

Università degli studi di Trieste

Dipartimento di Ingegneria ed Architettura

Aspetti della progettazione degli edifici alti

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Contenuti della presentazione

- Introduzione
- Strategie di progettazione
- Tipologie strutturali
- Elementi strutturali
- Fondazioni
- Construction engineering
- Carichi
- Dinamica strutturale
- Ingegneria del vento
- Ingegneria sismica

Introduzione

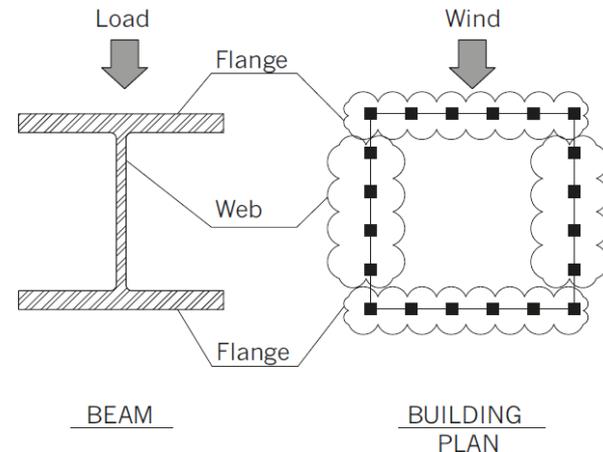
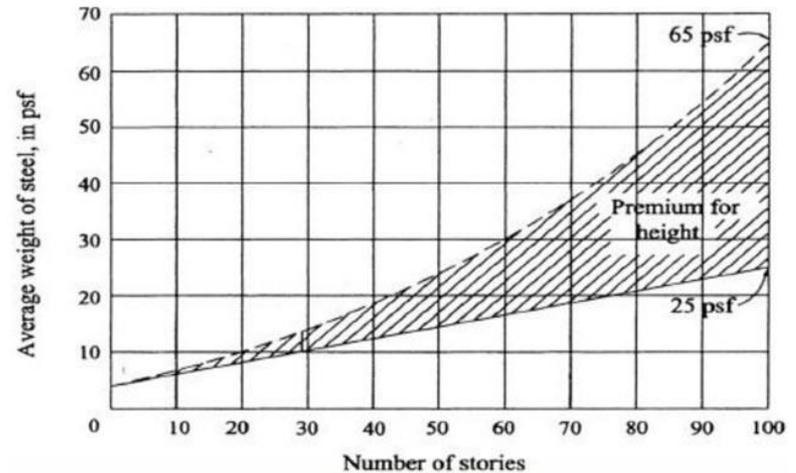
- Tempo = denaro
 - Ridurre la durata dell'investimento
- Valore generato
 - Nelle torri a destinazione uso uffici il parametro più importante è la NLA Net Lettable Area
 - Nelle torri residenziali la NFA Net Floor Area
 - Pressione per massimizzare entrambe e ridurre i tempi di progettazione e costruzione
- Vertical transport system è il “Driver”

Introduzione

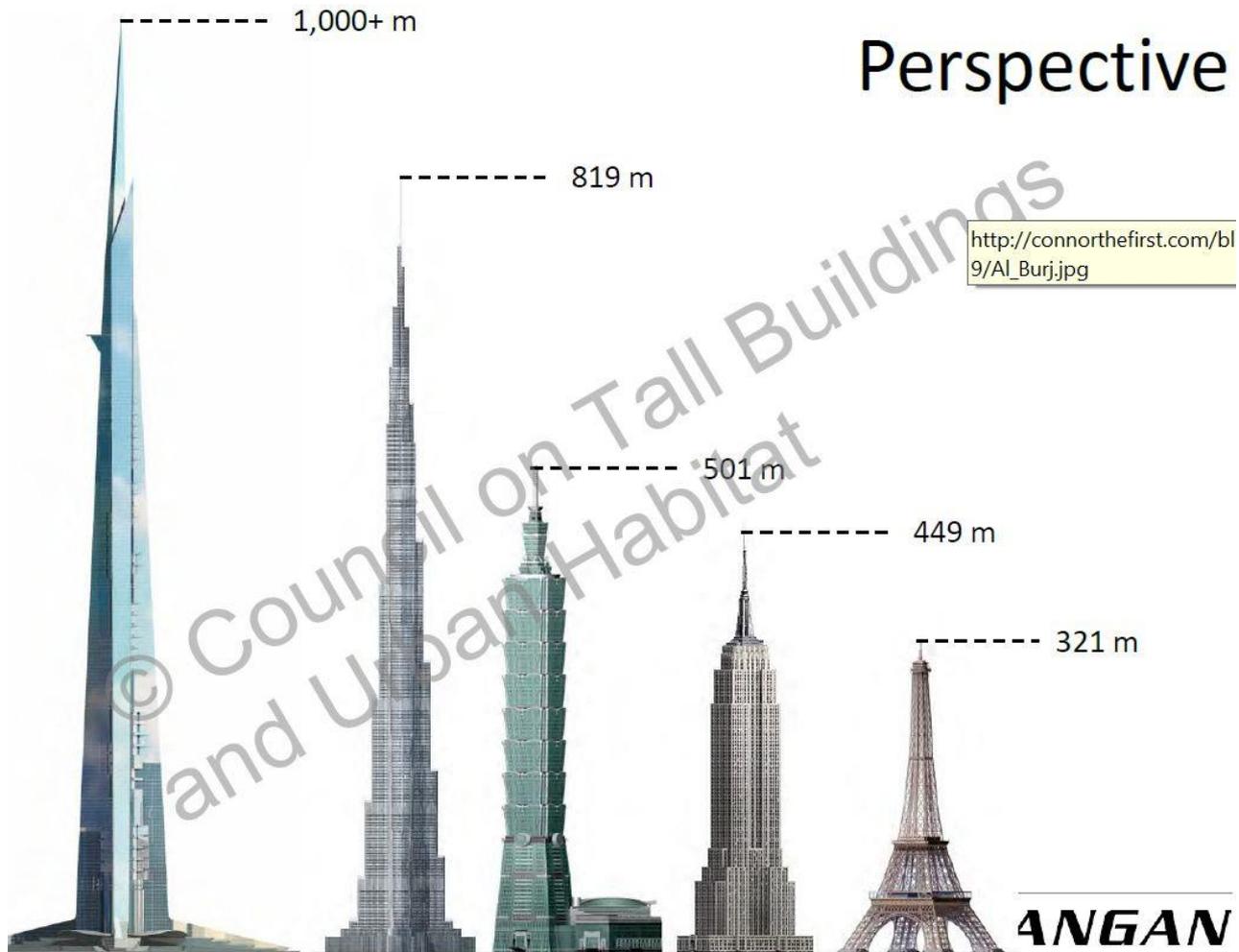
- Tempo = denaro
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- Vertical transport system è il “Driver”

Aspetti principali

- Analogia della mensola
- Carico verticale e laterale
 - Carico laterale determinante
 - Premium per l'altezza
- Stati limite ultimi
 - Resistenza
- Stati limite di servizio (in genere governano)
 - Rigidezza e spostamenti
 - Human Comfort



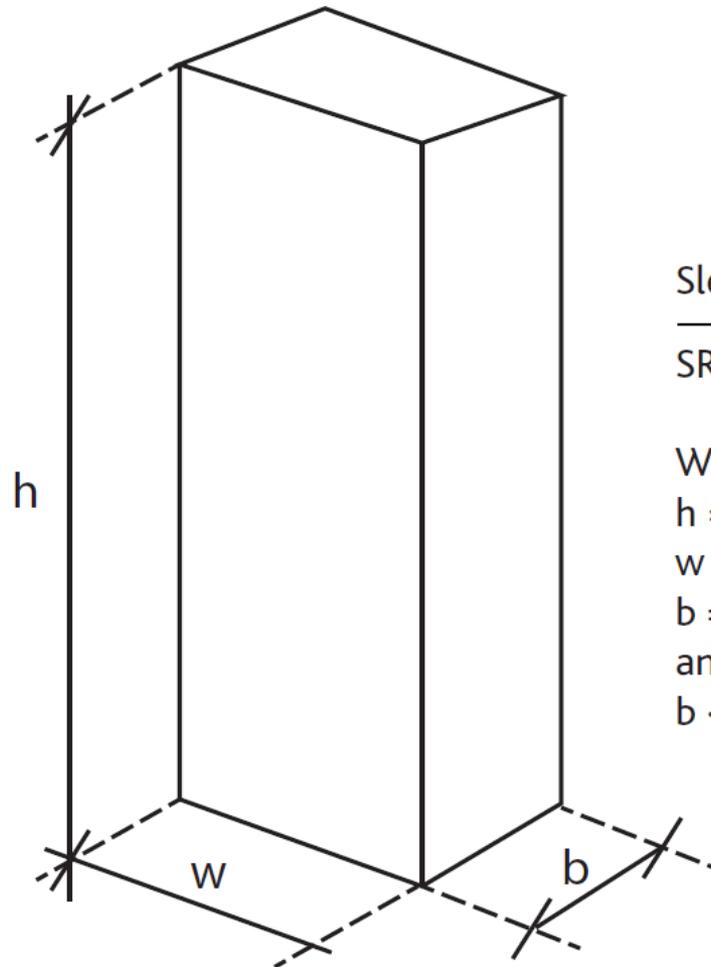
Oltre 1 Km...



Strategie di progettazione

- Rapporto di snellezza
 - Snellezza dell'edificio (>5:1)
 - Snellezza del sistema di stabilità laterale (target <10:1)
- Destinazione d'uso
 - Residenziale \ Hotel \ Uffici \ Mix
- Layout tipici
 - Sviluppo del sistema di comunicazione verticale (ascensori\impianti)

Intro - Snellezza



Slenderness Ratio,

$$SR = h/b$$

Where,

h = building height

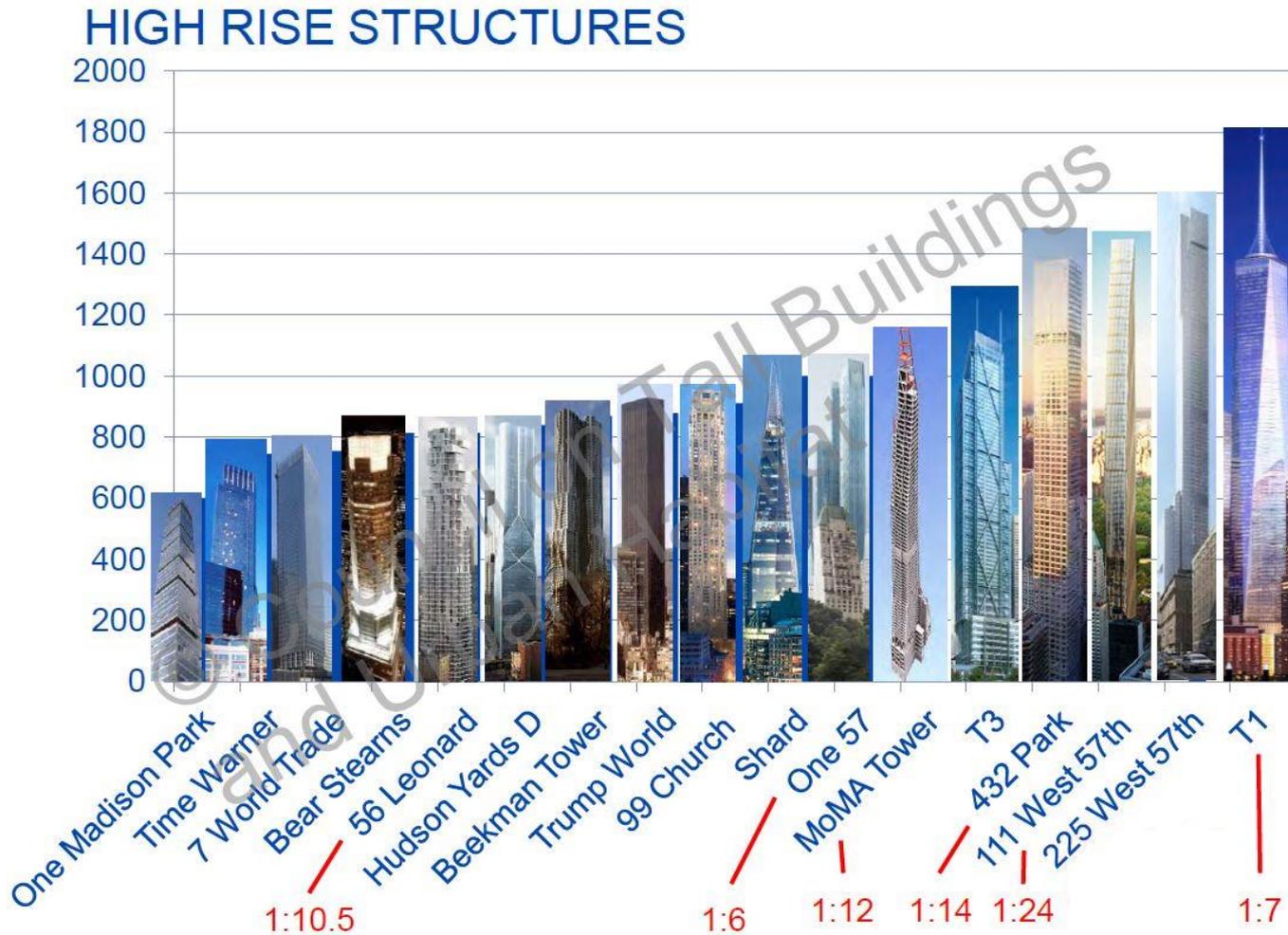
w = building width

b = building breadth

and where

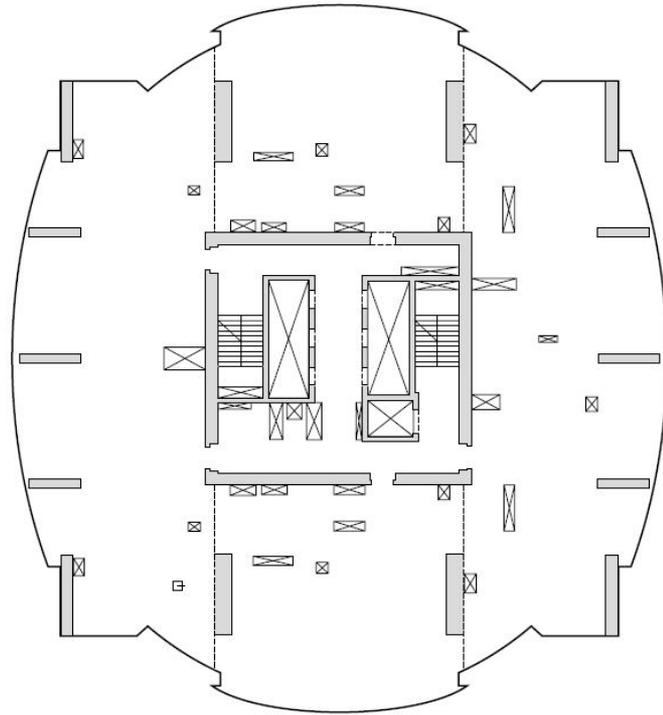
$$b < w$$

Snellezze record

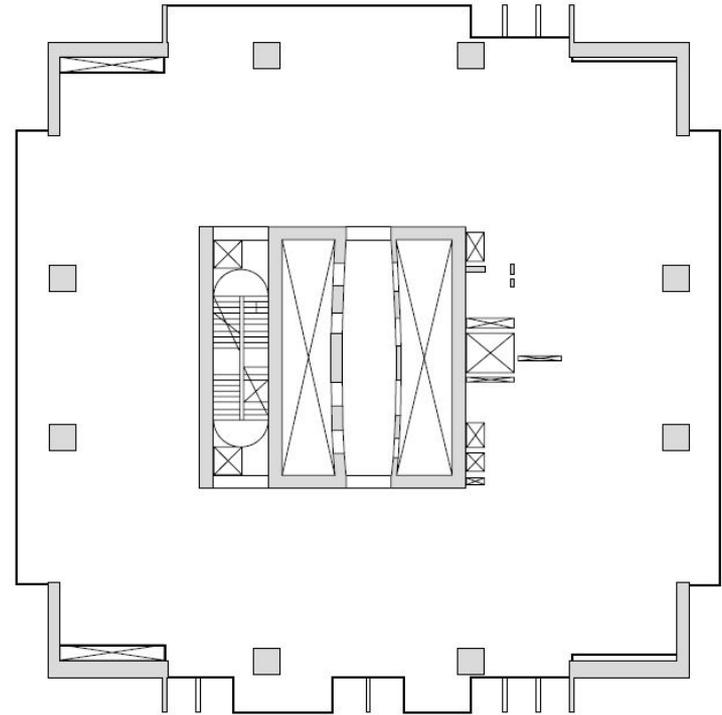


Layout tipici

Efficienza in pianta generalmente $< 70\%!!$

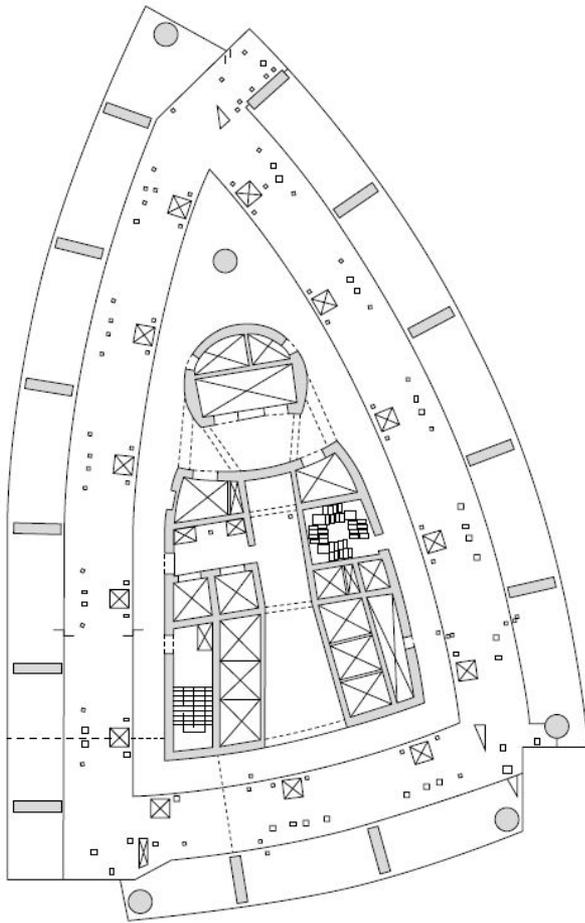


Office / Residential

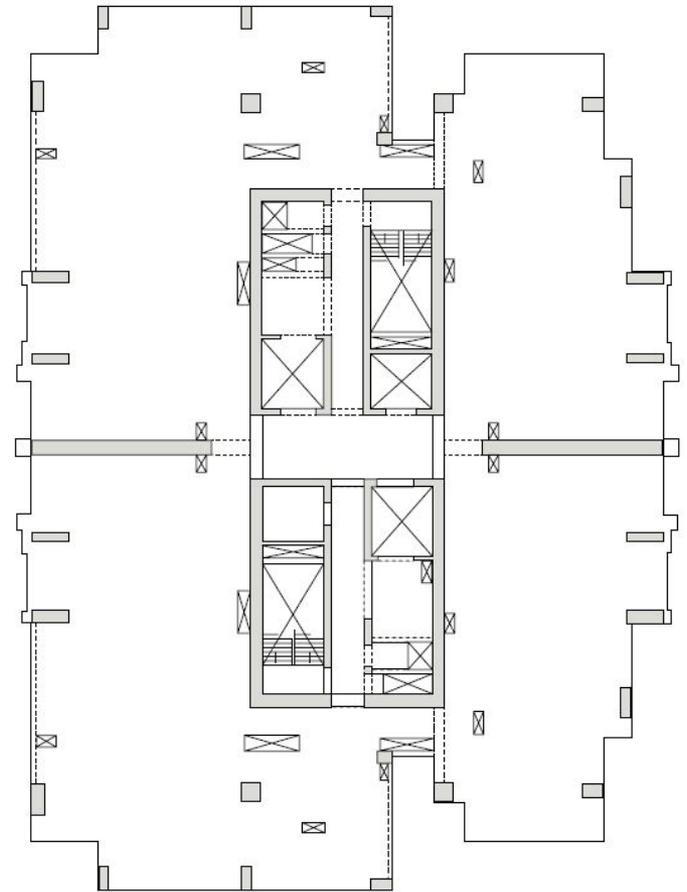


Office

Layout tipici

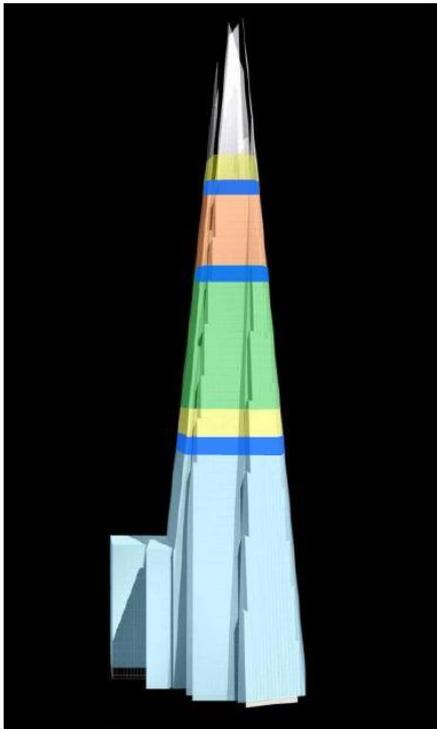


Hotel / Residential / Office

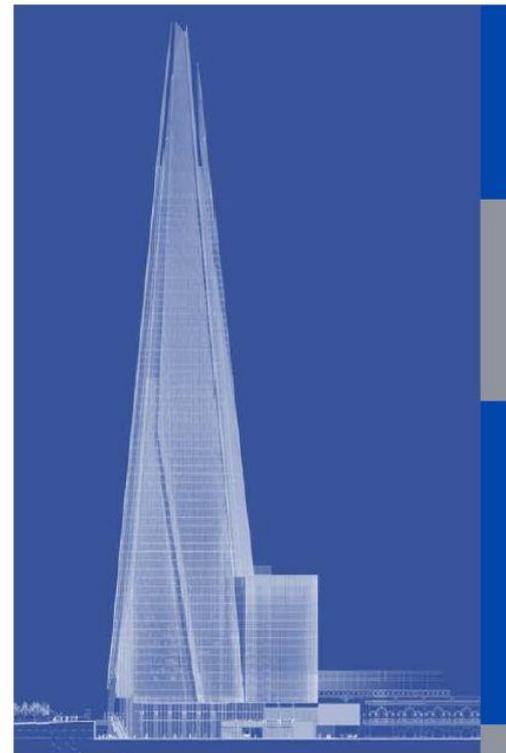


Residential

Destinazione d'uso



Spire	75-87
Viewing Gallery	68-72
Plant	66-67
Apartments	53-65
Plant	51-52
Hotel	34-51
Restaurants	31-33
Plant	29-30
Offices	04-28
Reception, retail	00-03
Basement plant	B1-B3



Steel

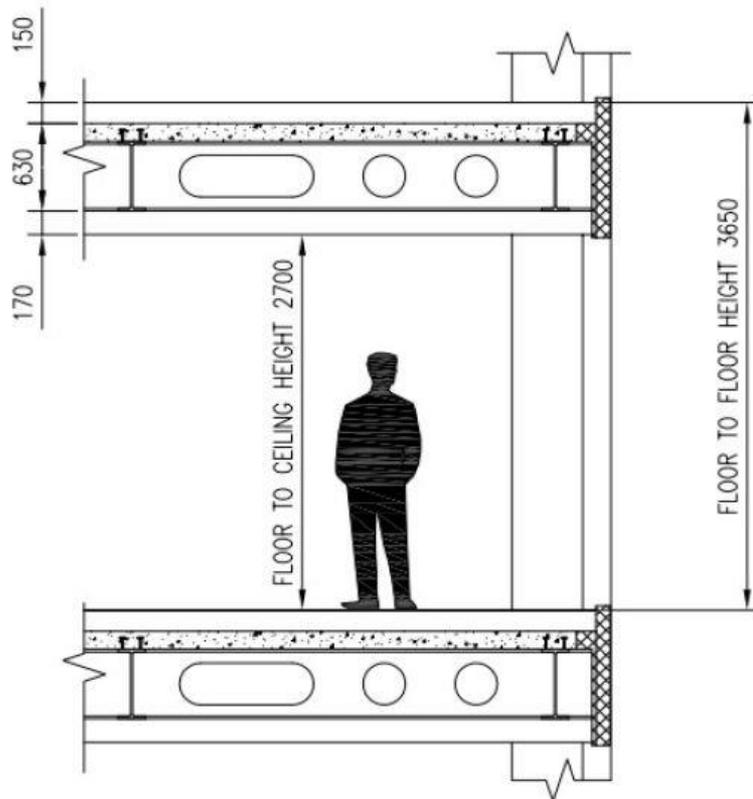
Concrete PT

Steel Composite

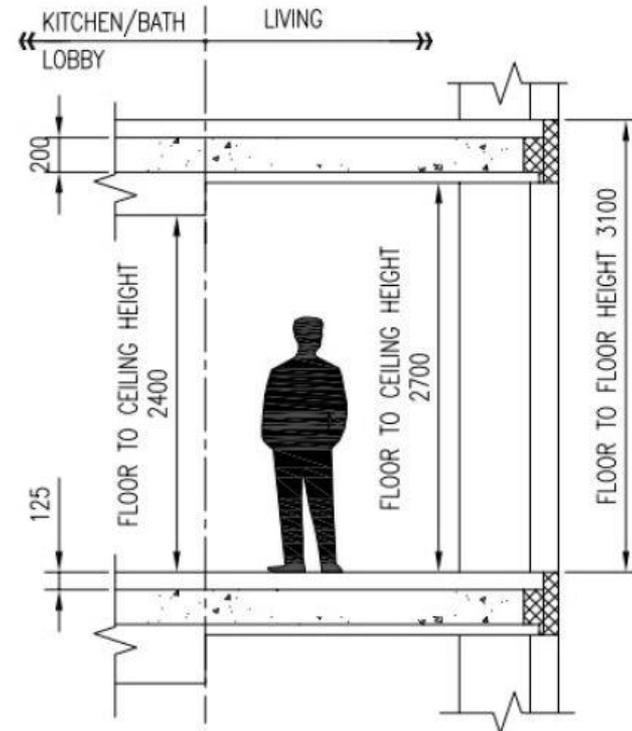
Concrete RC

Interpiano

Steel floors



Concrete floors

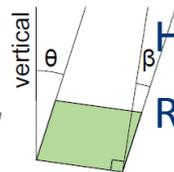
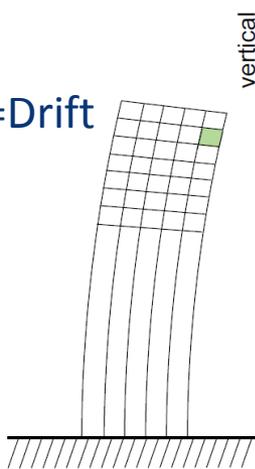


Strategie di progettazione

- Individuazione del potenziale sistema strutturale ed opzioni
- Integrazione e coordinazione con impianti
- Spostamenti e drifts
- Comfort
- Facciate
- Buildability tempo\efficienza
- Robustness
- Fire

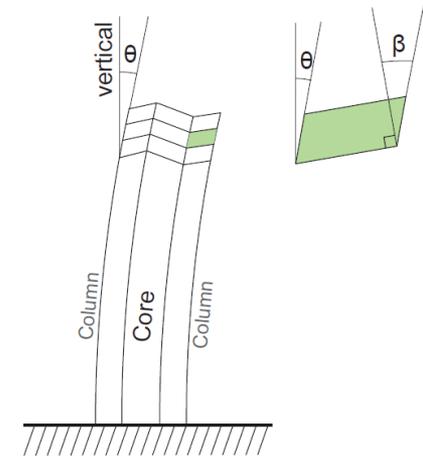
Introduzione - Drifts

Low rise
Racking=Drift

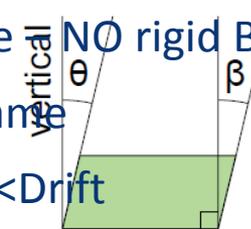
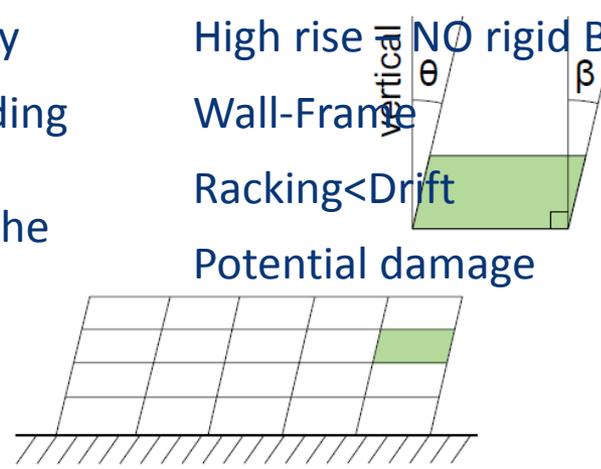


High rise - Rigid Body
Rotation of the building
and vertical
deformation of the
columns

