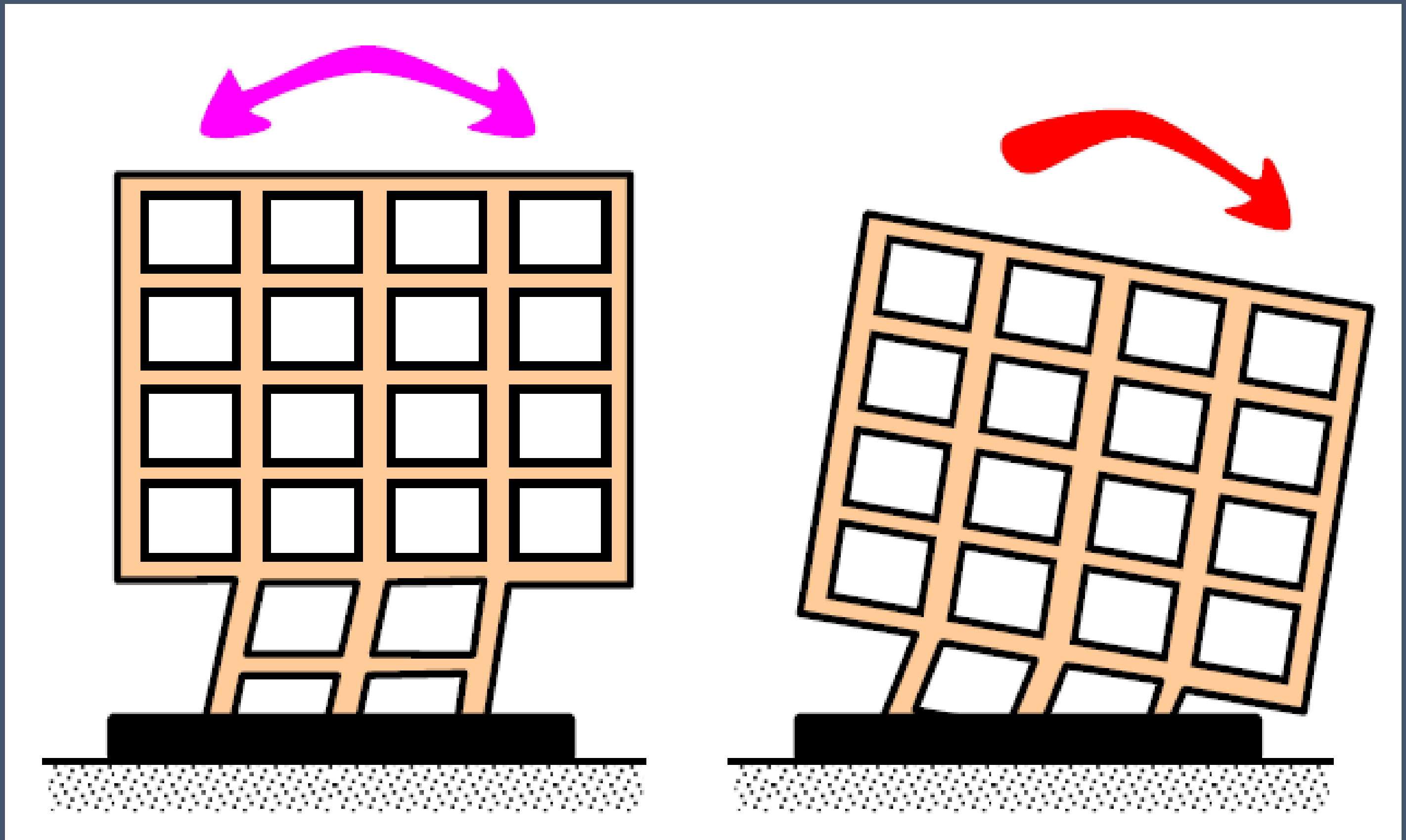


DISCONTINUITY IN LOAD PATH DUE TO FLOATING COLUMNS

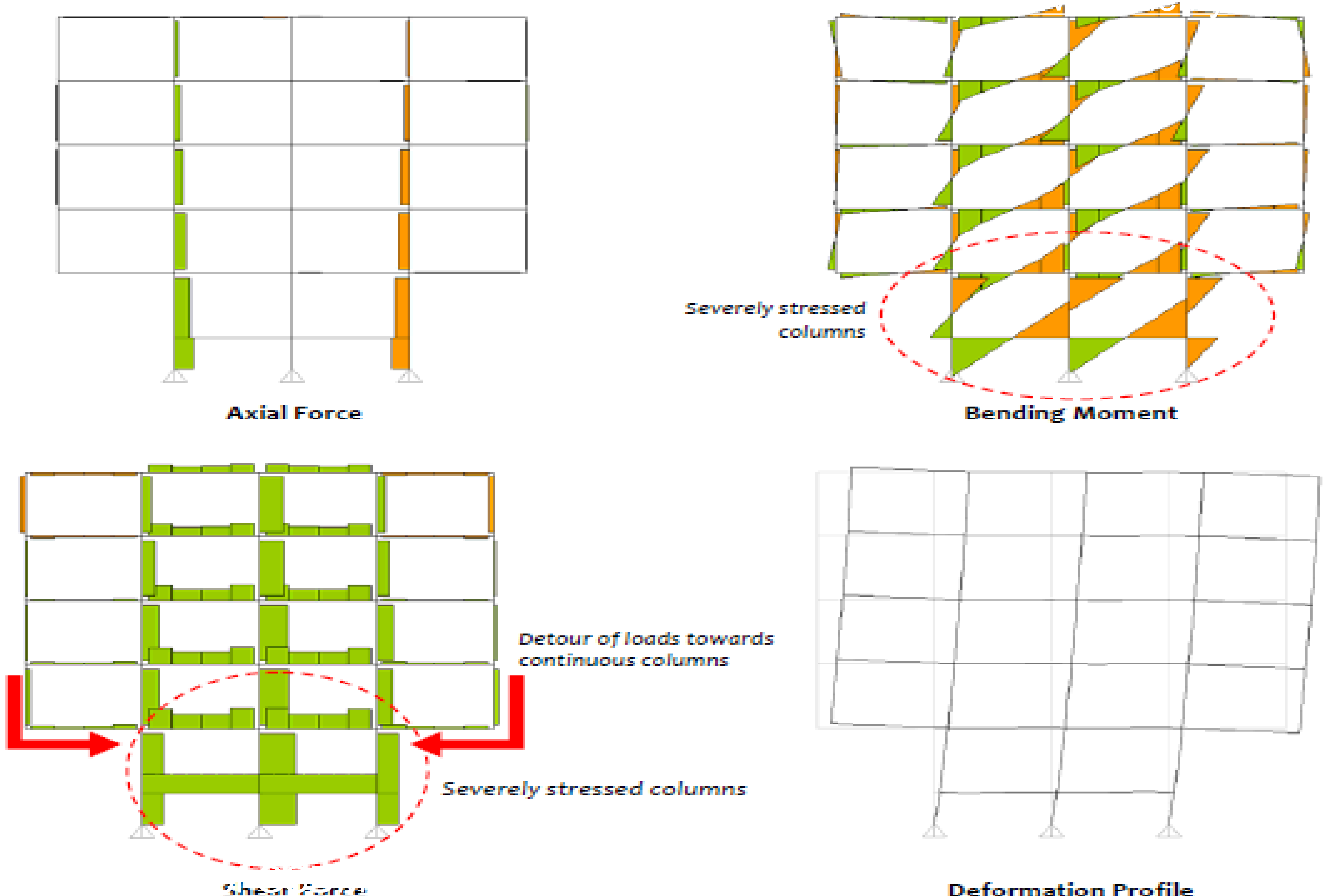
DISCONTINUITY IN LOAD PATH DUE TO FLOATING COLUMNS

WHAT ARE FLOATING COLUMNS ? WHY ARE THEY AVOIDED ?

- A common form of discontinuity in load path in moment frames arises with a *floating columns*, *i.e.,* when a column coming from top of the building is discontinued at a lower level, usually at the ground storey.
- In such cases, loads from the over hanging portions take a detour and travel to the nearest column that is continuous till the foundation. This leads to increased demand on the columns in the ground storey and can cause failure of these columns.



Images Property of GSDMA


Axial Force
Severely stressed
columns
Bending Moment
Detour of loads towards
continuous columns
Severely stressed columns
Shear Force
Deformation Profile

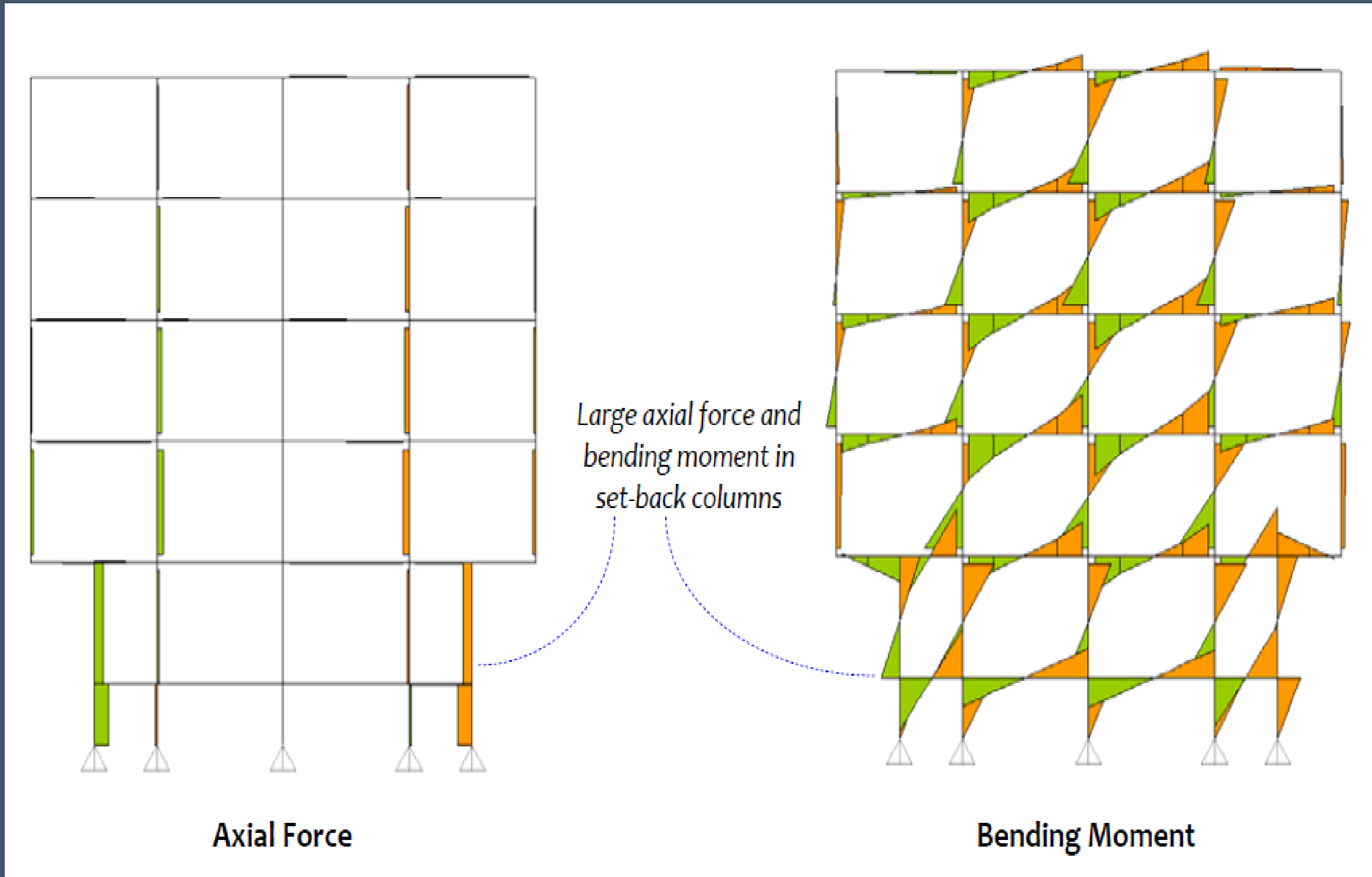
https://www.udemy.com/etabscourse/

Images Property of GSDMAM

DISCONTINUITY IN LOAD PATH DUE TO SETBACK COLUMNS

WHAT ARE SETBACK COLUMNS ? WHY ARE THEY AVOIDED ?

- Another common discontinuity in load path in moment frames arises with *set-back columns*, *i.e.,* when a column coming from top of the building is moved away from its original line, again usually at the ground storey.
- In such cases, loads from the over hanging portions take detour and cause severe stress concentration at the re-entrant corners while traveling to the nearest set-back column.
- In addition, the set-back divides the span of beams into smaller segments, and thereby, pushes these beams into shear action. These beams then draw large amount of shear force, and can fail in brittle shear mode.
- As a consequence, set-back columns subjected to large axial force, become vulnerable to combined axial-moment-shear failure

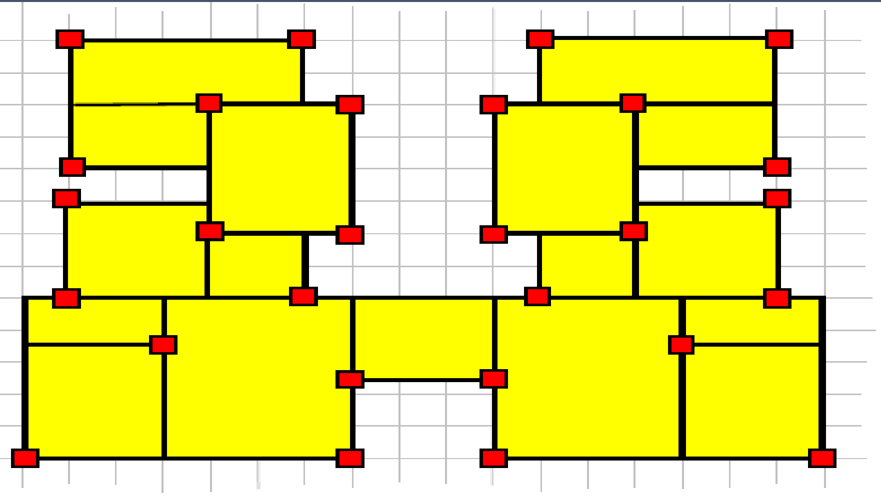


Images Property of GSDMA

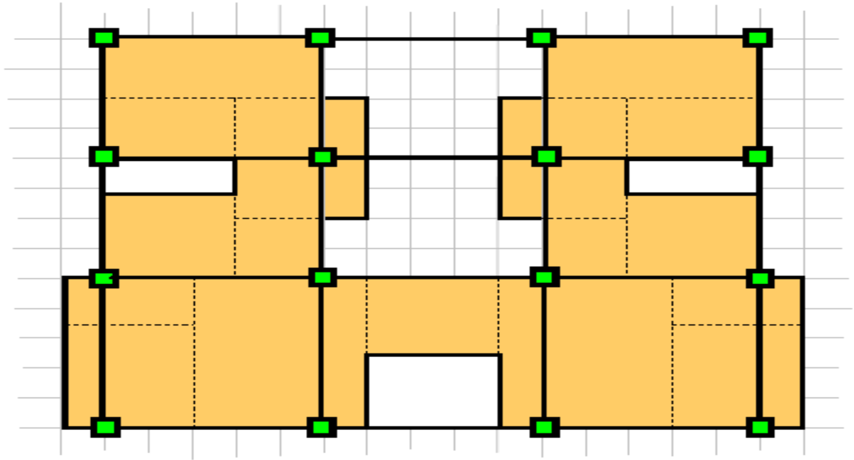
https://www.udemy.com/etabscourse/

DISCONTINUITY IN LOAD PATH DUE TO IMPROPER GRIDS

- Discontinuity of load path in the horizontal direction (in plan) occurs from *lack of grid* in the moment frame.
- Here, lateral load resisting columns are not aligned along a straight line in plan, but are inter-connected by beams that are at right angles to each other.
- Building A has columns not aligned along straight lines due to functional requirements but building B has all columns placed along proper grid in both directions.
- Such lack of grid (as in Building A) causes (i) torsion of the building (the first two modes of oscillation are torsional followed by translation in Y direction), and (ii) increase in shear in short span beams and consequently increase in axial load on columns

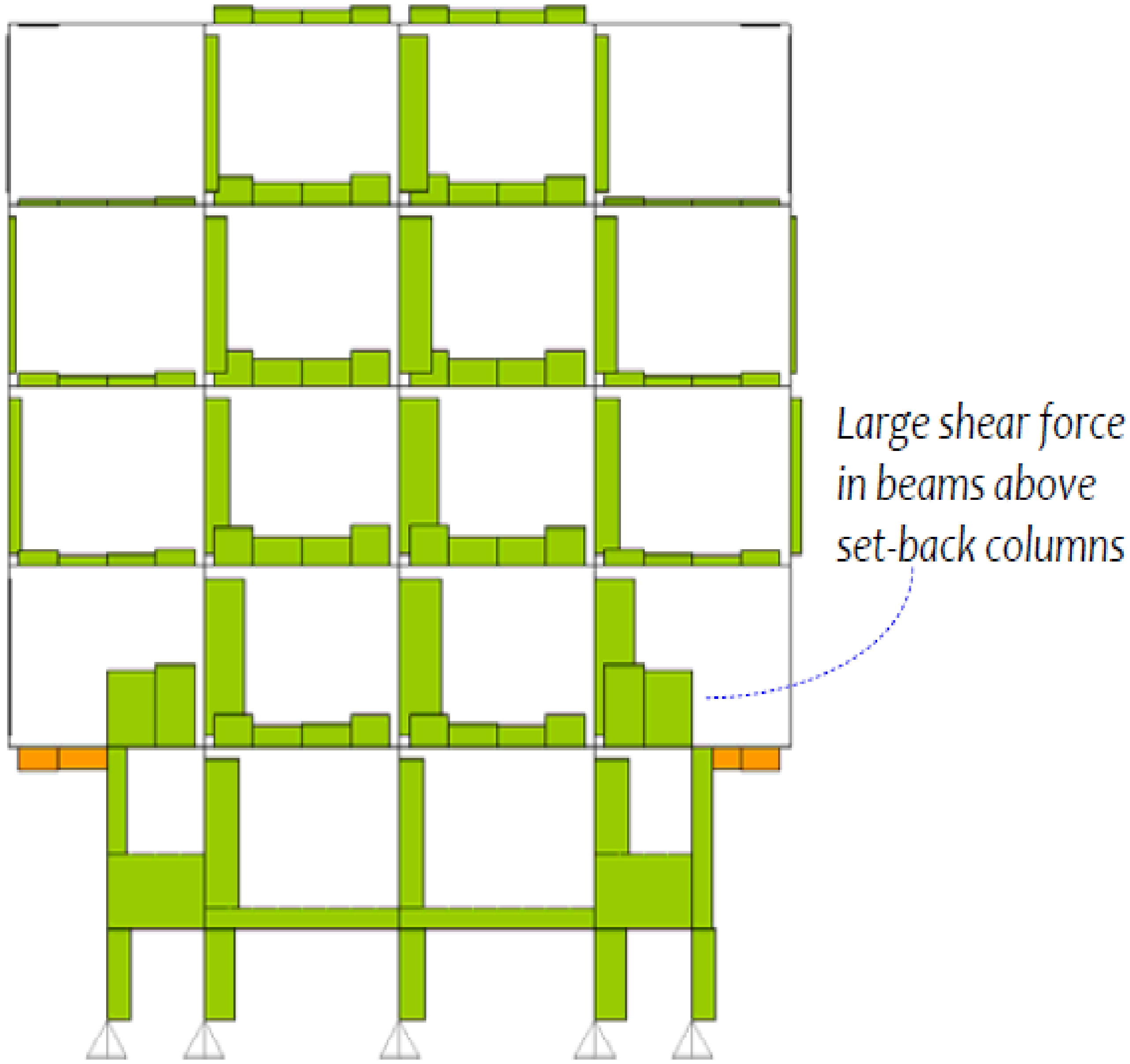


Building A
with lack of grid in plan

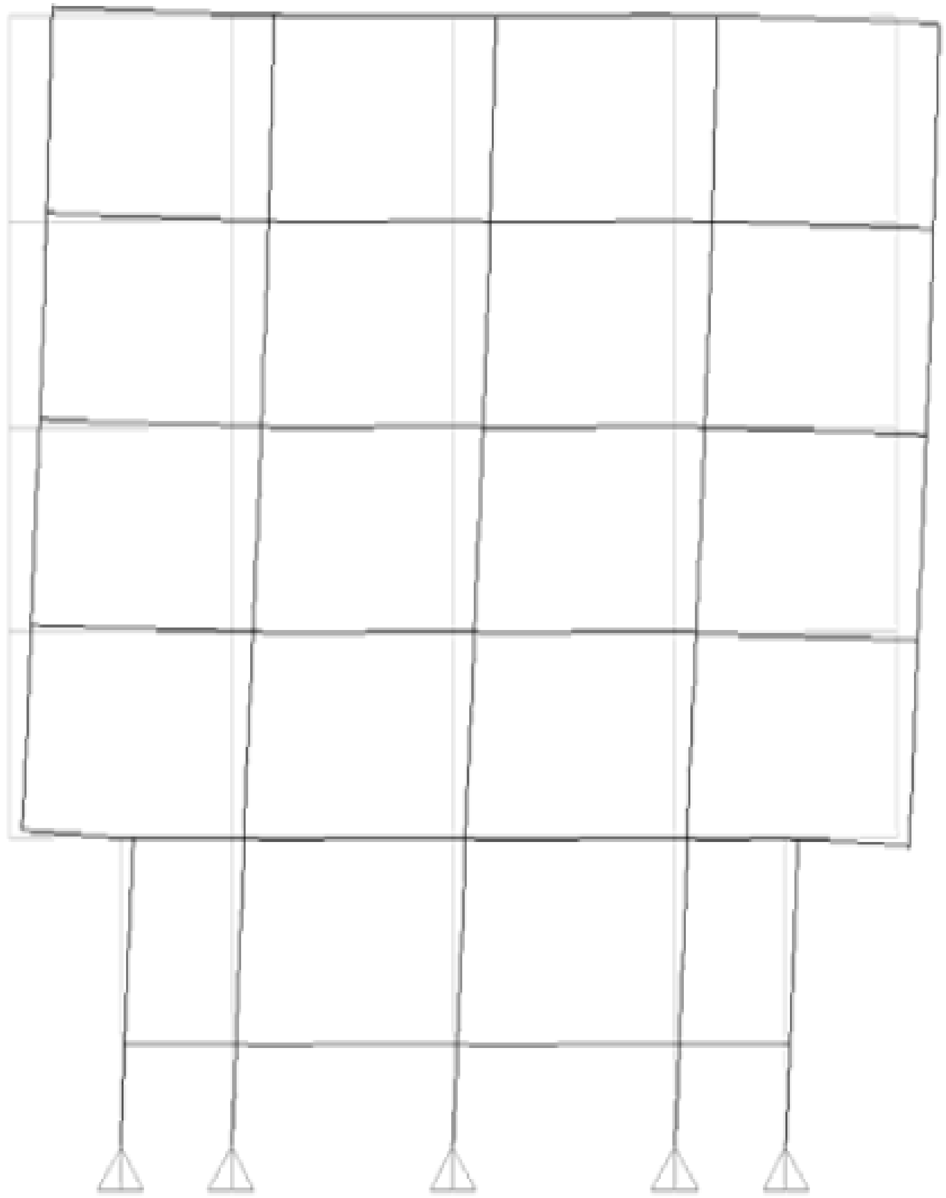


Building B
with proper grid in plan

Images Property of GSDMA

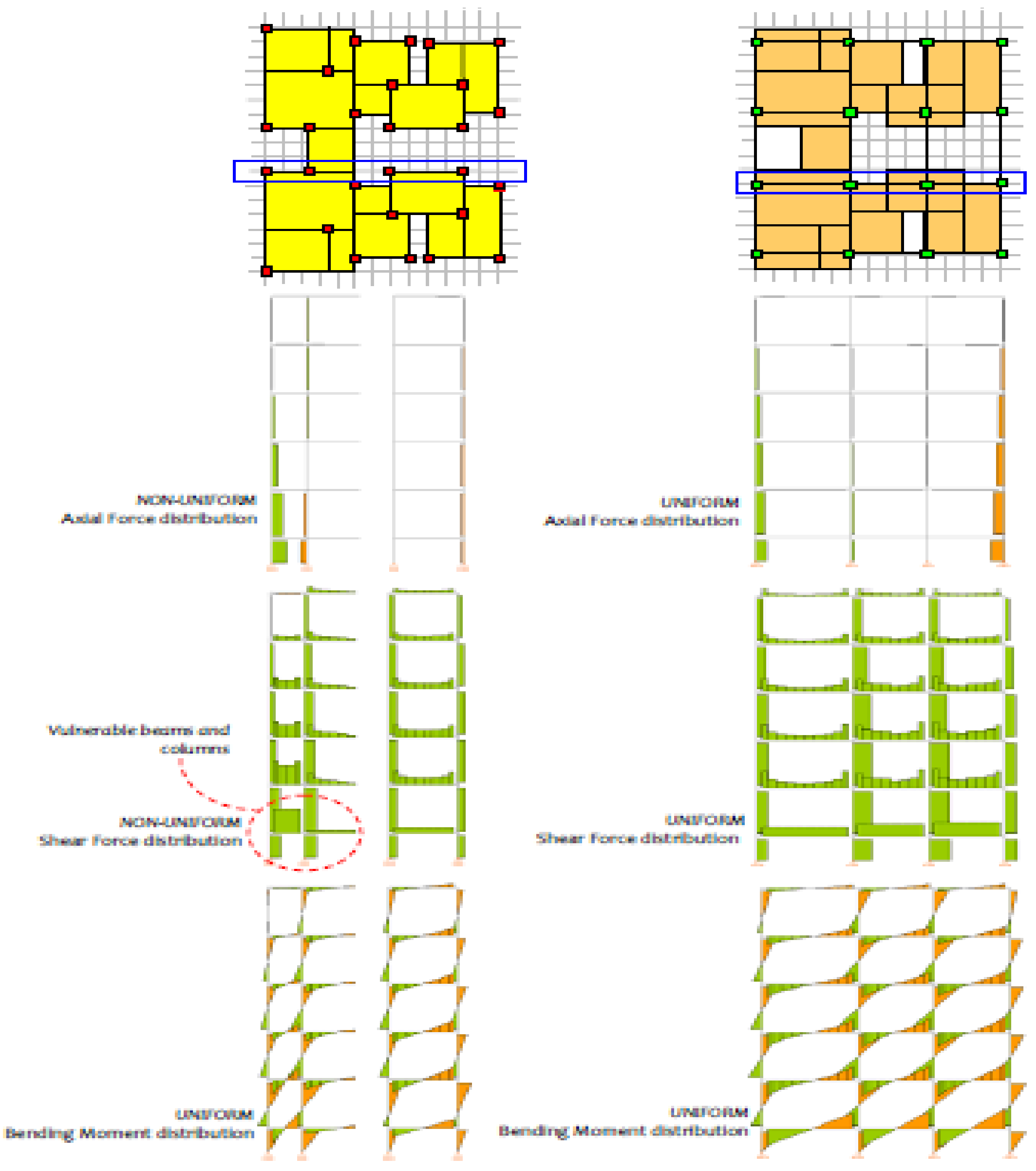


Shear Force



Deformation Profile

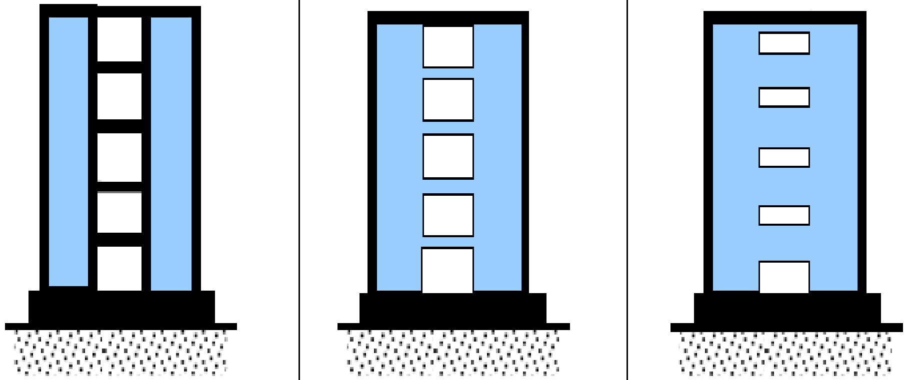
THIS NON-UNIFORM DISTRIBUTION OF LOADS TO DIFFERENT STRUCTURAL MEMBERS CAN INITIATE LOCALIZED FAILURES THAT IN TURN, CAN COMPROMISE THE STRUCTURAL INTEGRITY OF THE BUILDING, OR, EVEN TRIGGER GLOBAL COLLAPSE OF THE BUILDING.



Images Property of GSDMA

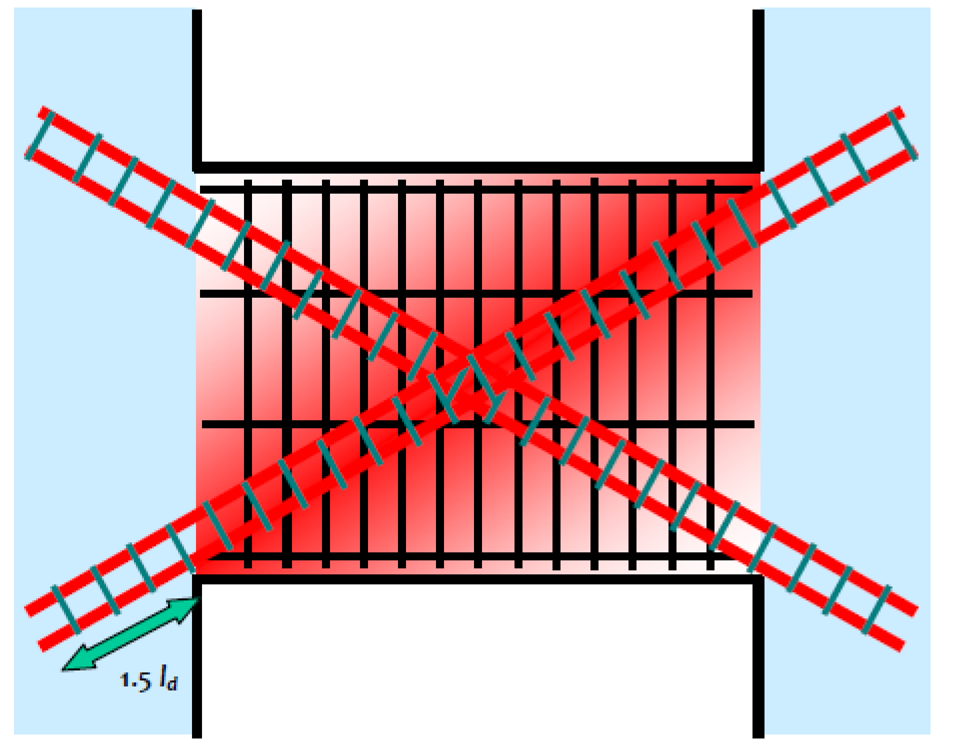
DISCONTINUITY IN LOAD PATH DUE TO STRUCTURAL WALLS

- Discontinuity in load paths in buildings with Structural Walls occurs due to openings in the wall; openings are required for doors and windows. Structural walls carry significant lateral load and help reduce demands on regular frame members, *i.e.,* columns and beams.
- However, openings, particularly of large sizes, in these walls affect the load path and alter structural response of buildings.

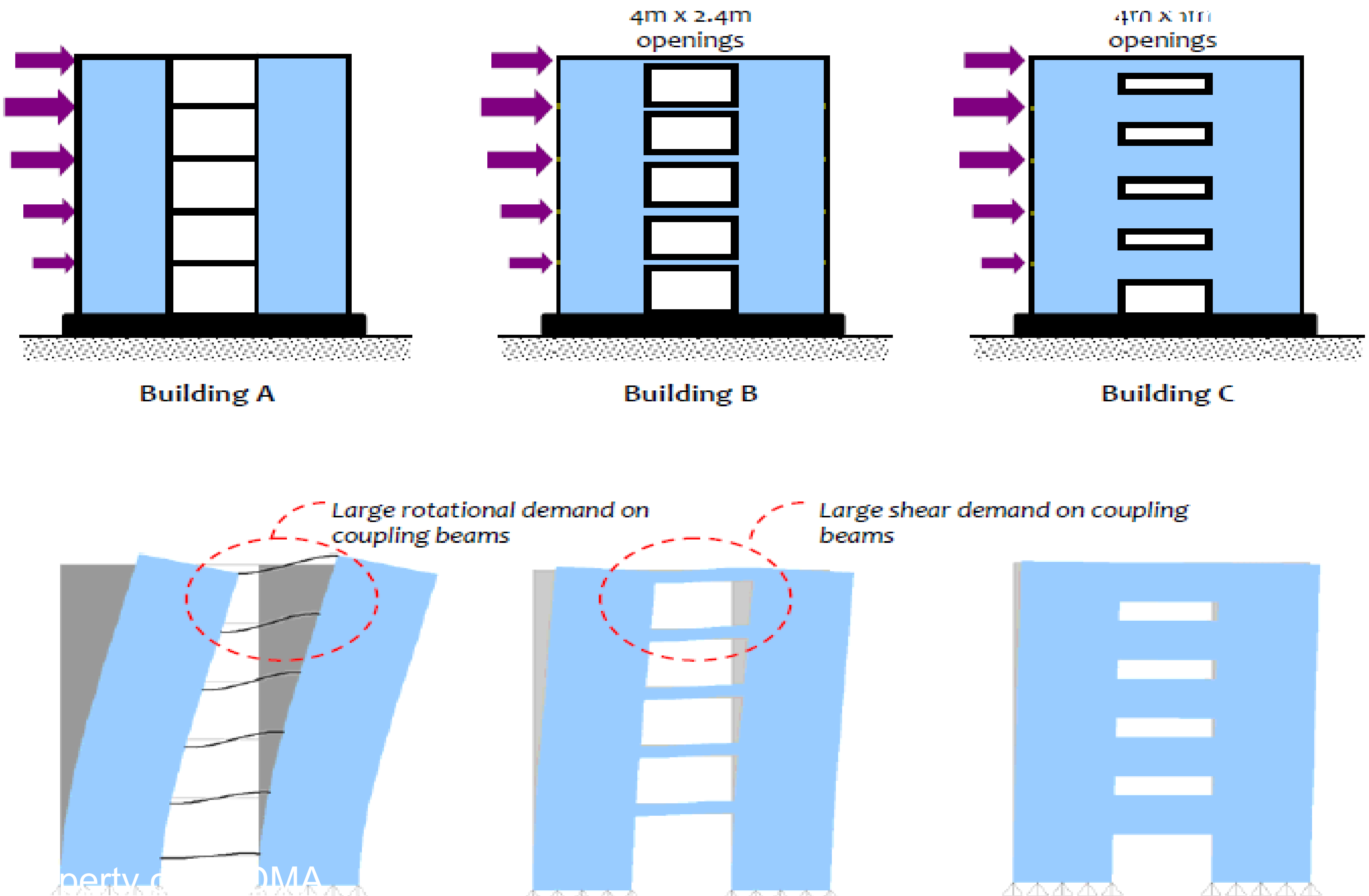


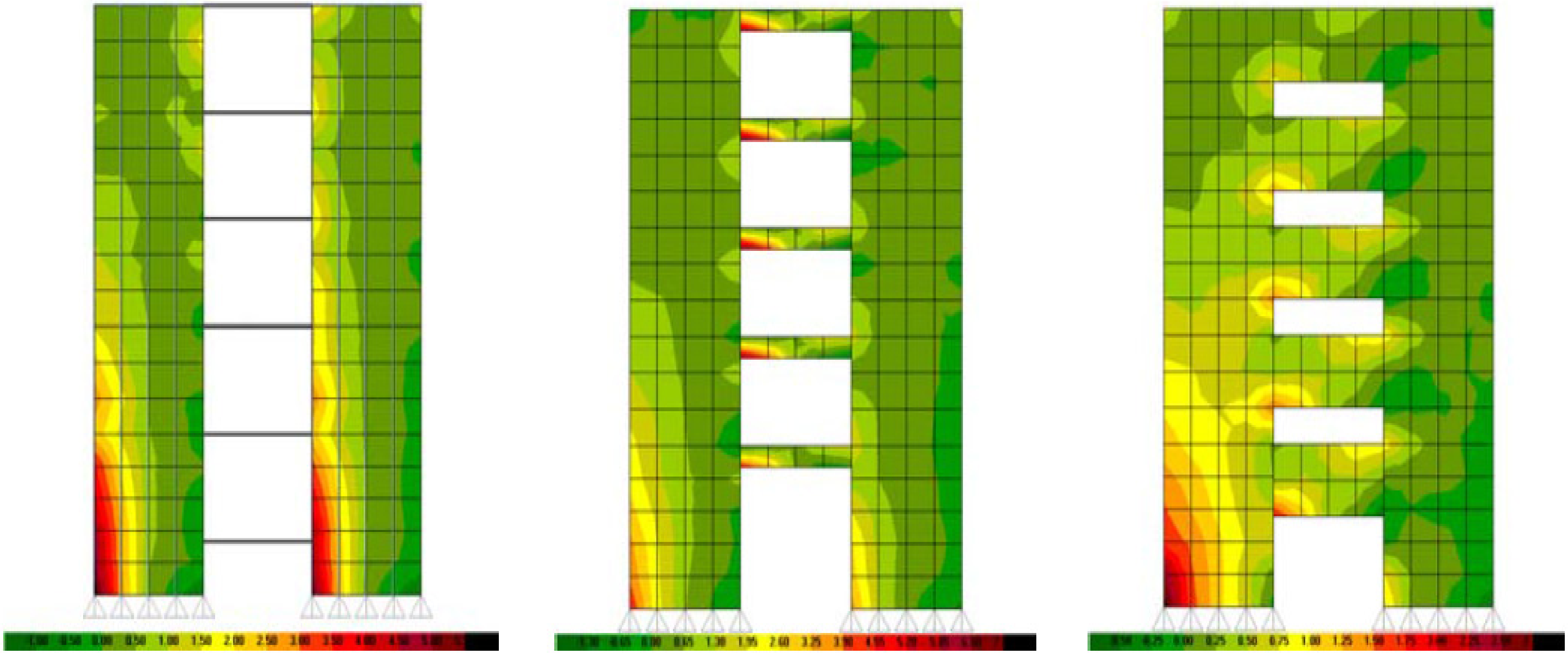
	Building A	Building B	Building C
Natural Period	0.38 s	0.30 s	0.19 s
Lateral Deformation	8.1 mm	4.4 mm	1.8 mm

- With reduction in opening, *i.e.,* with increase in depth of the coupling beams (as in building B), the overall lateral deformation is reduced, and the predominant action in the coupling beams changes from flexure to shear behavior. In such cases, special diagonal reinforcements along with confining reinforcement are to be provided in the coupling beams to resist the shear.
- With very small openings (as in building C), the coupling beams form a part of the entire wall and more uniform distribution of stresses is obtained in the wall.
- The lateral deformation is reduced with reduction in opening size; hence, large openings should not be provided in structural walls.



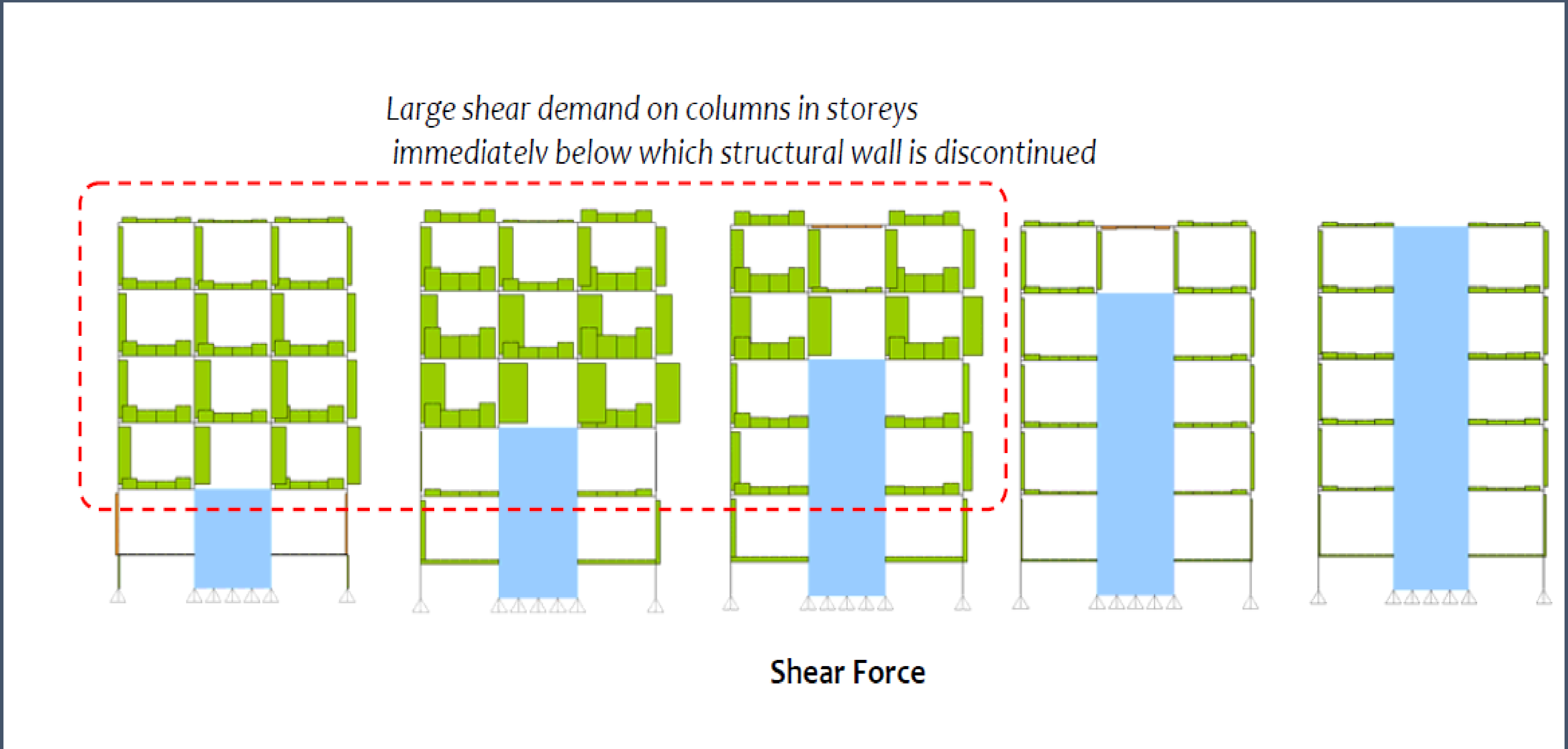
Images Property of GSDMA


4m x 2.4m
openings
openings
Building A
Building B
Building C
Large rotational demand on coupling beams
Large shear demand on coupling beams

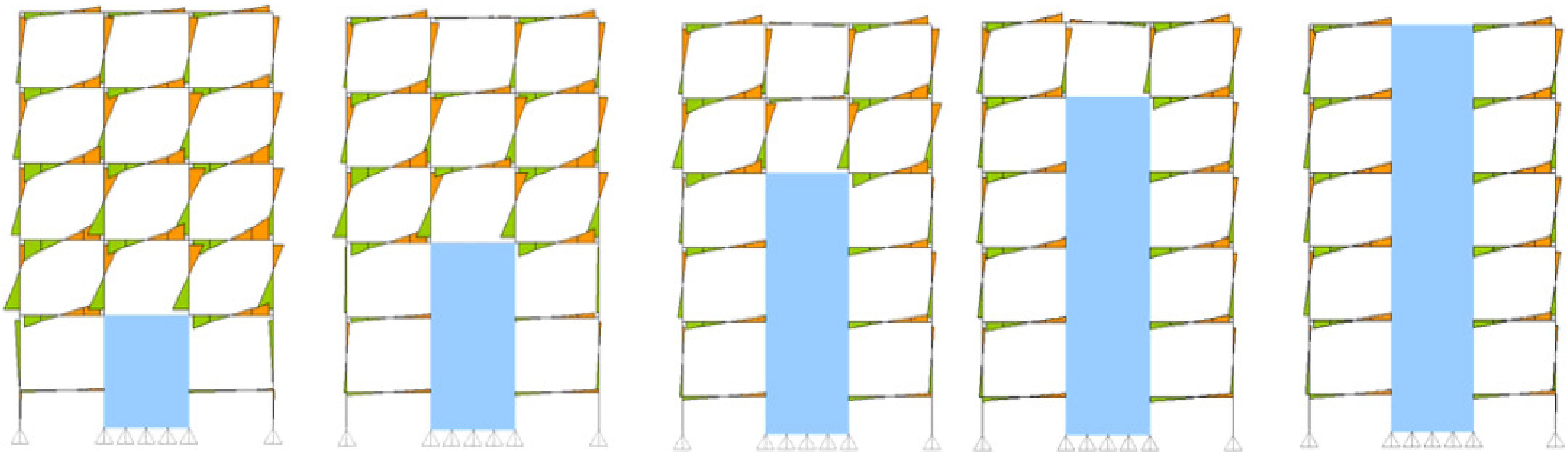


Principal Stresses

WHY STRUCTURAL WALL SHOULD BE PROVIDED THROUGH OUT THE HEIGHT OF THE BUILDING ?

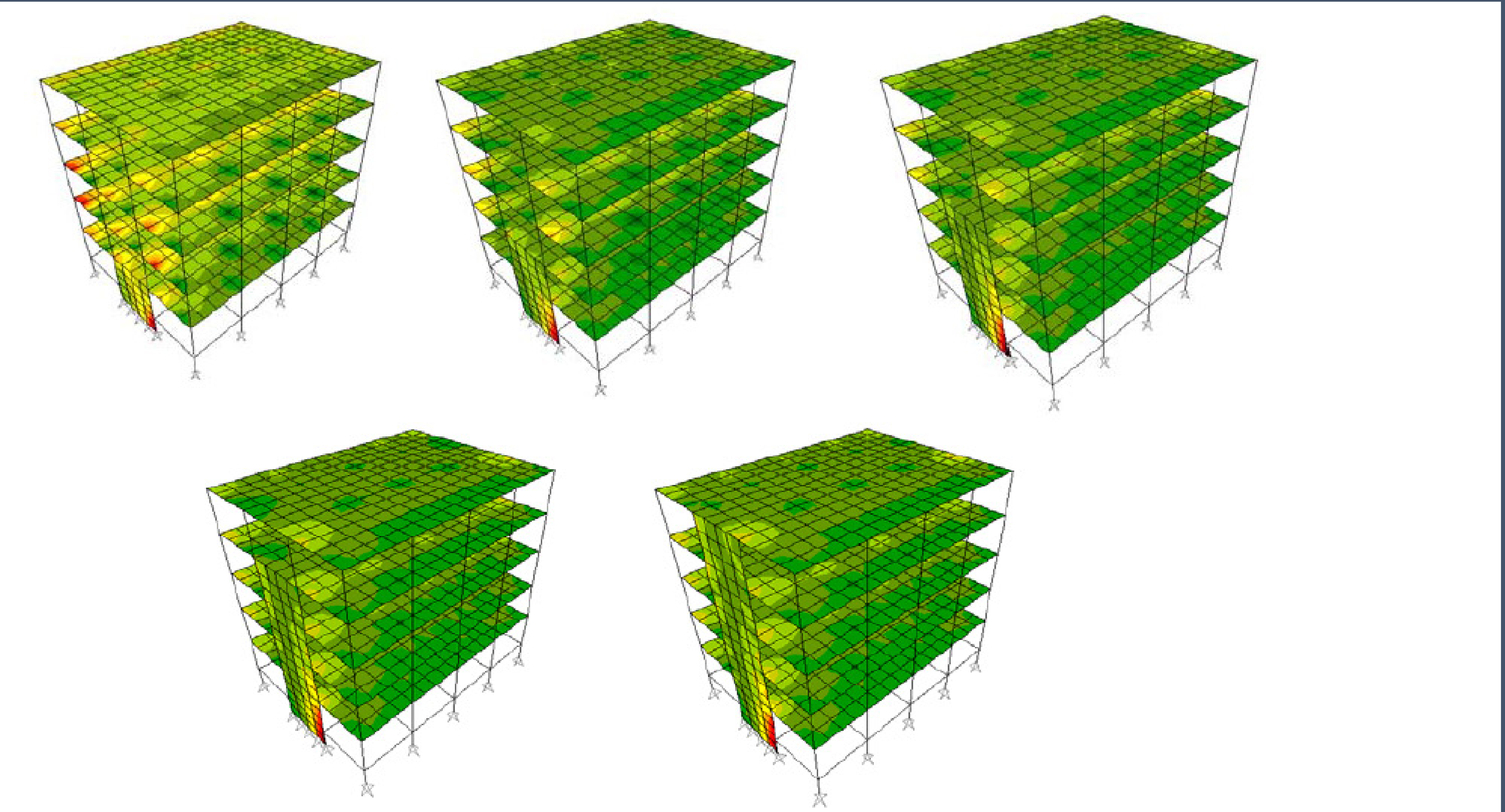


WHY STRUCTURAL WALL SHOULD BE PROVIDED THROUGH OUT THE HEIGHT OF THE BUILDING ?



Bending Moment

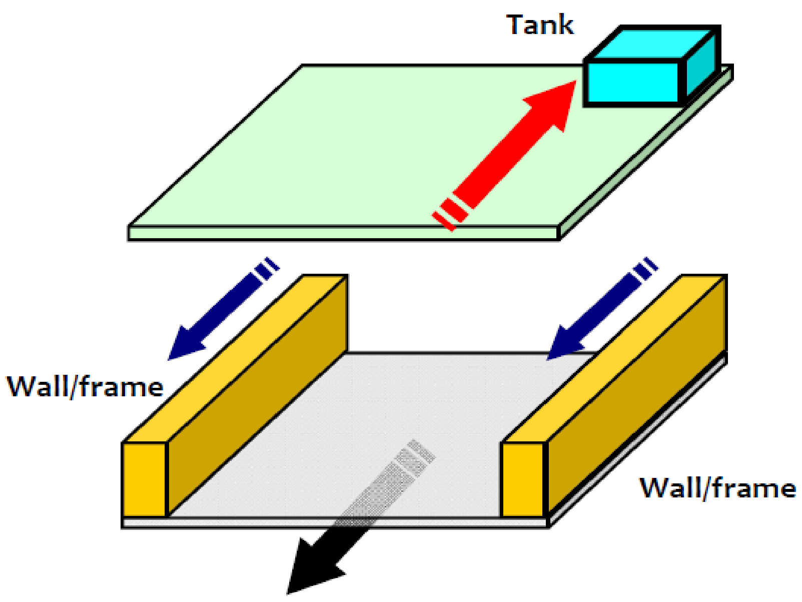
WHY STRUCTURAL WALL SHOULD BE PROVIDED THROUGH OUT THE HEIGHT OF THE BUILDING ?

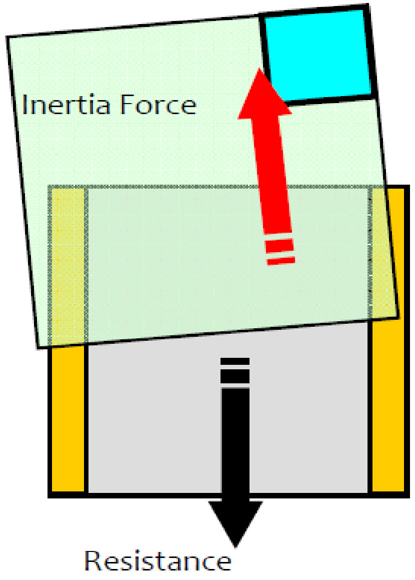


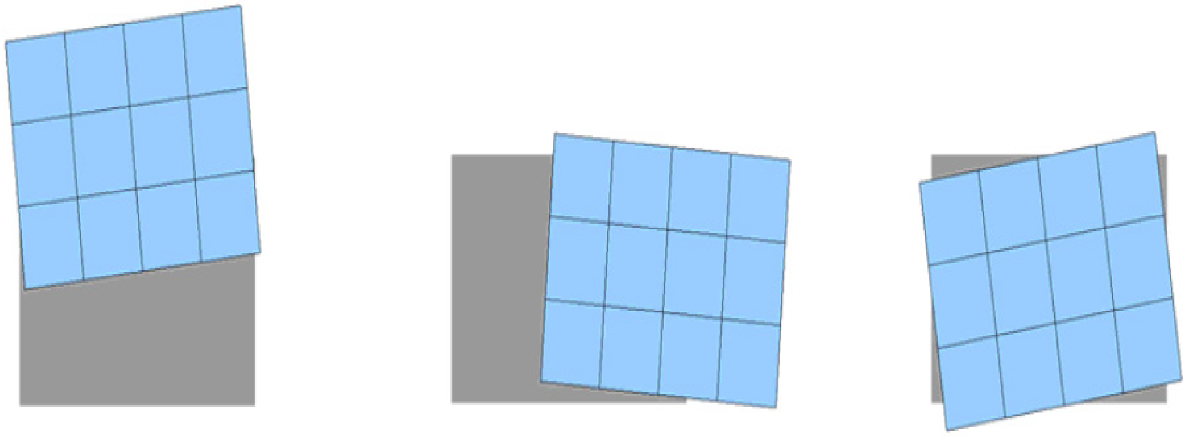
Images

WHY SHOULD WE WORRIED ABOUT THE ASSYMETRICAL MASS IN PLAN ?

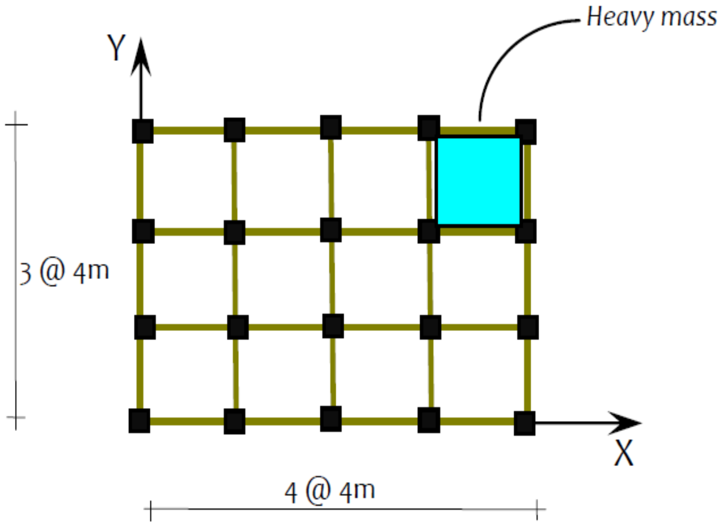
- It is a common practice to have water tanks at roof top. But usually, water tanks with large mass of water are placed at corners of buildings.
- This affects the distribution of mass in plan, at least at the roof level.
- This asymmetry in mass in plan causes twisting of buildings during earthquake shaking due to mismatch of center of mass and center of rigidity.