Racking > Drift

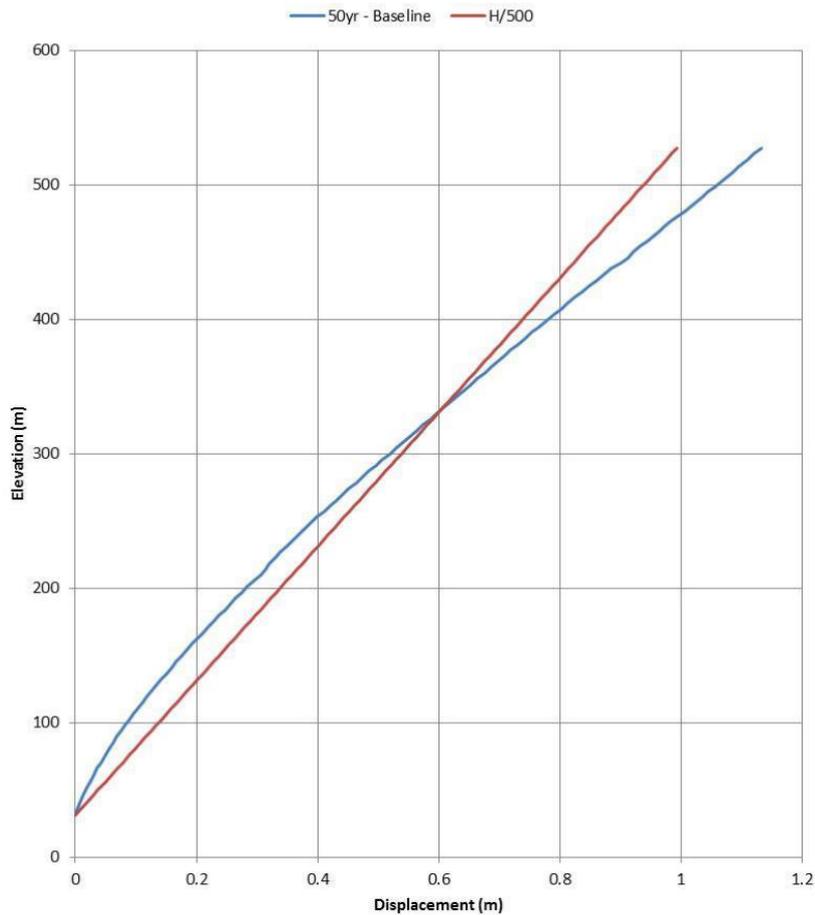


High rise NO rigid Body
Wall-Frame
Racking < Drift
Potential damage

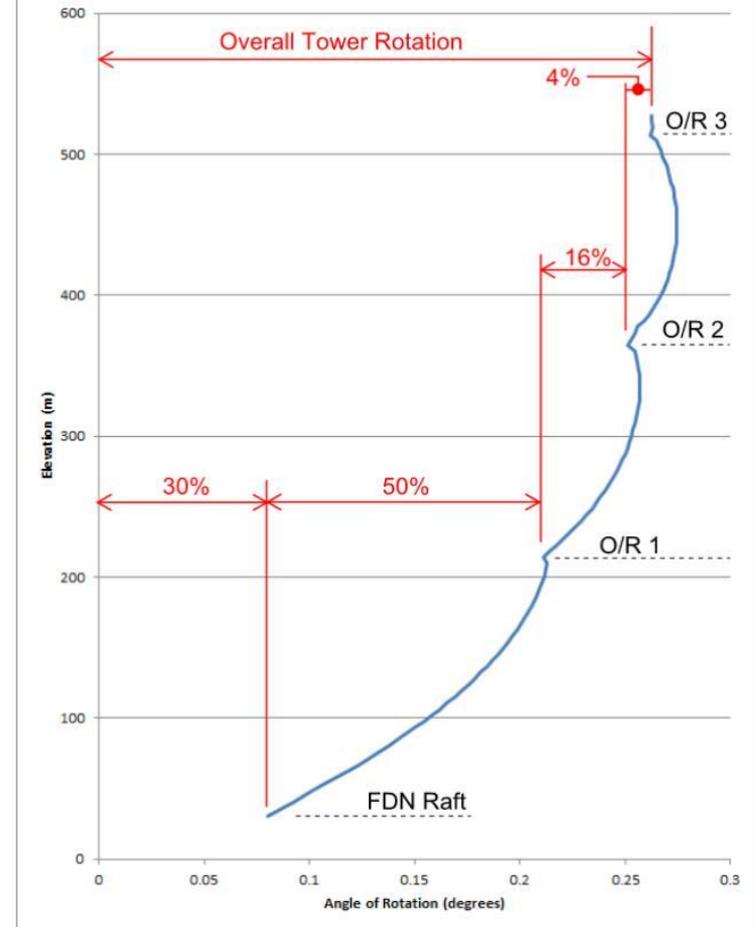


Introduzione - Drift e Displ

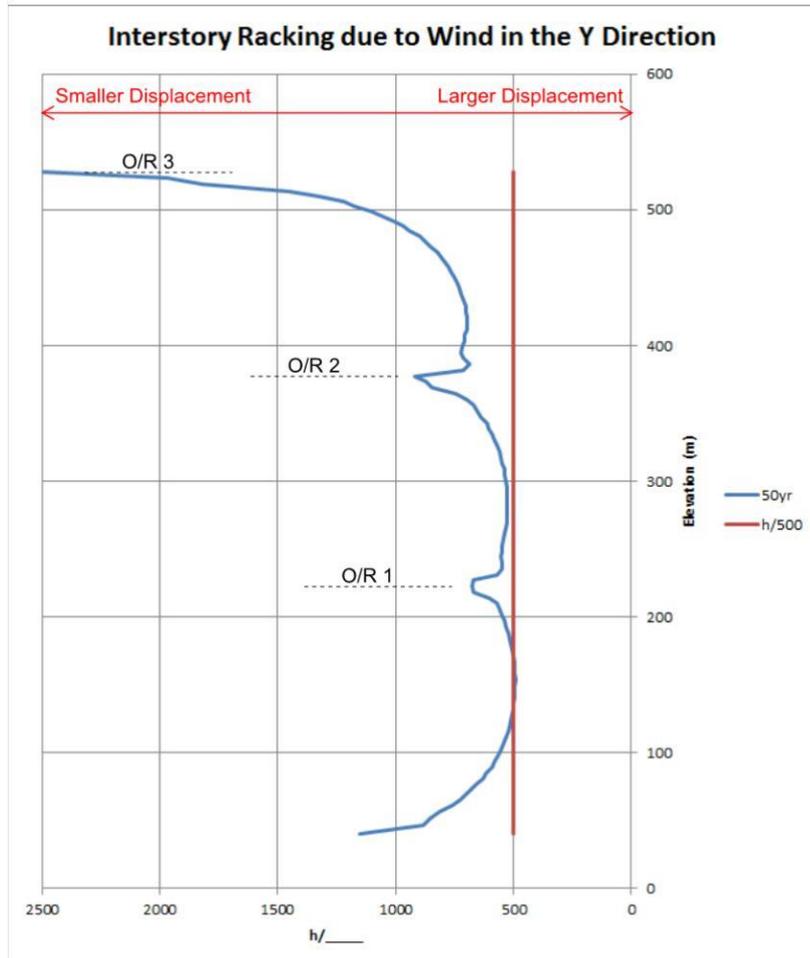
Tower Displacement due to Wind in the Y Direction



Rotation of Core Wall for 100yr Wind



Introduzione – Drifts e Displ



Introduzione - Drifts

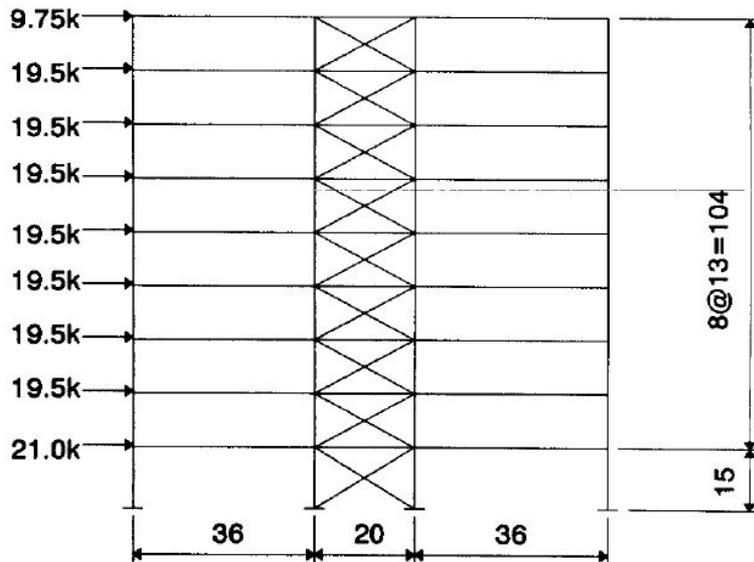
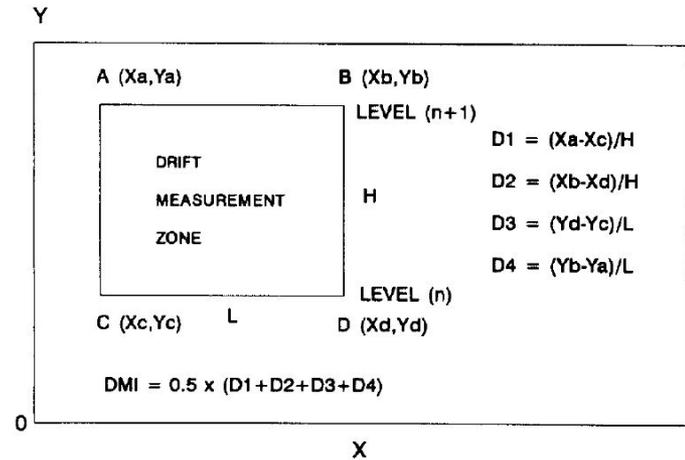
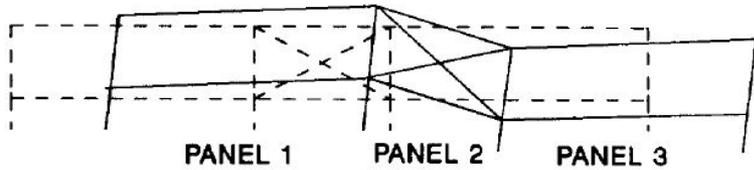


Figure 2



X_i = vertical displacement of point i

Y_i = lateral displacement of point i

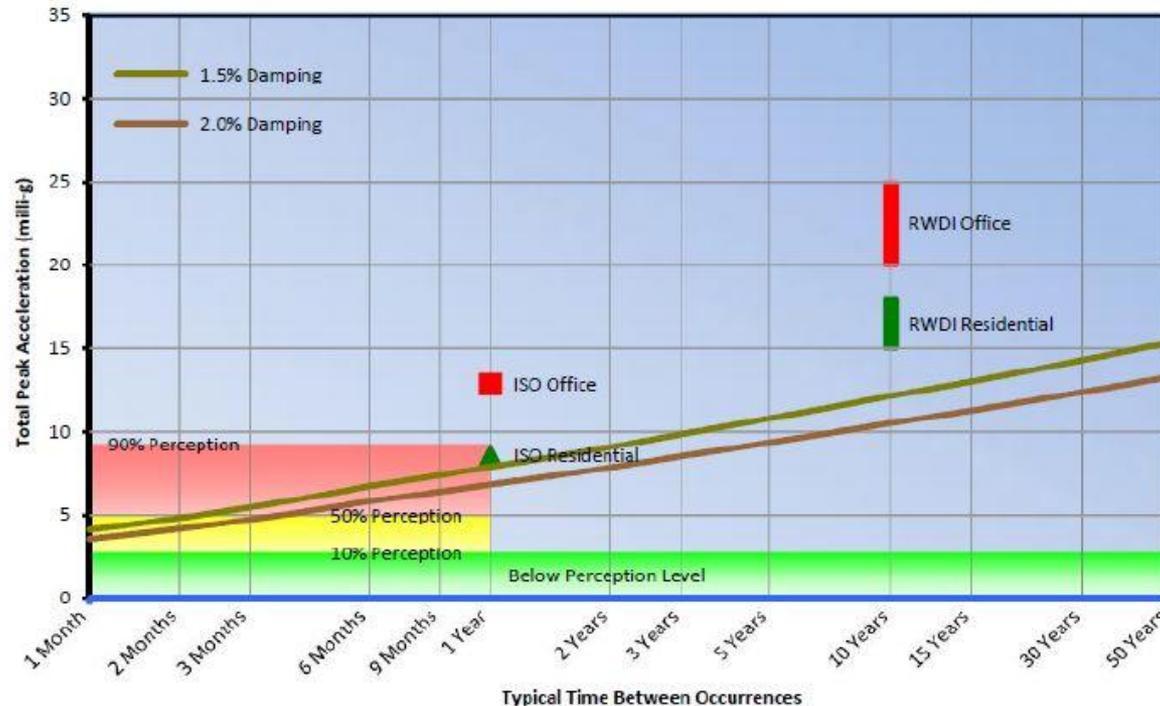
$D1 = (X_A - X_C)/H$, horizontal component of racking drift

$D2 = (X_B - X_D)/H$, horizontal component of racking drift

$D3 = (Y_D - Y_C)/L$, vertical component of racking drift

$D4 = (Y_B - Y_A)/L$, vertical component of racking drift

Introduzione – Accelerazioni

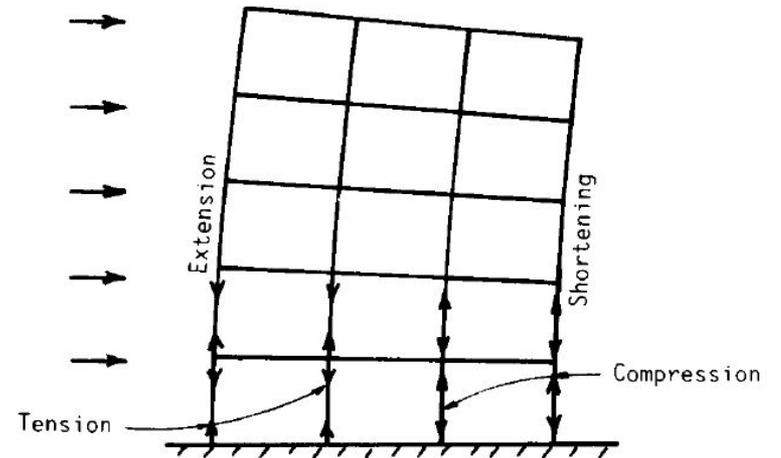
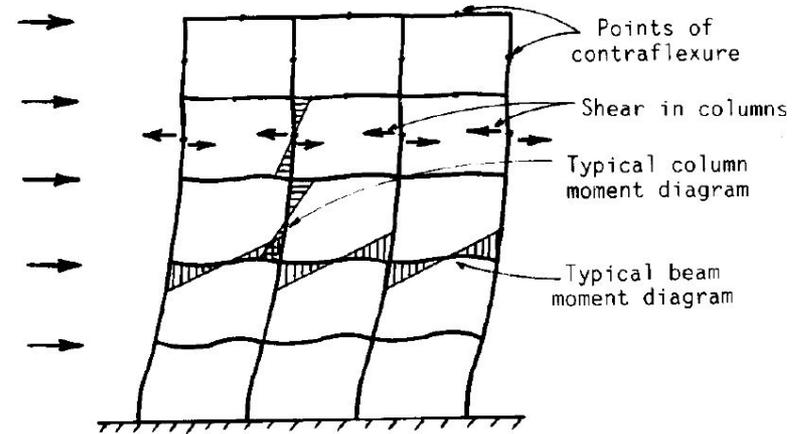
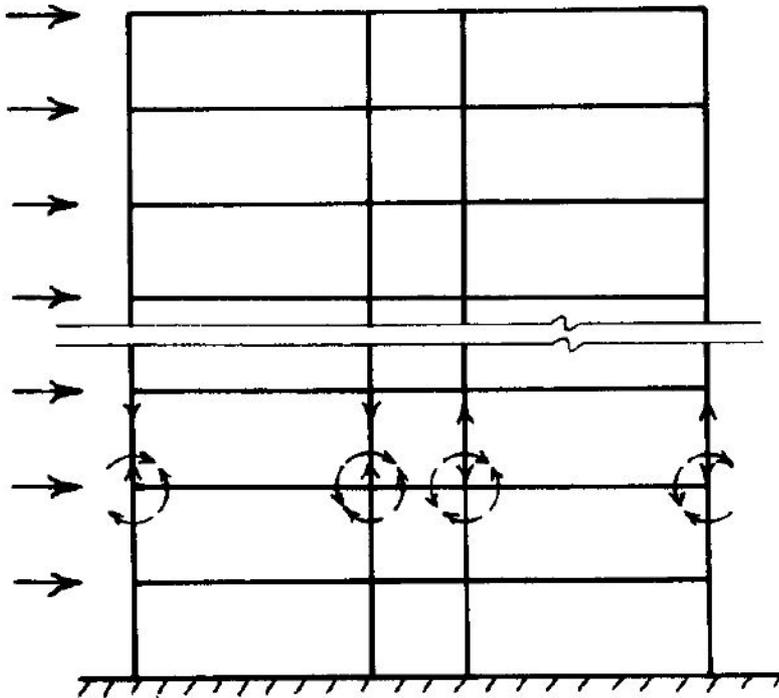


Return Period (Years)	Peak Accelerations ⁽²⁾ (milli-g) Total - [X, Y and torsional components]		Peak Torsional Velocities (milli-rads/sec)		
	1.5% Damping	2.0% Damping	1.5% Damping	2.0% Damping	CTBUH ⁽³⁾ Criteria
1	7.9 - [7.2, 7.3, 0.6]	6.8 - [6.2, 6.3, 0.5]	0.3	0.2	1.5
5	10.8 - [9.7, 10.1, 0.8]	9.4 - [8.4, 8.7, 0.7]	0.3	0.3	-
10	12.2 - [10.9, 11.5, 0.9]	10.5 - [9.4, 9.9, 0.7]	0.4	0.3	3

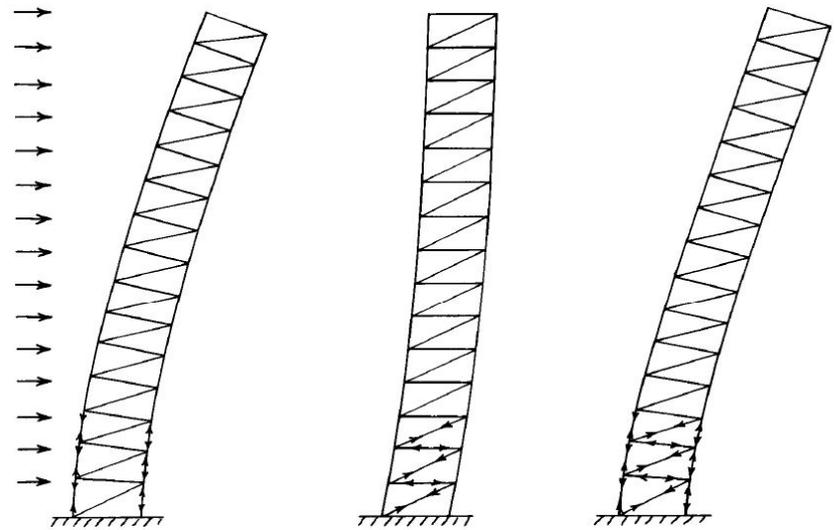
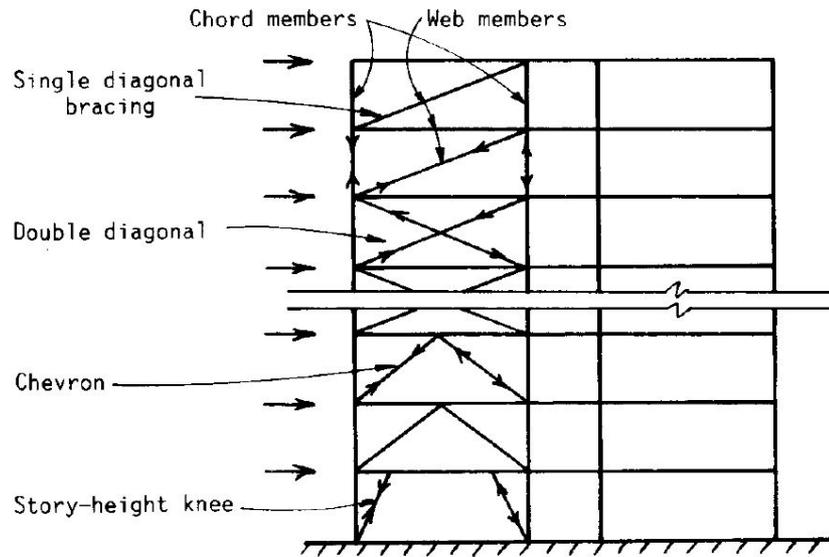
Tipologie strutturali

- Telaio controventato \ telaio a momento
- Pareti di taglio
- Pareti di taglio+telaio
- Framed tube
- Tube in tube
- Modular tube
- Braced tube
- Outriggers
- Buttressed core

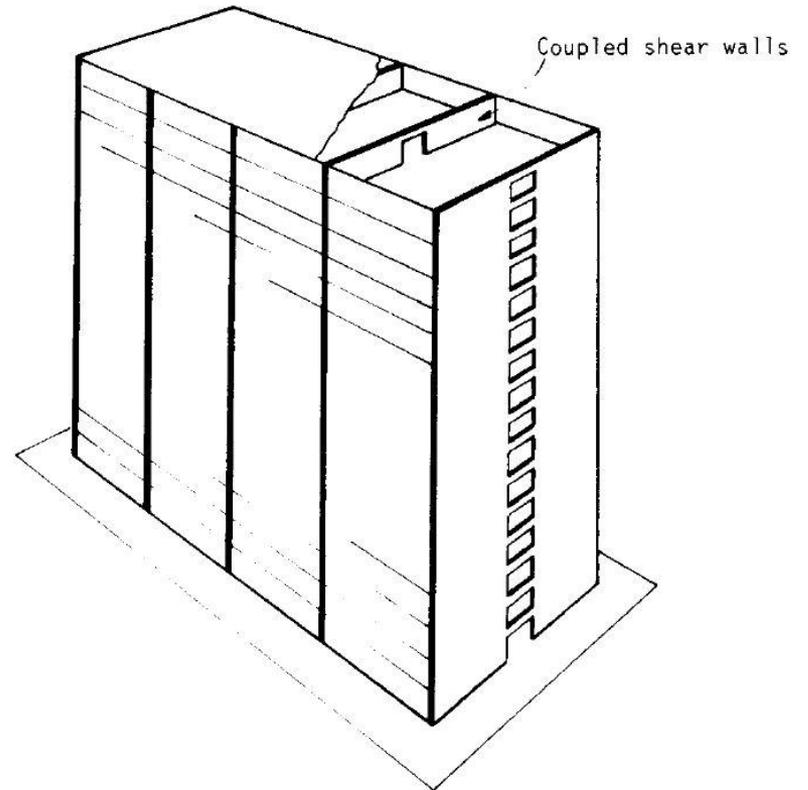
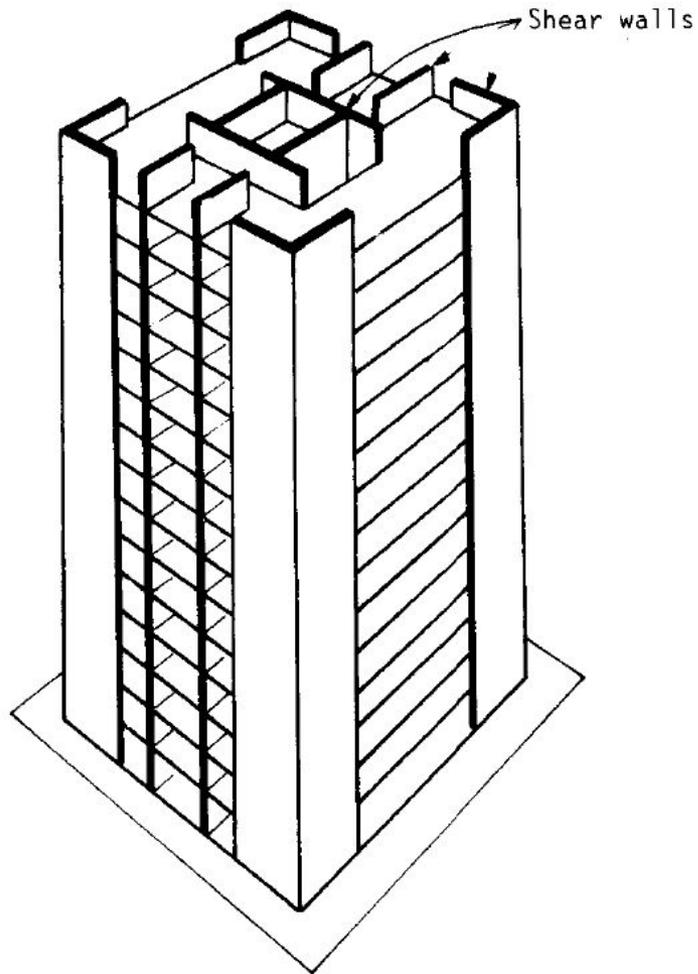
Tipologie – Moment frame



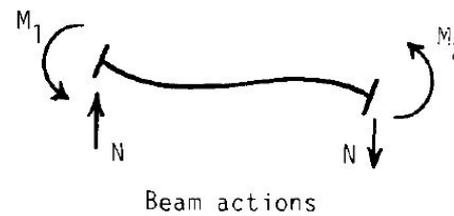
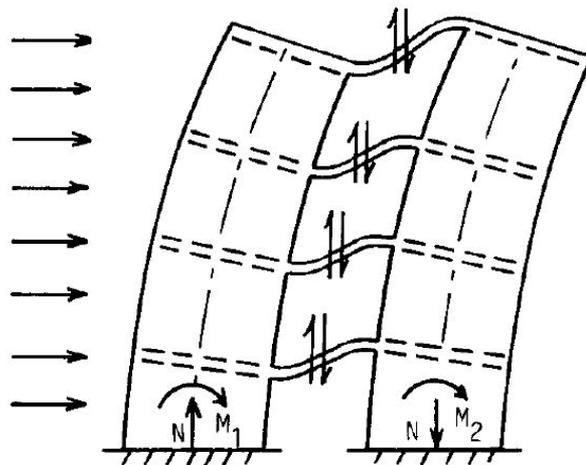
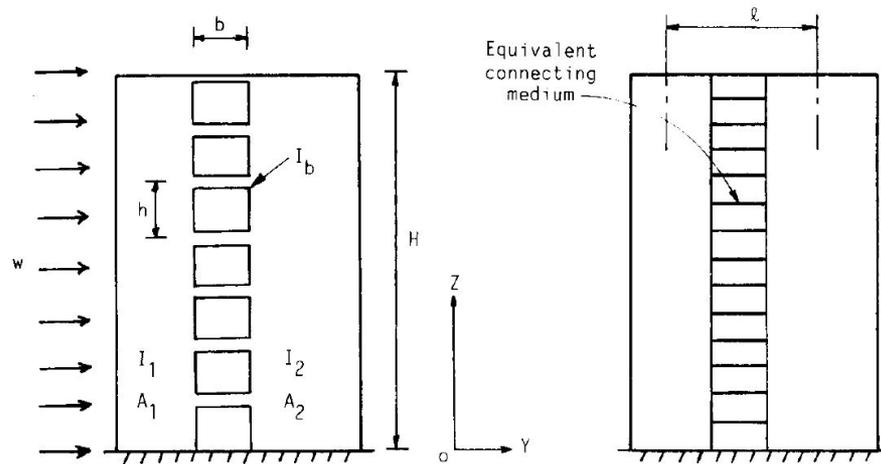
Tipologie – Braced frame



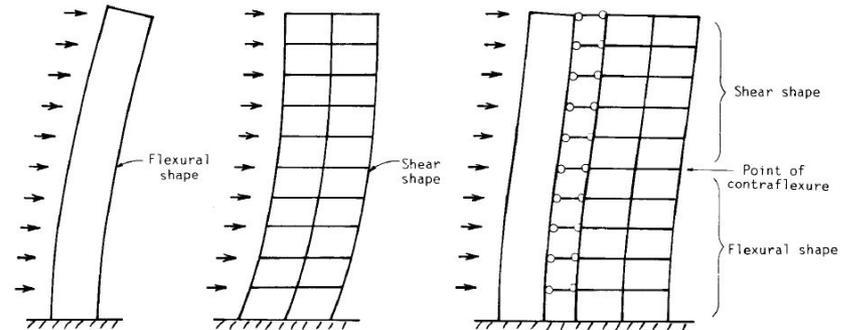
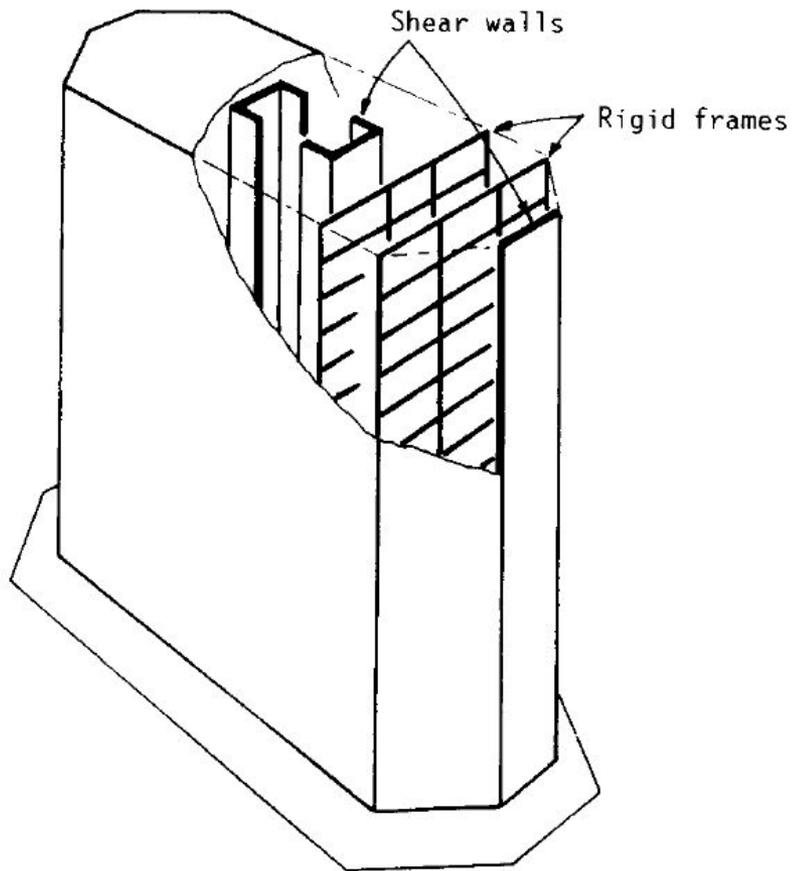
Pareti di taglio e pareti di taglio accoppiate