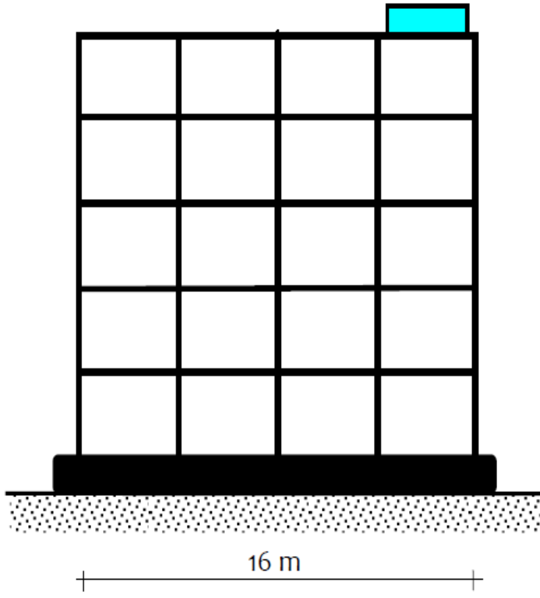




$T_1 = 0.91$ s $\quad$ $T_2 = 0.89$ s $\quad$ $T_3 = 0.70$ s



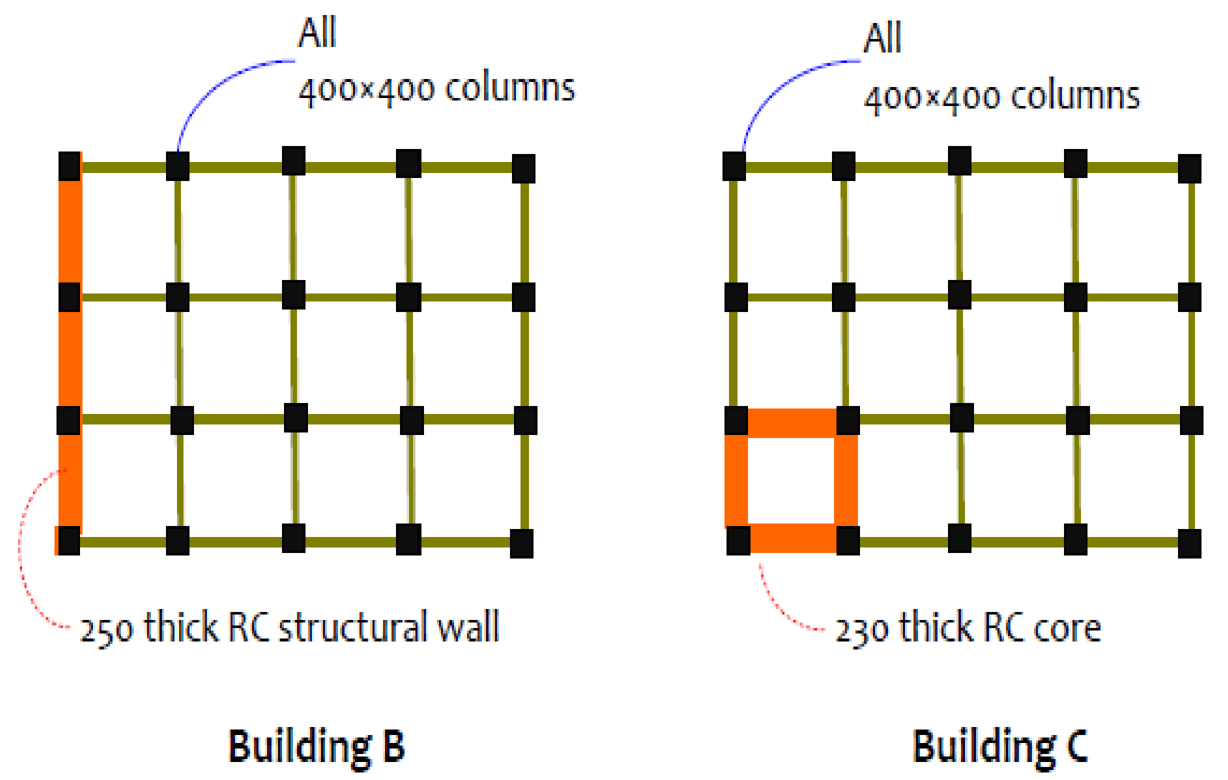
Plan

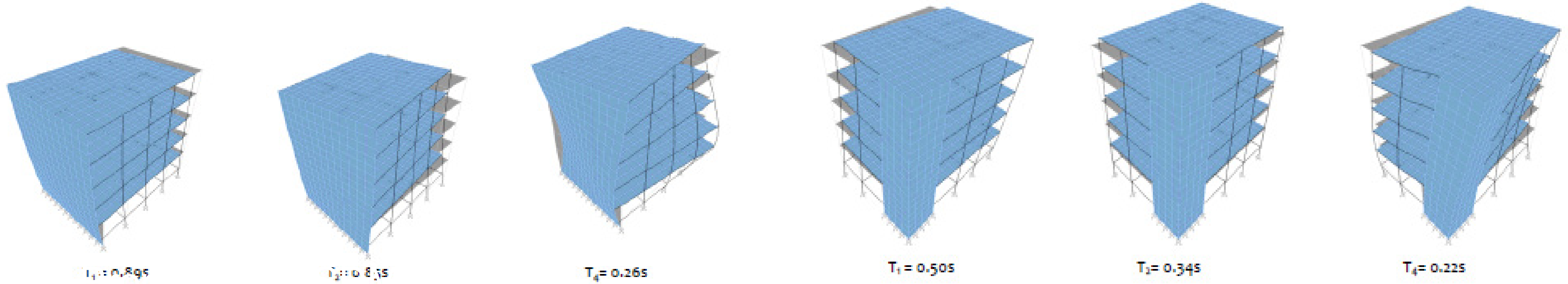


Elevation

WHY SHOULD WE WORRIED ABOUT THE ASSYMETRICAL STIFFNESS IN PLAN ?

- Irregularity in stiffness in plan occurs due to
- (a) use of columns of different sizes,
- (b) presence of structural wall on one side of buildings, or
- (c) presence of staircase or elevator core at one corner of buildings
- Stiffness irregularity in plan causes twisting of buildings under lateral load.

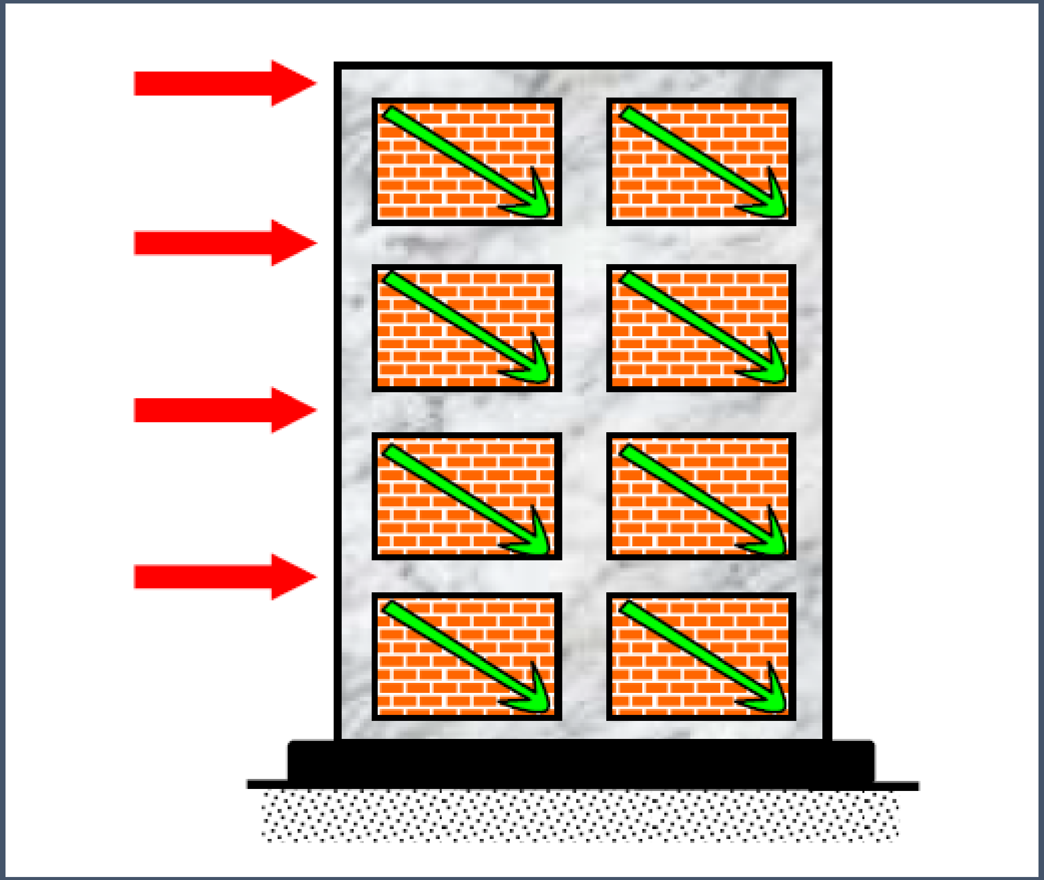




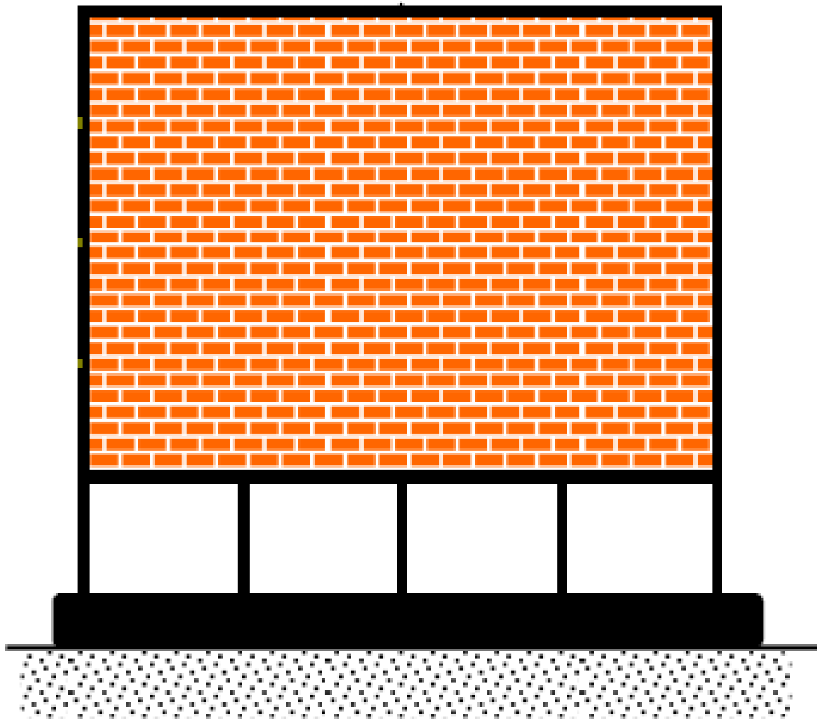
WHY SHOULD WE WORRIED ABOUT THE ASSYMETRICAL STIFFNESS IN ELEVATION ?

(A) OPEN OR FLEXIBLE STOREY IN BUILDINGS

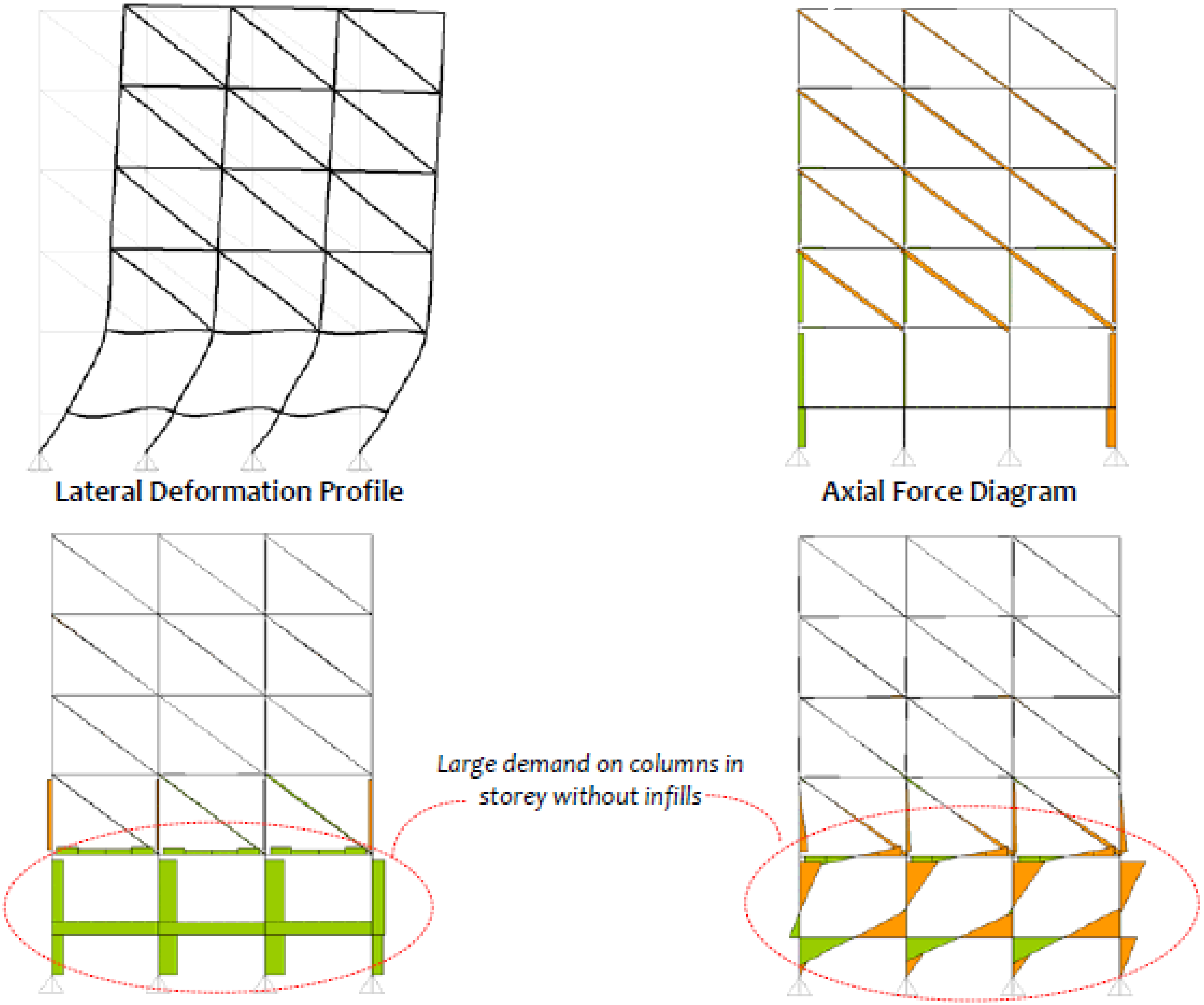
- Lateral stiffness irregularity occurs in elevation when
- (a) sizes of lateral load resisting elements are varied along the height of buildings, and
- (b) additional elements are added or existing elements are removed



HENCE, MODELING OF UNREINFORCED MASONRY INFILLED FRAME BUILDINGS FOR STRUCTURAL ANALYSIS SHOULD INCLUDE MASONRY INFILLS AS DIAGONAL COMPRESSION-ONLY STRUT MEMBERS.

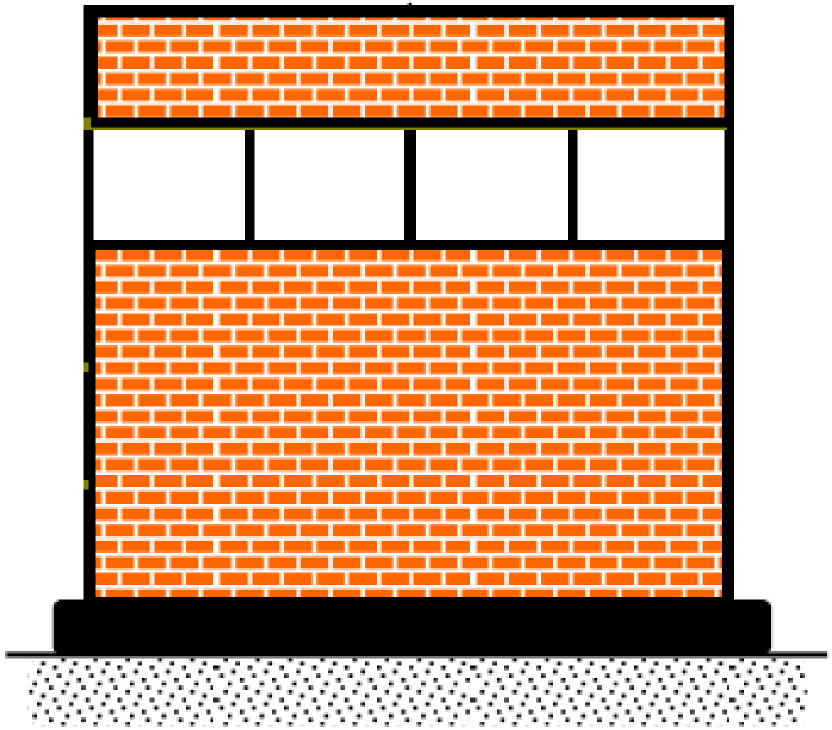


Building A

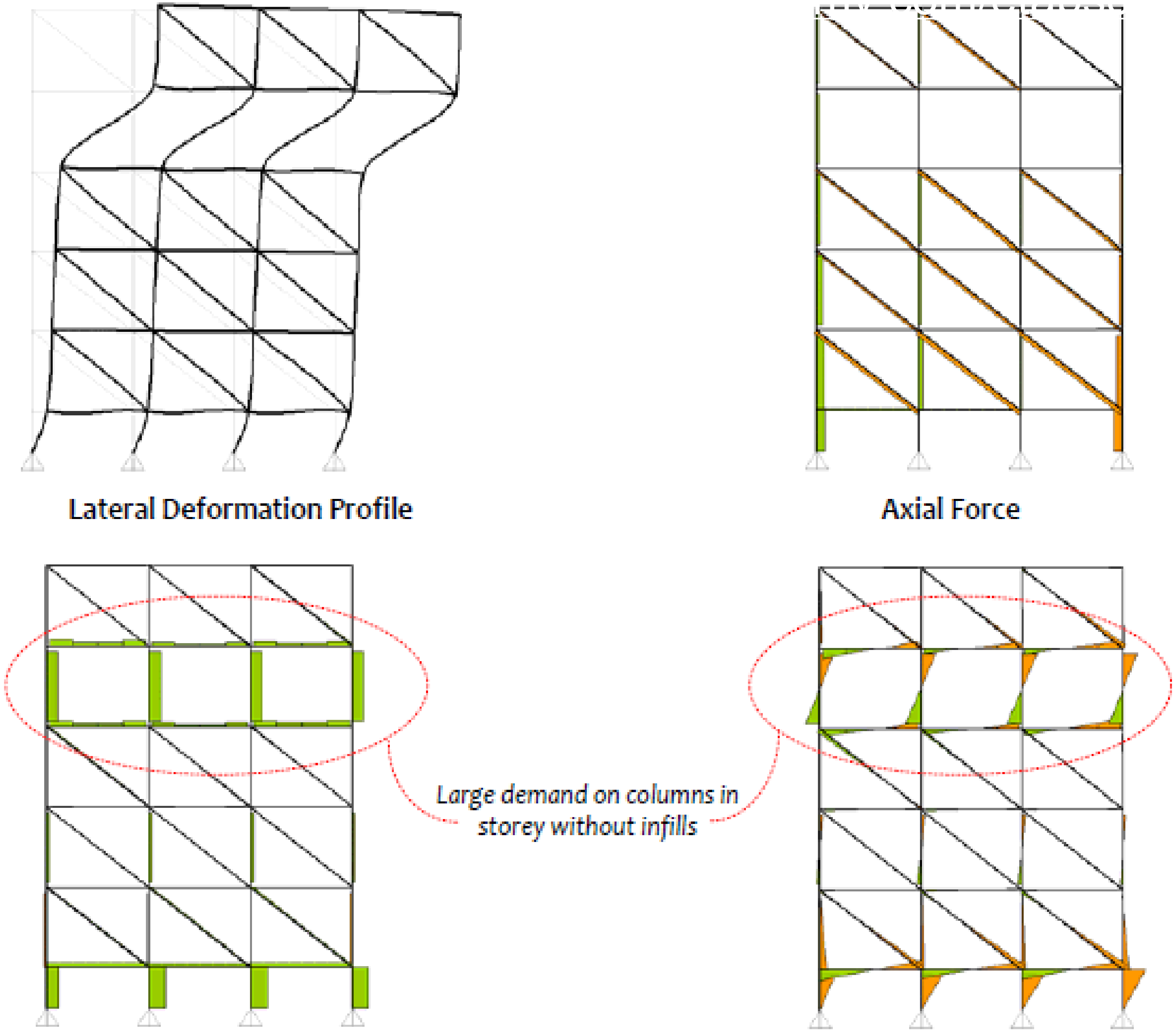


Building A
Open Ground Storey Building

Images Property of GSDMA

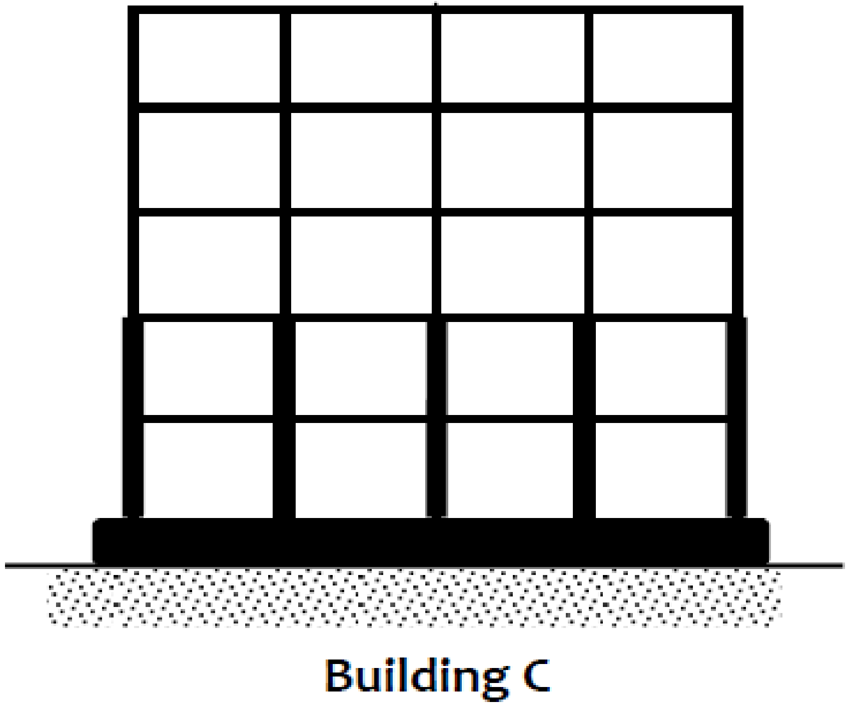


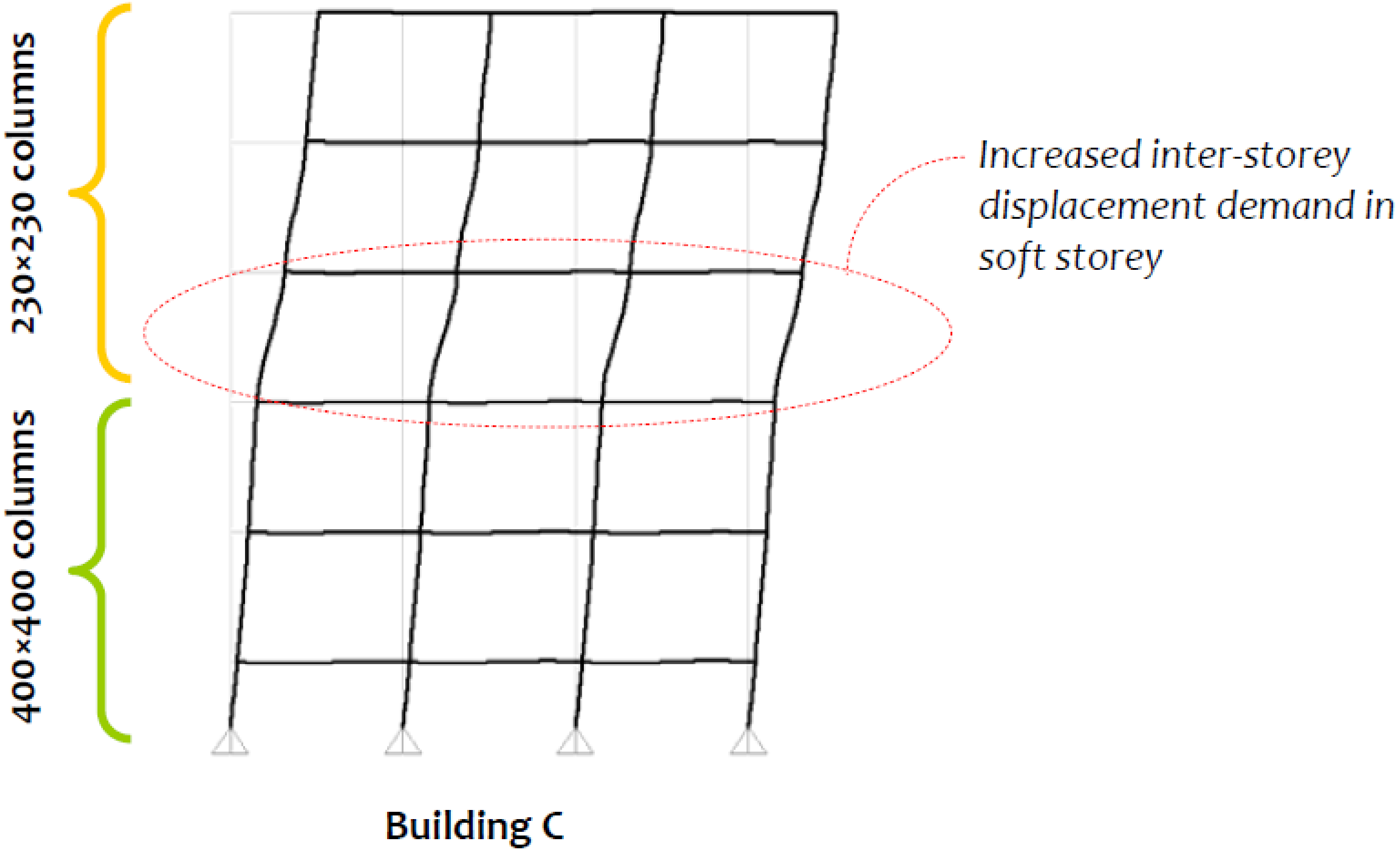
Building B



Building B

Images Property of GSDMA


Building C

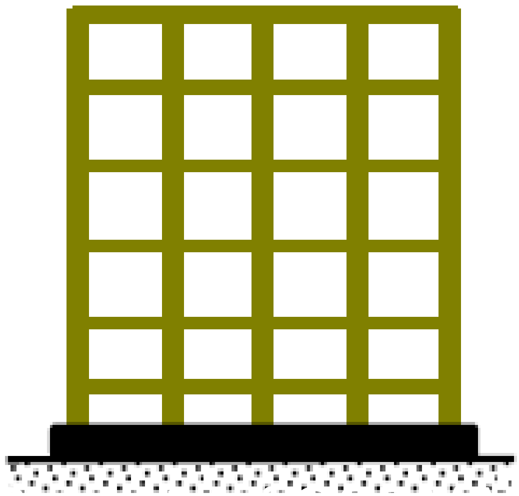

230×230 columns
400×400 columns
Increased inter-storey displacement demand in soft storey
Building C

WHY SHOULD WE WORRIED ABOUT THE ASSYMETRICAL STIFFNESS IN ELEVATION ?

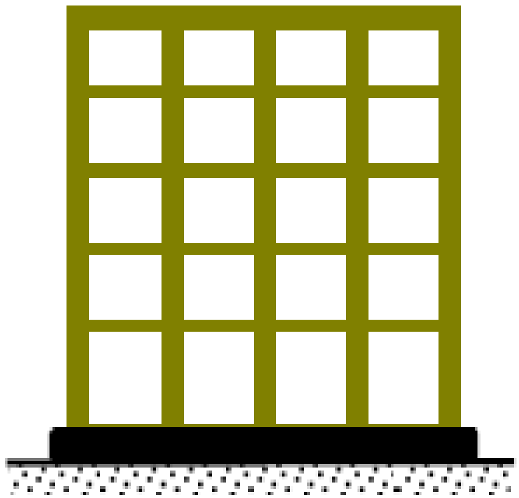
(B) PLINTH BEAMS

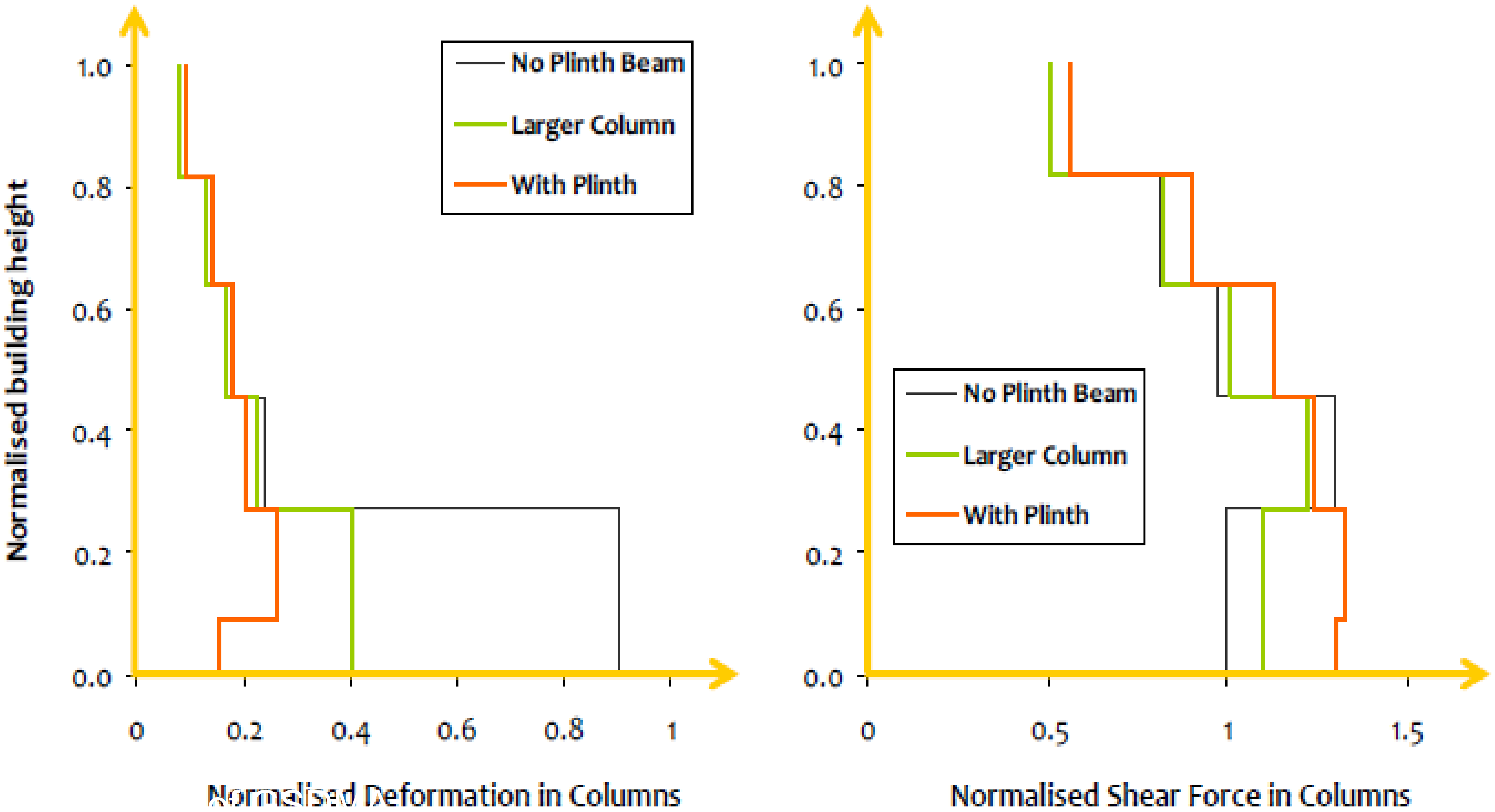
- *Plinth beams* are structural members (beams) and reduce the effective length of ground storey column which are generally longer than those in the upper storey.
- As a result, the stiffness of the ground storey columns is altered by the addition of plinth beams.
- The deformation demand on the building without plinth beam is largely concentrated at the ground storey level because of low lateral stiffness of the longer columns; this is reduced significantly by the addition of plinth beam. But, shear force increases with addition of plinth beam, particularly in the ground storey columns due to the short column effect.

Building with Plinth Beam



Building without Plinth Beam



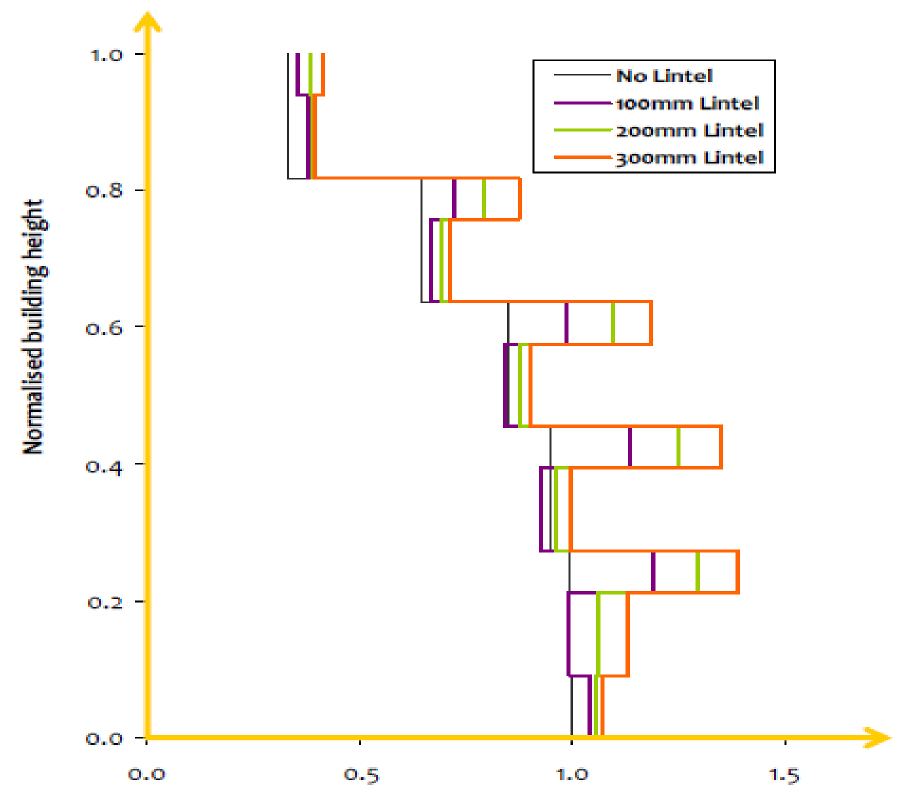


No Plinth Beam
Larger Column
With Plinth
Normalised building height
1.0
0.8
0.6
0.4
0.2
0.0
0
0.2
0.4
0.6
0.8
1
Normalised Deformation in Columns
No Plinth Beam
Larger Column
With Plinth
1.0
0.8
0.6
0.4
0.2
0.0
0
0.5
1
1.5
Normalised Shear Force in Columns

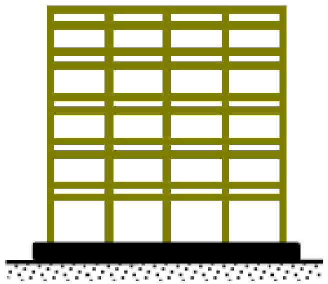
WHY SHOULD WE WORRIED ABOUT THE ASSYMETRICAL STIFFNESS IN ELEVATION ?

(C) LINTEL BEAMS

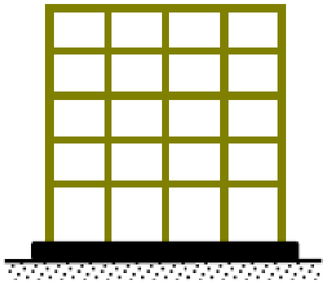
- *Lintel beams* introduce local deformation restraint at locations, when they frame into columns. The level of restraint depends on the relative stiffness of the lintel beam and the column.
- With increase in lintel size, deformation restraint offered increases, and the column region between the lintel and roof beam exhibits short column effect.
- The shear demand imposed on columns increases with increase in size of lintel.



Building with Lintel Beam



Building without Lintel Beam



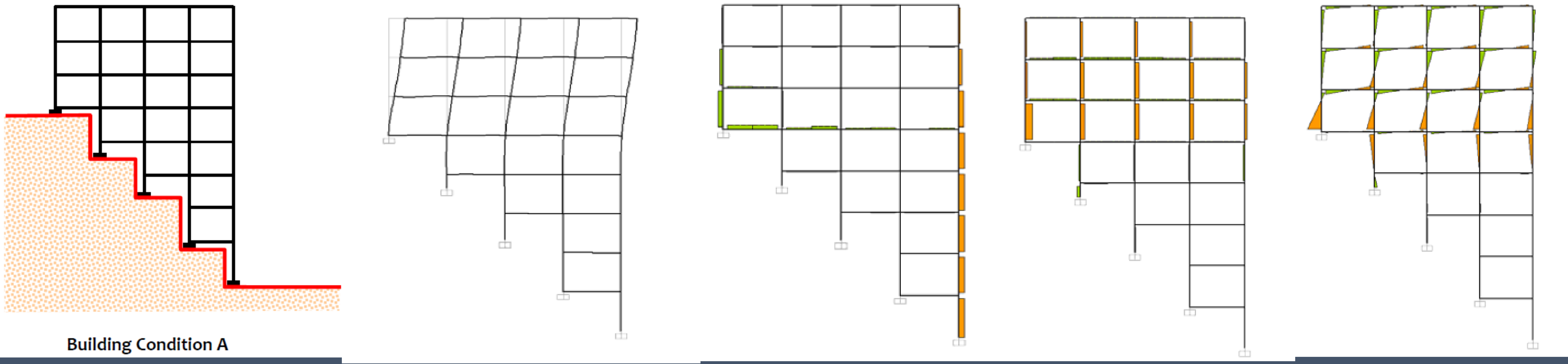
WHY SHOULD WE WORRIED ABOUT THE ASSYMETRICAL STIFFNESS IN ELEVATION ?

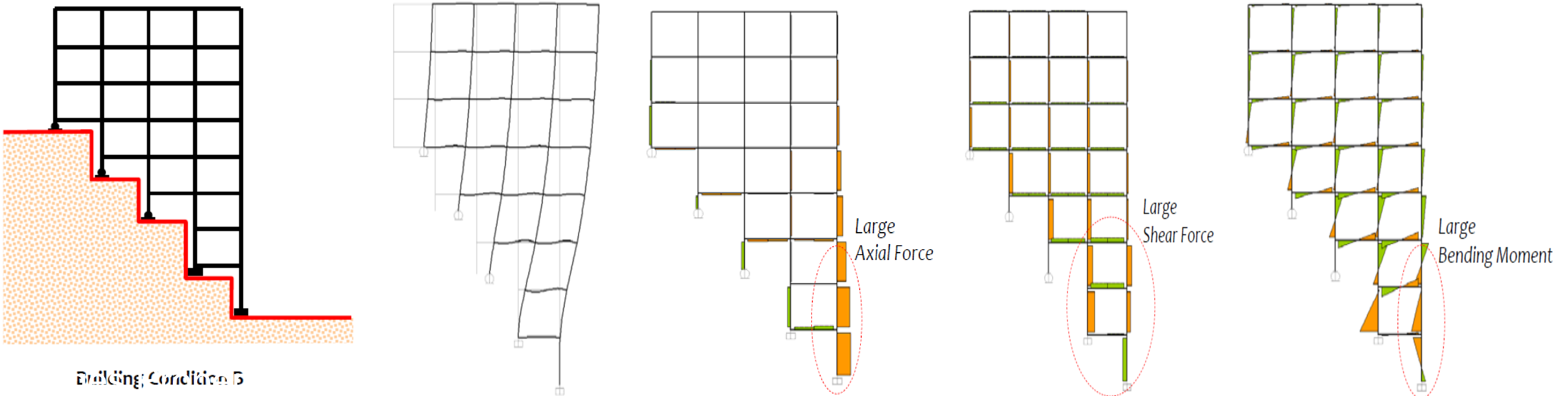
(C) BUILDINGS ON SLOPE

- Buildings are constructed on slopes in hill regions.
- Typical features of these buildings include *columns of unequal lengths along the slope*, and *lack of proper foundation well embedded into the soil underneath* to provide adequate translational fixity under lateral earthquake shaking.
- Two basic types of fixity conditions are achieved depending on construction type and local soil/rock strata;
- one that provides full translational and rotational restraints,
- and the other that do not provide the same.
- Lack of translational and rotational fixity occurs due to slope subsidence particularly during strong earthquake shaking. Actual degree of fixity (translational and rotational) varies

WHY SHOULD WE WORRIED ABOUT THE ASSYMETRICAL STIFFNESS IN ELEVATION ?

(C) BUILDINGS ON SLOPE



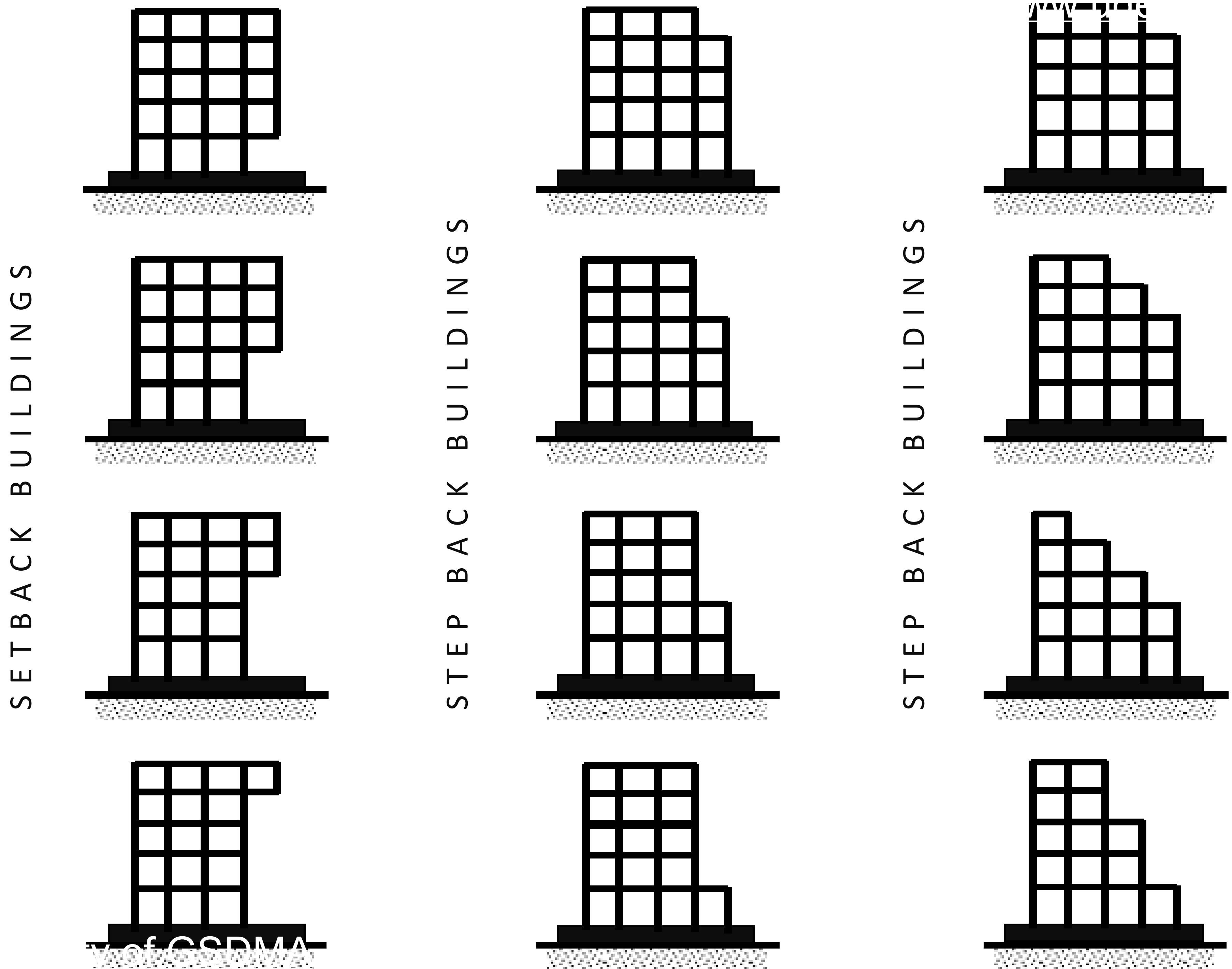


WHY SHOULD WE WORRIED ABOUT THE ASSYMETRICAL STIFFNESS IN ELEVATION ?

(C) SETBACK IN BUILDINGS

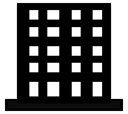
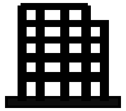
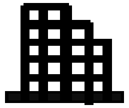
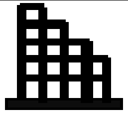
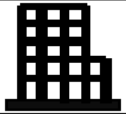
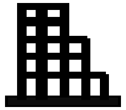
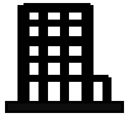
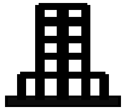
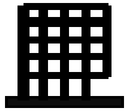
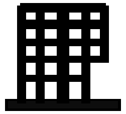
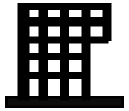
- Irregularity in overall geometry of the building in elevation also is detrimental to good earthquake behavior of buildings.
- The common types of overall geometric irregularities include *set-back buildings* and *step-back buildings*.
- These geometric forms arise largely from architectural extravaganzas, and result in concave geometries that have a number of re-entrant corners at which load paths are disturbed requiring sharp bends.

Images Property of GSDMA



SETBACK BUILDINGS
STEP BACK BUILDINGS
STEP BACK BUILDINGS

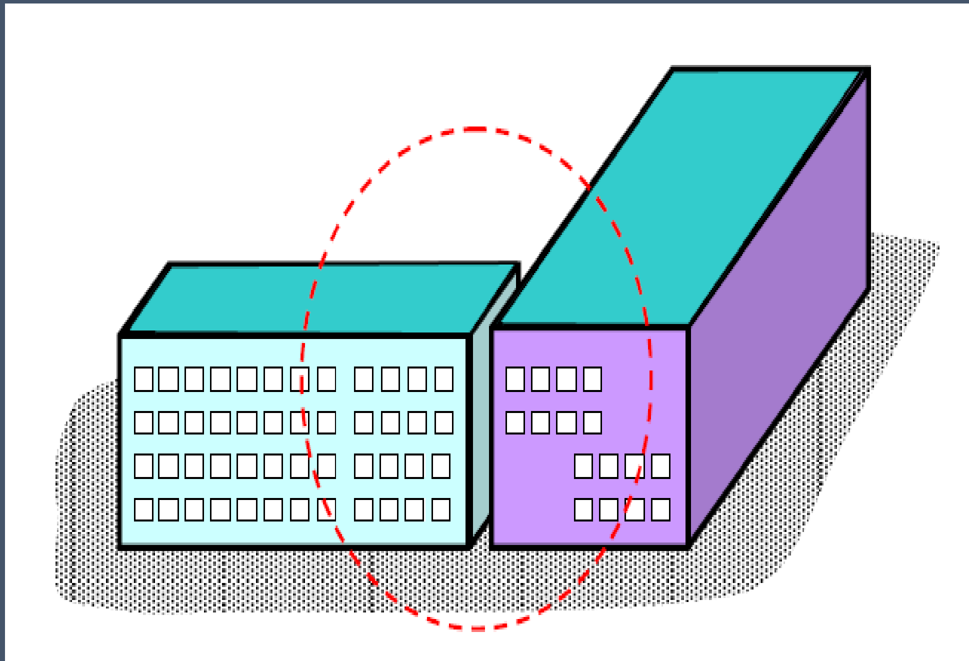
- Both mass and stiffness distribution changes along the height; the center of mass and center of stiffness of different storey do not lie along the same vertical line, as is the case in buildings with regular overall geometry. This results in twisting of buildings

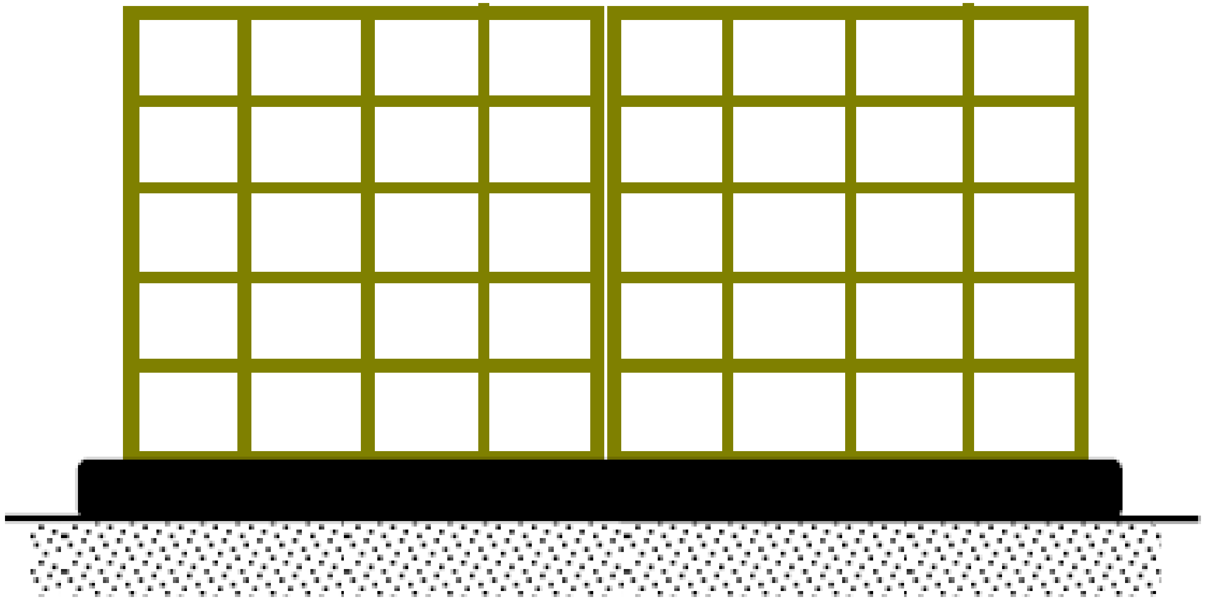
Type of Building	*Mode 1*	*Mode 2*	*Mode 3*
	Y-translation (*0.89 s*)	X translation (*0.87 s*)	*Torsion* (*0.79 s*)
	Y-translation with torsion (*0.87 s*)	X translation (*0.84 s*)	*Torsion* (*0.74 s*)
	Y-translation with torsion (*0.84 s*)	X translation (*0.78 s*)	*Torsion* (*0.65 s*)
	Y-translation with torsion (*0.78 s*)	X translation (*0.70 s*)	*Torsion* (*0.54 s*)
	Y-translation with torsion (*0.86 s*)	X translation (*0.81 s*)	*Torsion* (*0.67 s*)
	Y-translation with torsion (*0.82 s*)	X translation (*0.75 s*)	*Torsion* (*0.58 s*)
	Y-translation with torsion (*0.86 s*)	X translation (*0.83 s*)	*Torsion* (*0.69 s*)
	Y-translation (*0.73 s*)	X translation (*0.72 s*)	*Torsion* (*0.56 s*)
	Y-translation with torsion (*0.99 s*)	X translation (*0.96 s*)	*Torsion* (*0.82 s*)
	Y-translation with torsion (*1.03 s*)	X translation (*0.96 s*)	*Torsion* (*0.82 s*)
	Y-translation with torsion (*1.03s*)	X translation (*0.94 s*)	*Torsion* (*0.82 s*)

Images Property of GSDMA

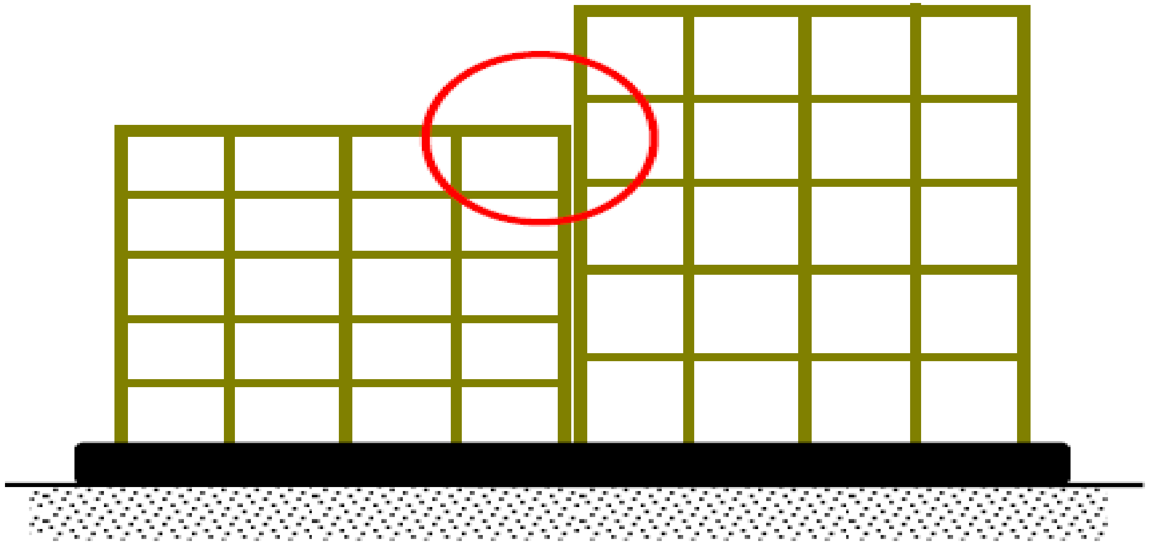
WE SHOULD ALWAYS AVOID POUNDING OF BUILDING WITH ADJACENT BUILDINGS ?