Coupling beams



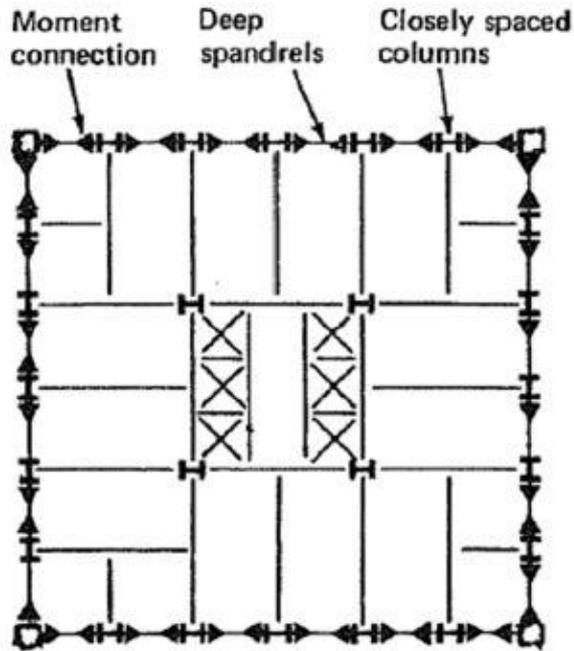
Sistema combinato Pareti telaio



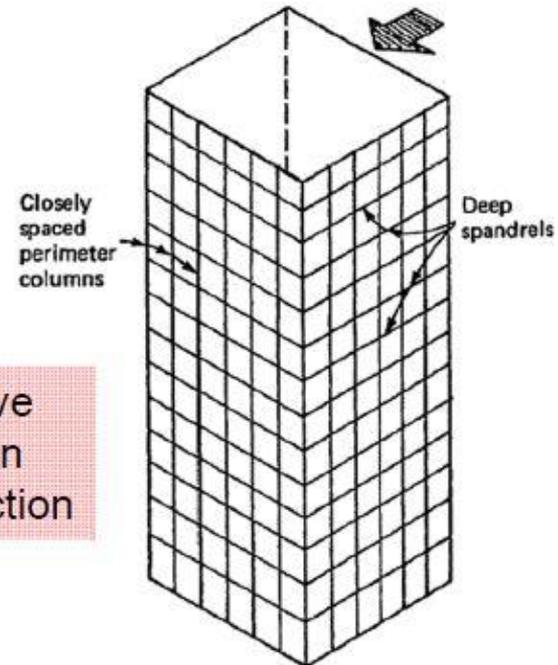
Tipologie – Tube

Tube effect

- Structures with closely spaced columns and deep spandrels (tube effect)



Schematic plan of framed tube

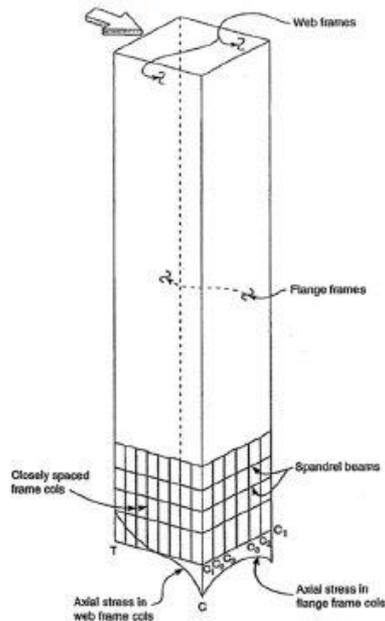


Columns have major axis on perimeter direction

Isometric view of framed tube

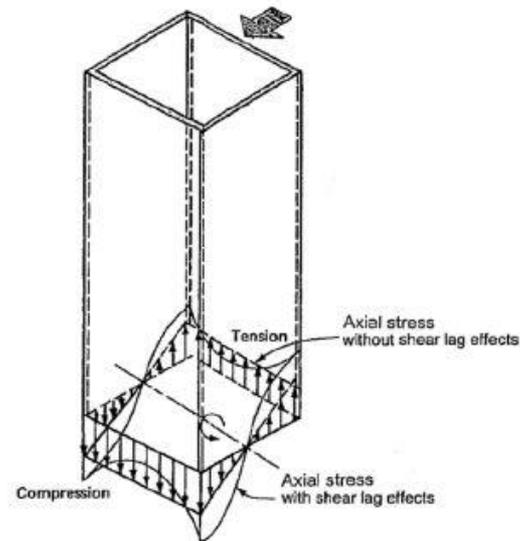
Tube – Shear lag

Shear lag effect



Bending effect and “shear lag” in case of a tube with free transversal displacement

Important: distribution of axial stresses in the square tube with/without “shear lag” effect



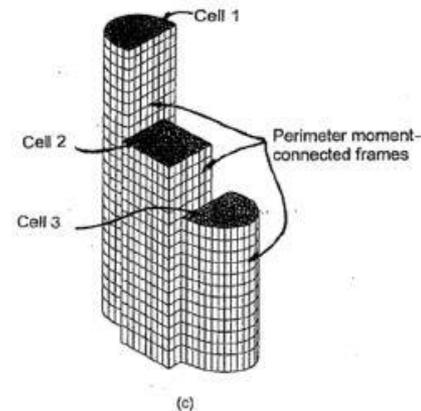
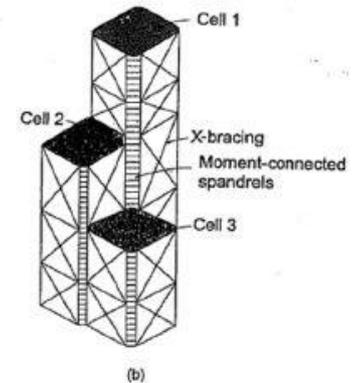
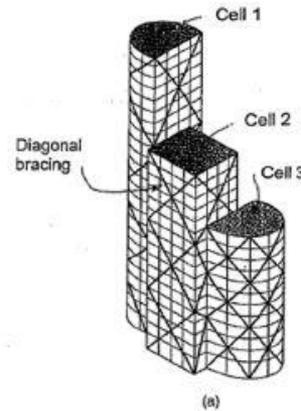
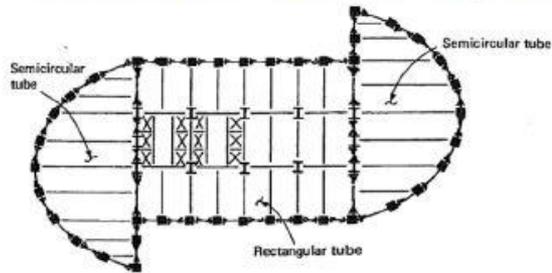
Bending effect and “shear lag” in case of a tube with closely spaced columns

“Shear lag” effect in the tube. Important: distribution of axial stresses is different comparing to classical bending theory

Tipologie – Bundled tubes

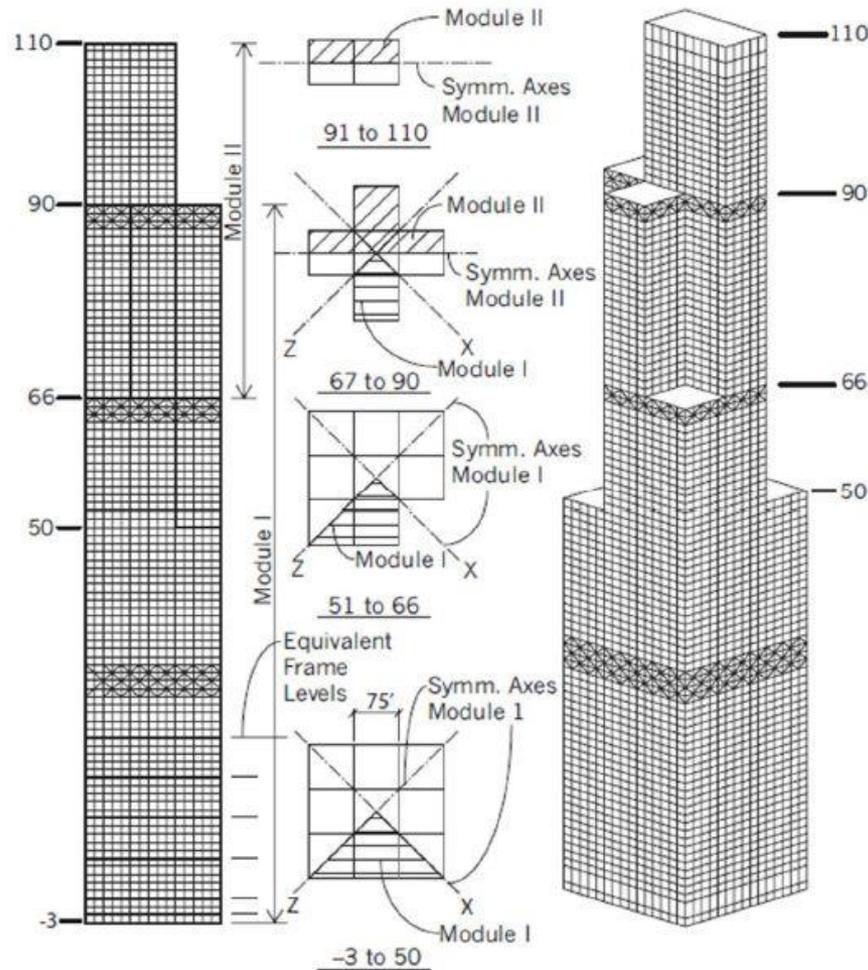
Multiple tubes

- Structures with multiple tubes



Concept of a structure with multiple tubes: a) perimetral diagonal bracings; b) X bracings and moment connected spandrels; c) perimeter moment connected frames

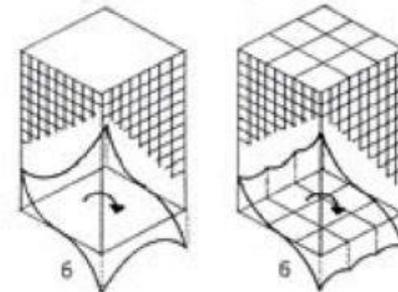
Tipologie – Bundled tubes



Willis Tower (formerly Sears Tower), Chicago, Illinois

Better distribution of stresses due to bundled cross section (smaller shear lag)

cross section



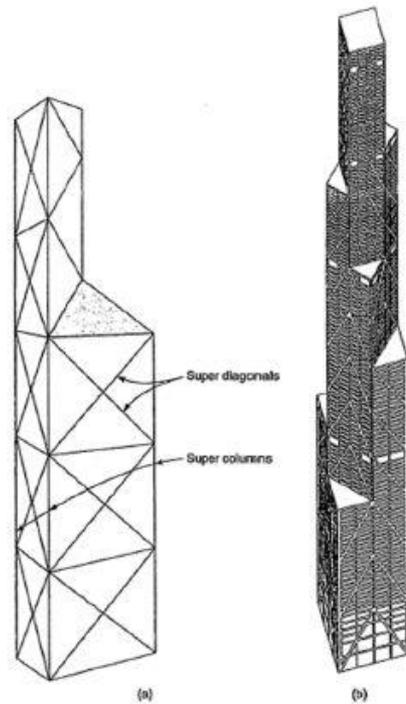
simple

bundled

Tipologie - Braced Tube

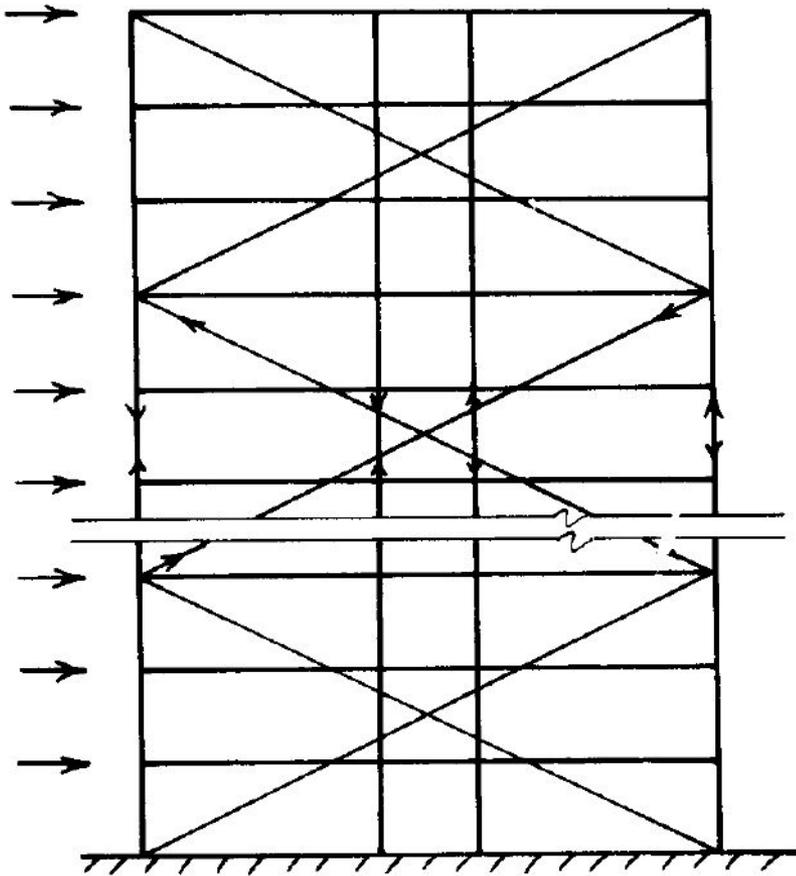
Tube building with diagonals

- Structures with closely columns (tube) and perimetral bracings

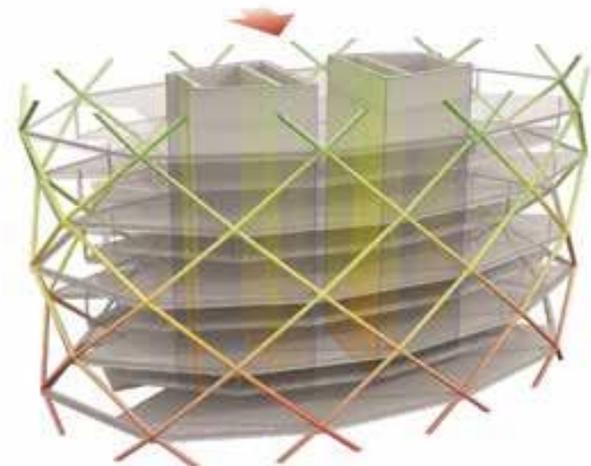
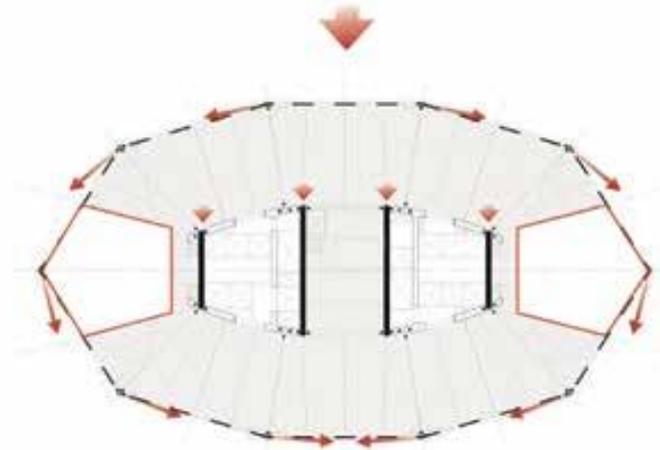


a) Tube building with diagonals on multiple stories; b) Building with rotated tubes and super diagonals

Tipologie - Braced tube



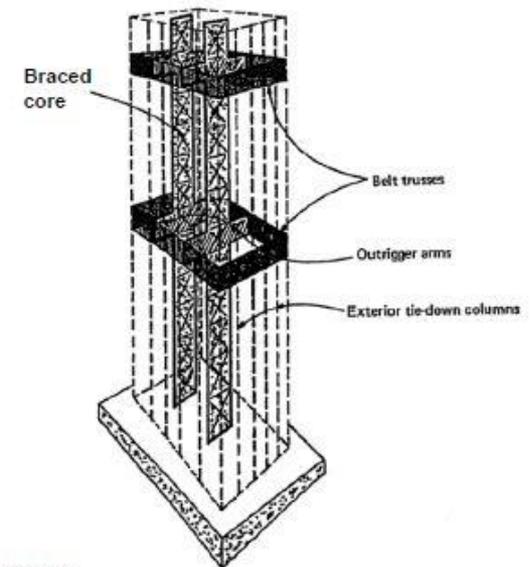
Tipologie - Diagrid



Tipologie – Outrigger & Belt truss

Outrigger and belt truss system

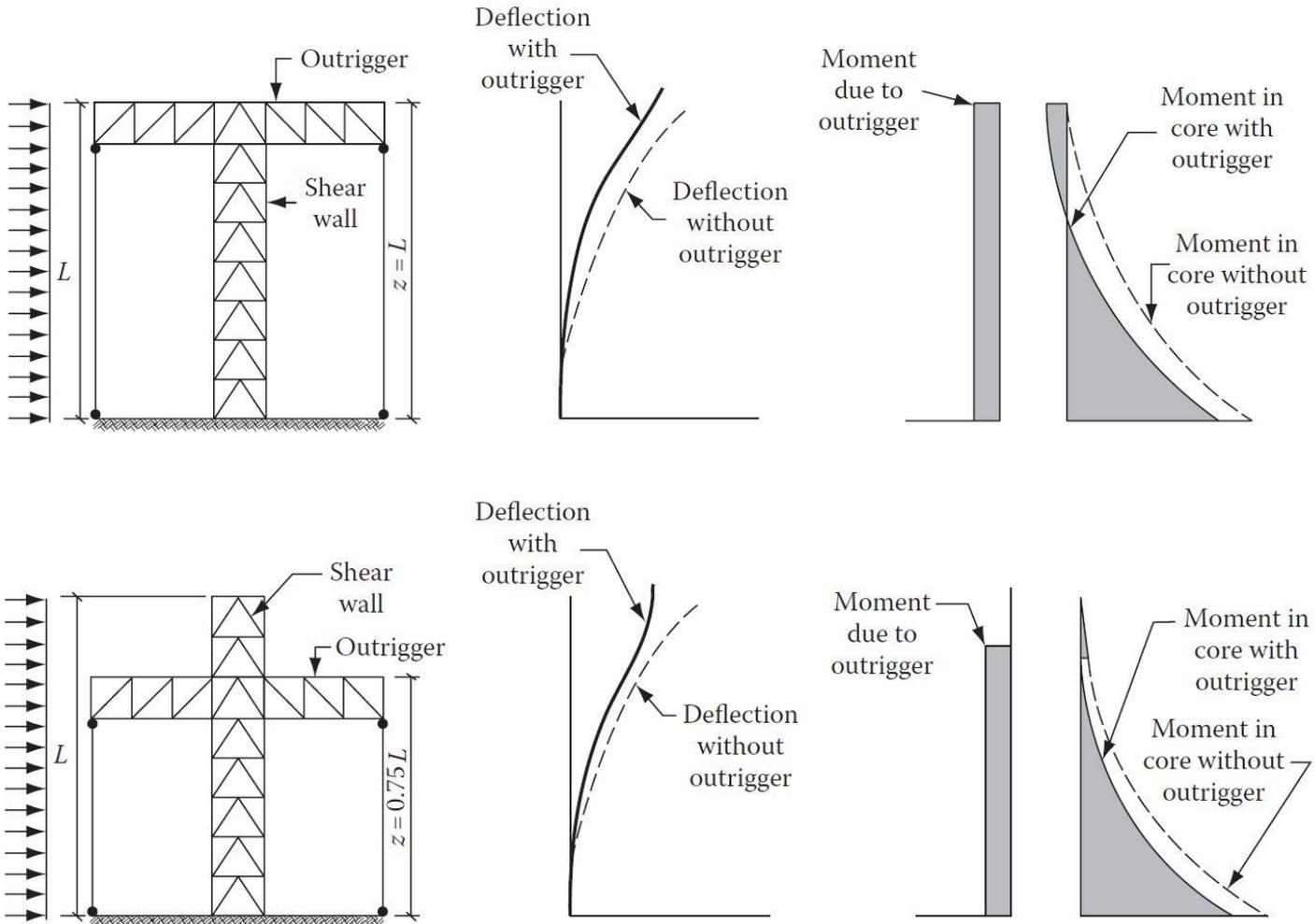
- ❑ The outriggers couple the columns and the core
- ❑ The lateral deflections are smaller than if the core is freestanding
- ❑ Belt trusses around the building



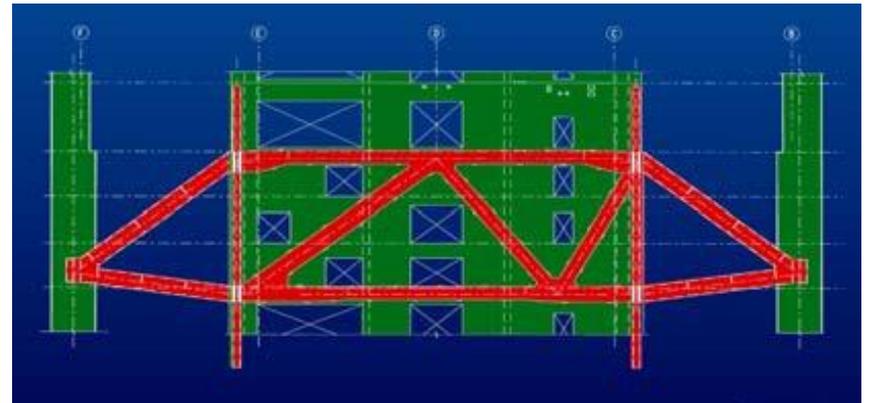
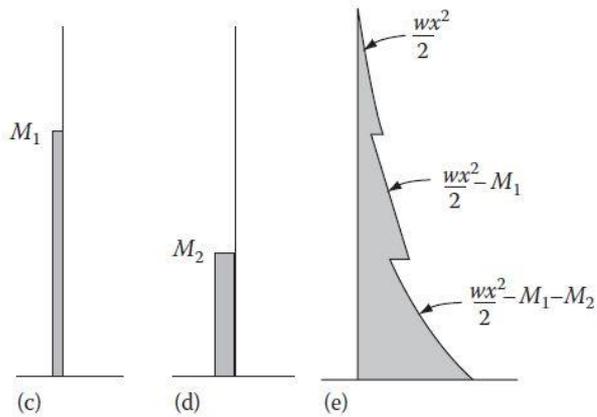
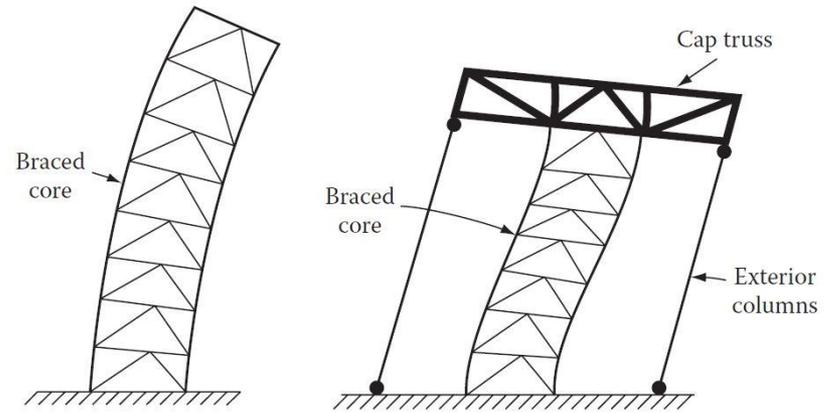
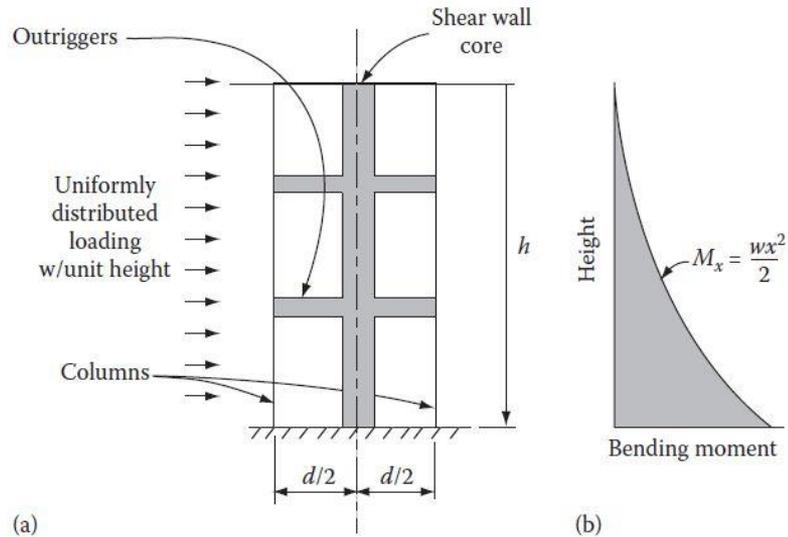
Advantages:

- ❑ Reduce building deflections and core bending stresses
- ❑ Reduce the rotational reactions
- ❑ Minimize the structural cost penalty associated with stability of slender buildings
- ❑ Effective for improving 3D behavior of irregular buildings

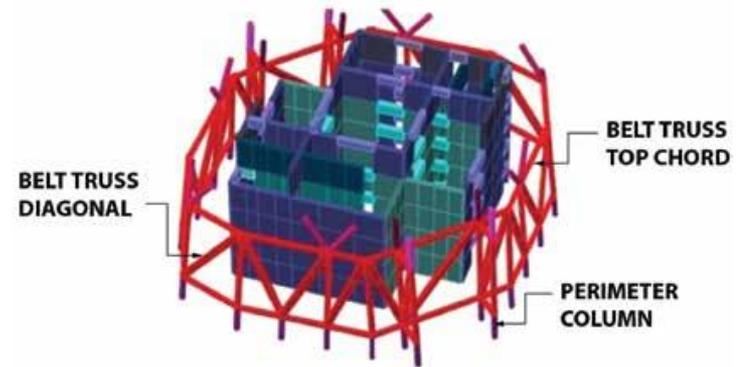
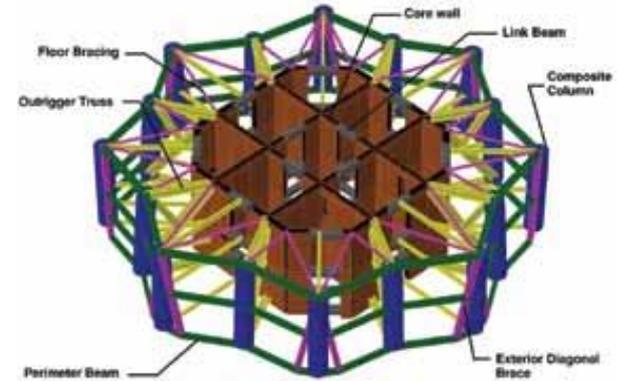
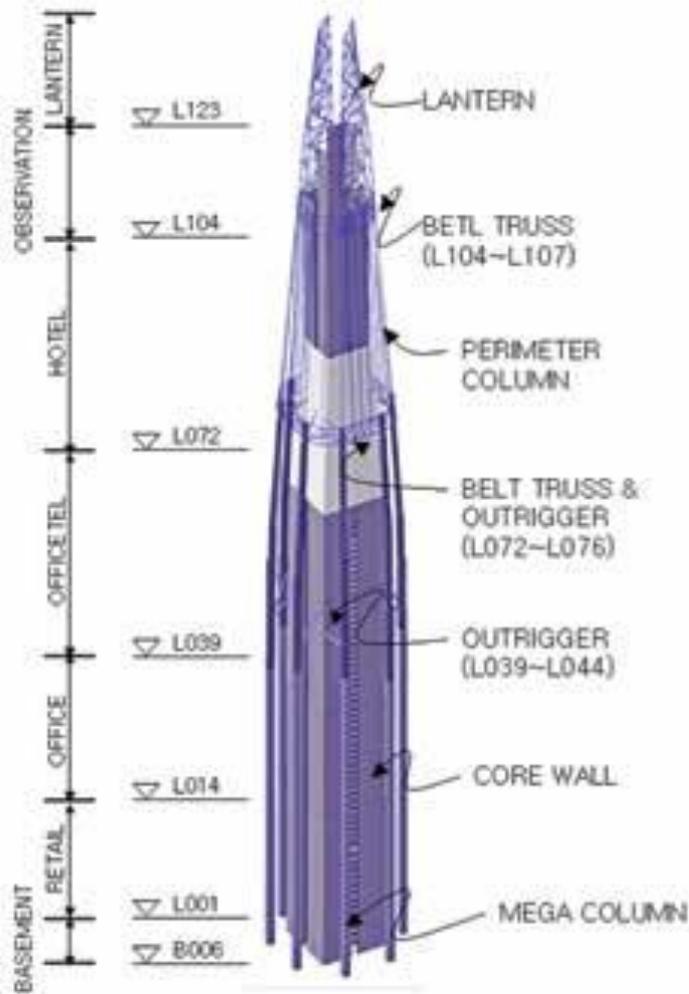
Outrigger&BT