- it is possible that the adjacent buildings or parts may collide with each other during earthquake shaking.
- Hence, at least a minimum design separation distance needs to be provided to avoid pounding of two adjacent buildings or parts of a building during earthquake shaking.
- Thus, when a designer is compelled to build close to an adjacent building or make a building in two parts, there is a need to recognize the actual lateral displacement of each building or part of the building, and provide calculated amount of gap that they need between them.
- When this is done, the junction of the two buildings or two parts of the same building is called a *Seismic Joints.*

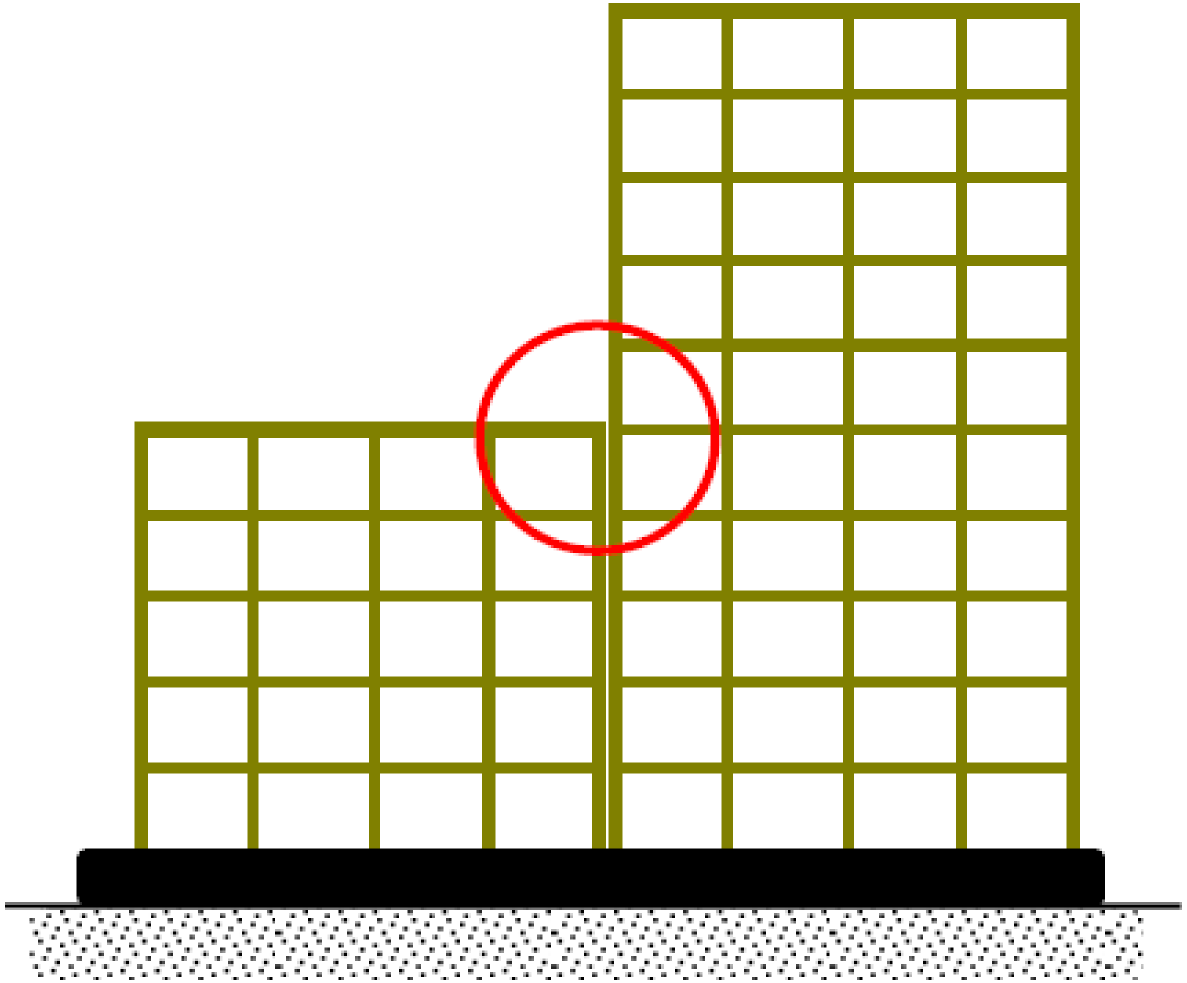




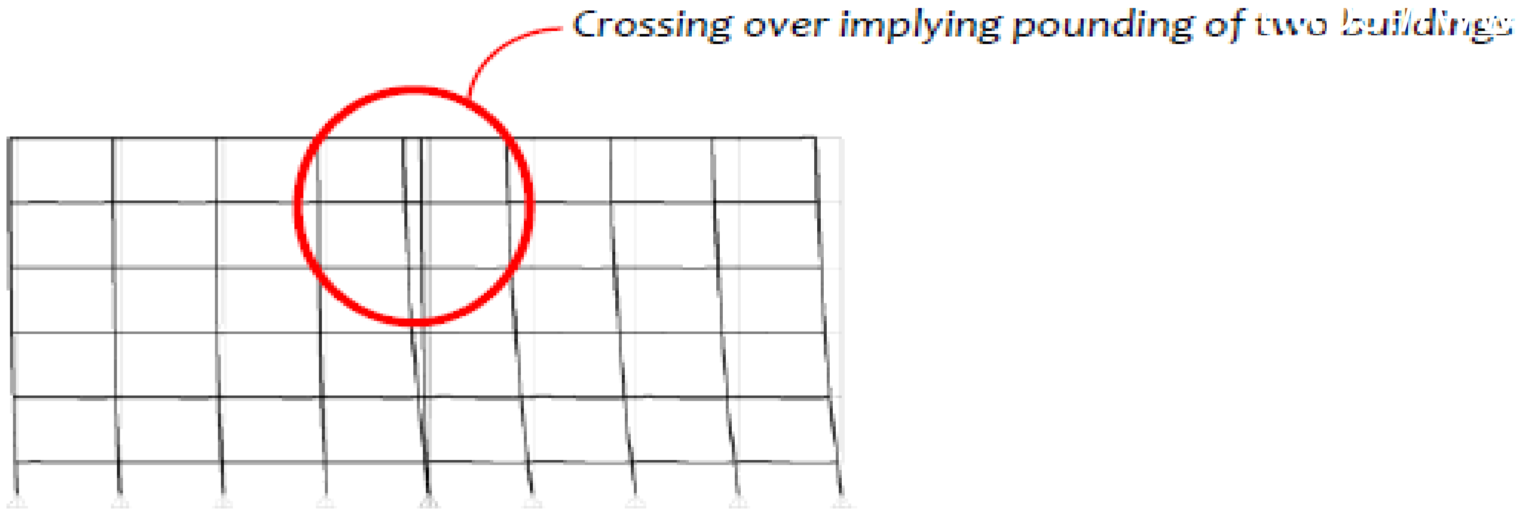
Buildings of same overall height



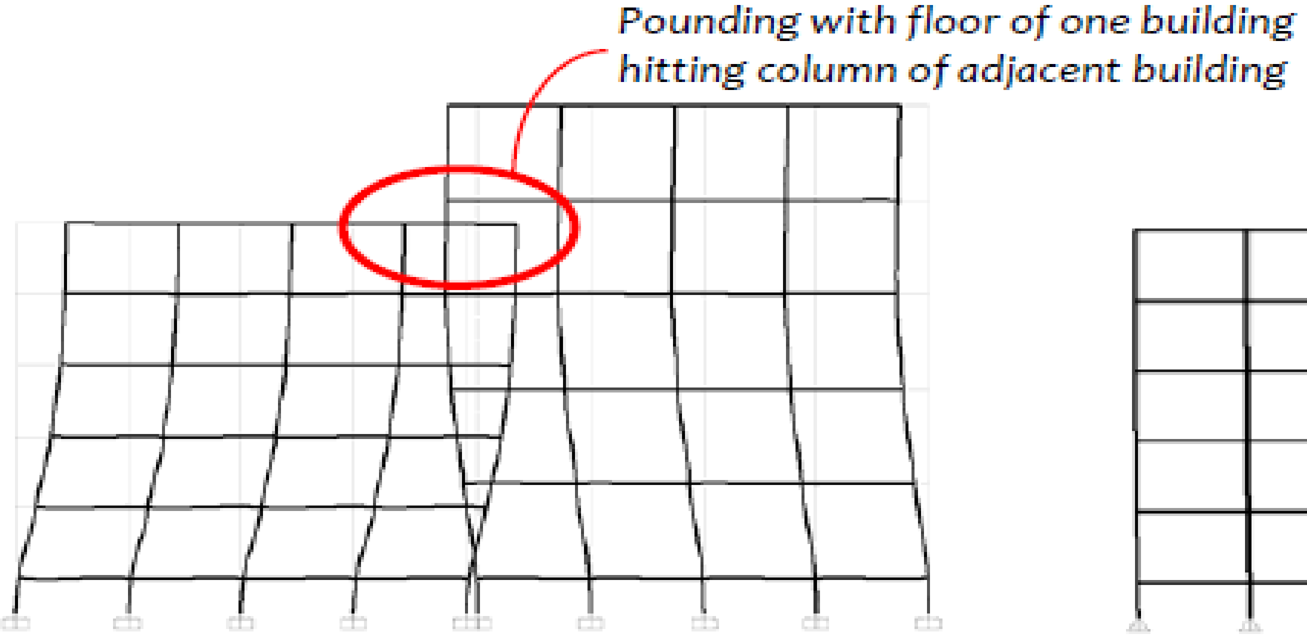
Buildings of different storey height



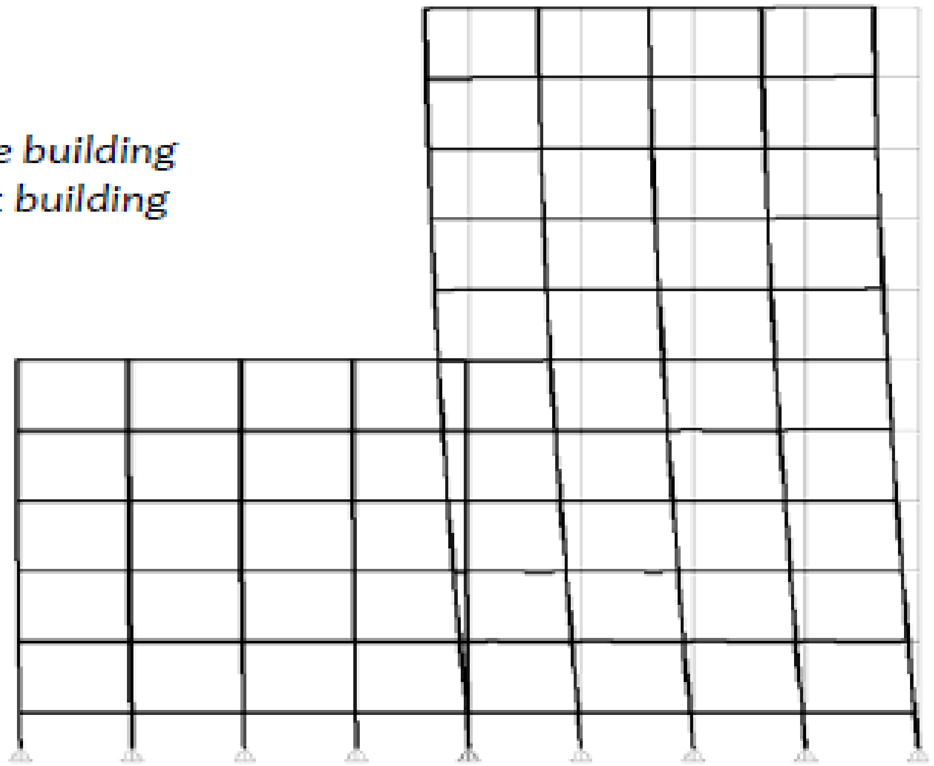
Buildings of different overall heights



Buildings of same overall height



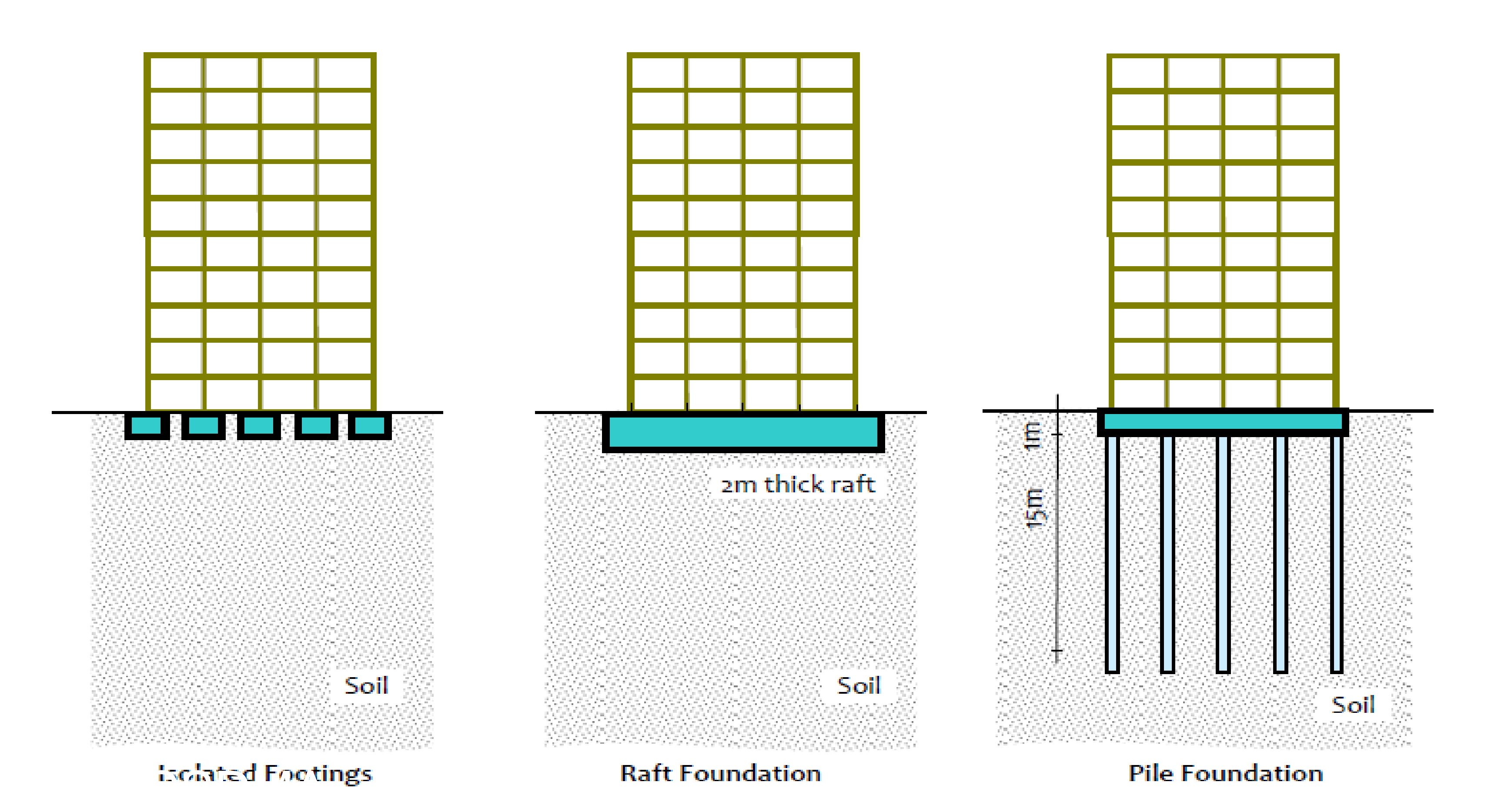
Buildings of different storey height



Buildings of different overall heights

WHAT IS THE EFFECT OF SOIL ON THE STRUCTURE

- Flexibility of soil on which buildings are founded greatly affects earthquake behavior of buildings. Besides, the choice of foundation system also contributes to overall response of buildings.
- For understanding effect of soil flexibility on earthquake behavior of buildings, the following are considered:
- (a) Three types of soil (flexible, medium and stiff); (b) Three types of foundations (isolated footings, pile and raft)



WHAT IS THE EFFECT OF SOIL ON THE STRUCTURE

Results of the analyses of these nine building-soil systems indicate that:

(1) Buildings with isolated footings perform poorly when rested on flexible soil systems, especially in high seismic zones, and hence, should be avoided. Preferably, such buildings should be rested on raft foundations;

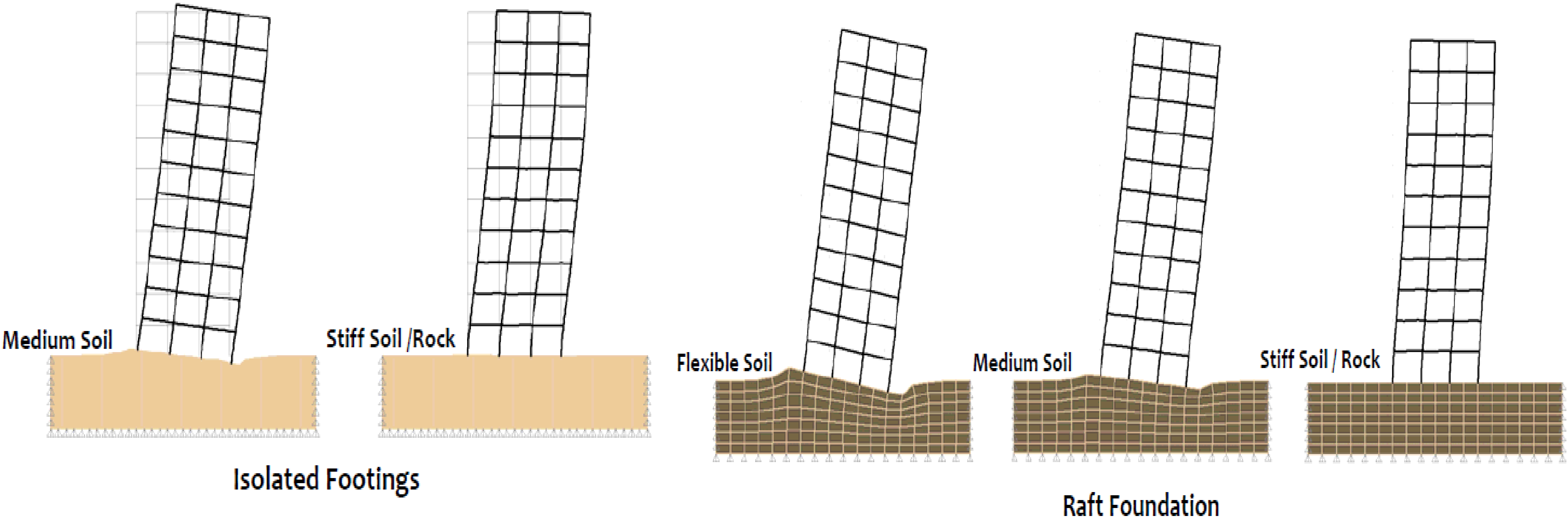
(2) Columns, and the building, are close to being hinged in flexible soils at the base

(3) Large stresses are generated in soils at the windward and leeward edges of the building, when buildings are subjected to large lateral forces, especially when the soil is stiffer

WHAT IS THE EFFECT OF SOIL ON THE STRUCTURE

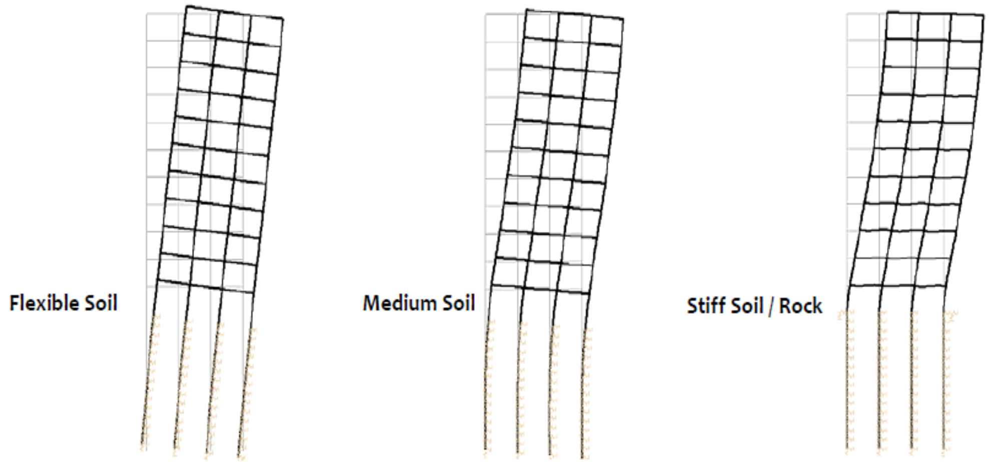
Results of the analyses of various building-soil systems indicate that:

(1) Buildings with isolated footings perform poorly when rested on flexible soil systems, especially in high seismic zones, and hence, should be avoided. Preferably, such buildings should be rested on raft foundations.

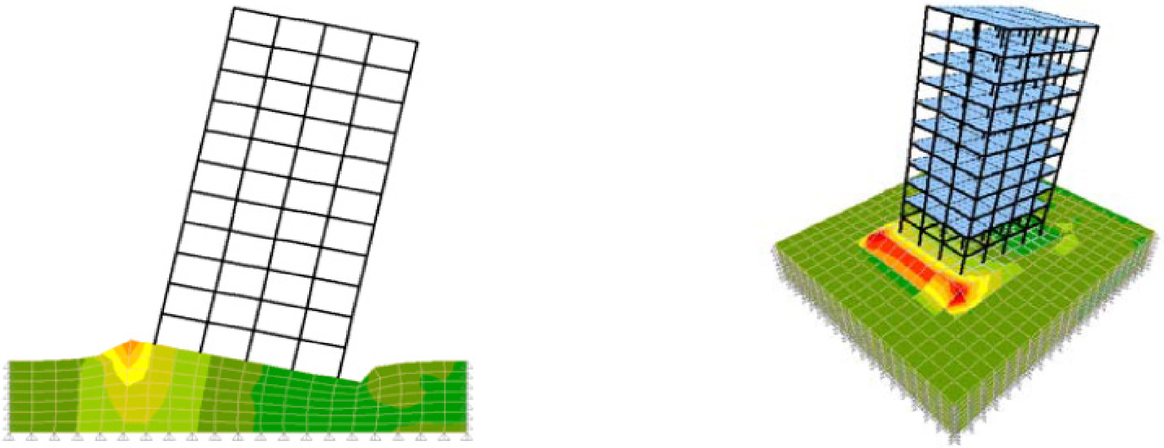


https://www.udemy.com/etabscourse/

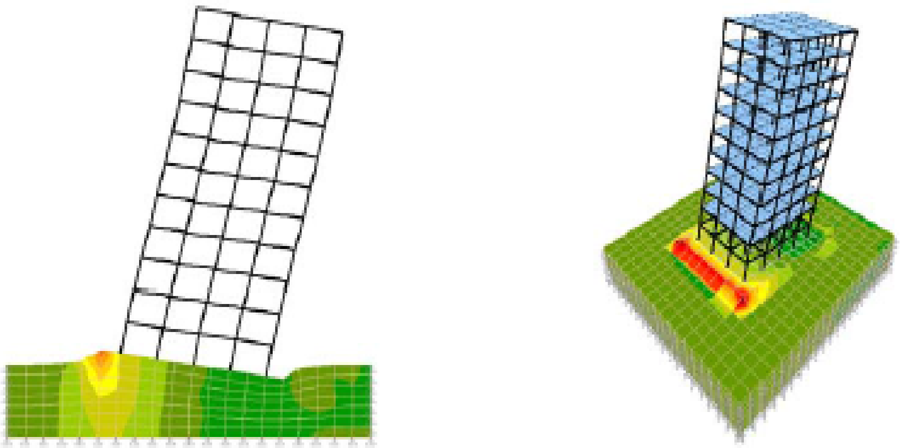
WHAT IS THE EFFECT OF SOIL ON THE STRUCTURE



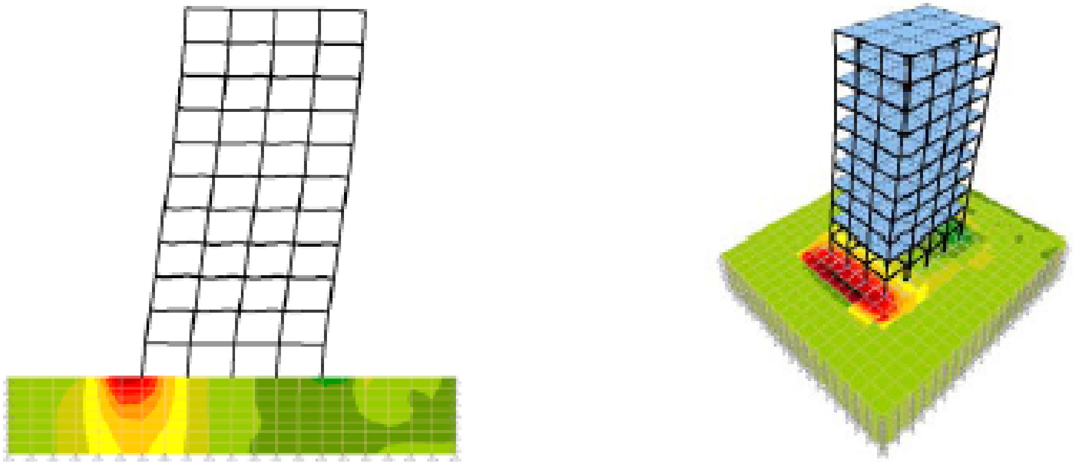
Pile Foundation



Flexible Soil



Medium Soil



Stiff Soil / Rock

Im

EARTHQUAKE CAPACITY OF BUILDINGS – INELASTIC BEHAVIOUR – MOST IMPORTANT CONCEPT

- Some structural damage is allowed during strong earthquake shaking in normal buildings, even though *no collapse* must be ensured.
- This implies that nonlinearity will arise in the overall response of buildings, which originates from the material response being nonlinear.
- This nonlinearity arising from the material stress-strain curve is called *material nonlinearity*.
- But, sometimes, the stress-strain curve may be nonlinear and *also* elastic, whereby on unloading, the material retraces the loading path.

EARTHQUAKE CAPACITY OF BUILDINGS – INELASTIC BEHAVIOUR – MOST IMPORTANT CONCEPT

- Structural steel has definite yield behavior and does not retrace its loading path when unloaded after yielding. Such a response is more commonly referred to as *inelastic response*.
- When an inelastic material is subjected to reversed cyclic loading (of displacement type) which takes the material beyond yield, *hysteresis* takes place, *i.e.*, the material under the applied loading absorbs/dissipates energy.
- Reinforced concrete and structural steel are candidate materials for inelastic behavior. Under strong earthquake shaking, normal reinforced concrete and steel buildings experience inelastic behavior.
- Inelasticity is the basis for the second two of the four virtues of earthquake-resistant buildings, namely *strength* and *ductility*.
- In this chapter, these are discussed to present the basic concepts related to the inelastic behavior of buildings. It is not possible to discuss *strength* only without discussing *ductility*, and *vice-versa*.

STRONG COLUMN WEAK BEAM CONCEPT

- The load path in a moment frame building starts from the slabs, and goes along beams, beam-column joints, columns and foundations to the soil underneath. Strength hierarchy is essential along the load path, and follows the load path.
- Structural elements that are supporting (other structural elements and items of the buildings) are required to be stronger than those that are being supported by them.
- The only exceptions are the connections, especially the *beam-column joints*.
- Connections should be made stronger than the column members below it. This is a special situation, because in the aftermath of an earthquake, it is not easy to strengthen the beam-column joint; especially reaching its interiors is particularly difficult. And, often the damage accrued in such connections is of brittle type no matter what the material of construction is.

STRONG COLUMN WEAK BEAM CONCEPT

Hence, the items to be checked in an earthquake resistant building are :

(1) Beams stronger than adjoining braces, if any;

(2) Beam-column joints stronger than the adjoining beams;

(3) Columns stronger than adjoining beams;

(4) Beam-column joint stronger than the adjoining columns;

(5) Foundations stronger than adjoining columns; and

(6) Soil strata underneath stronger than foundations.

THE EARTHQUAKE ENERGY IS DISSIPATED NOW QUITE UNIFORMLY THROUGHOUT THE ENTIRE BUILDING RATHER THAN BEING CONCENTRATED IN ONE FLOOR.

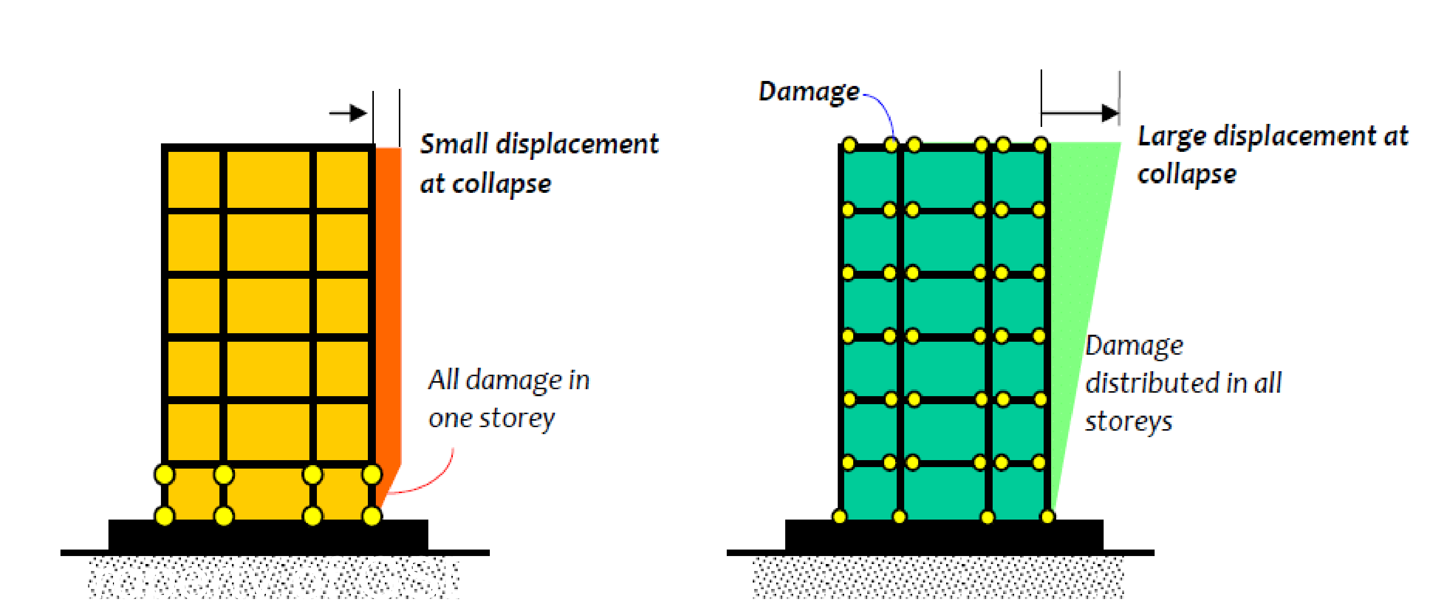
THE BUILDING HAS DAMAGE OF THE DUCTILE TYPE DISTRIBUTED AT MANY LOCATIONS; EACH OF THESE LOCATIONS ABSORBS GOOD AMOUNT OF ENERGY OUT OF THE INPUT ENERGY RECEIVED FROM THE GROUND.