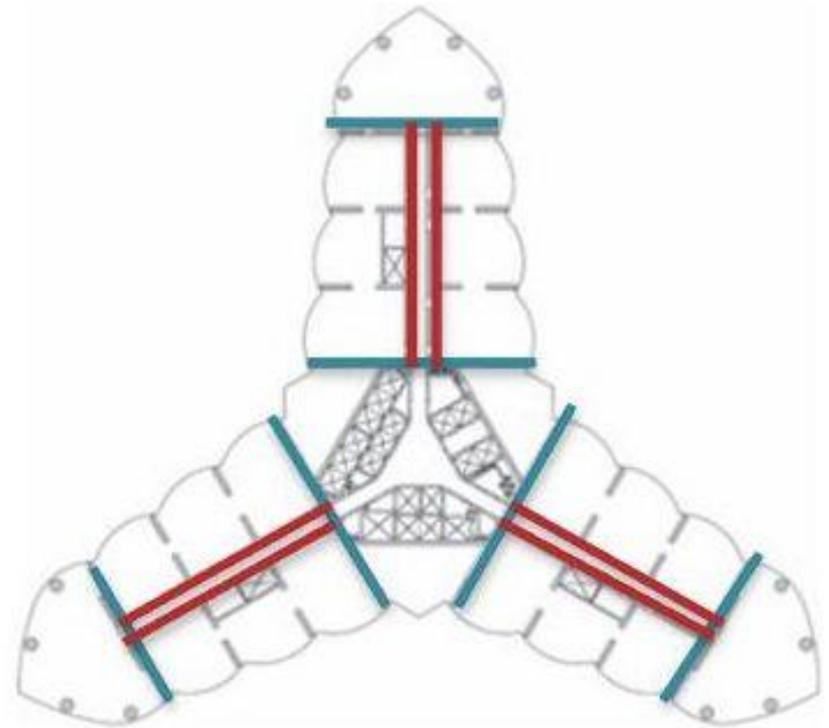
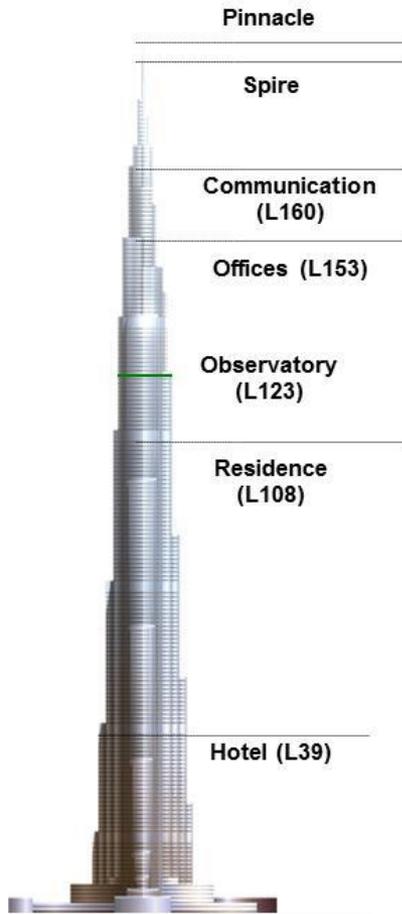
Outrigger&BT



Outrigger&BT



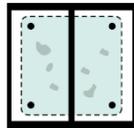
Tipologie – Buttressed core



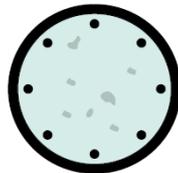
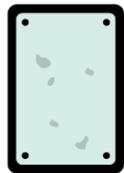
Elementi strutturali-Colonne



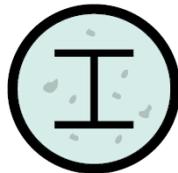
Fully encased



Partially encased



Concrete filled tubes



Beams and column elements

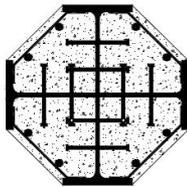
Optimized solutions based on rolled profiles



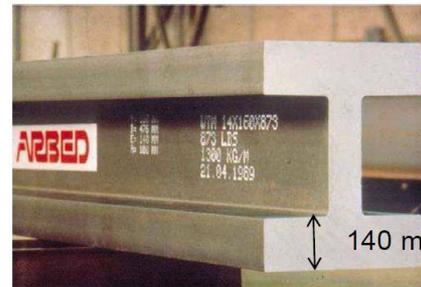
Beams and column elements

Composite action:

- Partially encased columns
- Fully encased columns



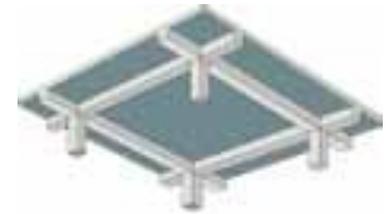
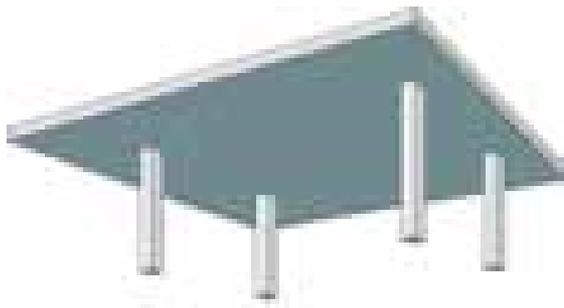
Jumbo sections for High-rise buildings



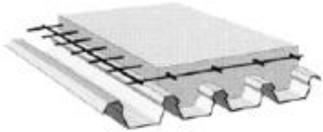
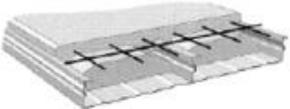
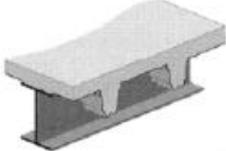
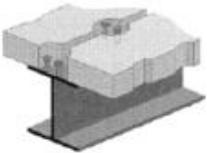
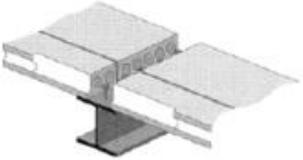
900 high-rise buildings in the U.S.A.

1500 high-rise buildings worldwide

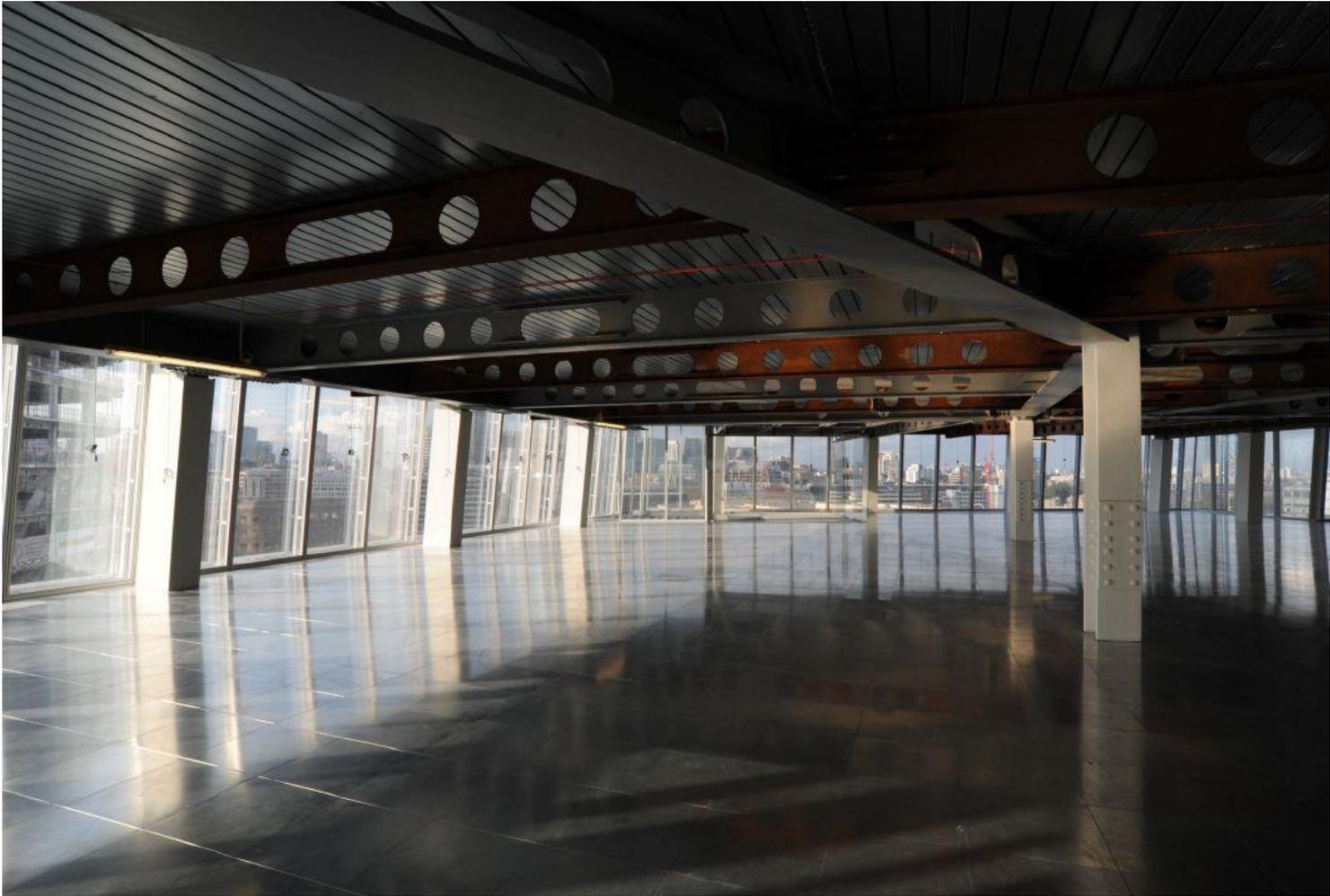
Elementi strutturali / RC slabs



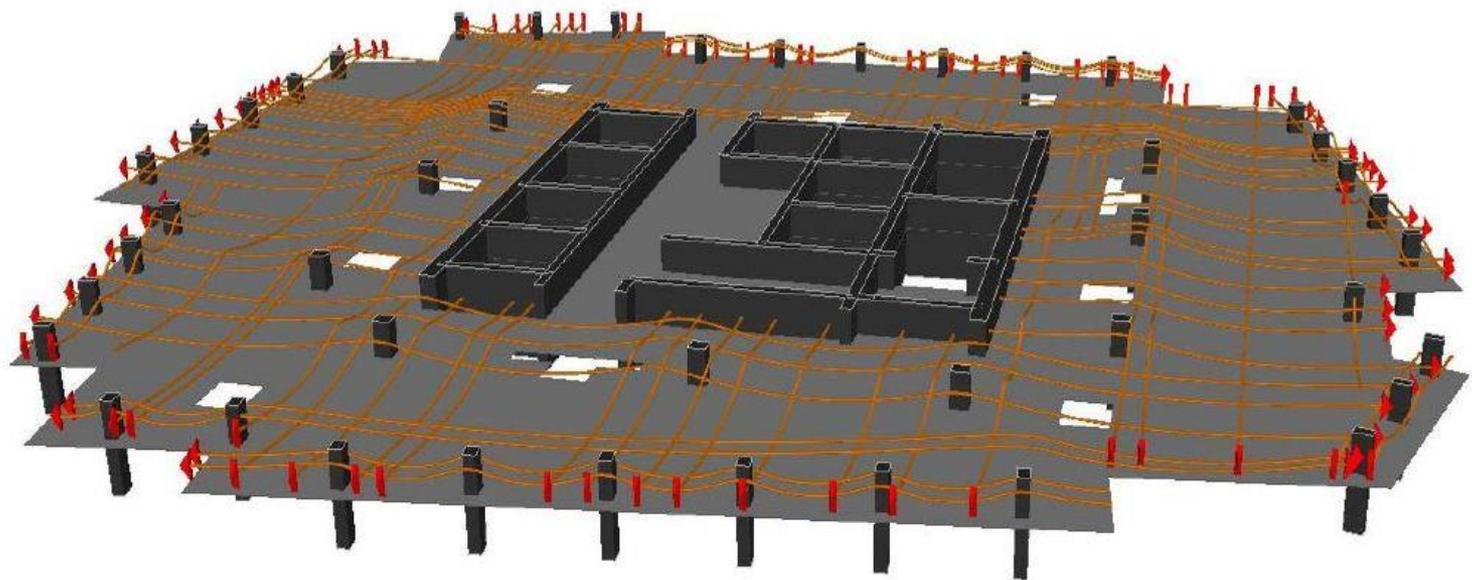
Elementi strutturali – Composite slab

Type	Application	Example
Composite slab	$10\text{cm} \leq d \leq 30\text{cm}$ $2\text{kN/m}^2 \leq q \leq 6\text{kN/m}^2$ for spans $2\text{m} \leq L \leq 6\text{m}$	
Prefabricated composite slabs	Sheeting / Rockwool / Concrete for $d = 20\text{cm} \Rightarrow q = 2\text{kN/m}^2$ for spans $4\text{m} \leq L \leq 7\text{m}$	
Slabs with deep rolled profile sheetings	$h = \text{ca. } 200\text{mm}$, $d = \text{ca. } 25\text{cm}$ for spans $L \leq 6\text{m}$	
Concrete slab	on-site or partially prefabricated $d = \text{ca. } 20\text{cm} \Rightarrow q = 5\text{kN/m}^2$ for spans $L \leq 6\text{m}$	
Prestressed hollow core slabs	$16\text{cm} \leq d \leq 40\text{cm}$ (1.20m width) $2.5\text{kN/m}^2 \leq q \leq 6\text{kN/m}^2$ for spans $8\text{m} \leq L \leq 14\text{m}$	

Composite floor



PT slab



Core Walls

- Alcuni dati tipici...

Levels	Walls Thk	Concrete Grade	Reo rates
[-]	[mm]	[Mpa]	[kg/m ³]
RAFT to L14	800	C70/85	220
L15 to L34	600	C70/85	200
L35 to L54	400	C60/75	180
L54 to ROOF	400	C50/60	160

Notes

These reo rates do not allow for coupling beams reinforcement

30% allowance included for laps, etc.

Lintels 5/7/8 Reinforced concrete beams average reo rate 300Kg\m³

Construction engineering

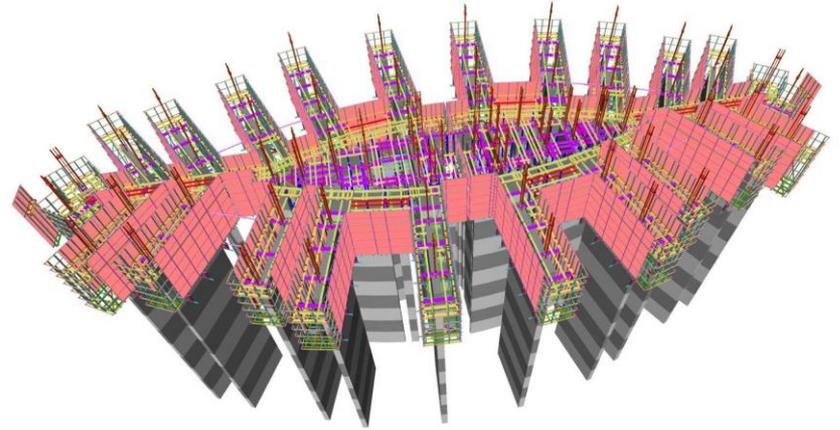
- Fasi e tecniche di costruzione aspetto molto importante perchè possono determinare le condizioni di vincolo\carico
- Importanza di un programma di costruzione
- Condizione temporanea e permanente
 - Attenzione ai dettagli costruttivi pensando alla costruzione finale
- Costruzione del core
 - Jump form
 - Slip form
- Tipico ciclo di Costruzione

Construction engineering

- Analisi per stage di costruzione
- Spostamenti e i movimenti della struttura e la migrazione dei carichi fanno sì che si debbano considerare dei preset
 - Marina bay sand
- Cranes
- Tolleranze



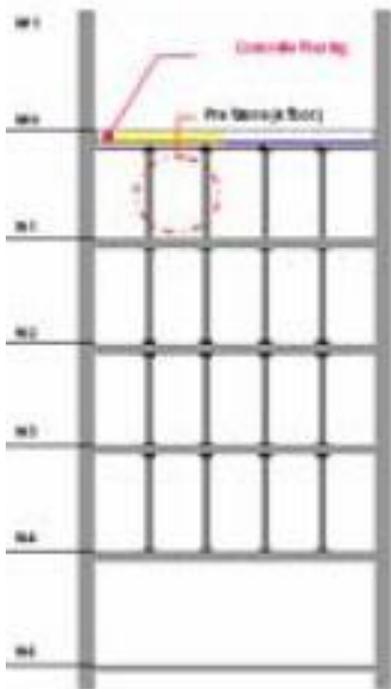
Construction engineering



Construction engineering

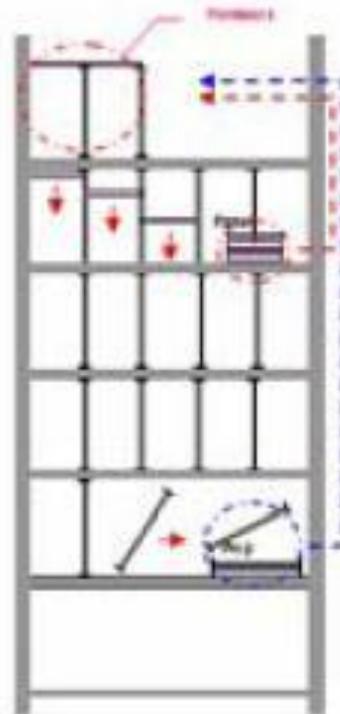
Day 1 (Day of pour)

- Re-bar completed.
- Concrete pouring (n+0)



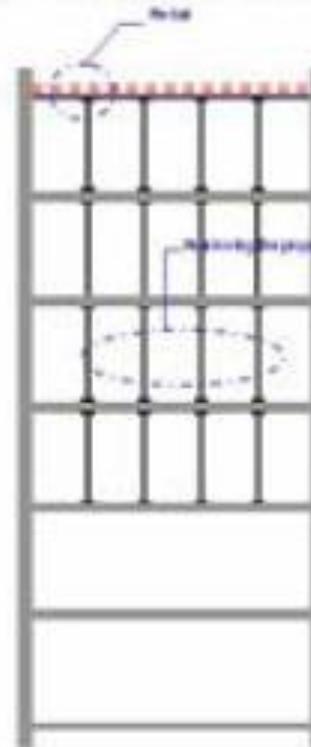
Day 2

- Erect prop & panel. (n+1)
- Remove Panels after 24 hours or 15 Mpa achieved (n+0)



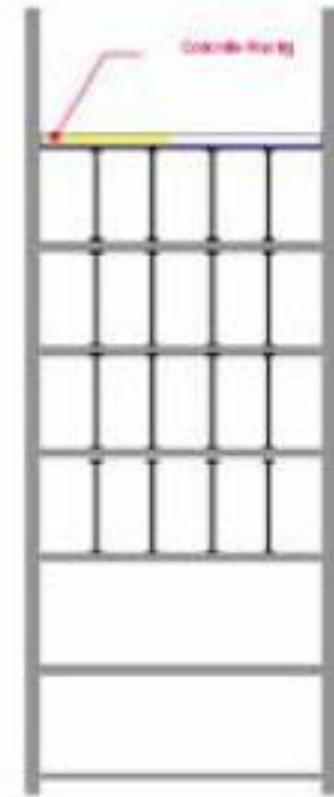
Day 3

- Formwork completed (n+1)
- Re-bar. (n+1)
- Re-shoring the props.(n-2)



Day 4 (Day of pour)

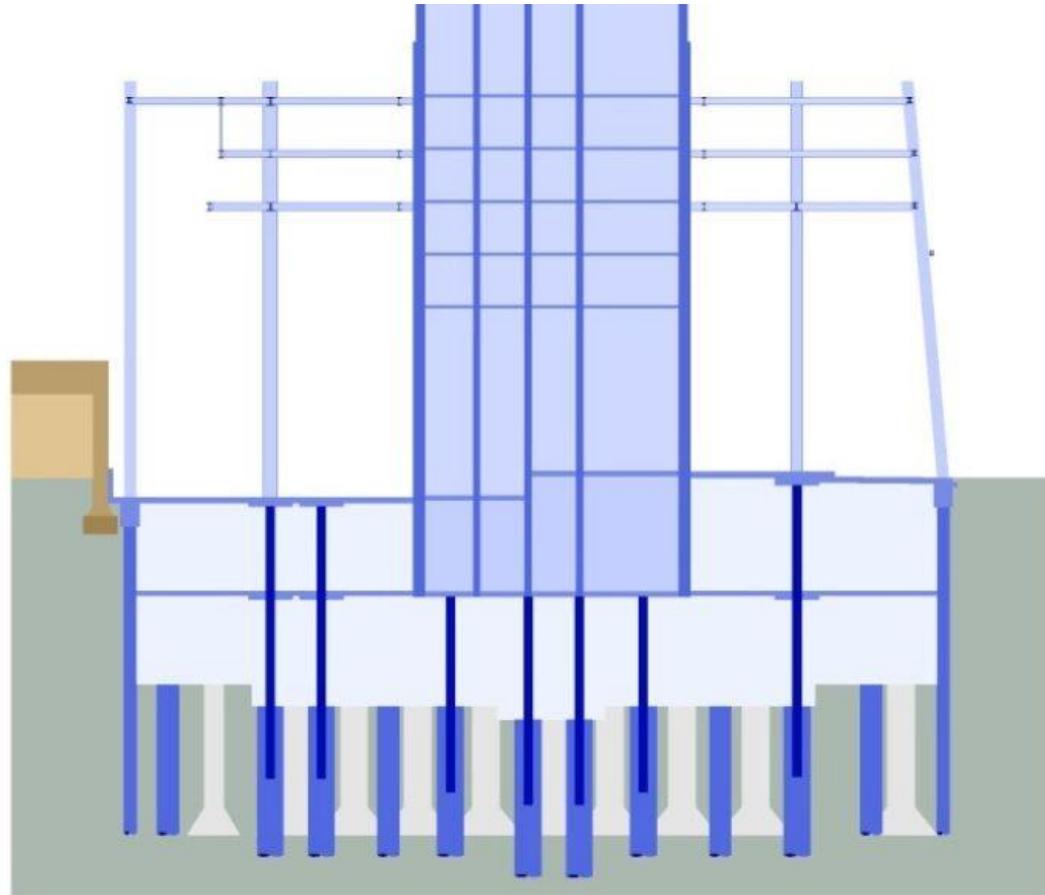
- Re-bar completed.(n+1)
- Concrete pouring.(n+1)



Core progression & Top Down

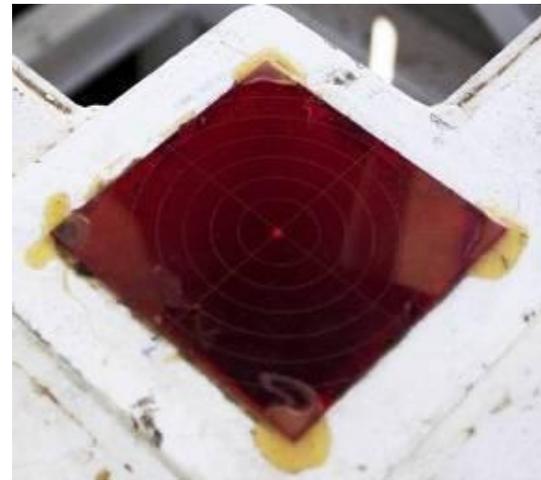
- Filosofia di costruzione tradizionale bottom up
- Top down tecnica innovativa che permette
 - Risparmiare tempo sulla costruzione
 - Limitare i movimenti delle opere controterra
 - Limitare l'uso di opere temporanee
- Caso dello Shard a Londra

Construction Engineering – Bottom Up & Top Down

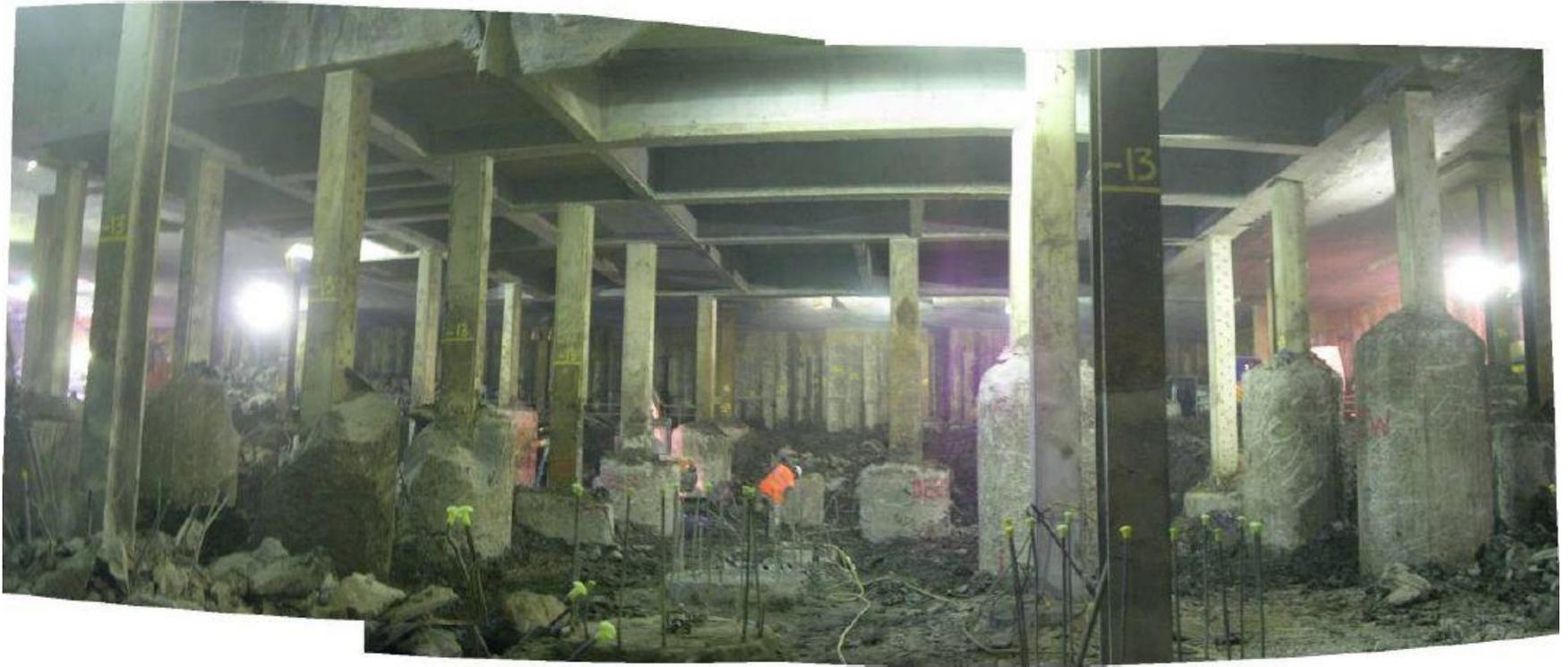


Top down 4: excavation to B3, core built to L21

Construction Engineering – Bottom Up & Top Down



Construction Engineering – Bottom Up & Top Down



Carichi

- Carichi verticali

- Statici

- Peso proprio, permanenti, carichi accidentali e carichi accidentali riducibili

- Dinamici

- Floor plate vibration

- Peso proprio e carichi verticali

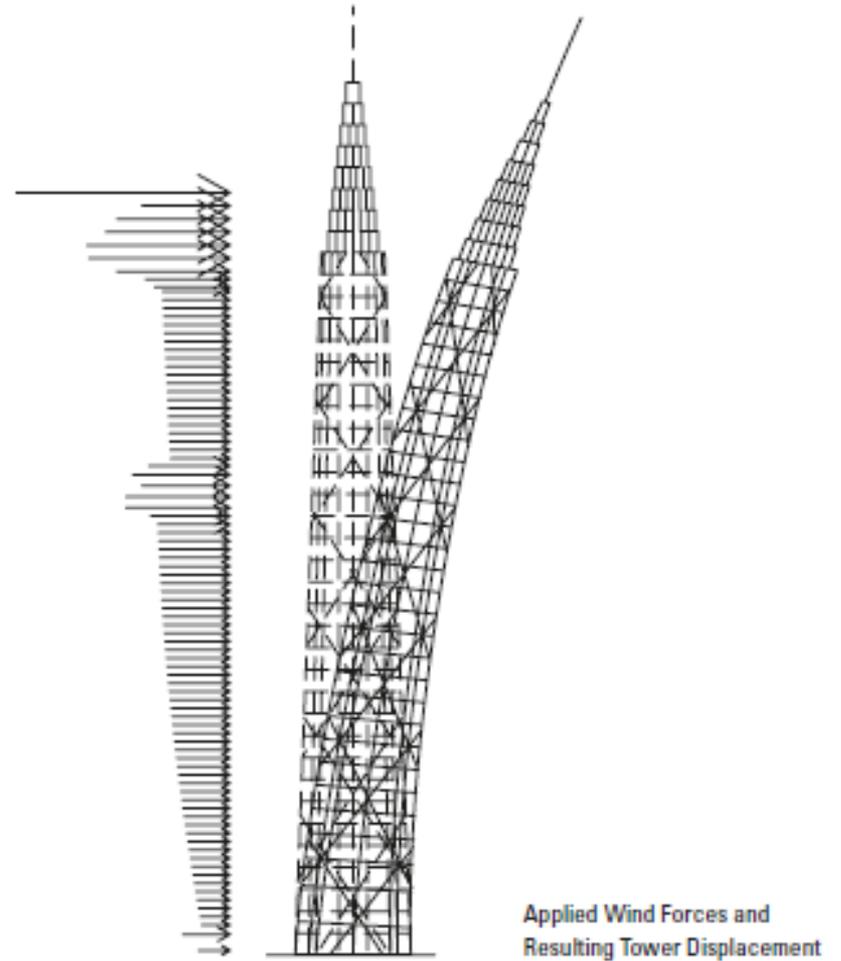
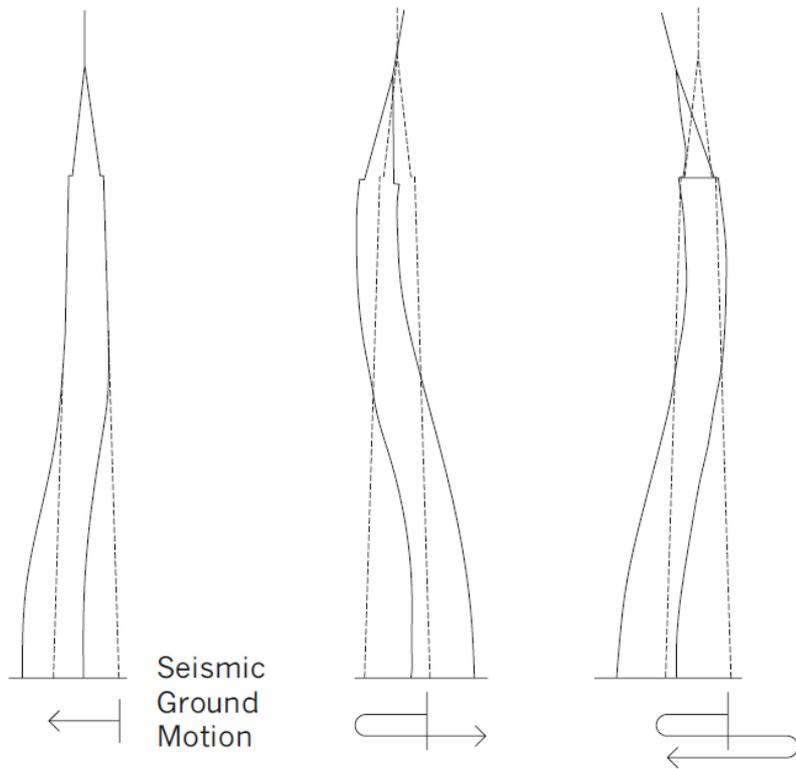
- Effetto benefico della gravità per stabilizzare il sistema -
Eccentricità del Core

- Carichi laterali

- Vento

- Sisma

Carichi



Fasi di progettazione ed organizzazione

- Team

- Verticale
- Laterale

- Interazione stretta con processi iterativi

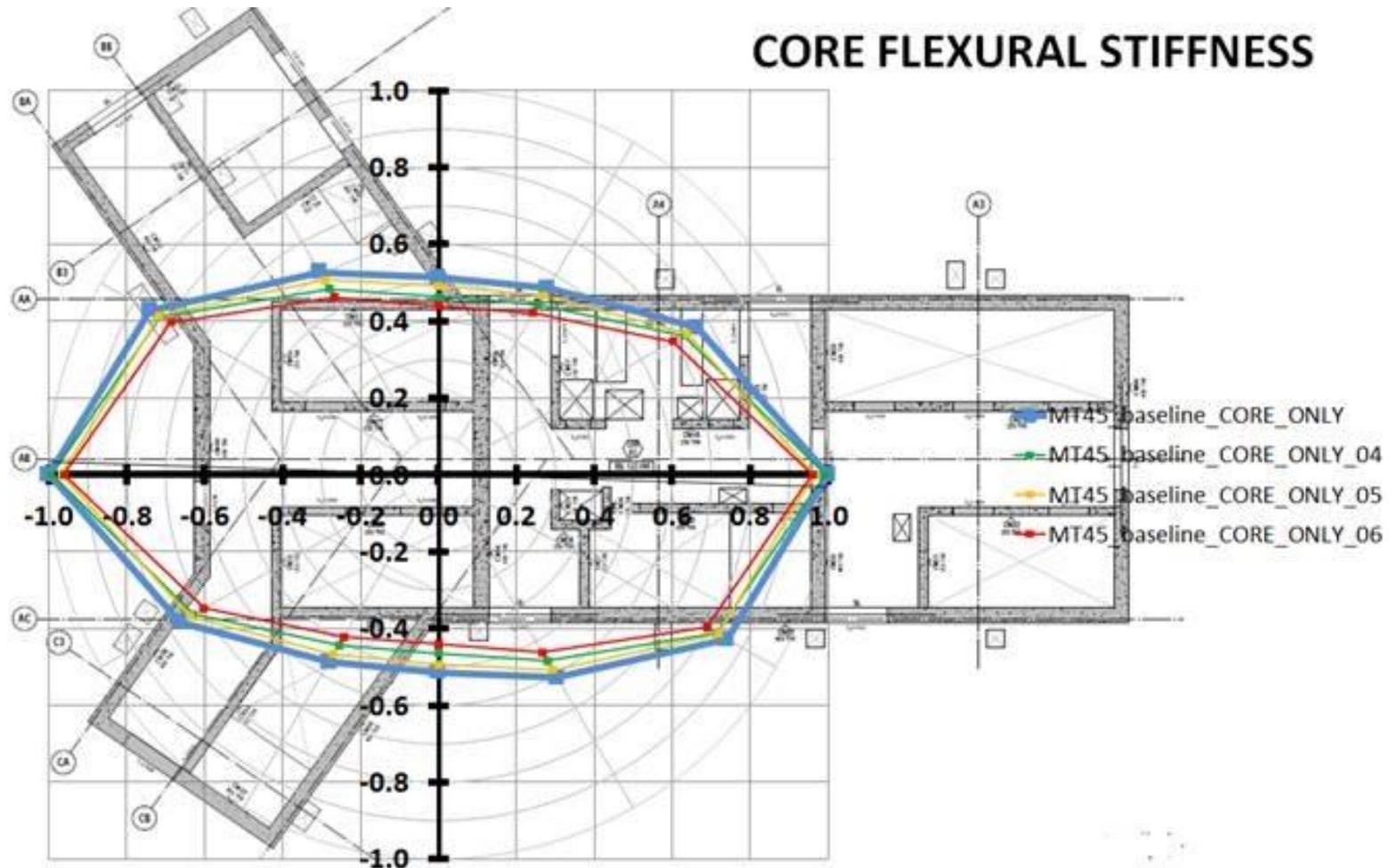
- In fase di concept modelli di calcolo laterale molto semplificati

- “stick model” e foglio excel

- Rigidezza del core
- Distribuzione delle masse
- Carico del vento secondo I codici
- Sisma

- Si ottiene una informazione preliminare su spostamenti,

Fasi di progettazione ed organizzazione

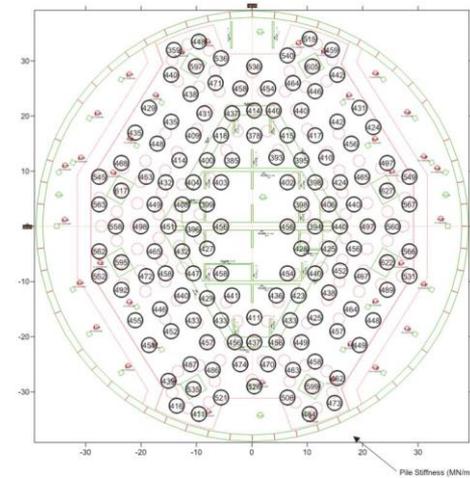


Fasi di progettazione ed organizzazione

- In seguito validazione con modelli 2D e 3D della struttura verticale e degli orizzontamenti
- Varie fasi di progettazione
 - Schematic design
 - Design development
 - Construction design
- Scopo della modellazione strutturale
 - Diversi modelli per diversi scopi e differenti scenari
 - Upper e lower boundary, ridondanza
 - Il target è minimizzare il contenitore delle possibili soluzioni plausibili

Fondazioni

- Tipologie del terreno
 - Chicago\New York\Brisbane\Sydney - roccia
 - London - argilla
 - Middle east - sabbie
- Caratterizzazione del terreno
- Tipologie di fondazione
 - Platea di fondazione
 - Platea di fondazione su pali
 - 4m spessore tipico con



Fondazioni

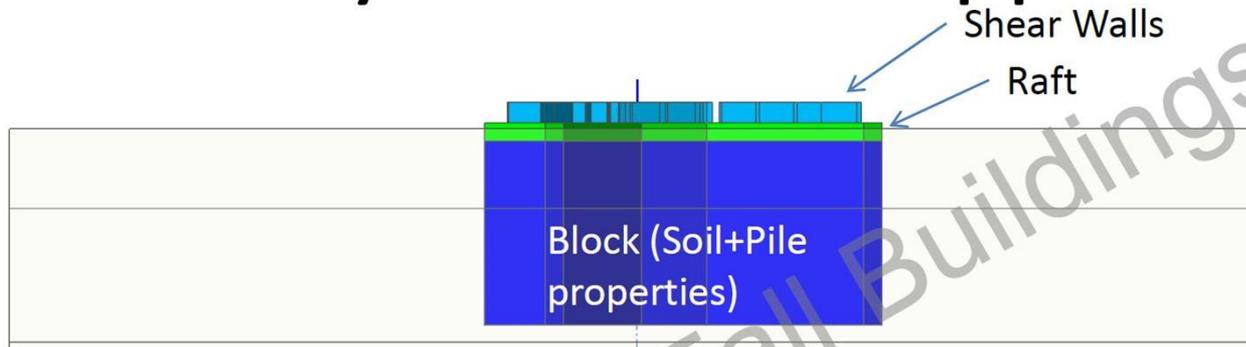
- Presenza di falda
 - Dewatering
 - Considerazione dell'uplift
- Podium e diffusione dei carichi all'esterno della pianta della torre
- Interazione terreno struttura, estremamente importante per stabilire un range di valori per la rigidità della fondazione
 - condizione statica e dinamica
 - per carichi verticali e laterali

Fondazioni

- Interazione e iterazioni con l'ingegnere geotecnico
- Modelli sviluppati dall'ingegnere geotecnico
 - 2D dei retaining walls
 - 3D con la stratificazione del terreno ed i pali
 - Proprietà del terreno

• Breve termine e lungo termine

FE Analysis – “Block Approach”



Fondazioni

- Cosa chiediamo all'ingegnere geotecnico
 - Valori di rigidezza
 - Valori di portanza

3857 HM

List of stiffness values to be obtained from Geotech

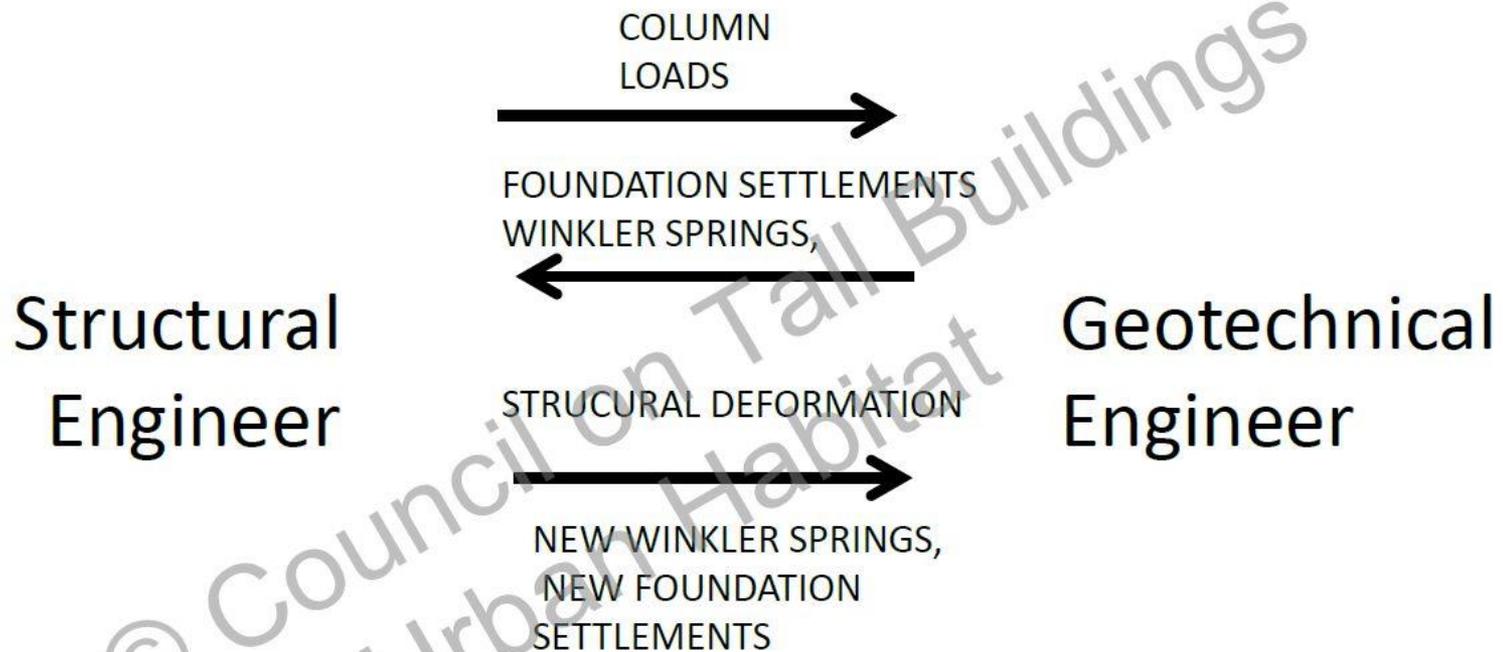
Servicelability Limit States		SLS		
ITEM	Set of loads	Concrete and soil properties	Purpose of stiffness values	Comments
1	Gravity Loads only	Long term values for either soil and concrete Static properties of soil?	Deflections Settlements Differential settlements	
2	Gravity Loads + Transient Loads WIND SLS Loads (20/50 yrs return period)	Short term values for either soil and concrete Dynamic properties of soil?	Deflection Interstorey drifts	
3	Gravity Loads + Transient Loads WIND SLS Loads (1/5/10 yrs return period)	Short term values for either soil and concrete Dynamic properties of soil?	Occupancy comfort Accelerations	

Ultimate Limit States		ULS		
ITEM	Set of loads	Concrete and soil properties	Purpose of stiffness values	Comments
4	Gravity Loads + Transient Loads WIND ULS Loads	Short term values for either soil and concrete Dynamic properties of soil?	Strength forces & overall stability	

Backstay Effect				
ITEM	Set of loads	Concrete and soil properties	Purpose of stiffness values	Comments
5	Loads on retaining walls form soil input from geotech to structural engineer	N/A	Lateral stiffness to be applied to the retaining walls (perpendicular to in-plane axis)	

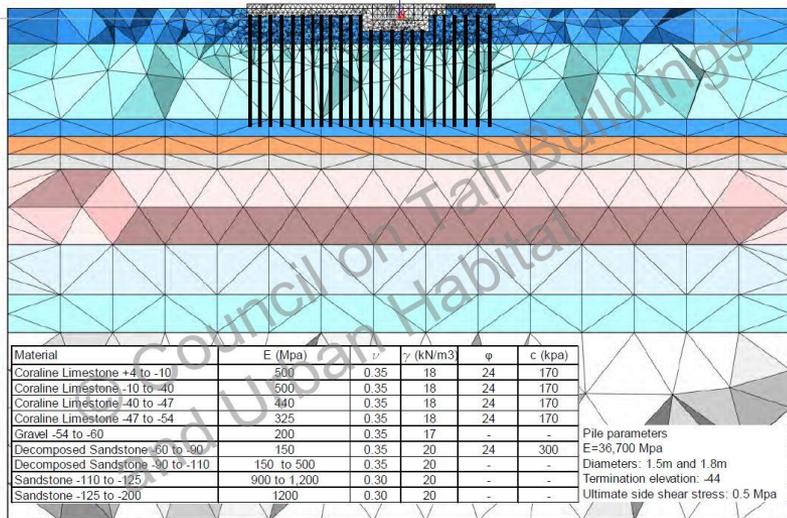
Fondazioni - Interazione

Iterative Process General Steps

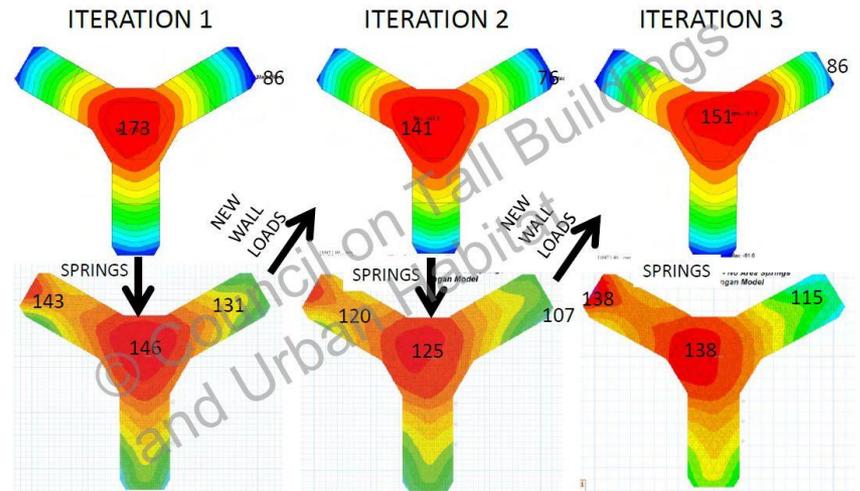


Fondazioni-1st pass

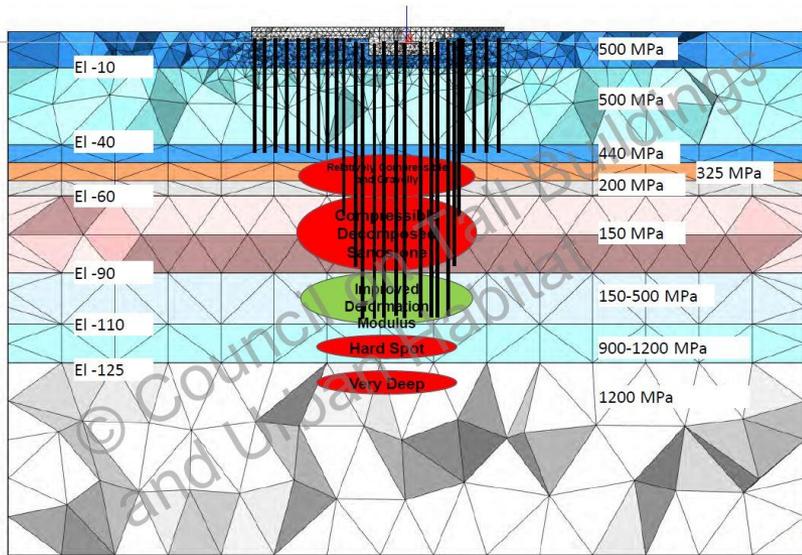
Foundation and Geologic Profile



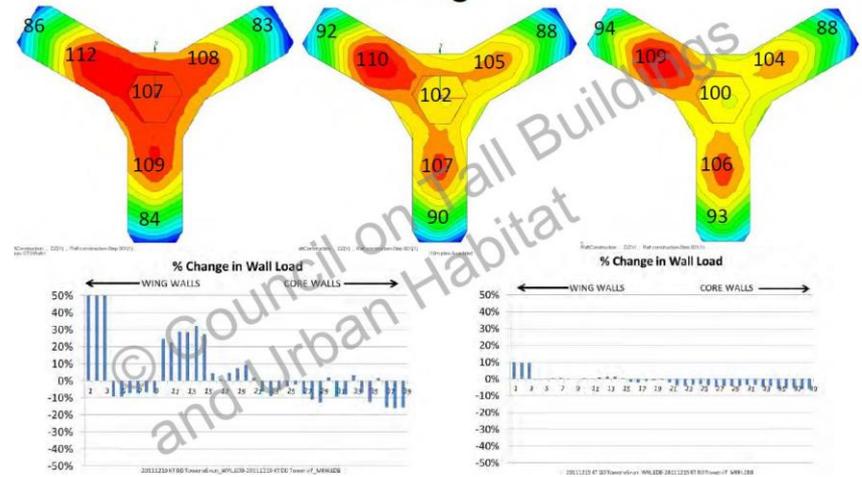
Multi-Step Winkler Spring Adjustment



Fondazioni-2nd pass



Settlement Contour Progression as Wall Load Changed



Processo iterativo

- Oltre ai cedimenti la convergenza e la stabilità della soluzione è controllata per
 - Carichi sui pali
 - Stress nelle colonne\pareti
 - Iterazione continua fino a raggiungimento di $\Delta < 5 = 10\%$

Fondazioni – Rigidezza e smorzamento

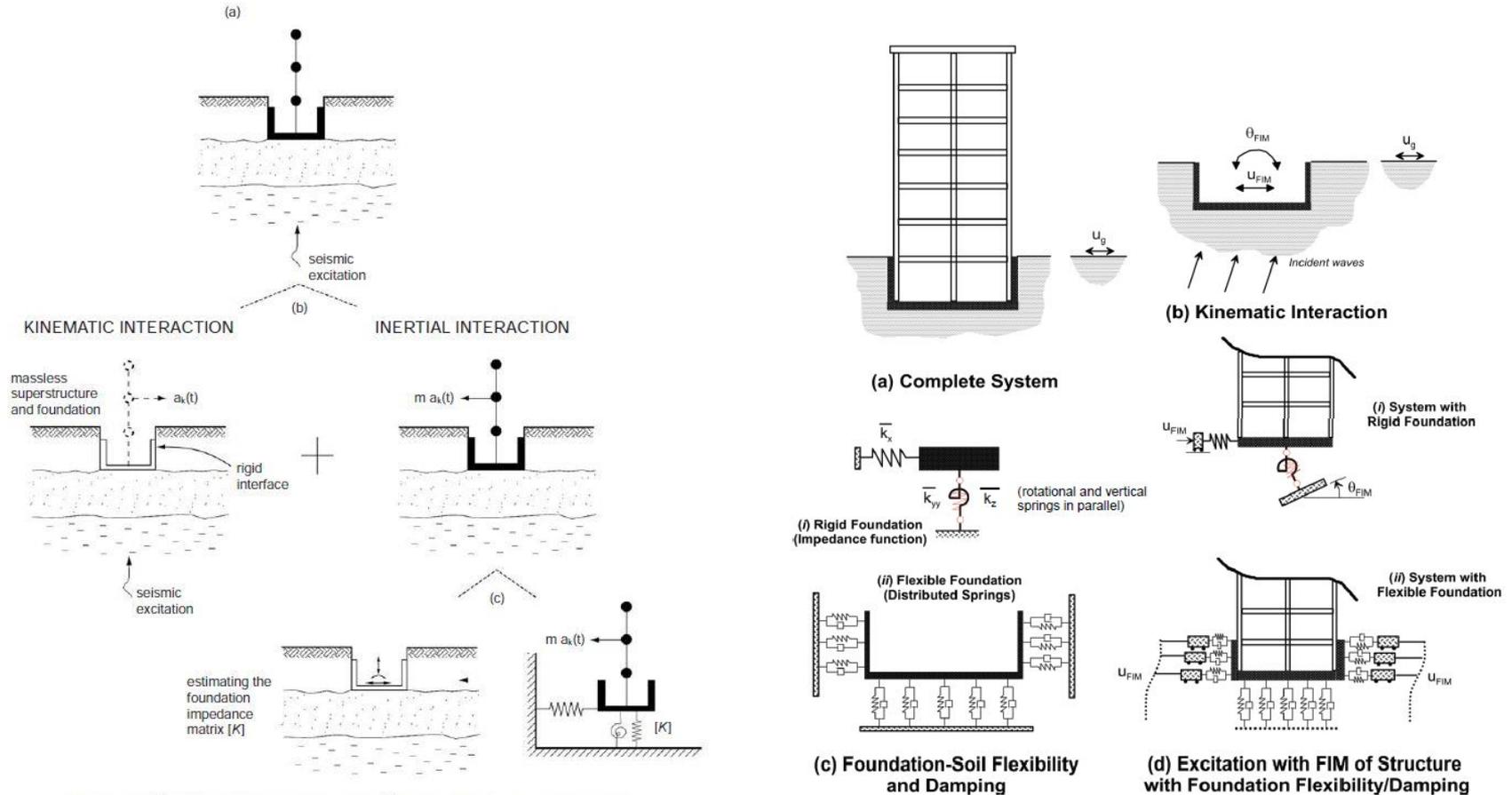


Figure 4-3 – (a) Geometry of soil-structure interaction, (b) decomposition of response into kinematic and inertial interaction, (c) two-step analysis of inertial interaction.

Fondazioni

Incremento della flessibilità
Incremento del periodo

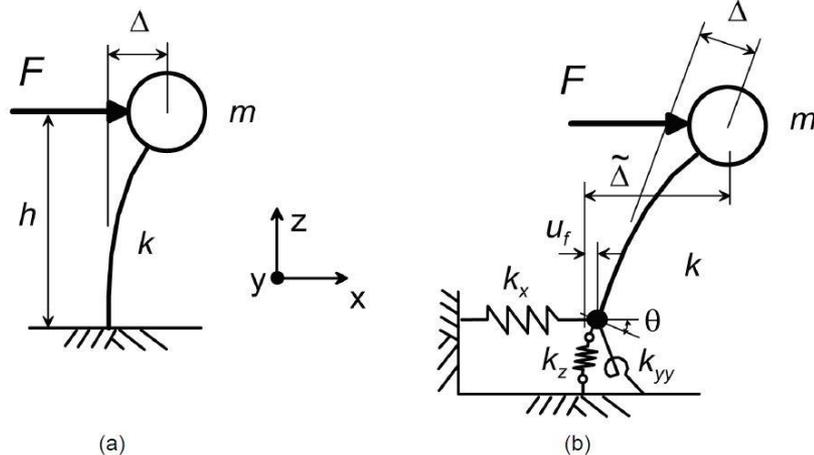
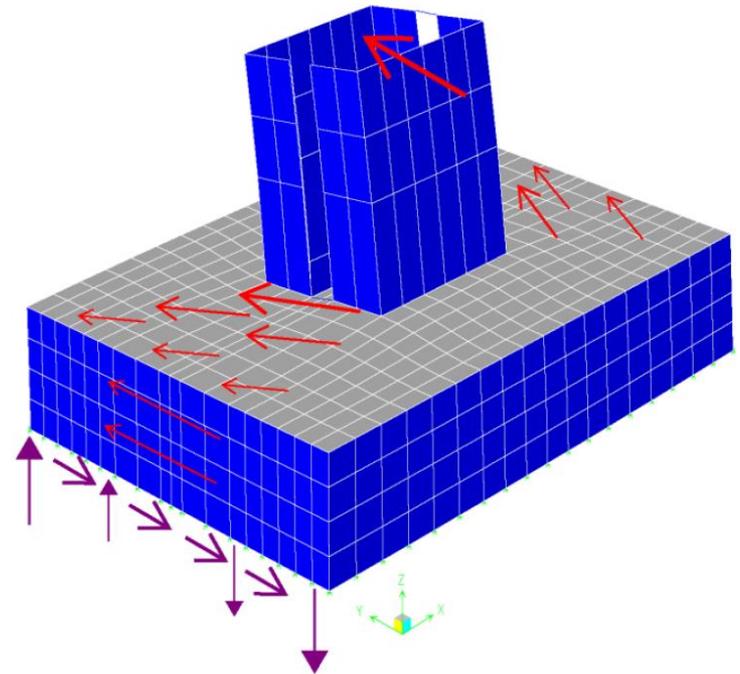
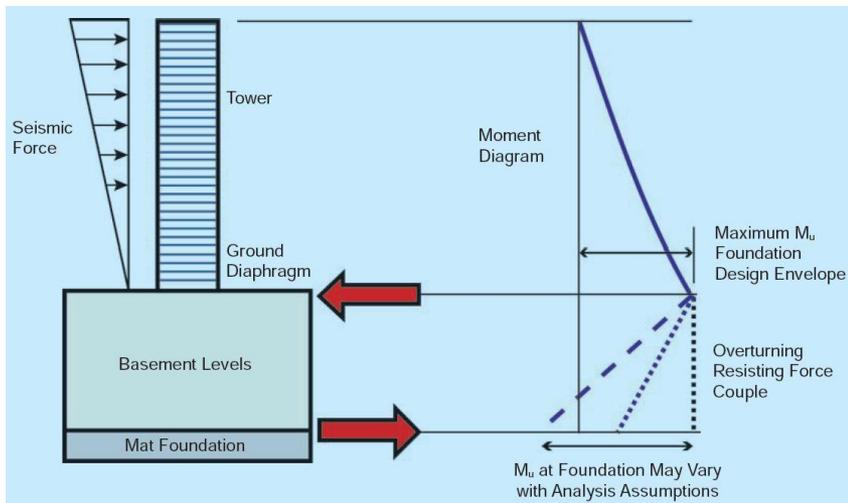


Figure 2-1 Schematic illustration of deflections caused by force applied to: (a) fixed-base structure; and (b) structure with vertical, horizontal, and rotational flexibility at its base.