THUS, THE TOTAL ENERGY ABSORBED BY THE WHOLE BUILDING BECOMES LARGE (AND OF DUCTILE TYPE),

AND THE BUILDING IS SAVED FROM BRITTLE COLLAPSE.

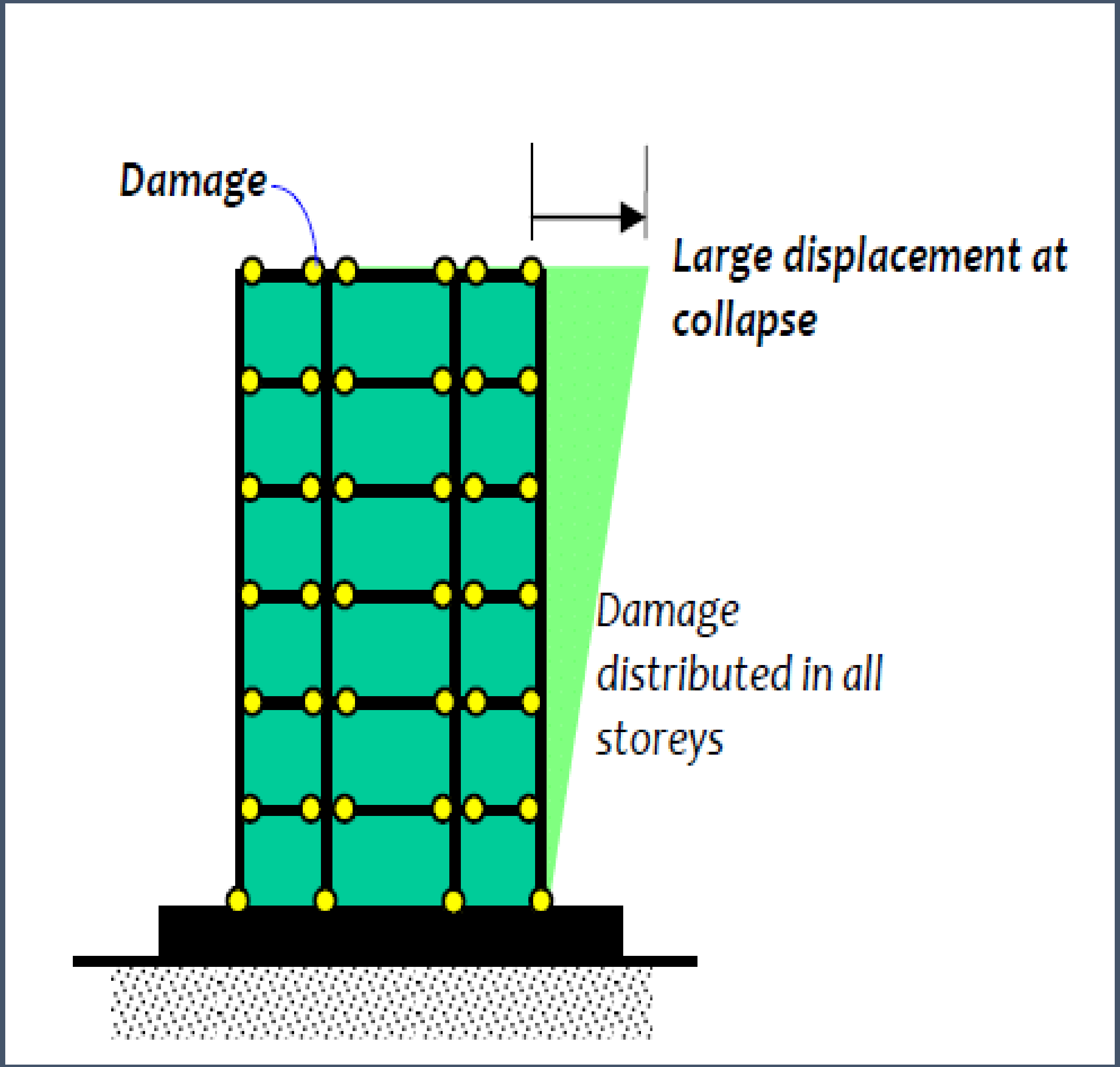
ALSO, NOW ENERGY IS ABSORBED PRIMARILY BY THE BEAMS AND NOT THE COLUMNS. THIS IS THE IDEAL SITUATION BECAUSE BEAMS, WITH NO/RELATIVELY LESS COMPRESSION LOADS ON THEM, INHERENTLY CAN BE DESIGNED AND DETAILED TO BE MORE DUCTILE THAN COLUMNS, AND ABSORB LARGE AMOUNTS OF ENERGY THROUGH INELASTIC ACTIONS

Image



DESIRABLE MECHANISM UNDER EARTHQUAKE

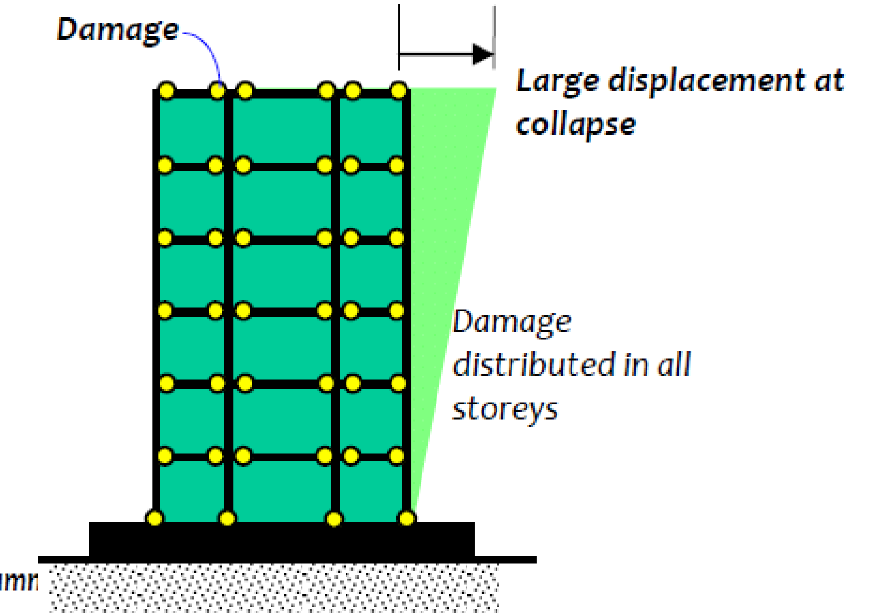
- The combination of inelastic hinges at the ends of beams and columns, which when formed in a building eventually makes it unstable and causes its collapse, is called the *collapse mechanism*.
- Good ductility is achieved in a building when the collapse mechanism is of the desirable type

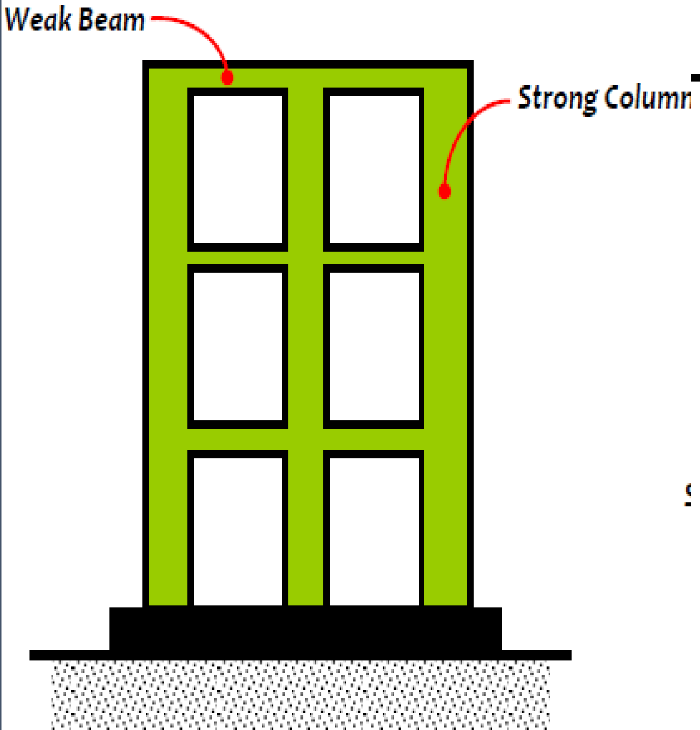


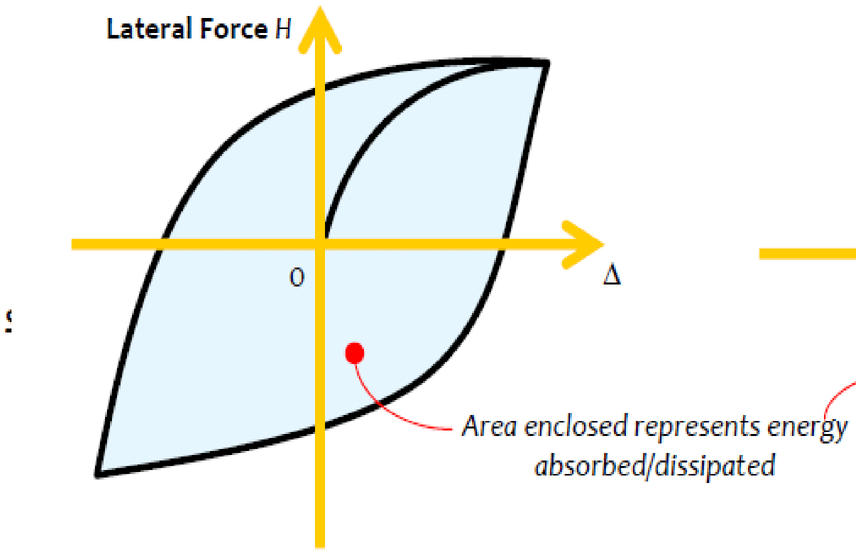
Images Property of GSDMA

DESIRABLE MECHANISM UNDER EARTHQUAKE – SWAY MECHANISM

- Good ductility is achieved in a building when the collapse mechanism is of the desirable type.
- In such a case, the hysteretic loops of its load-deformation curve are stable and full. These type of hysteretic loops imply good energy dissipation in the building through each of the inelastic hinges at the beam ends.
- Such a behavior is observed in buildings that fail in *Sway Mechanism*, which ensures that beams yield before columns, and ductile flexural damages occur at beam-ends; this happens when the building has *strong column – weak beam* (*SC-WB*) design (in which beams are made to be weaker in bending moment capacity and ductile links, and columns stronger in bending moment capacity)



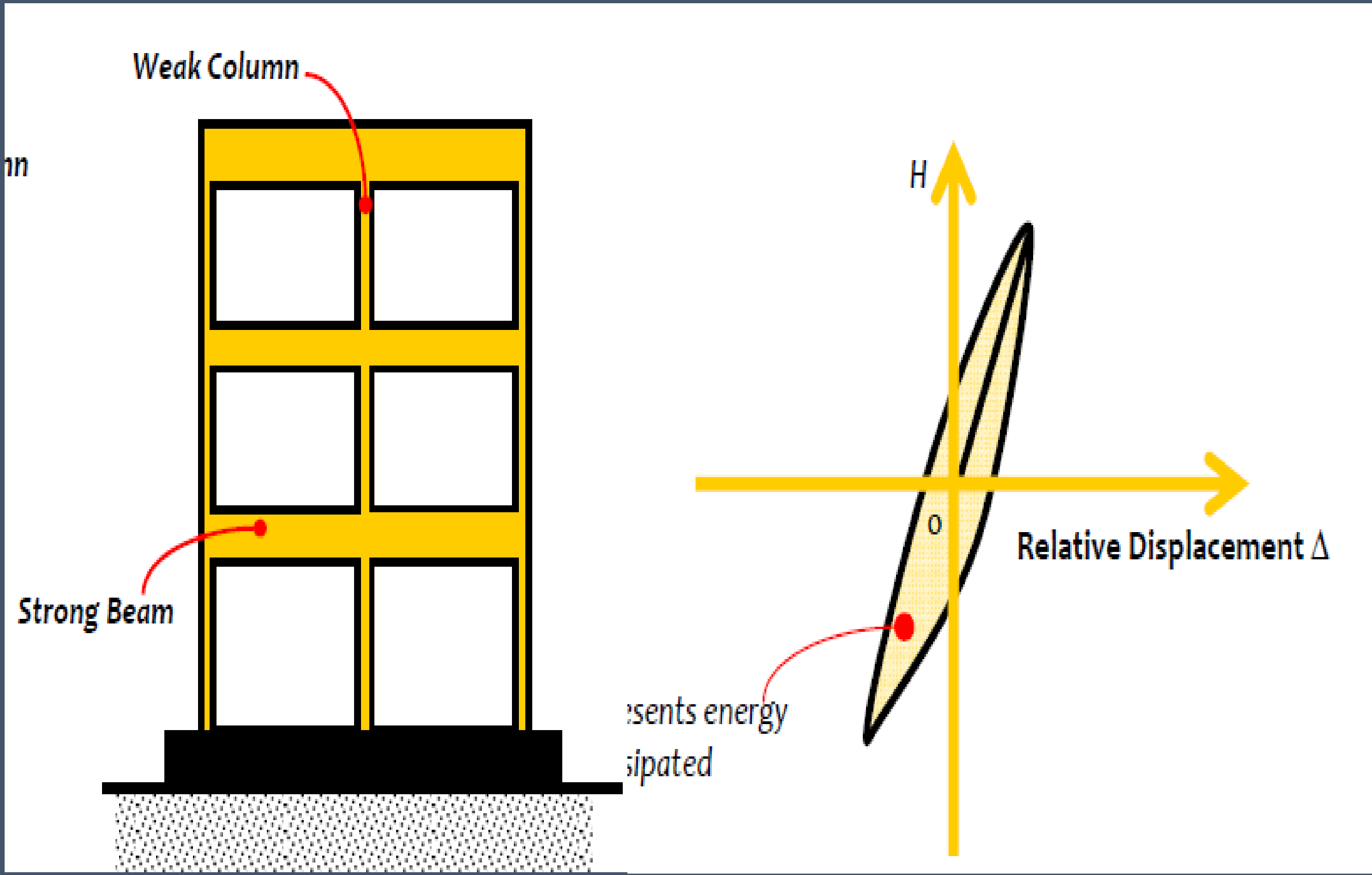




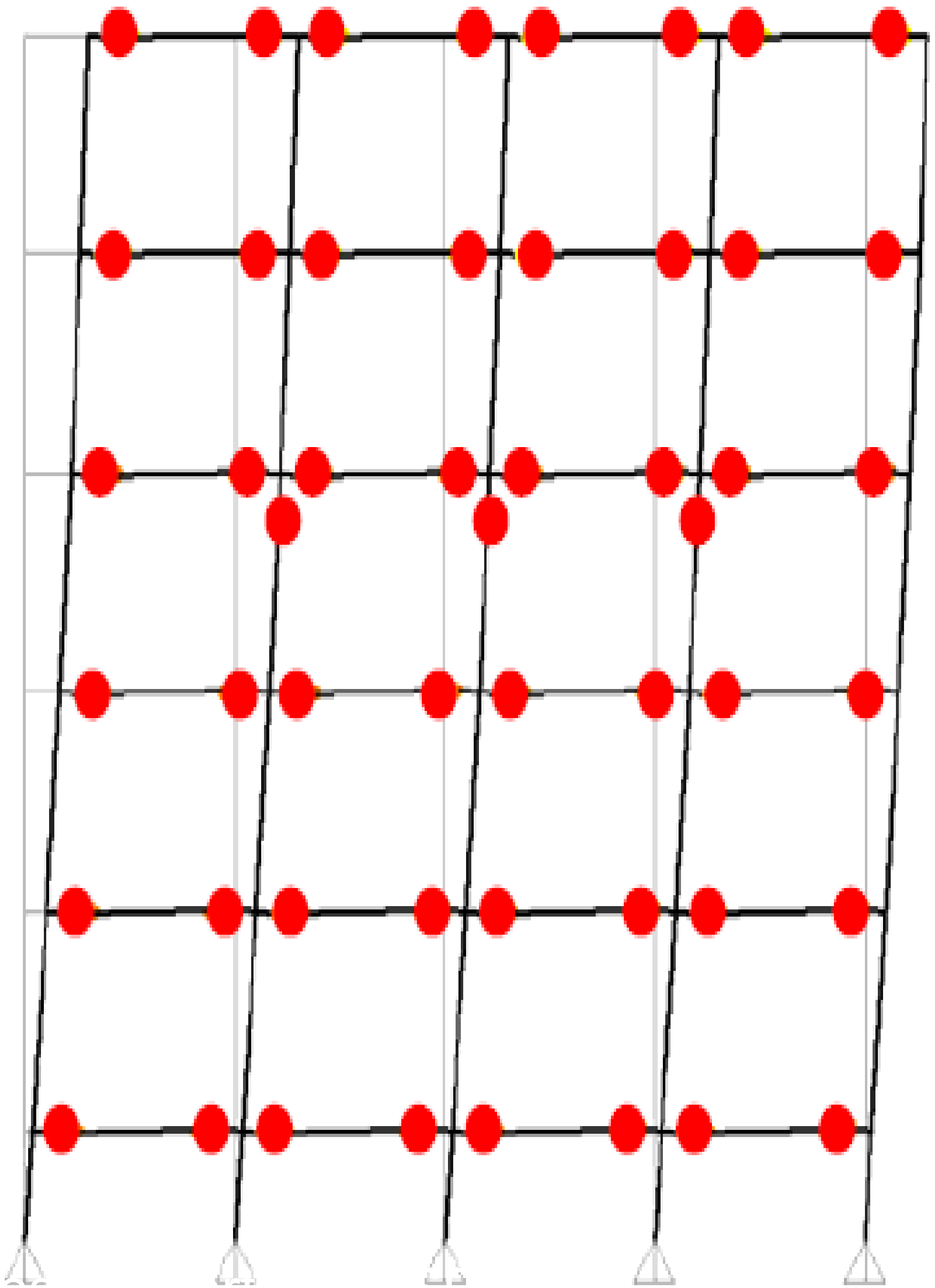
Images Property of GSDMA

DESIRABLE MECHANISM UNDER EARTHQUAKE – SWAY MECHANISM

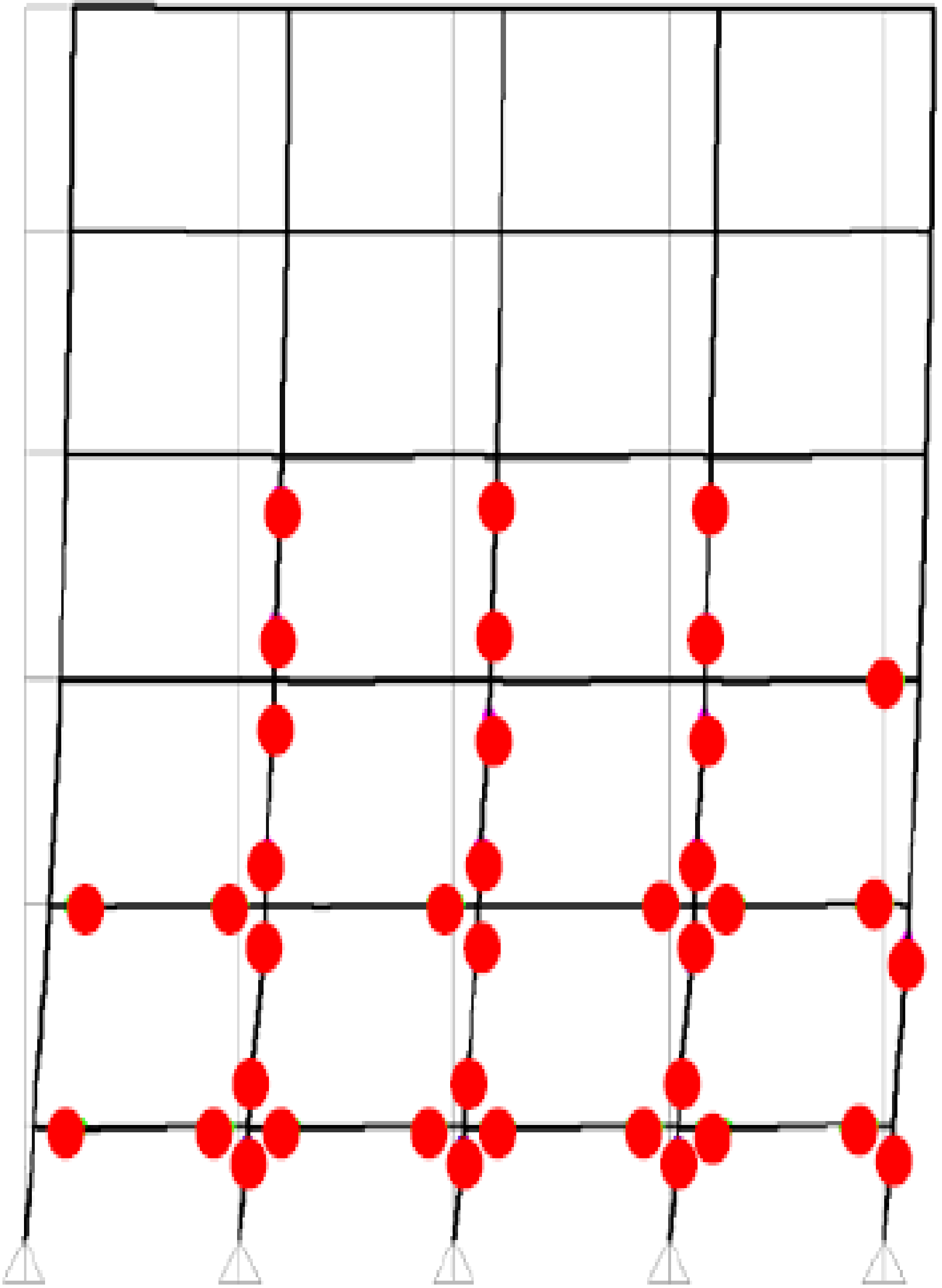
- On the other hand, in buildings that fail in *Storey Mechanism, damages* are concentrated in the *columns* and that too of a single storey.
- Here, the ductility demand on the columns is large.
- This situation arises when the building has *weak column – strong beam (WC-SB) design* (in which columns are weaker in bending moment capacity and beams stronger in bending moment capacity)
- This collapse mechanism dissipates less energy in the building and that too all of that energy in one storey.



STRONG COLUMN – WEAK BEAM

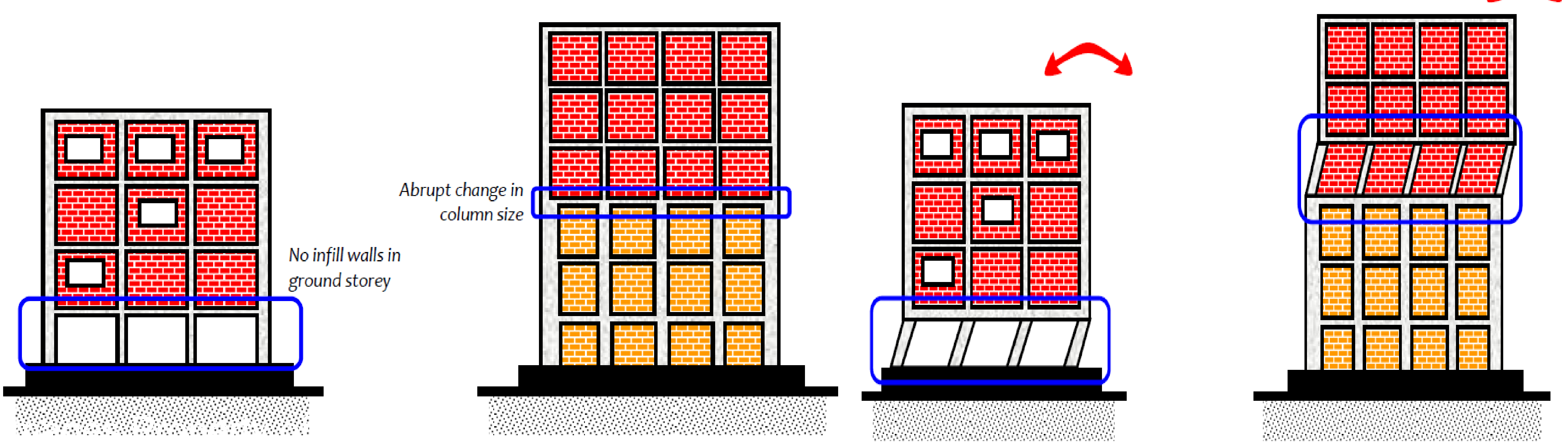


WEAK COLUMN STRONG BEAM



STRENGTH DISCONTINUITY IN ELEVATION

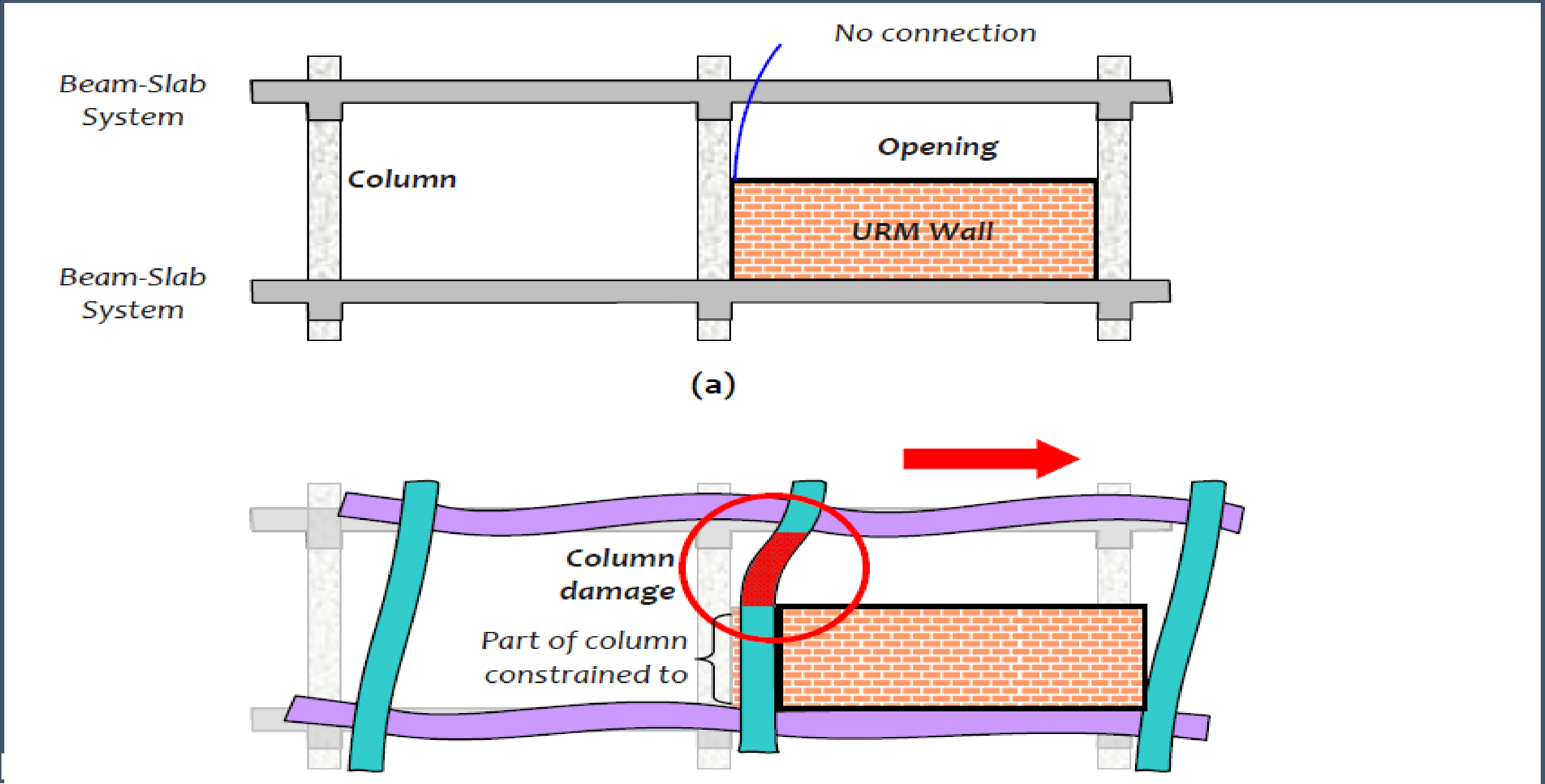
- Strength discontinuity or sudden reduction in lateral strength of the building is more serious when along the height of the building than in plan.
- This discontinuity or reduction causes large inelastic demand at the junctions where this discontinuity or reduction is present.
- Performances during past earthquakes have shown how sudden changes in configuration leads to concentration of damage and ductility demand in a few adjoining regions



WHAT IS SHORT COLUMN EFFECT ?

- Short column effect arises when a column in a RC frame building is restricted from moving owing to any obstruction. The obstruction can be:

(1) Presence of unreinforced masonry infills of partial height of adjoining RC column.

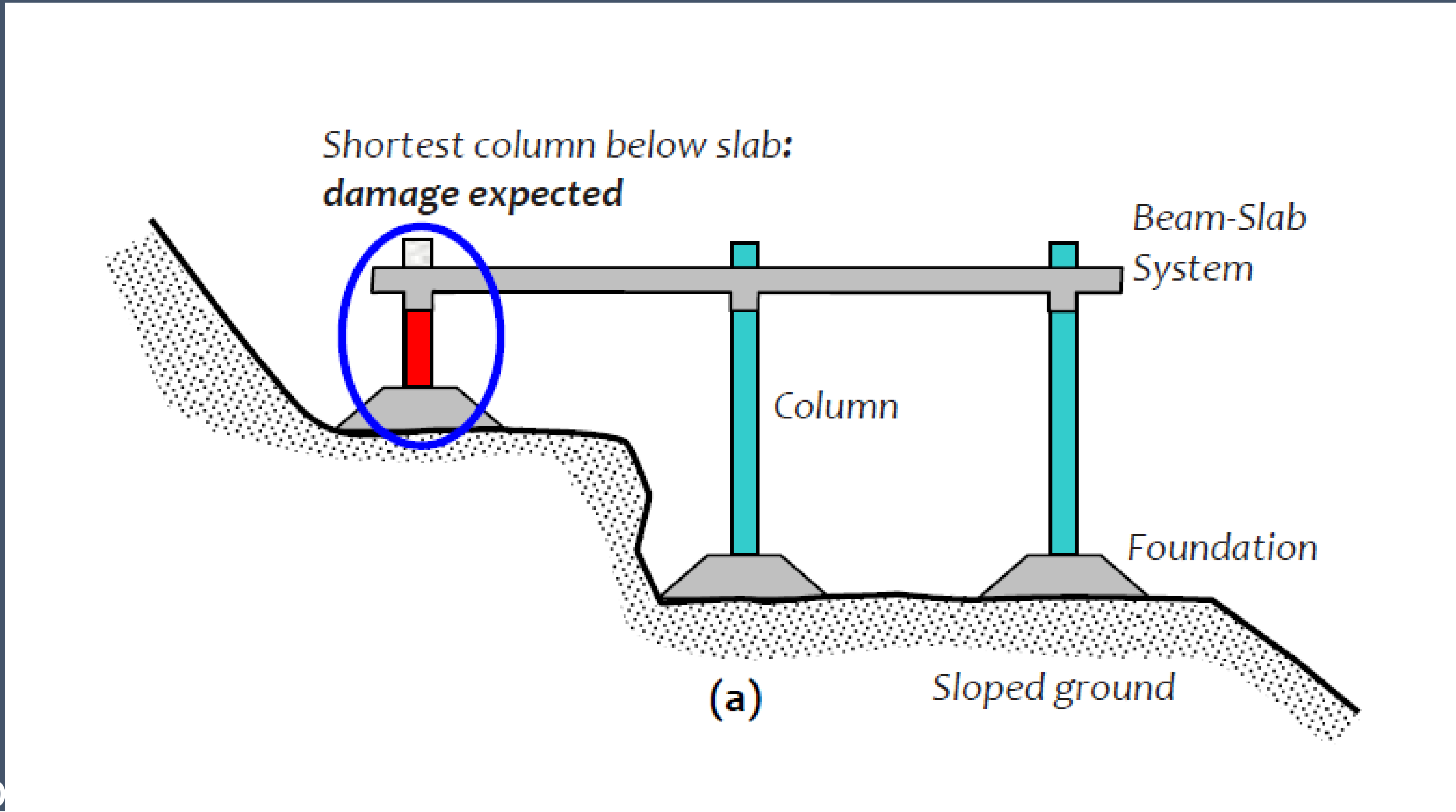


Images Proper

WHAT IS SHORT COLUMN EFFECT ?

- Short column effect arises when a column in a RC frame building is restricted from moving owing to any obstruction. The obstruction can be:

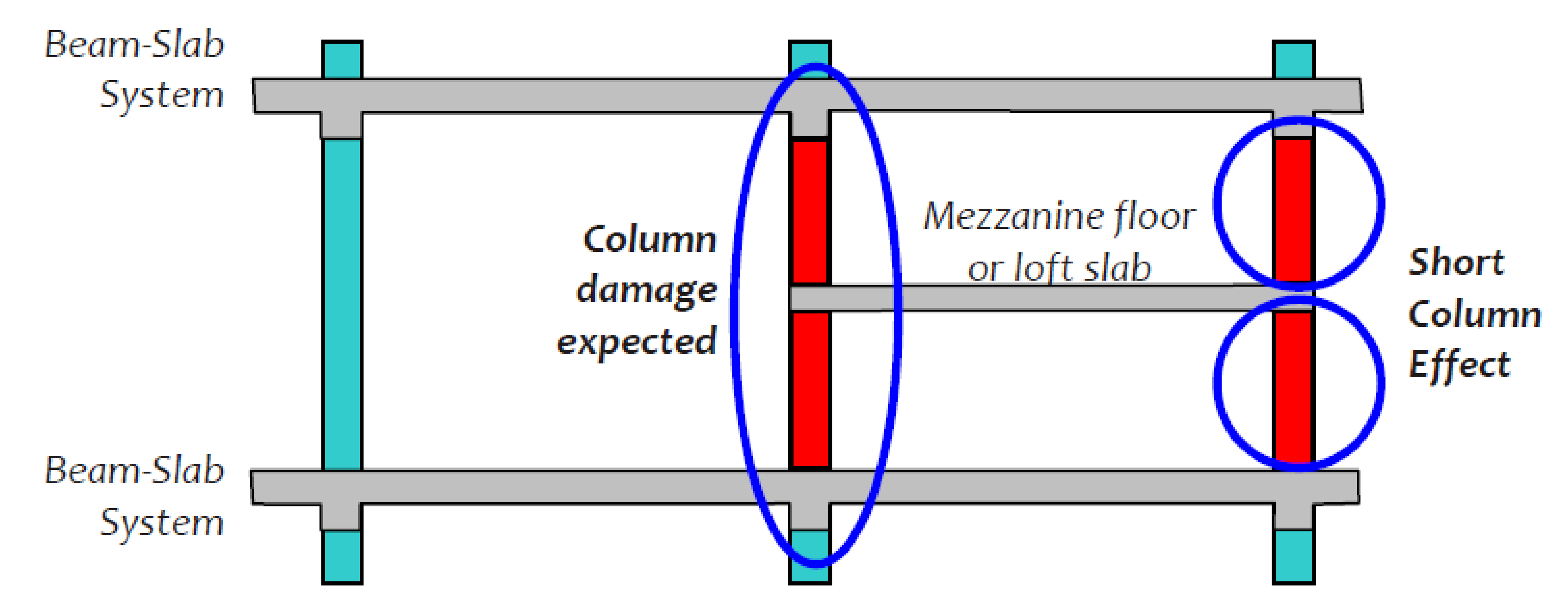
(1) Conditions arising from sloping ground, when some basement columns are shorter than others.



WHAT IS SHORT COLUMN EFFECT ?

- Short column effect arises when a column in a RC frame building is restricted from moving owing to any obstruction. The obstruction can be:

(1) Presence of a mezzanine slab (which meets the columns at an intermediate height between the usual beam-slab system of the floors in RC buildings);



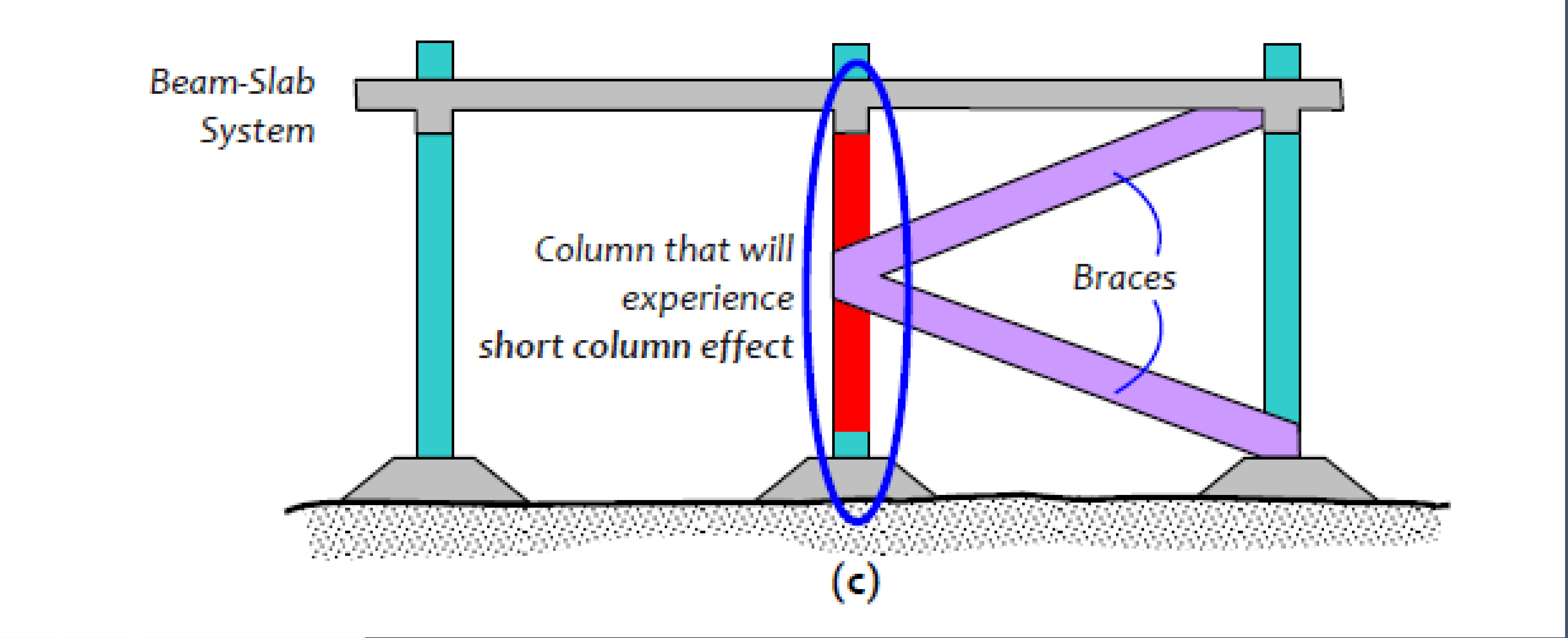
(b)

Images F

WHAT IS SHORT COLUMN EFFECT ?

- Short column effect arises when a column in a RC frame building is restricted from moving owing to any obstruction. The obstruction can be:

(1) Presence of a staircase beam/slab or K-braces on building columns (which meets the columns at an intermediate height between the usual beam-slab

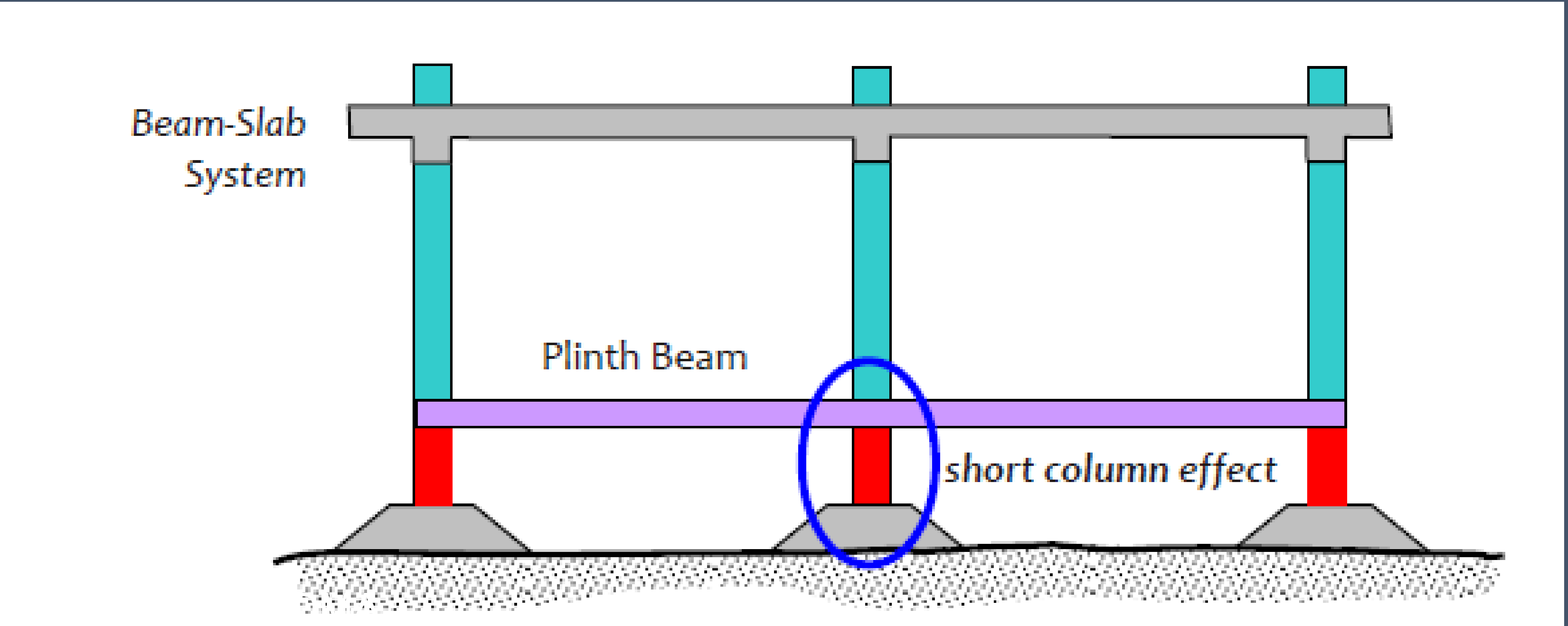


Images F

WHAT IS SHORT COLUMN EFFECT ?

- Short column effect arises when a column in a RC frame building is restricted from moving owing to any obstruction. The obstruction can be:

(1) Presence of a plinth beam making the height of the column below it to be shorter than that of the column above

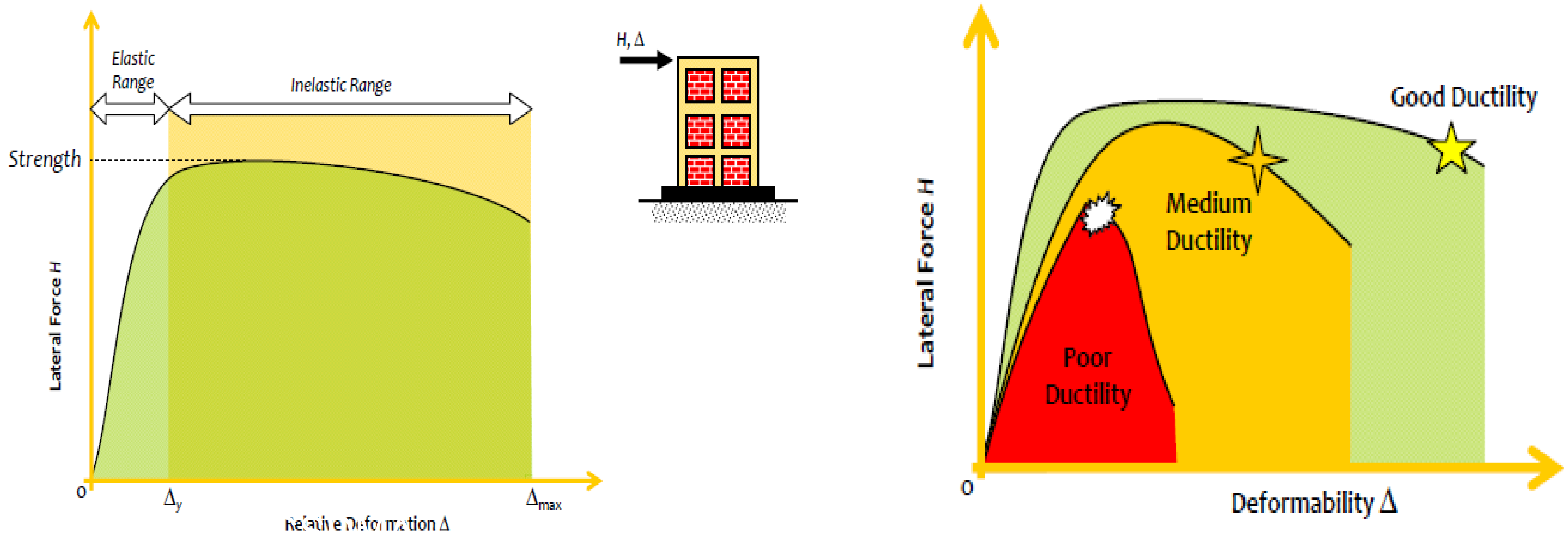


Images

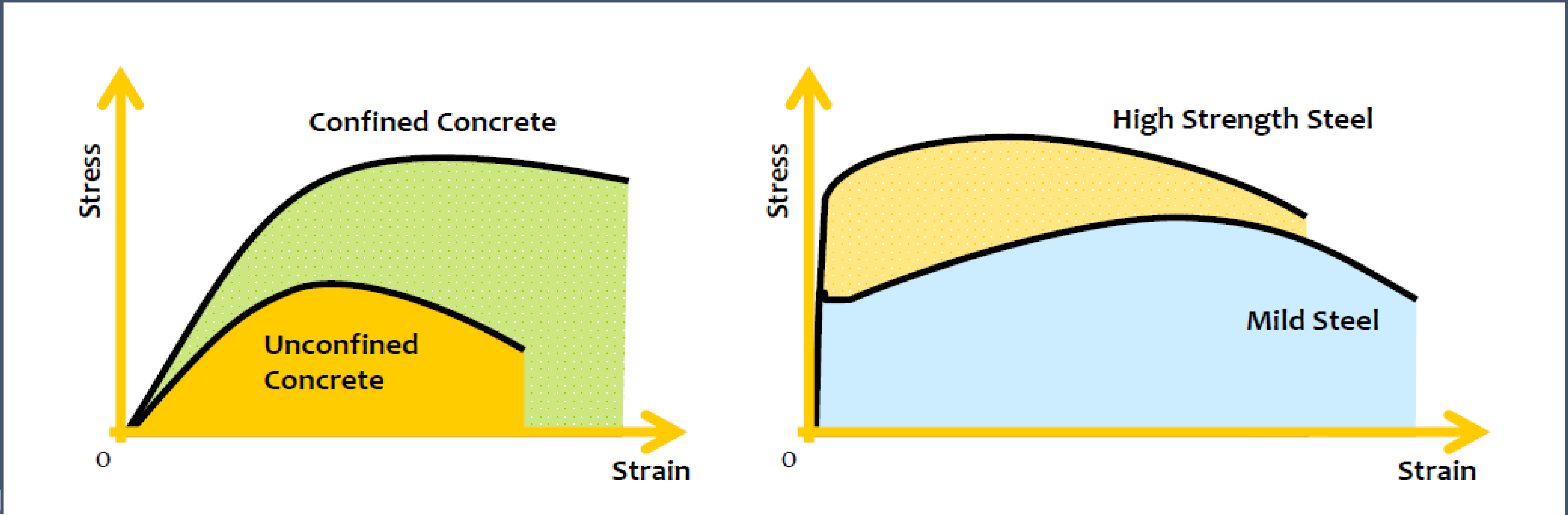
WHAT IS DUCTILITY IN A STRUCTURE ?

- Ductility of a building is its capacity to accommodate large lateral deformations along the height.
- It is quantified as the ratio μ of *maximum deformation* Δ_{max} that can be sustained just prior to collapse (or failure, or significant loss of strength) to the *yield deformation* Δ_y. Thus, a ductile building exhibits large inelastic deformation capacity without significant loss of strength capacity.
- The state of the building prior to collapse or at failure is called the *plastic* condition of the building.
- Through seismic design, buildings are designed and detailed to develop favorable failure mechanisms that possess *specified lateral strength*, *reasonable stiffness* and, above all, *good post yield deformability*.

- In a ductile building, the structural members and the materials used therein can stably withstand inelastic actions without collapse and undue loss of strength at deformation levels well beyond the elastic limit.
- Ductility helps in dissipating input earthquake energy through hysteretic behavior

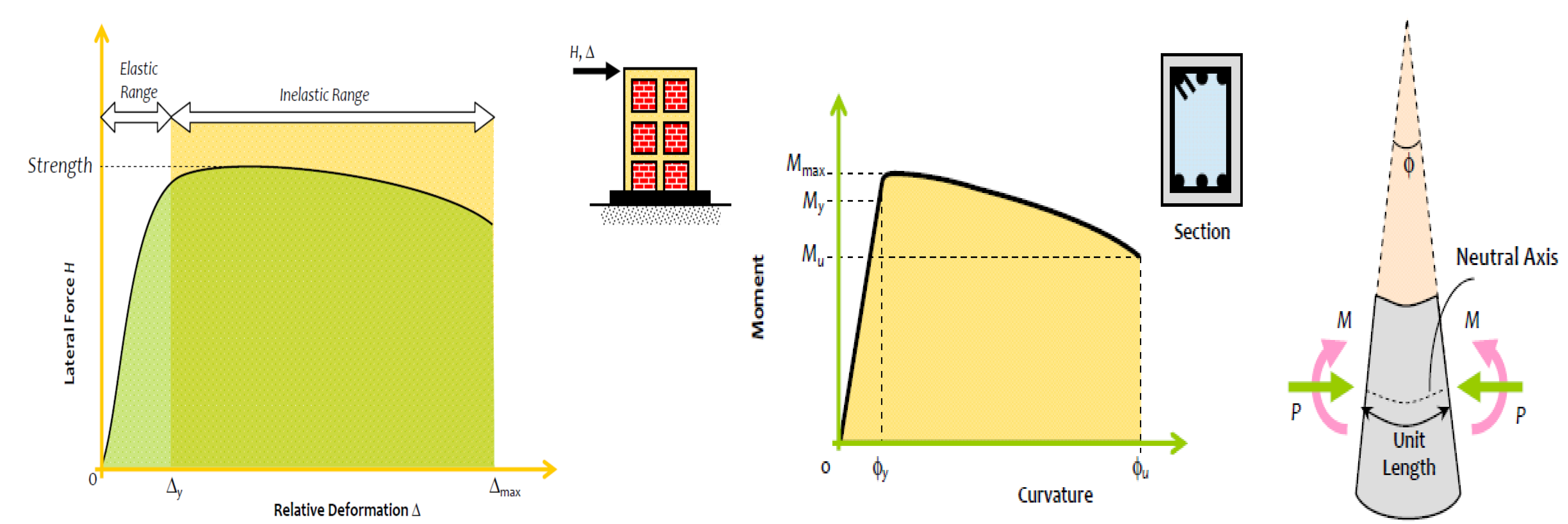


- Making individual members of the frame ductile is the key effort in earthquake resistant design and construction.
- Making a RC member ductile is challenging, because most of the volume of the material in reinforced concrete is concrete, which is extremely brittle in comparison to reinforcing steel.
- The concrete inside the lateral ties is confined by the closed loop lateral ties with 135° hook ends; this prevents the failure of concrete during cyclic earthquake loading.
- Steel by nature is far more ductile than even confined concrete