$$T^2 = (2\pi)^2 \frac{m}{(F/\Delta)} = (2\pi)^2 \frac{m\Delta}{F}$$

$$\frac{\tilde{T}}{T} = \sqrt{1 + \frac{k}{k_x} + \frac{kh^2}{k_{yy}}}$$

Fondazioni / Effetto “backstay”



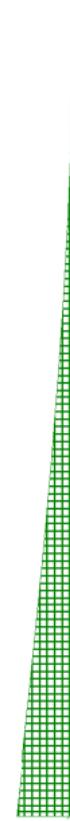
Fondazioni / Effetto “backstay”



Simple Cantilever Model



Shear Diagram

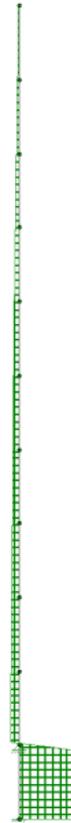


Moment Diagram

Fondazioni / Effetto “backstay”



Pinned Ground Model



Shear Diagram

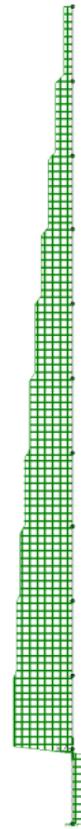


Moment Diagram

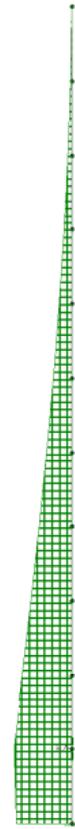
Fondazioni / Effetto “backstay”



Spring Ground Model

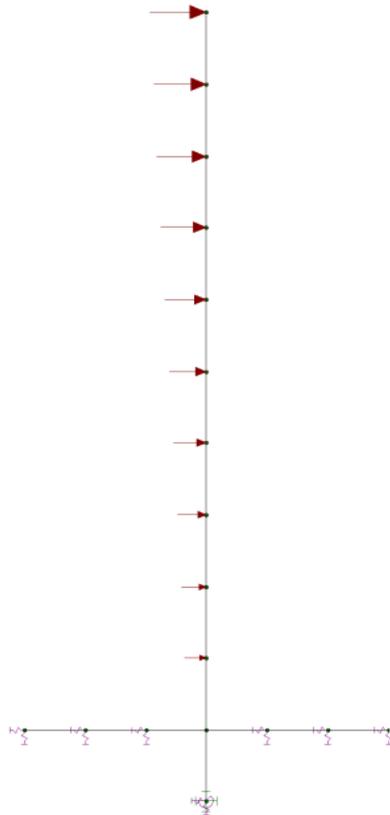


Shear Diagram

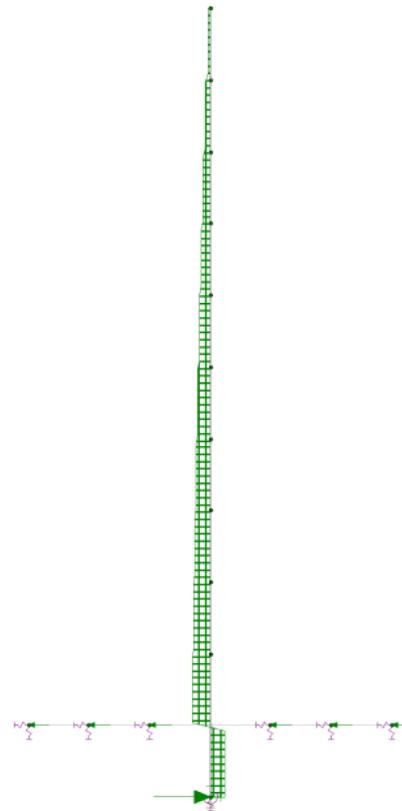


Moment Diagram

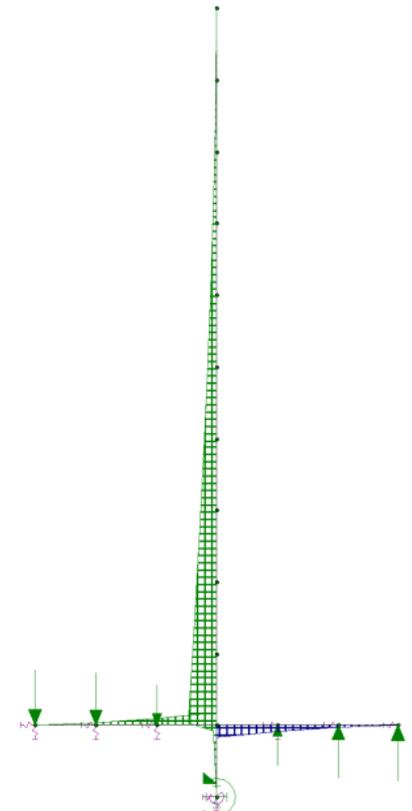
Fondazioni / Effetto “backstay”



Outrigger Model



Shear Diagram

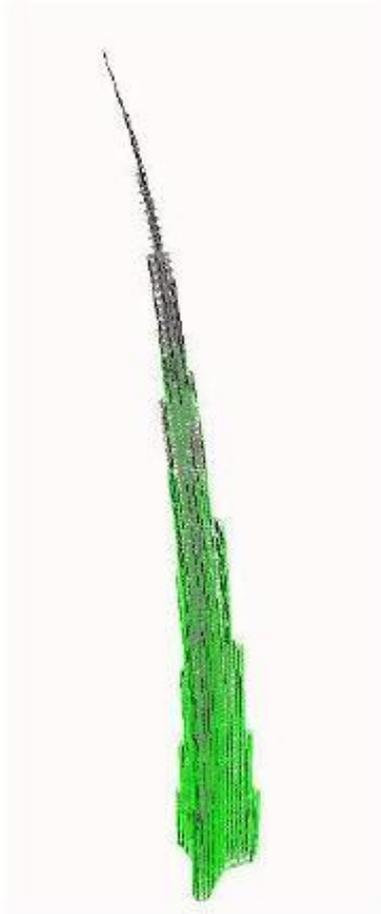


Moment Diagram

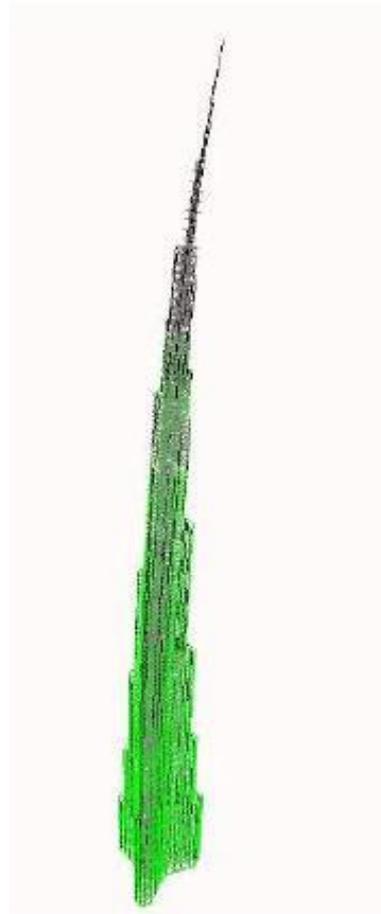
Dinamica strutturale

- Determina le azioni del vento e sisma e delle risposte strutturali
- Analogia con la mensola, oscillatore a multipli gradi di libertà smorzato
- Massa e rigidezza sono i due principali parametri da tarare
- Modi di vibrare della struttura
 - Considerare un numero di modi per almeno il 95% della massa
- Gruppi o “cluster” di modi di vibrare
 - Modi principali 1,2 e 3
 - Modi secondari 4, 5, 6

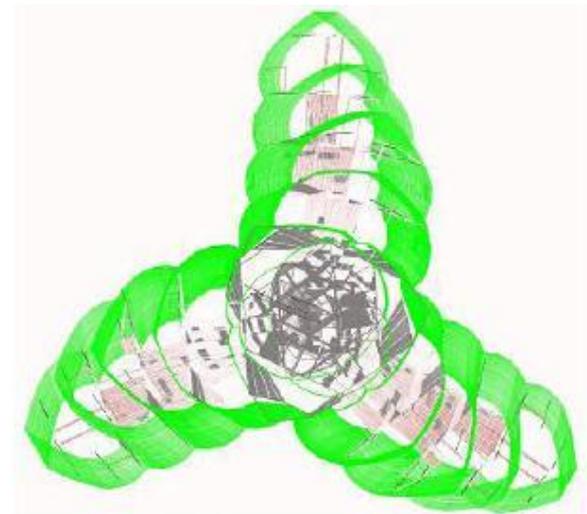
Dinamica – Modi principali Cluster 1



a) Mode 1; $T = 11.3s$

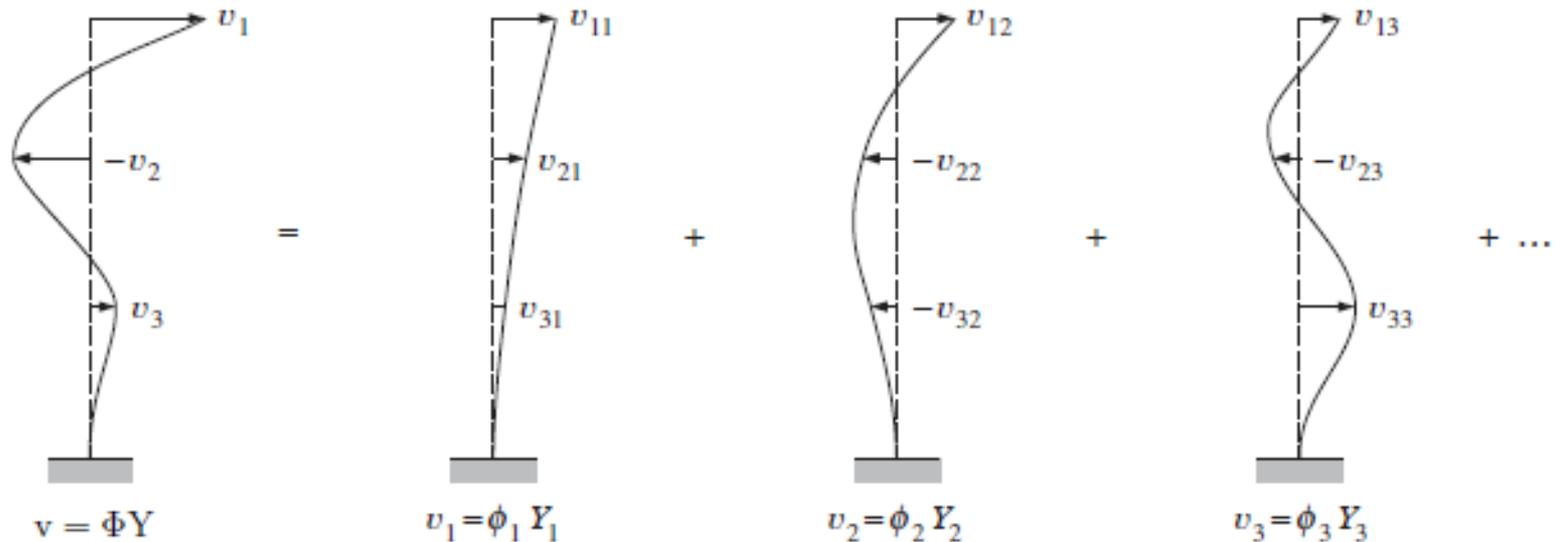


b) Mode 2; $T = 10.2s$



c) Mode 5 (torsion); $T = 4.3s$

Dinamica – Modi secondari Cluster 2



Dinamica – Modi secondari Cluster 2

Case	Mode	Period sec	UX	UY	UZ	Sum UX	Sum UY
Modal	1	5.42	0.2689	0.1771	0	0.2689	0.1771
Modal	2	4.83	0.1665	0.2679	0	0.4354	0.445
Modal	3	2.38	0.0147	0.0007	0	0.4501	0.4458
Modal	4	1.84	0.2272	0.0011	0	0.6773	0.4469
Modal	5	1.66	0.0062	0.2081	0	0.6835	0.655
Modal	6	1.30	0.0017	0.0176	0	0.6852	0.6725
Modal	7	0.96	0.0982	0.0026	0	0.7834	0.6751
Modal	8	0.79	0.0001	0.0828	0	0.7835	0.7579
Modal	9	0.75	0.0029	0.0117	0	0.7864	0.7696
Modal	10	0.60	0.0355	0.0003	0	0.8219	0.7699
Modal	11	0.54	0.0198	0.0005	0	0.8417	0.7705
Modal	12	0.45	0.0099	0.0044	0	0.8516	0.7749
Modal	13	0.43	0.0072	0.0314	0	0.8588	0.8062
Modal	14	0.37	0.0256	0.0007	0	0.8844	0.807
Modal	15	0.36	0.0056	0.0021	0	0.89	0.8091
Modal	16	0.32	0.01	0.03	0	0.9	0.8391
Modal	17	0.29	0.0045	0.0027	0	0.9046	0.8418
Modal	18	0.28	0.0129	0.0193	0	0.9174	0.8611
Modal	19	0.26	0.0166	0.0176	0	0.934	0.8788
Modal	20	0.24	0.0027	0.0001	0	0.9367	0.8789
Modal	21	0.23	0.0066	0.0333	0	0.9433	0.9122
Modal	22	0.21	0.0009	0.0001	0	0.9443	0.9122
Modal	23	0.21	0.0031	0.0116	0	0.9474	0.9239
Modal	24	0.18	0.0025	0.0032	0	0.95	0.9271
Modal	25	0.18	0.0002	0.0016	0	0.9502	0.9287
Modal	26	0.17	0.0026	0.0075	0	0.9528	0.9362
Modal	27	0.15	0.0028	0.000003283	0	0.9556	0.9362
Modal	28	0.15	0.0002	0.0065	0	0.9558	0.9427
Modal	29	0.15	0.0091	0.00004861	0	0.9649	0.9428
Modal	30	0.14	0.00001563	0.0032	0	0.9649	0.9459

Dinamica strutturale

- Regole semplificate per l'individuazione della frequenza o periodo proprio
 - $H/46$
 - $n \text{ piani} / 10$
 - torsionale $0.05 * n \text{ piani}$
- Individuazione di potenziale risposta flessibile\rigida
- Strutture sempre più flessibili e snelle
- Il trend a NY sono le “pencil towers”, generalmente una spinta verso la massimizzazione del footprint da parte del developer
- Una volta ottenuto schema stabile si studiano diverse

Dinamica - Smorzamento

Material	Return period for wind			
	1–10 year	50 year	100 year	1000 year (collapse prev.)
Concrete	2%	3%	5%	7%
Steel	1%	2%	3%	4%

The building damping values may be specifically calculated as follows:

$$\xi = \xi_N + \xi_M + \xi_{SD} + \xi_{AE} + \xi_{SDS}$$

where,

ξ = total building damping ratio

ξ_N = non-structural component damping (1–1.5%)

ξ_M = material damping (concrete uncracked members = 0.75%,
steel = 0%)

ξ_{SD} = structural damping (concrete cracked members = 0.5–1.5%,
steel = 0–0.5%)

ξ_{AE} = aero-elastic damping (0–0.75%)

ξ_{SDS} = supplemental damping systems (visco-elastic = 5–30%,
vibration absorbers = 1–5%)

2nd order effects

EC 2 Part 1-1 - Annex H - STIFFNESS EVALUATION

(1) For a bracing system without significant shear deformations (e.g. shear walls without openings), global second order effects may be ignored if:

$$F_{V,Ed} \leq 0,1 \cdot F_{V,BB} \quad (\text{H.1})$$

where:

$F_{V,Ed}$ is the total vertical load (on braced and bracing members)
 $F_{V,BB}$ is the nominal global buckling load for global bending, see (2)

(3) In the absence of a more accurate evaluation of the stiffness, the following may be used for a bracing member with *cracked* section:

$$EI \approx 0,4 E_{cd} I_c \quad (\text{H.3})$$

where:

$E_{cd} = E_{cm} / \gamma_{cE}$, design value of concrete modulus, see 5.8.6 (3)
 I_c second moment of area of bracing member

If the cross-section is shown to be *uncracked* in the ultimate limit state, constant 0,4 in Expression (H.3) may be replaced by 0,8.

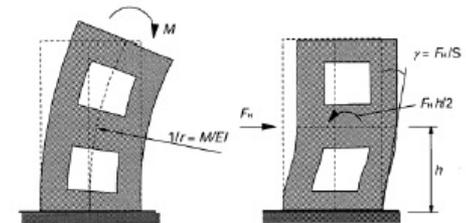
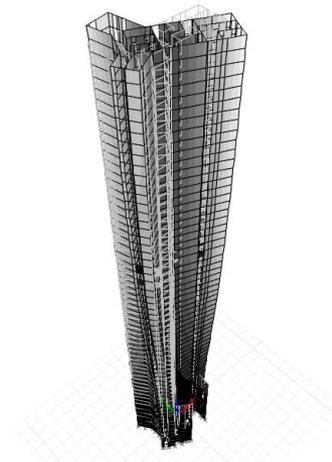
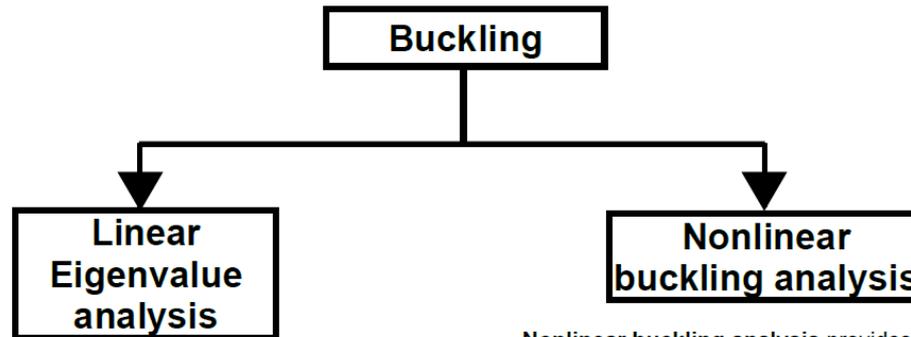


Figure H.1: Definition of global bending and shear deformations ($1/r$ and γ respectively) and the corresponding stiffnesses (EI and S respectively)

3-D View (buckling) - Mode 1 - Factor 21,16967

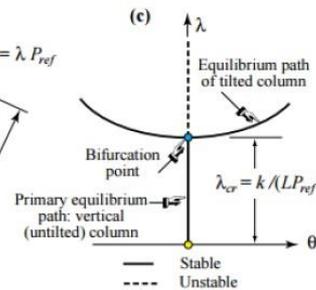
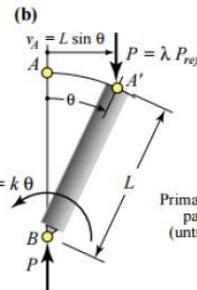
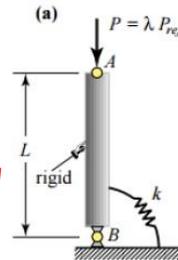


2nd order effects



Eigenvalue analysis predicts the theoretical buckling strength of a structure which is idealized as elastic. For a basic structural configuration, structural eigenvalues are computed from constraints and loading conditions. Buckling loads are then derived, each associated with a buckled mode shape which represents the shape a structure assumes under buckling

Nonlinear buckling analysis provides greater accuracy than elastic formulation. Applied loading incrementally increases until a small change in load level causes a large change in displacement. This condition indicates that a structure has become unstable



Approximate Formulation
(Adopted formulation by ETABS)

$$[K_{ij} - \lambda G_{ij}] q_j = 0$$

K - Linear Stiffness Matrix
G - Geometrical Stiffness Matrix
 λ - Bifurcation Load
q - Mode Shapes

Exact Formulation

$$[K_{ij}(\lambda)] q_j = 0$$

K - Exact Stiffness Matrix
 λ - Bifurcation Load
q - Mode Shapes

Ingegneria del vento

- Nella maggior parte dei casi il carico determinante
 - Fondazioni ed il sistema di stabilità laterale
 - Spostamenti globali ed interpiano
 - Livello di comfort in termini di accelerazioni
- Potenzialmente influenza il pattern del vento per gli edifici circostanti e soprattutto al livello della base
 - Pedestrian comfort
- Limitazioni dei codici, generalmente
 - $H < 200\text{m}$
 - Periodi $< 5\text{sec}$
 - Rapporti di snellezza < 6

• A parte le limitazioni del codice si necessita di un

Ingegneria del vento

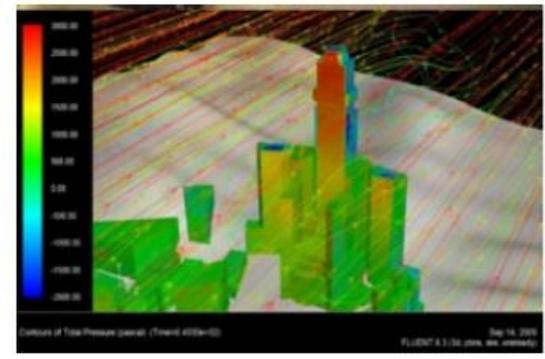
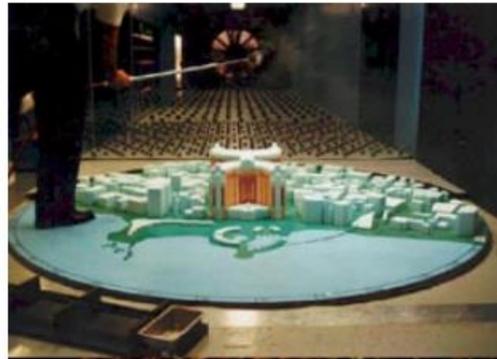
WIND LOADING APPROACHES

CODE BASED:
EN 1991-1-4

WIND TUNNEL
TEST

COMPUTATION
FLUID DYNAMICS
(CFD)

→ Desktop Study



Il carico del vento

- Wind climate

- Caratterizzazione del vento e dei fenomeni ad esso legati per il particolare sito
- Zone del mondo dove fenomeni meteorologici come tifoni, uragani, etc causano picchi di carico del vento
- Uso di stazioni meteorologiche

- Individuazione della velocità di base

- per le varie direzioni
- per determinati periodi di ritorno
- Soddisfazione dei requisiti minimi dei codici

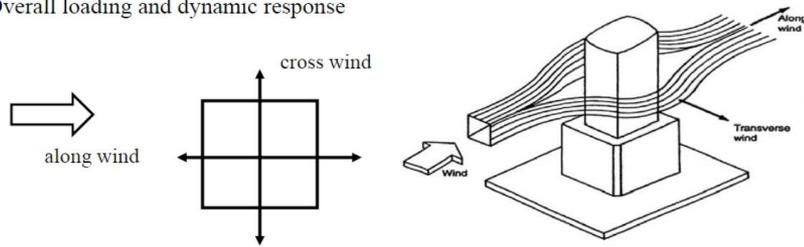
Il carico del vento

- Interazione tra vento e struttura
 - il carico è determinato dalla risposta strutturale
- Componente statica e dinamica della risposta
- Componente
 - Along wind
 - Across wind
 - Torsional
- Un fenomeno di interazione è il distacco di vortici
 - Carico ortogonale alla direzione del vento
 - Molto importante se la frequenza di distacco è vicina a quella naturale della struttura
 - risonanza

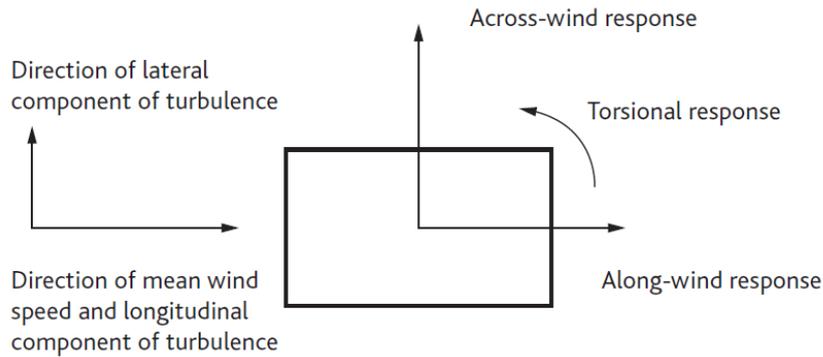
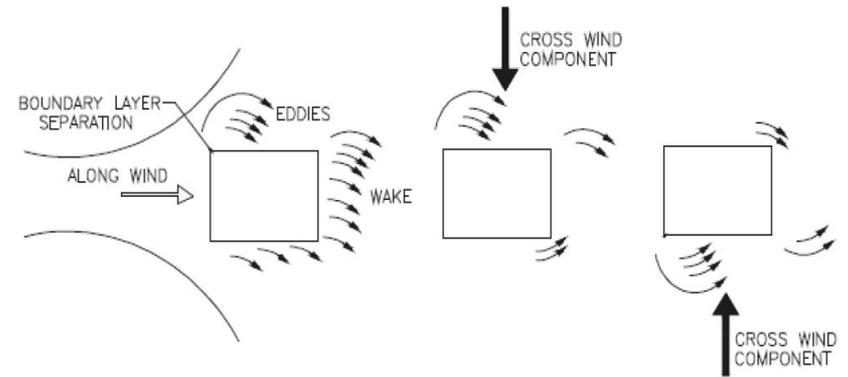
Ingegneria del vento

Tall buildings

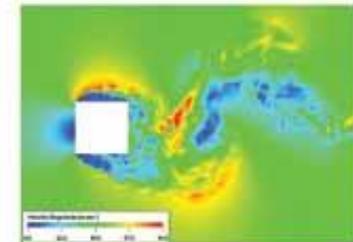
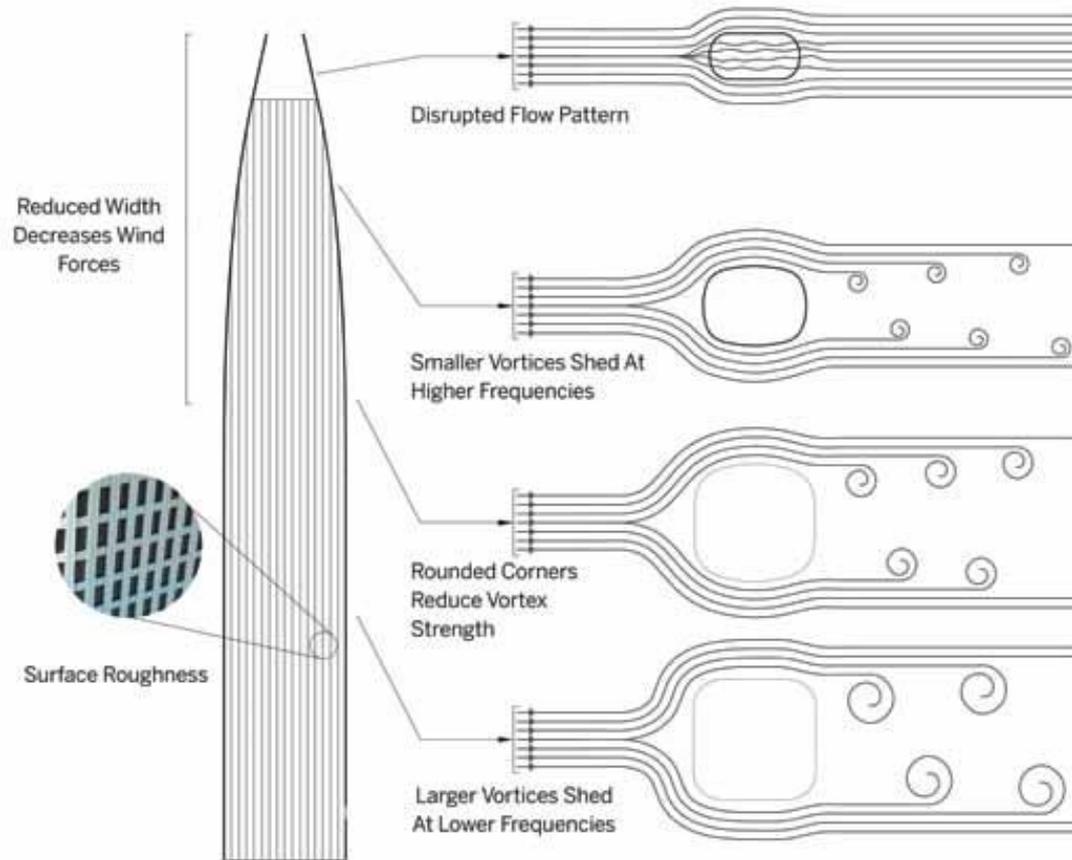
- Overall loading and dynamic response



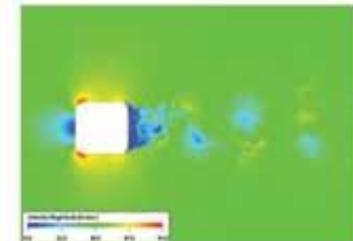
Cross-wind vibrations are usually greater than along-wind vibrations for buildings of heights greater than 100m (330 feet)