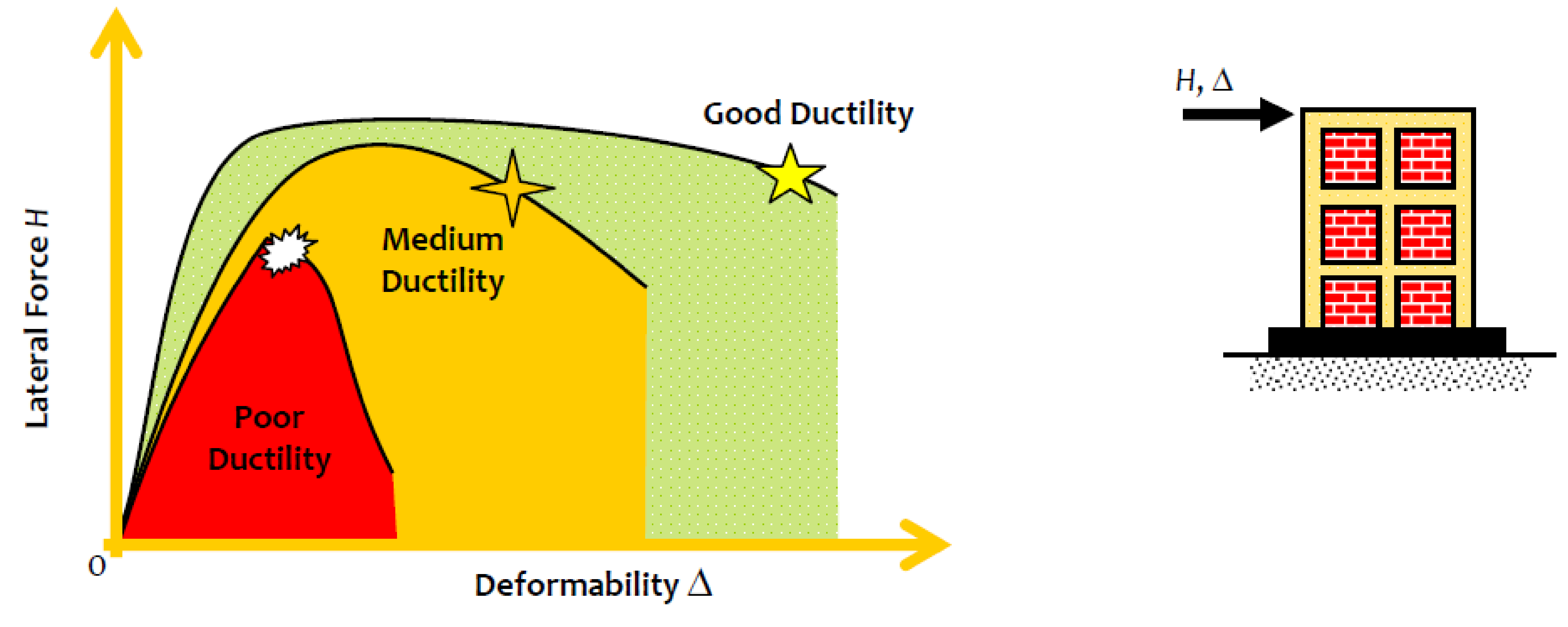


Imag

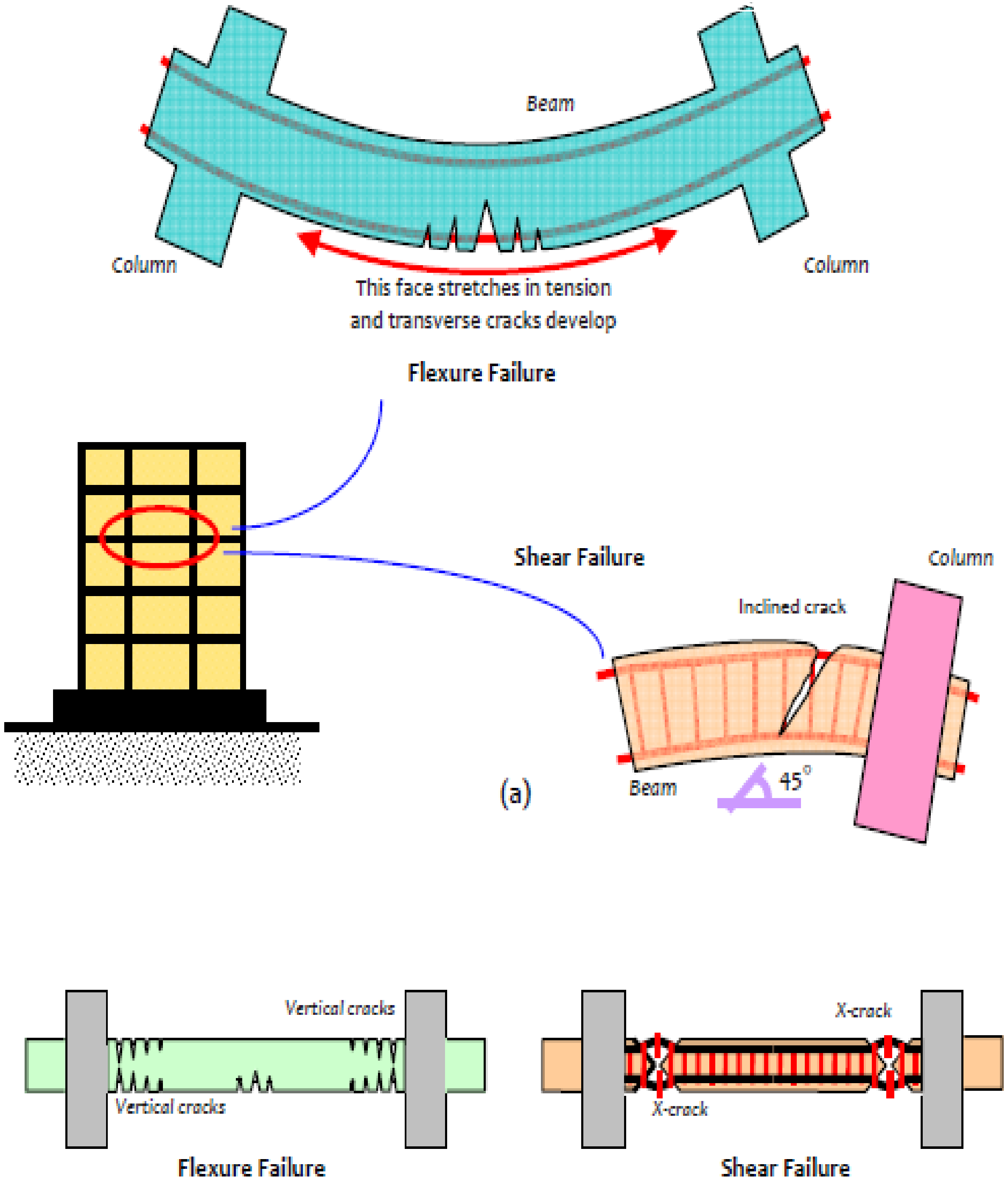
- Material ductility is directly reflected in section ductility through the cross-section property
- of the member, namely *moment-curvature relationship*.
- With under-reinforced flexural behavior of the section, good section ductility can be achieved through use of proper choice of quantity and distribution of steel, grade of concrete, and geometry of cross-section.
- Good member ductility (member-end *moment* versus *rotation relationship*) is then a direct consequence of good section ductility (*moment* versus *curvature relationship*) and is reflected in structure ductility *(say, total seismic force* versus *roof displacement*).



- Section ductility increases as flexural yielding increases, concrete grade increases, steel grade decreases, tension reinforcement decreases, compression reinforcement increases, and axial force in the member decreases.
- Thus, beams are more ductile than columns.

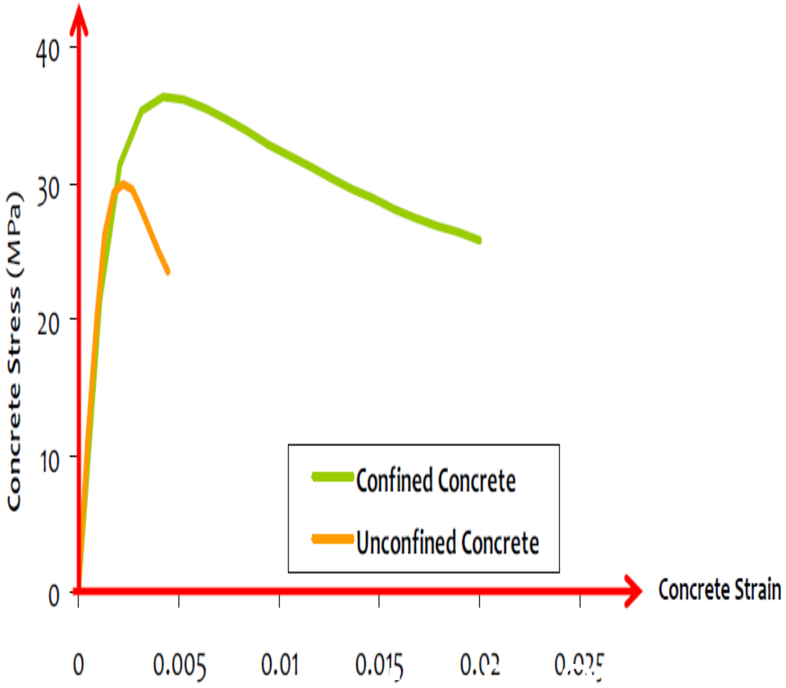


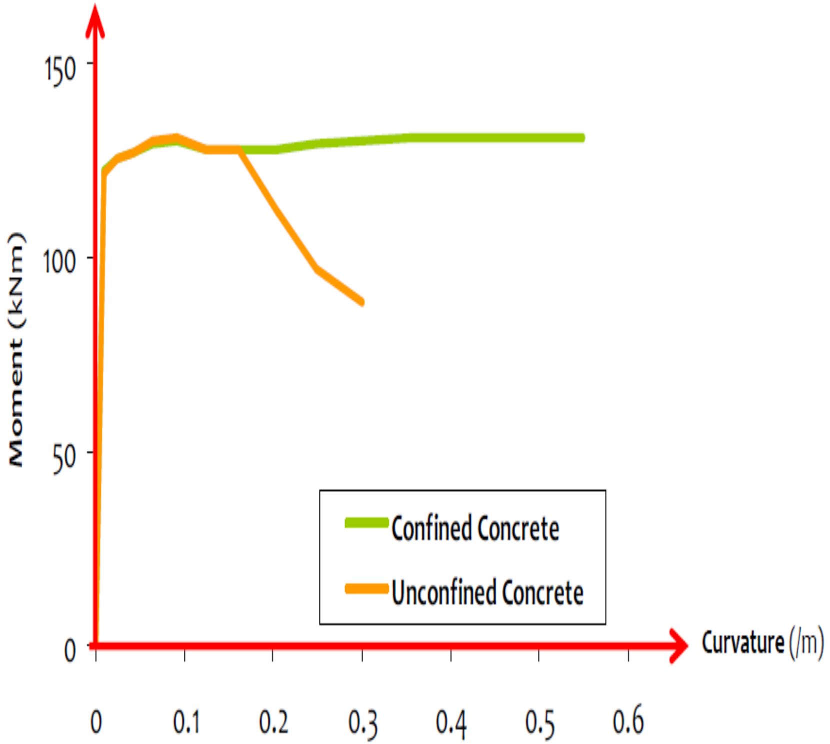
- RC frame members fail owing to a number of deficiencies. These failures manifest as shear failure (diagonal tension and diagonal compression), bond slip failure, flexural over-reinforced failure, flexural under-reinforced failure, and torsional failure.
- Of these, the preferred failure mode is the flexural under-reinforced failure.
- When this happens, the RC member stretches in flexure on the tension side (without any failure in the concrete on the compression side) and exploits the ductility of the steel bars.
- This condition of the RC member is called the *plastic hinge*; typically, this plastic action spreads over a small length of the member, called *plastic hinge length*.

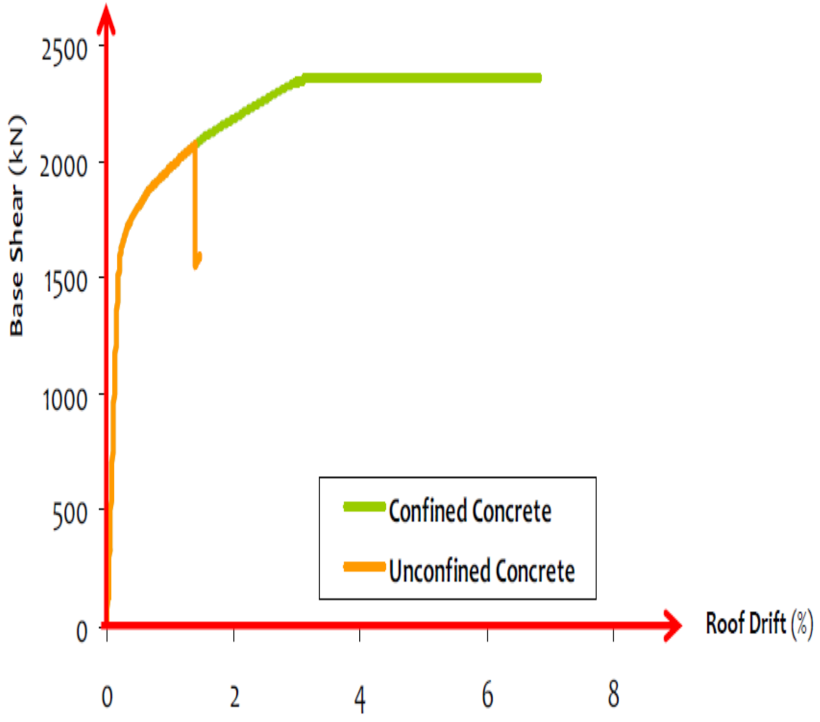


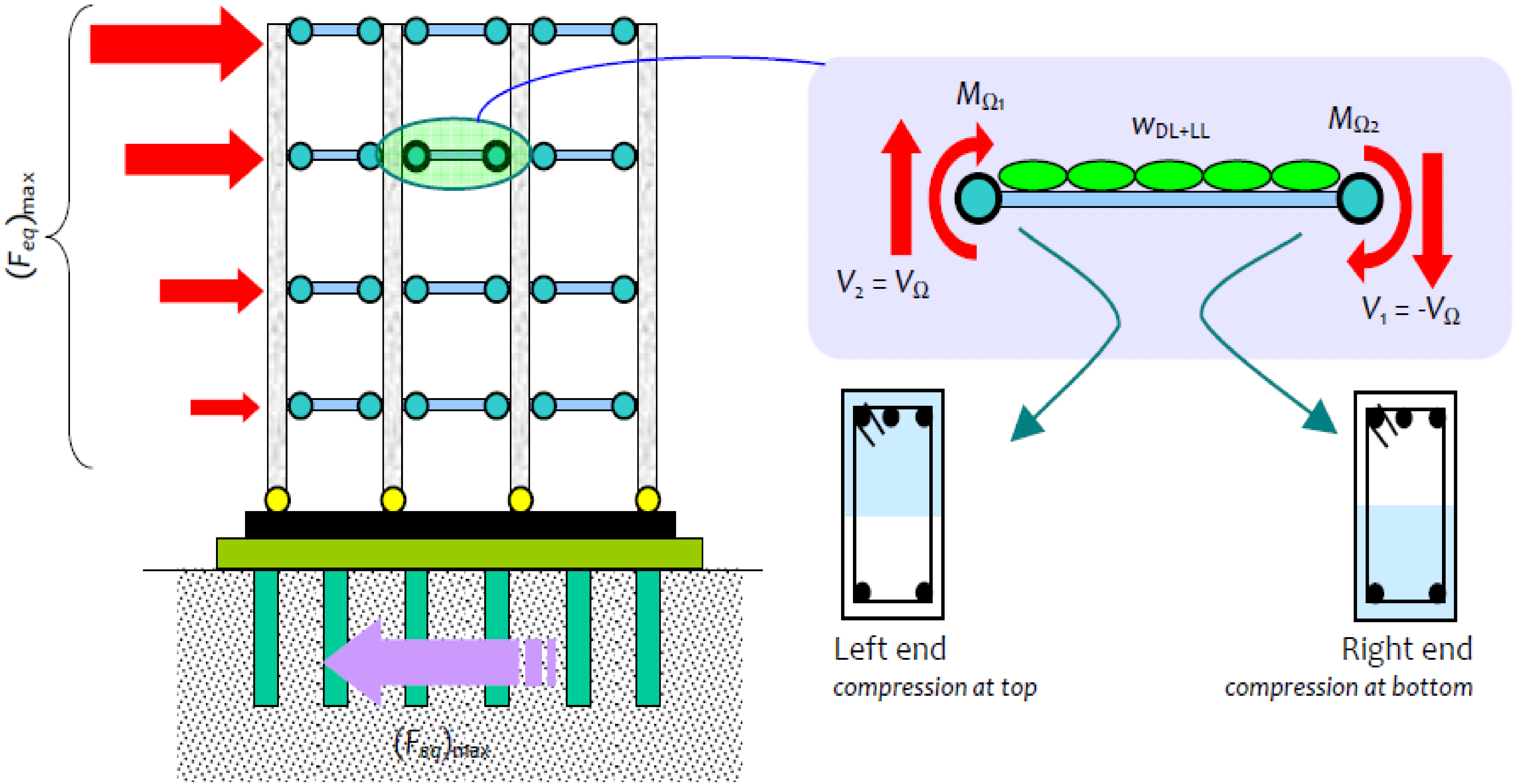
Images Property of GSDMA

- Seismic design codes recommend the use of closely spaced transverse reinforcement at all locations where plastic hinges are likely to be formed. This increases confinement of concrete that is one of the main contributors to ductility.

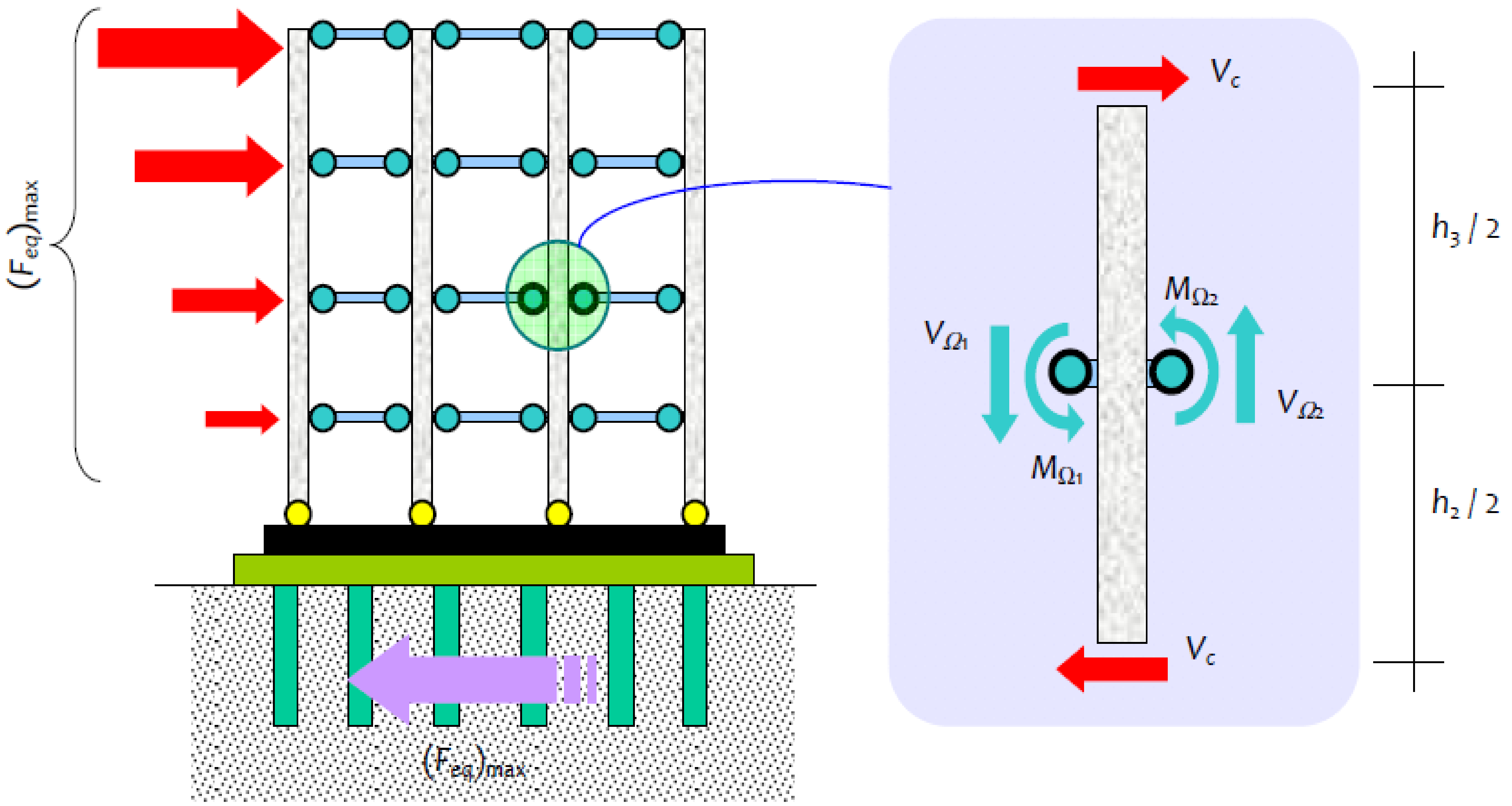




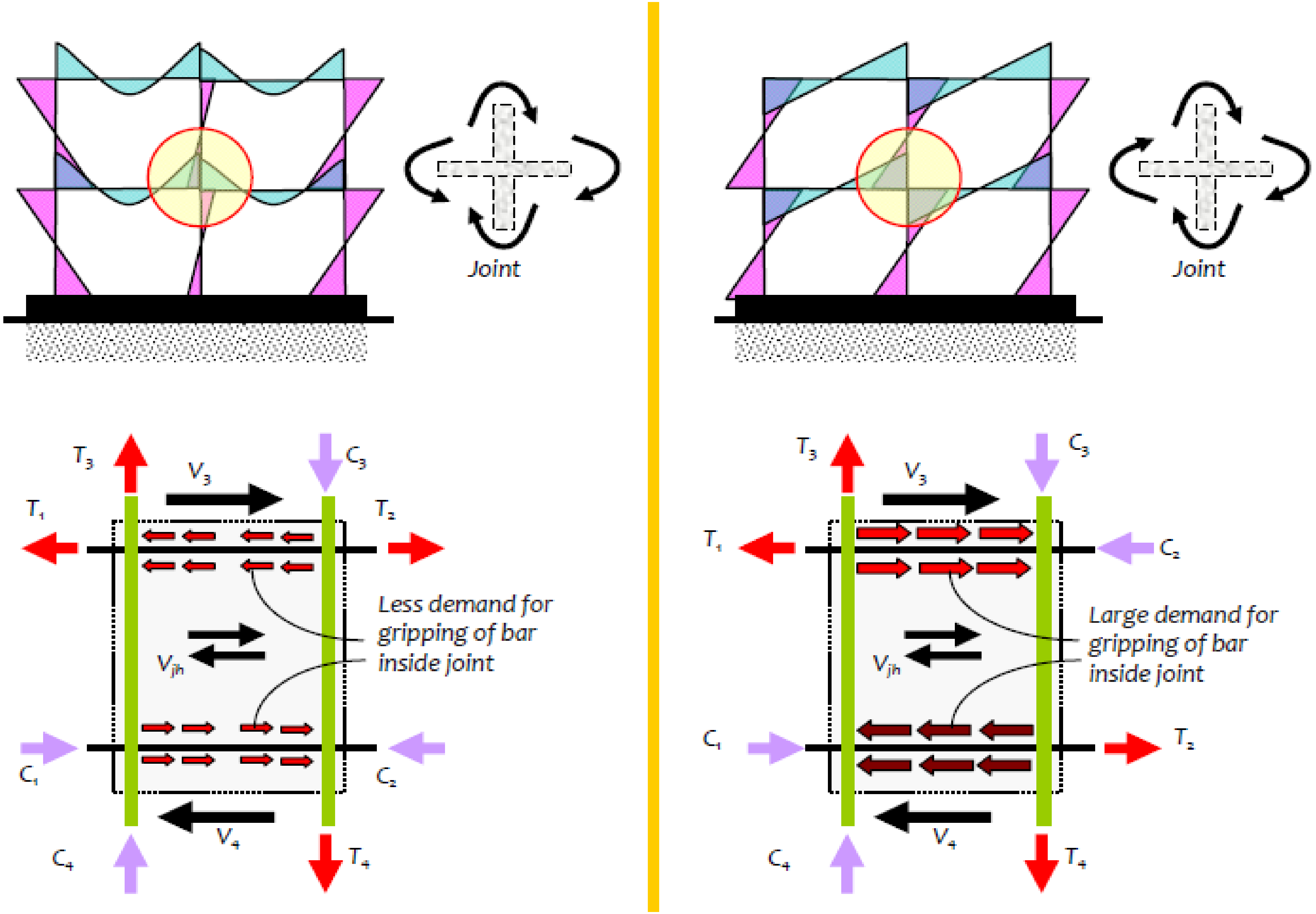




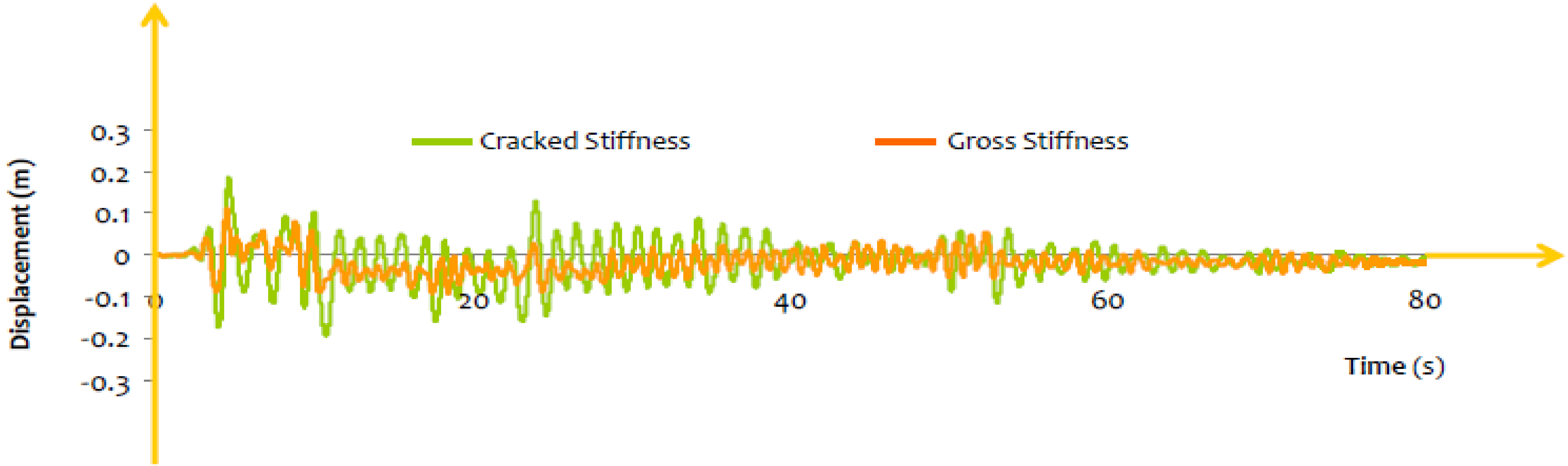
$(F_{eq})_{max}$
$M_{\Omega 1}$
w_{DL+LL}
$M_{\Omega 2}$
$V_2 = V_\Omega$
$V_1 = -V_\Omega$
Left end
compression at top
Right end
compression at bottom
$(F_{eq})_{max}$



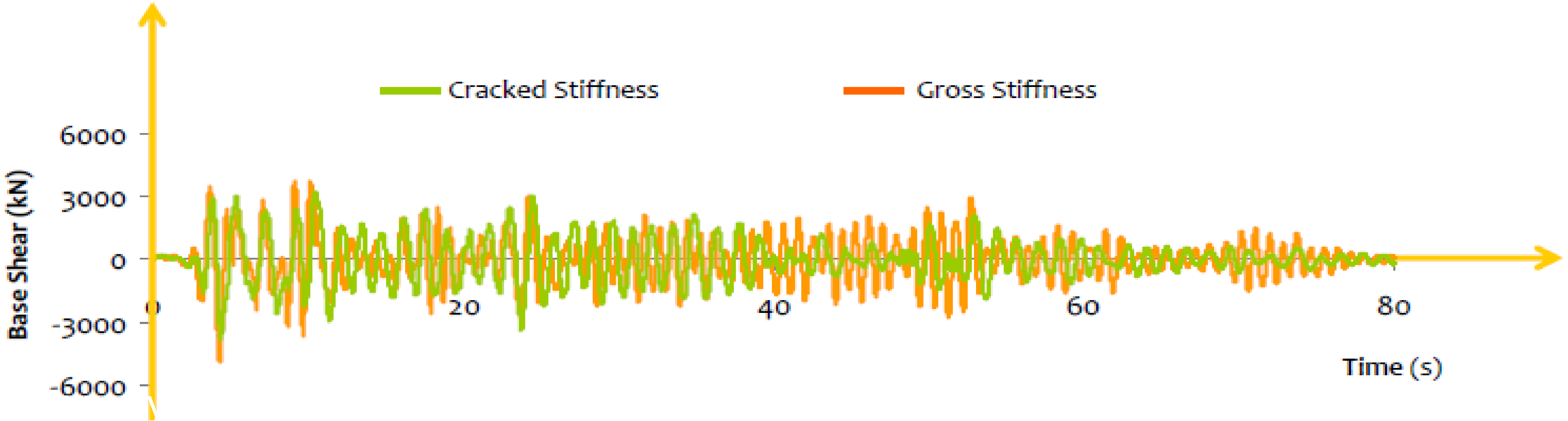
$(F_{eq})_{max}$
$(F_{eq})_{max}$
V_c
$h_3 / 2$
$M_{\Omega 2}$
$V_{\Omega 1}$
$V_{\Omega 2}$
$M_{\Omega 1}$
$h_2 / 2$
V_c



Joint
Joint
T_3
C_3
V_3
T_1
T_2
Less demand for gripping of bar inside joint
V_{jh}
C_1
C_2
C_4
V_4
T_4
T_3
C_3
V_3
T_1
C_2
Large demand for gripping of bar inside joint
V_{jh}
C_1
T_2
C_4
V_4
T_4


Cracked Stiffness
Gross Stiffness
Displacement (m)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
20
40
60
80
Time (s)

(a)


Cracked Stiffness
Gross Stiffness
Base Shear (kN)
6000
3000
0
-3000
-6000
0
20
40
60
80
Time (s)