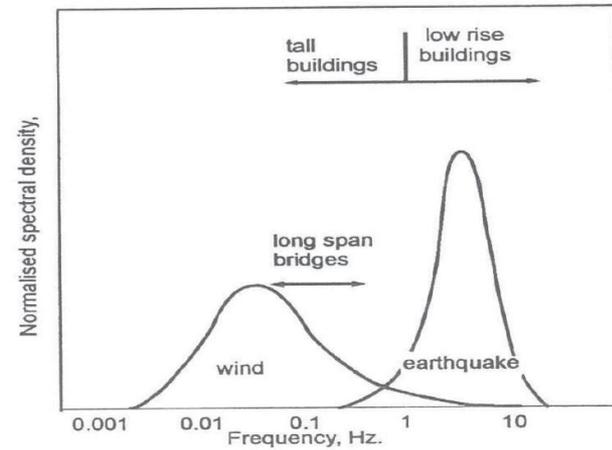
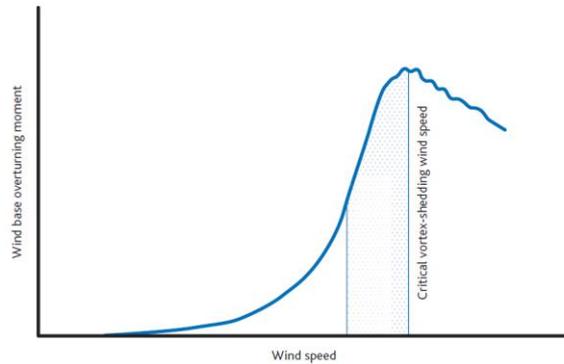
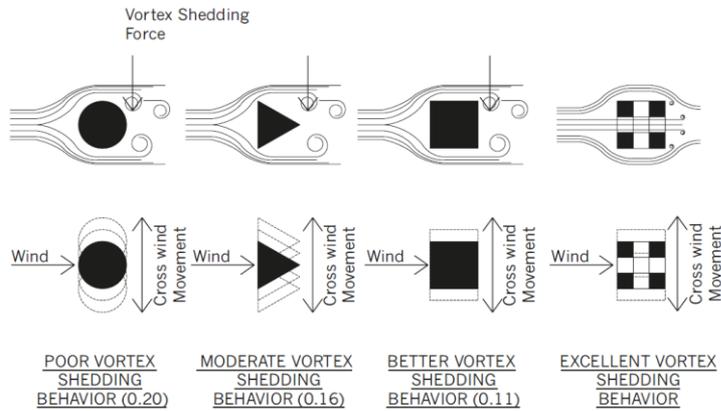
Ingegneria del vento



Wind Velocities Showing Vortex Shedding
Square Corners (Above)
Rounded Corners (Below)

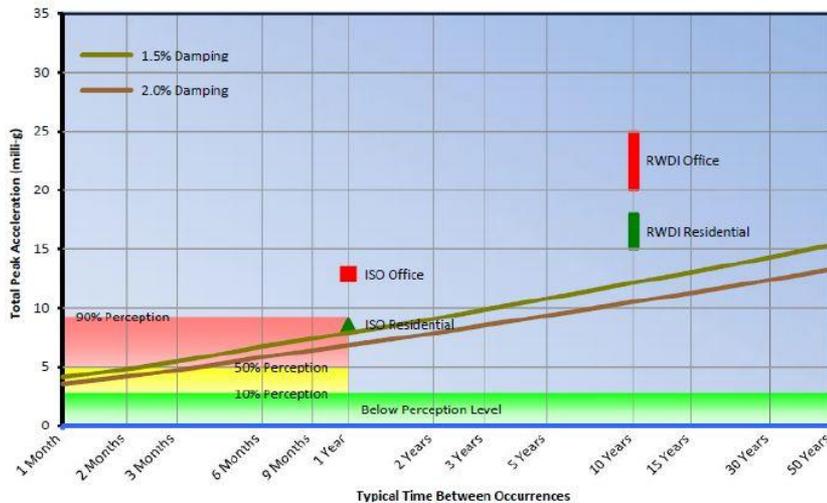


Ingegneria del vento



Ingegneria del vento

- Valori di picco o valori RMS@
- Generalmente si considerano valori di picco e periodo di ritorno di
 - 1 anno standard ISO
 - 10 anni RWDI



Return Period (Years)	Peak Accelerations ⁽¹⁾ (milli-g) Total - [X, Y and torsional components]		Peak Torsional Velocities (milli-rads/sec)		
	1.5% Damping	2.0% Damping	1.5%	2.0%	CTBUH ⁽⁶⁾ Criteria
			Damping	Damping	
1	7.9 - [7.2, 7.3, 0.6]	6.8 - [6.2, 6.3, 0.5]	0.3	0.2	1.5
5	10.8 - [9.7, 10.1, 0.8]	9.4 - [8.4, 8.7, 0.7]	0.3	0.3	-
10	12.2 - [10.9, 11.5, 0.9]	10.5 - [9.4, 9.9, 0.7]	0.4	0.3	3

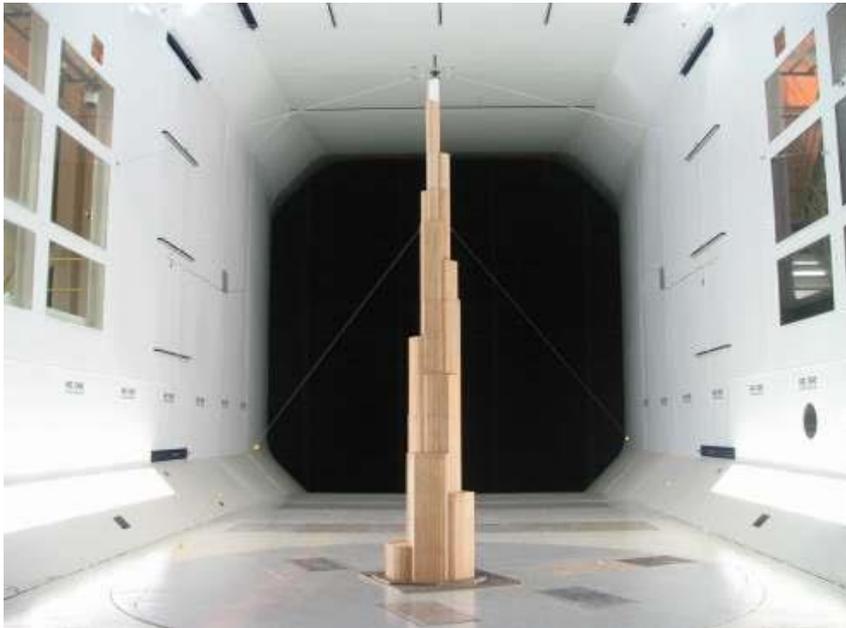
Ingegneria del vento

- Si controllano gli spostamenti globali e quelli interpiano ma le accelerazioni possono essere più stringenti
- Mitigare gli effetti del vento
 - Incrementare la rigidezza
 - Incrementare la massa, particolarmente nel terzo superiore della torre
- Aumentare lo smorzamento strutturale
 - Dispositivi di smorzamento ausiliari
- TMD,
- Inverted pendulum
- Dispositivi come damper localizzati
- Cambiare l'aerodinamica della torre
 - Aperture, rugosità della facciata

Wind tunnel test - Tipologie

- “HFFB” High Frequency Force Balance
- “HFPI” High Frequency Pressure Integration
- Aerolastic model
- Viene testato un modello che comprende gli edifici circostanti, anche futuri a livello di concept
- Vengono registrati i dati per diversi angoli di attacco e per diverse velocità del vento
- I dati vengono poi post processati sulla base delle proprietà dinamiche fornite dallo strutturista

Ingegneria del vento



Ingegneria del vento



Ingegneria del vento



Scopo dello studio

- Risposta strutturale globale
- Risposta strutturale particolare (antenne, etc)
- Distribuzione delle pressioni sulla facciata
- Comfort dei pedoni alla base
- Studio sull'impatto della dispersione dei fumi
- Studio sull'inquinamento acustico

Obiettivi

- Set di forze e momenti indotti dal vento ULS
 - Periodi di ritorno 50/100/1000yrs
- Previsione delle accelerazioni ai piani alti SLS
 - 1/5/10 yrs
- Diverse configurazioni
 - Valori di smorzamento
 - Base e +/- 0.5%
 - Frequenze
 - Base e +/- 10%
 - Massa
 - Base e +/- 10%

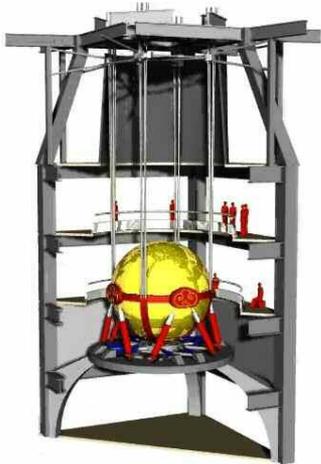
Input al wind consultant

- Proprieta dinamiche del modello strutturale
 - Frequenze
 - Almeno I primi 2 cluster di tre modi e >95%
 - Massa per ogni livello (traslazionale e rotazionale)
 - Centro di massa ad ogni livello
 - Output della deformata modale come da frequenze
- La geometria dell'edificio, altezza, orientamento, etc fornite dall'architetto

Ingegneria del vento



Dispositivi di smorzamento

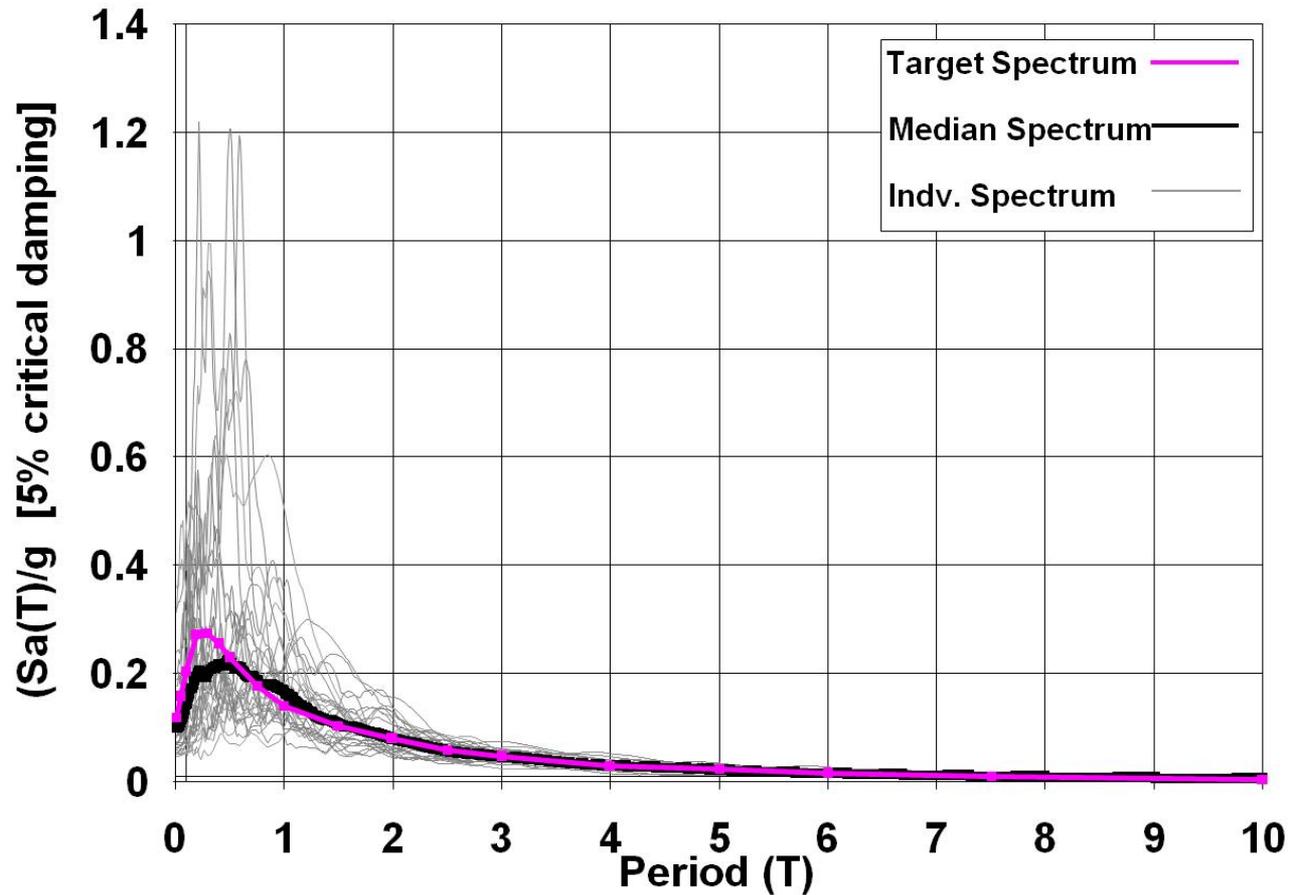


Ingegneria sismica

- Particolarità dei tall building
 - Modi principali di vibrazione $T > 2$ sec, parte “discendente” dello spettro
 - Partecipazione della massa nei modi superiori importante
- Limitazioni dei codici, pensati per strutture < 150 m o < 5 sec come periodo naturale
- Vari tipi di analisi, analisi modale quella più frequentemente usata in regioni di bassa sismicità
- Tagli alla base minimi spesso governati dal valore minimo. Questo può essere un problema perché il minimo può essere irragionevolmente alto
- Limitazione dell'analisi modale per i Tall building

Sismica

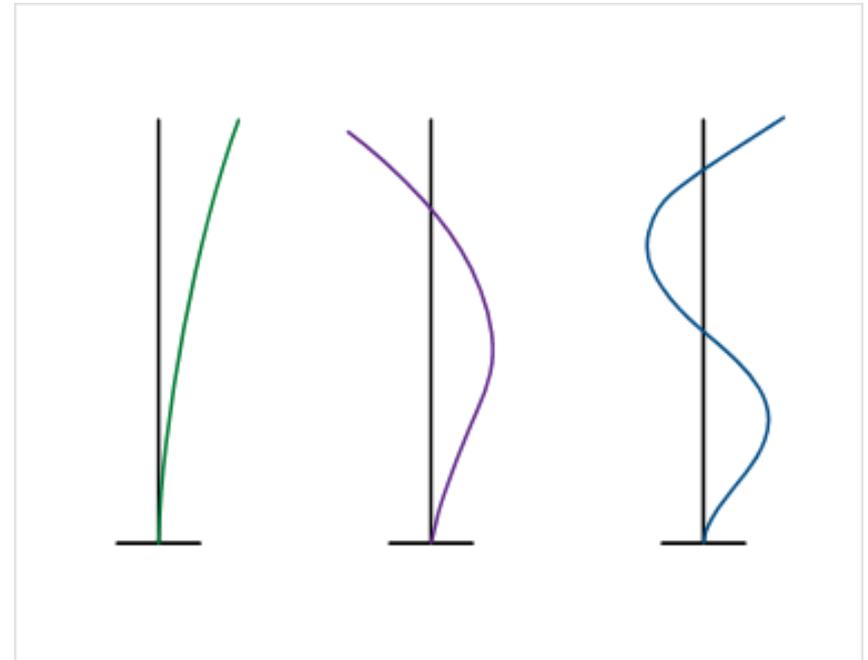
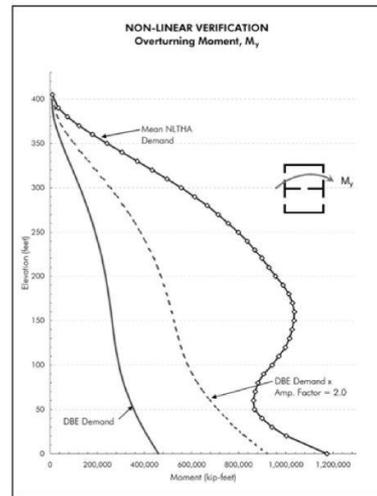
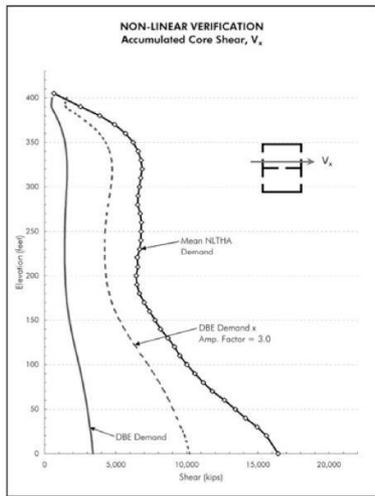
Matched Spectra for TBI (SLE25, 3 & 0.1, 7 & 0.6)



Ingegneria sismica

- Pubblicazioni statunitensi
 - Tall Building Initiative “TBI”
 - NEHRP, ATC
- Vari livelli di performance dell'edificio
- Il TBI suggerisce di condurre un'analisi
 - Allo SLS per un sisma di “servizio” probabilità 43% in 50 anni
 - analisi modale con spettro di risposta su modello semplificato
 - Allo ULS per un sisma con probabilità 2% in 50 anni
 - analisi dinamica non lineare, complessa e dispendiosa

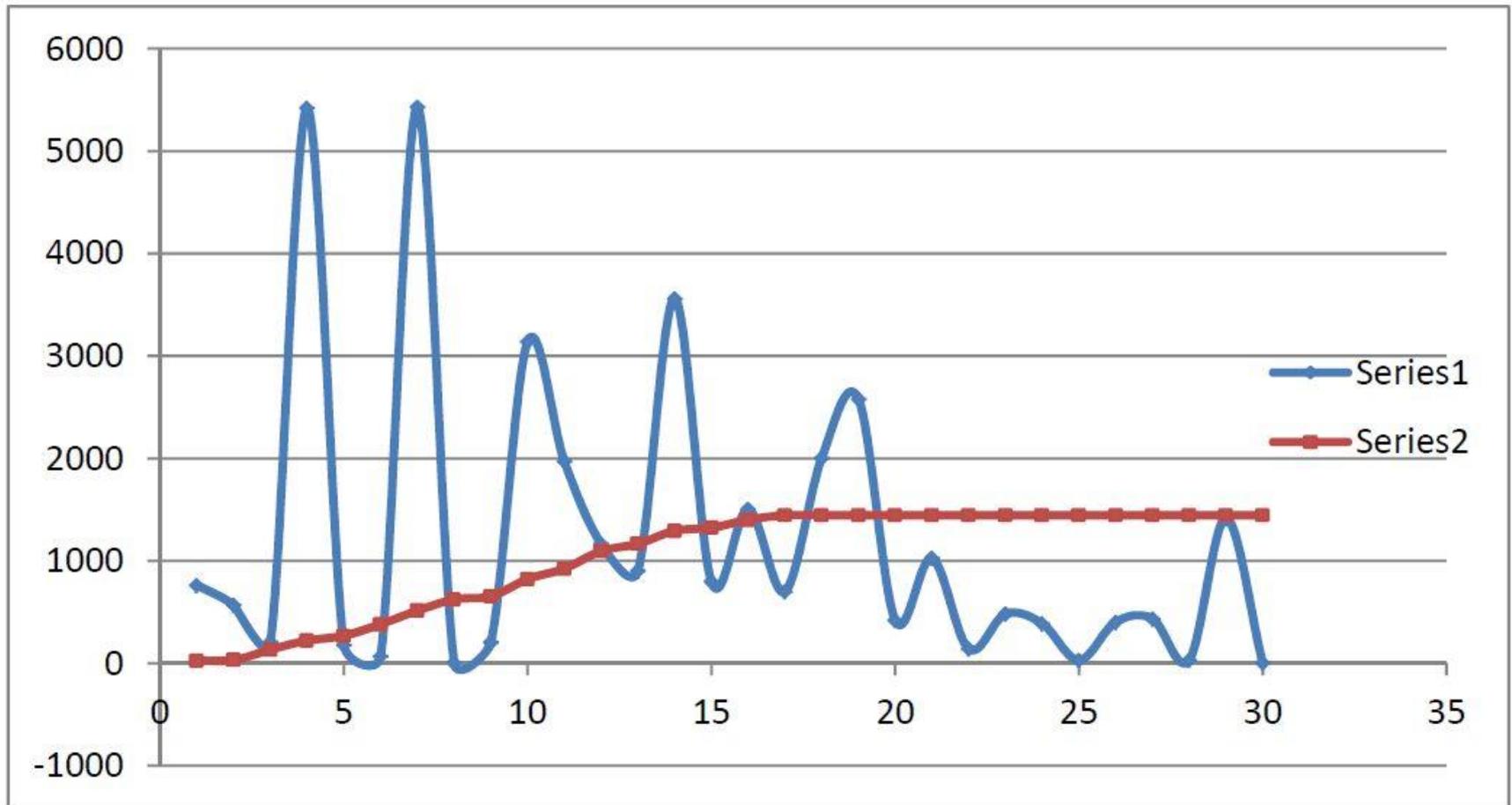
Modi di vibrare superiori



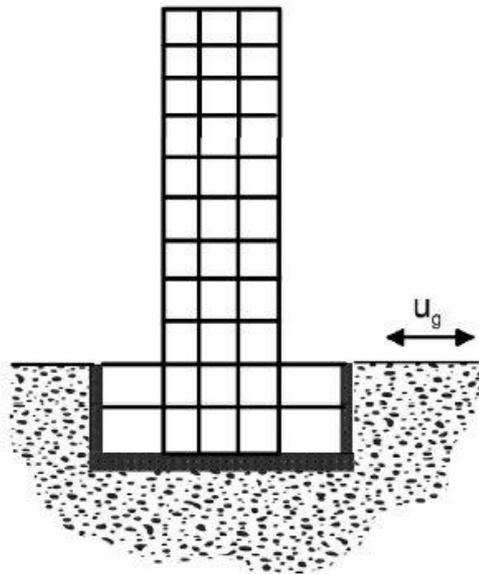
Modi di vibrare superiori

Response Spectrum Case	Modal case	Mode	Period sec	Damping Ratio	U1 Acceleration mm/sec ²	U2 Acceleration mm/sec ²	UX
SPECX	Modal	1	5.42	0.05	26	8	764
SPECX	Modal	2	4.833	0.05	32	10	569
SPECX	Modal	3	2.38	0.05	134	40	211
SPECX	Modal	4	1.84	0.05	222	67	5419
SPECX	Modal	5	1.66	0.05	269	81	179
SPECX	Modal	6	1.299	0.05	382	115	70
SPECX	Modal	7	0.958	0.05	514	154	5429
SPECX	Modal	8	0.788	0.05	624	187	7
SPECX	Modal	9	0.754	0.05	654	196	204
SPECX	Modal	10	0.598	0.05	822	247	3138
SPECX	Modal	11	0.535	0.05	925	278	1970
SPECX	Modal	12	0.453	0.05	1096	329	1167
SPECX	Modal	13	0.425	0.05	1167	350	903
SPECX	Modal	14	0.37	0.05	1293	388	3560
SPECX	Modal	15	0.356	0.05	1323	397	797
SPECX	Modal	16	0.321	0.05	1400	420	1506
SPECX	Modal	17	0.29	0.05	1445	434	700
SPECX	Modal	18	0.28	0.05	1445	434	2005
SPECX	Modal	19	0.256	0.05	1445	434	2580
SPECX	Modal	20	0.242	0.05	1445	434	420
SPECX	Modal	21	0.233	0.05	1445	434	1026
SPECX	Modal	22	0.211	0.05	1445	434	140
SPECX	Modal	23	0.206	0.05	1445	434	482
SPECX	Modal	24	0.182	0.05	1445	434	389
SPECX	Modal	25	0.178	0.05	1445	434	31
SPECX	Modal	26	0.168	0.05	1445	434	404
SPECX	Modal	27	0.152	0.05	1445	434	435
SPECX	Modal	28	0.149	0.05	1445	434	31
SPECX	Modal	29	0.145	0.05	1445	434	1415
SPECX	Modal	30	0.138	0.05	1445	434	2

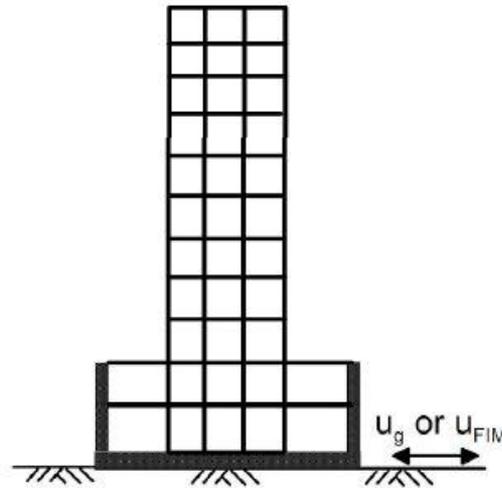
Modi di vibrare superiori



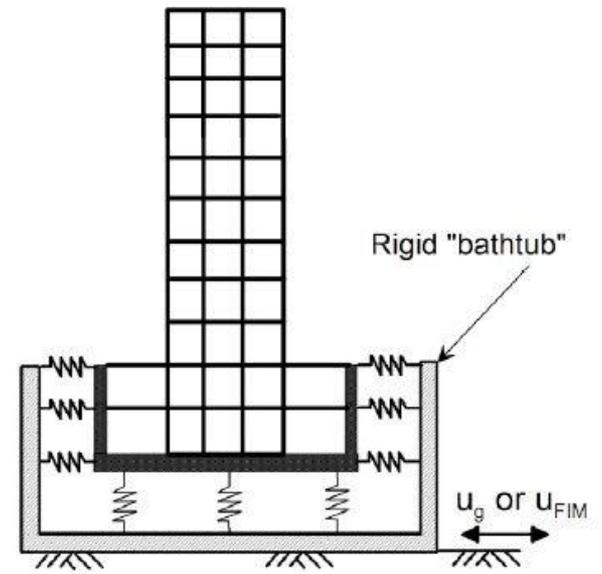
Livelli di performance



(a) Complete System



(b) Model for service-level earthquake



(c) Model for maximum-considered earthquake

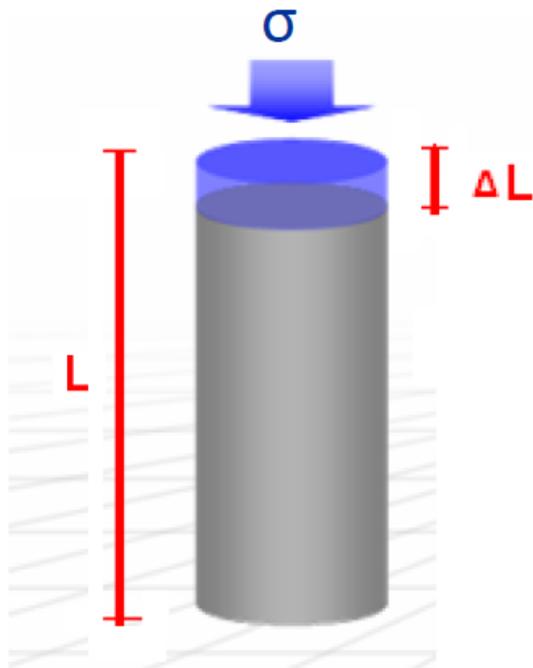
Spostamenti e fenomeni longterm

- Concetto di “wished in place”
- Deviazioni dall'assetto teorico
- Spostamenti a breve termine e lungo termine
- Stage di costruzione e fenomeni inelastici
- Axial shortening degli elementi verticali
- Acciaio
 - le deformazioni\spostamenti sono elastici
- RC
 - Componente elastica
 - Componente inelastica dovuta a viscosità e ritiro
- La parte inelastica può essere uguale o addirittura

Spostamenti – Fenomeni lungo termine

→ Column Shortening and Related Issue

When any member is loaded with Axial Load, it undergoes axial deformation



**Why is
this
Important**

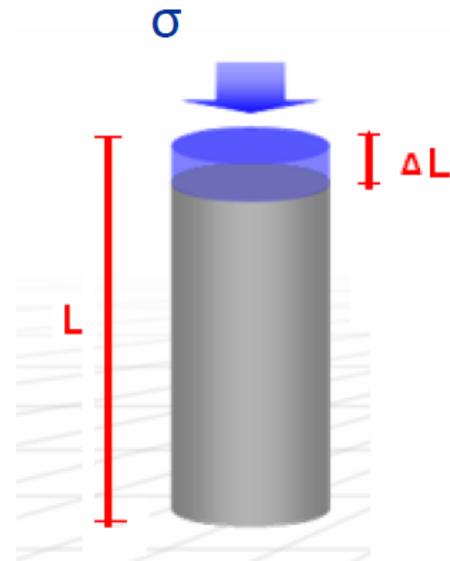
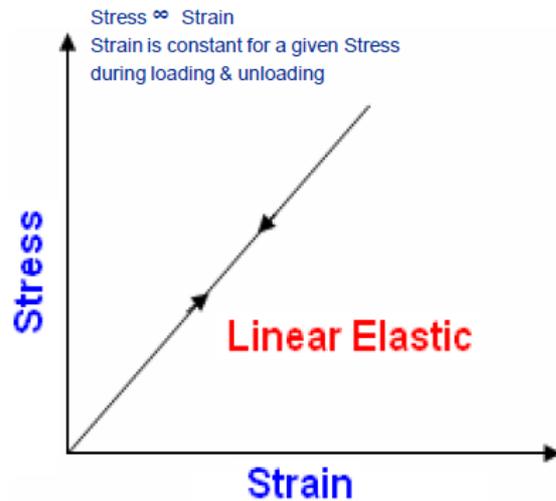
$$E = (\sigma / \varepsilon)$$

$$\Delta L = (PL/A E)$$

Spostamenti – Fenomeni lungo termine

Steel Structures

- Linear elastic Behavior



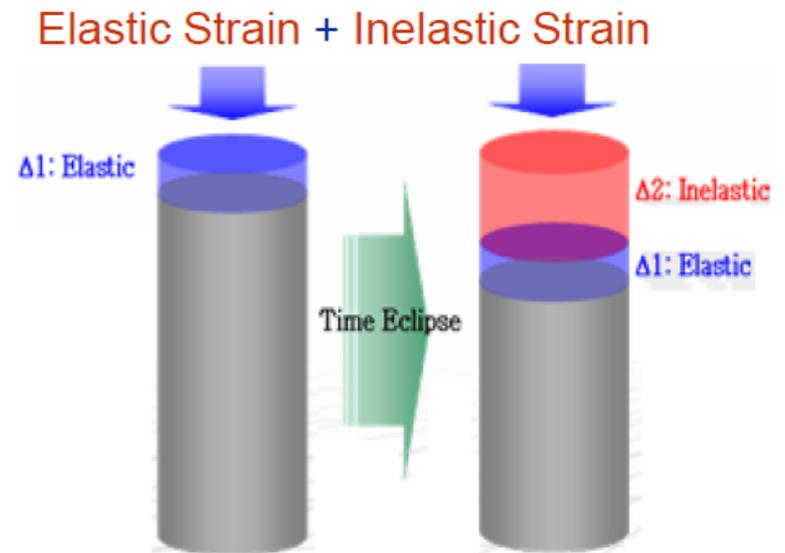
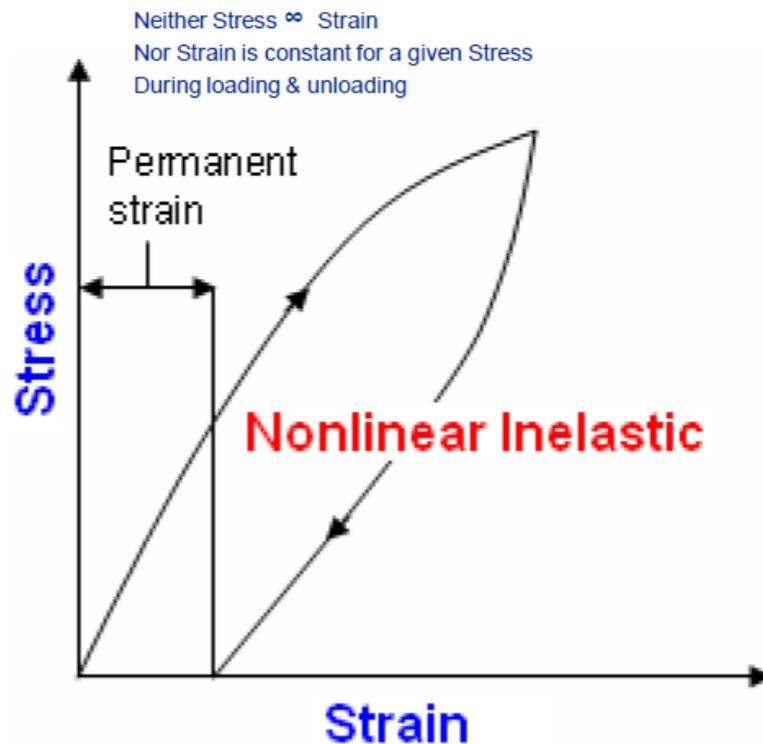
$$E = (\sigma / \epsilon)$$

$$\Delta L = (PL/A E)$$

Spostamenti – Fenomeni lungo termine

Concrete Structures

- Nonlinear Inelastic Behavior
- But in general analysis and design behavior of concrete is treated as Linear Elastic Material



Spostamenti – Fenomeni lungo termine

Inelastic Shortening = Creep + Shrinkage

Creep

Creep is time-dependent increment of strain under sustained stress.

➤ **Basic creep** occurs under the condition of no moisture movement to and from the environment.

➤ **Drying creep** is the additional creep caused by drying.

Drying creep has its effect only during the initial period of load.

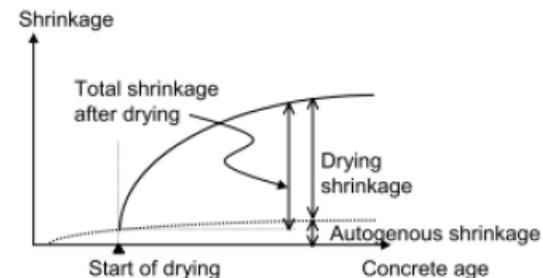
Shrinkage

Shrinkage is the time-dependant decrease in concrete volume compared with the original placement volume of concrete.

➤ **Drying Shrinkage** is due to moisture loss in concrete.

➤ **Autogenous Shrinkage** is caused by hydration of cement.

➤ **Carbonation shrinkage** results as the various cement hydration products are carbonated in the presence of CO



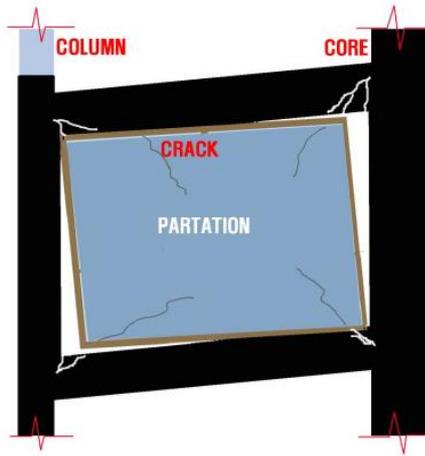
Spostamenti – Fenomeni lungo termine

Factors affecting the Creep & Shrinkage of Concrete		
Concrete (Creep & Shrinkage)	Concrete Composition	Cement Paste Content Water – Cement ratio Mixture Proportions Aggregate Characteristics Degrees of Compaction
	Initial Curing	Length of Initial Curing Curing Temperature Curing Humidity
Member Geometry and Environment (Creep & Shrinkage)	Environment	Concrete Temperature Concrete Water Content
	Geometry	Size and Shape
Loading (Creep Only)	Loading History	Concrete age at load Application During load Period Duration of unloading Period Number of load Cycles
	Stress Conditions	Type of Stress and distribution across the Section Stress/Strength Ratio

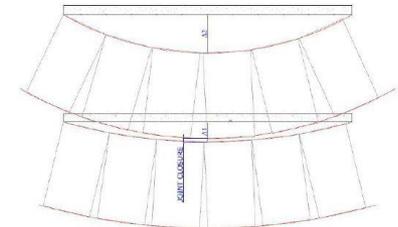
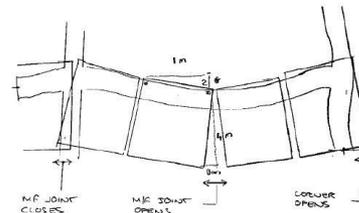
Spostamenti e fenomeni longterm

- Dipendenza della deformazione elastica e viscosa dal livello di stress
- Generalmente le colonne si dimensionano per uno stress di $0.3\text{--}0.4 \cdot f_{ck}$ ed il core wall per la stabilità laterale
- Gli stress del core sono più bassi quindi le colonne si accorciano di più del core
- Effetti
 - mancanza di planarità
 - shearing dei pannelli interni
 - disuniformità della facciata

Possibili effetti



4. Slab edge deflections
Cause panels to open up at the bottom but can also cause panel joint to close.
Relative Slab edge deflections between adjacent floors must also be considered. Especially where floors may be fully loaded and others with perhaps no live load.
Double height panels generate larger opening and closing (for the same slab deflection / rotation).



Spostamenti e fenomeni longterm

- Analisi non lineare con proprietà dei materiali dipendenti dal tempo per stage di costruzione con output in varie fase della costruzione e della vita della struttura
 - Target a 1yr \3 yr \30yr
 - Movimento “UPTO” e “SUBTO” e “R.L.” Reference Level
- Il movimento UPTO deve essere livellato in fase di costruzione
- Il movimento SUBTO è quello che interessa, generalmente il picco è a $2/3$ di altezza dell'edificio
- Target sul differenziale di

$1/100$ e $1/500$ min di 258-30 mm e normale di 10mm

Analisi per stage

Time Dependant Material Properties

- Define Creep and Shrinkage Properties .
- Define time Dependant Material Properties.
- Define Time Dependant Material Link.
- Change Element Dependant Material Property

Define Construction Stage

- Define Construction stages using Building Wizard for CS analysis
- Create LL group and add LL to LL group.
- Define CS for LL

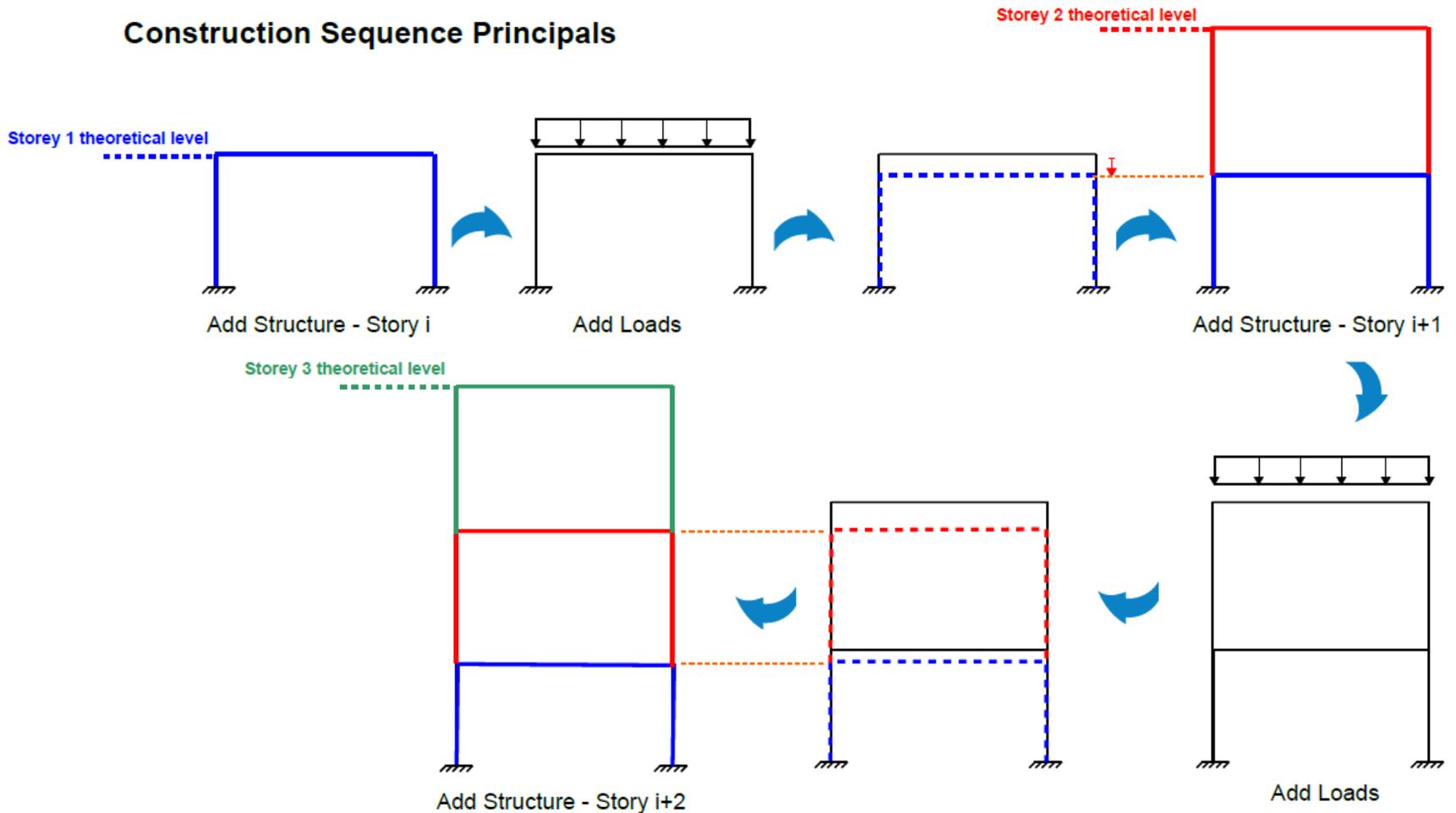
Perform Analysis

Results

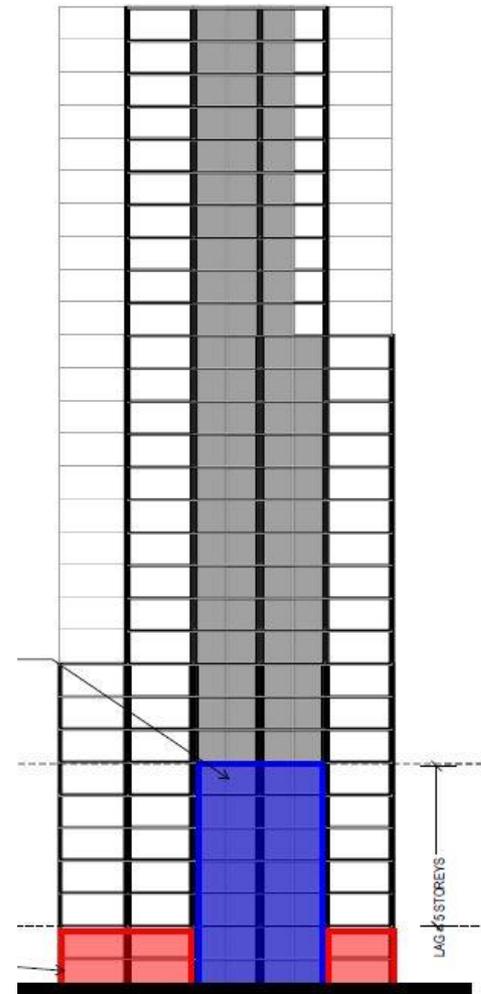
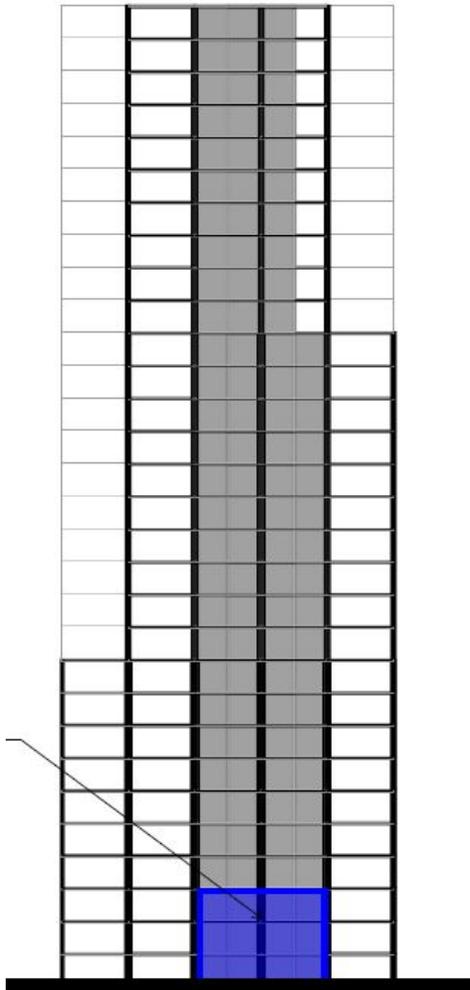
- BMD's and SFD's for different CS.
- Deformations for different CS.
- Column Shortening Graph.

Analisi per stage

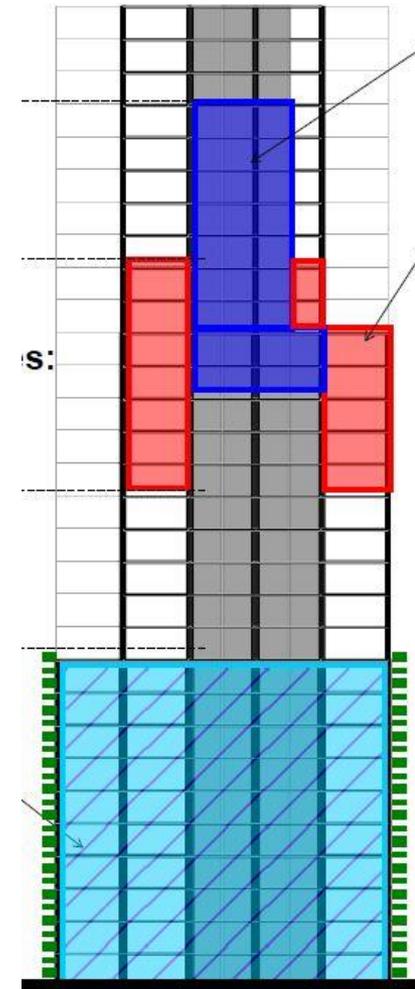
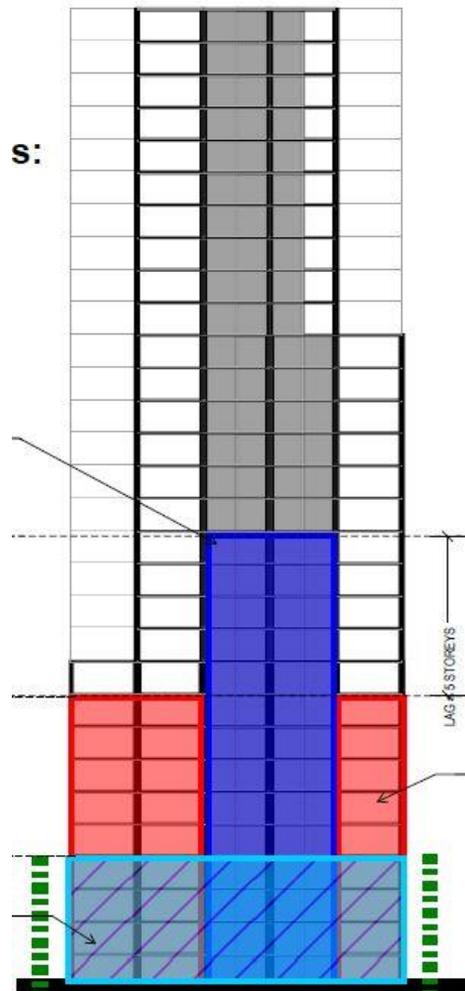
Construction Sequence Principals



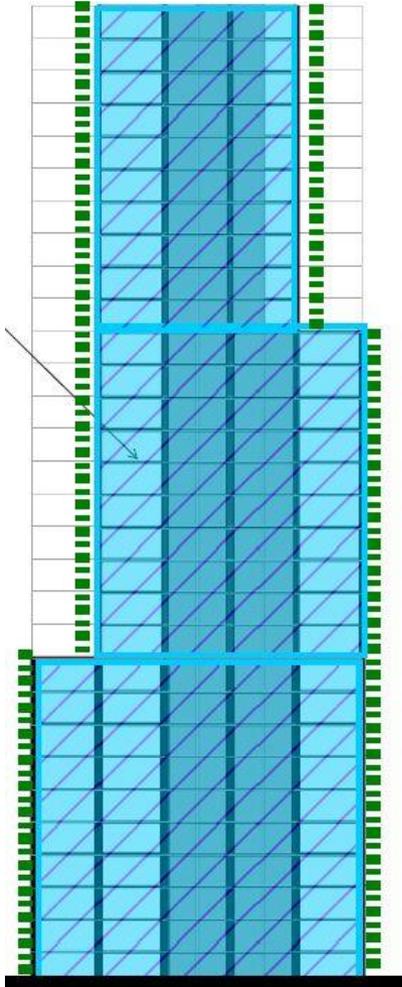
Analisi per stage



Analisi per stage



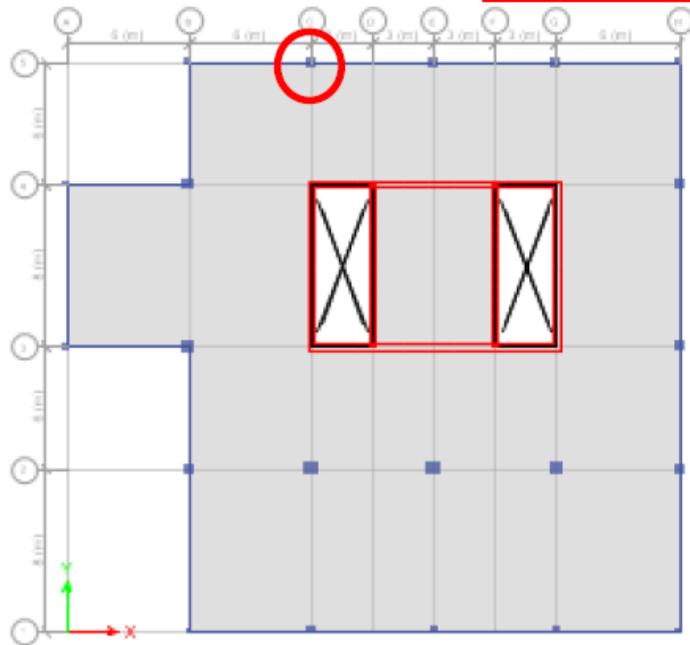
Analisi per stage



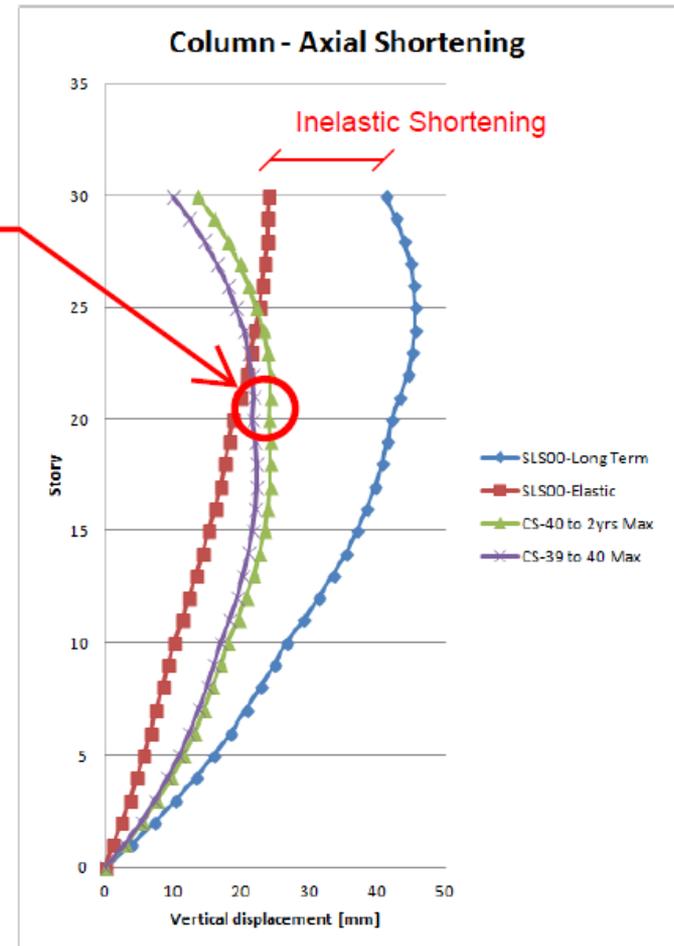
- Comportamento a lungo termine
- 1000gg
- 10000gg

Curve di spostamento

1. Model Explorer -> Tables -> Analysis -> Results -> Displacements -> Joint Displacements



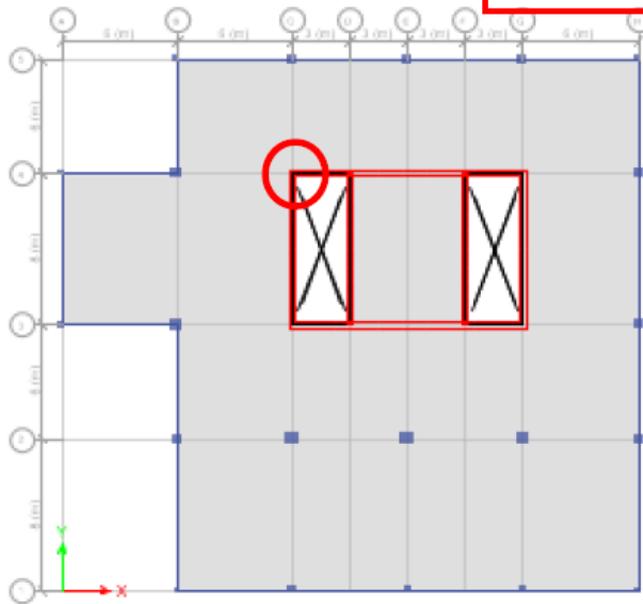
Maximum Axial Shortening happens approx. at 2/3 of the building height



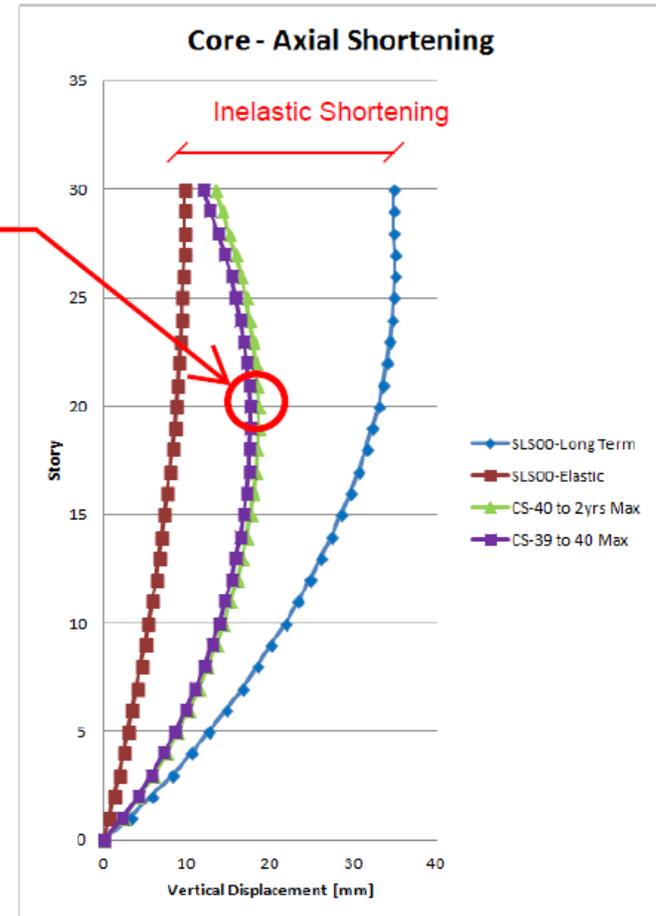
Curve di spostamento

TW1 Core SLS- Vertical Deflection

1. Model Explorer -> Tables -> Analysis -> Results -> Displacements -> Joint Displacements



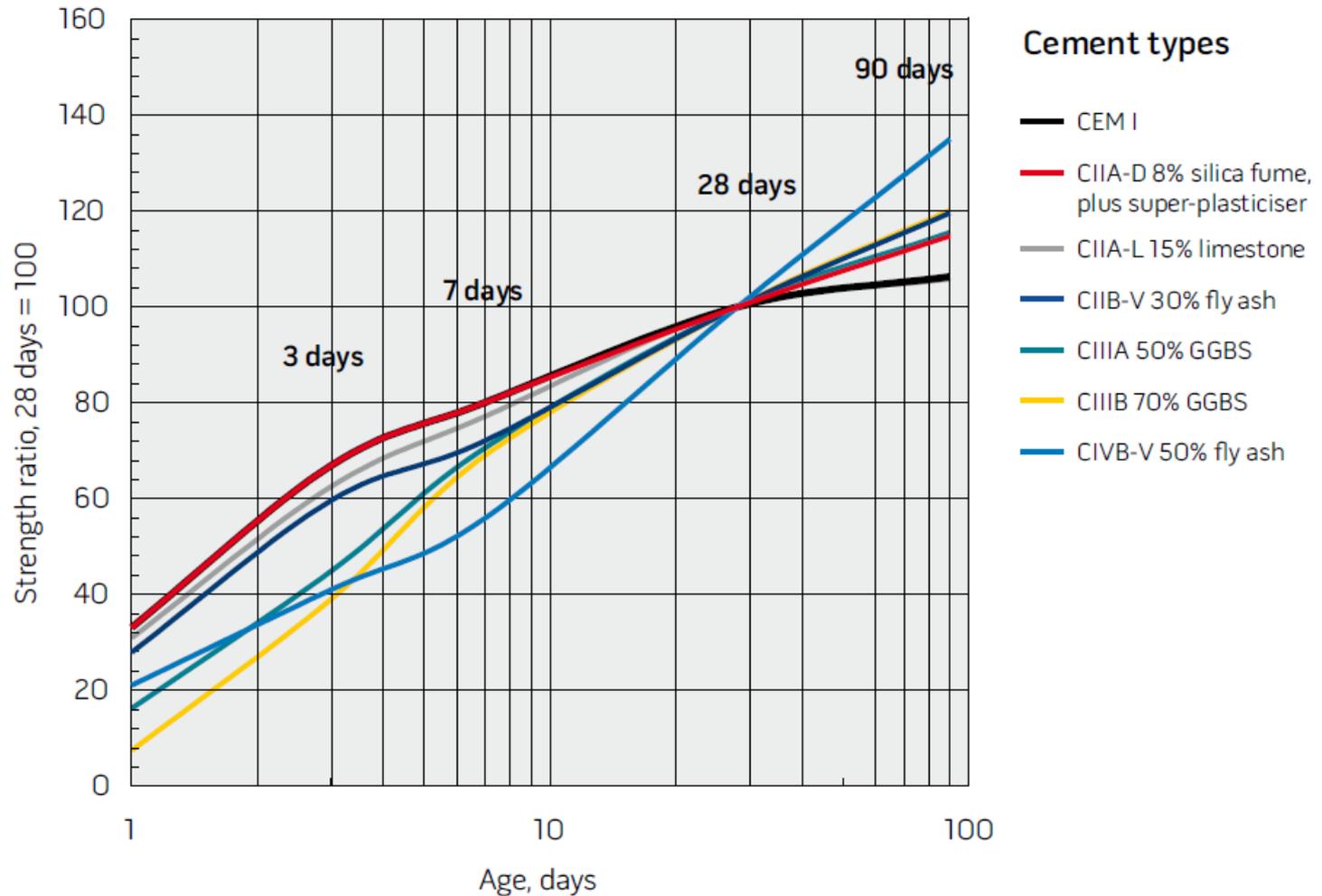
Maximum Axial Shortening happens approx. at 2/3 of the building height



Spostamenti e fenomeni longterm

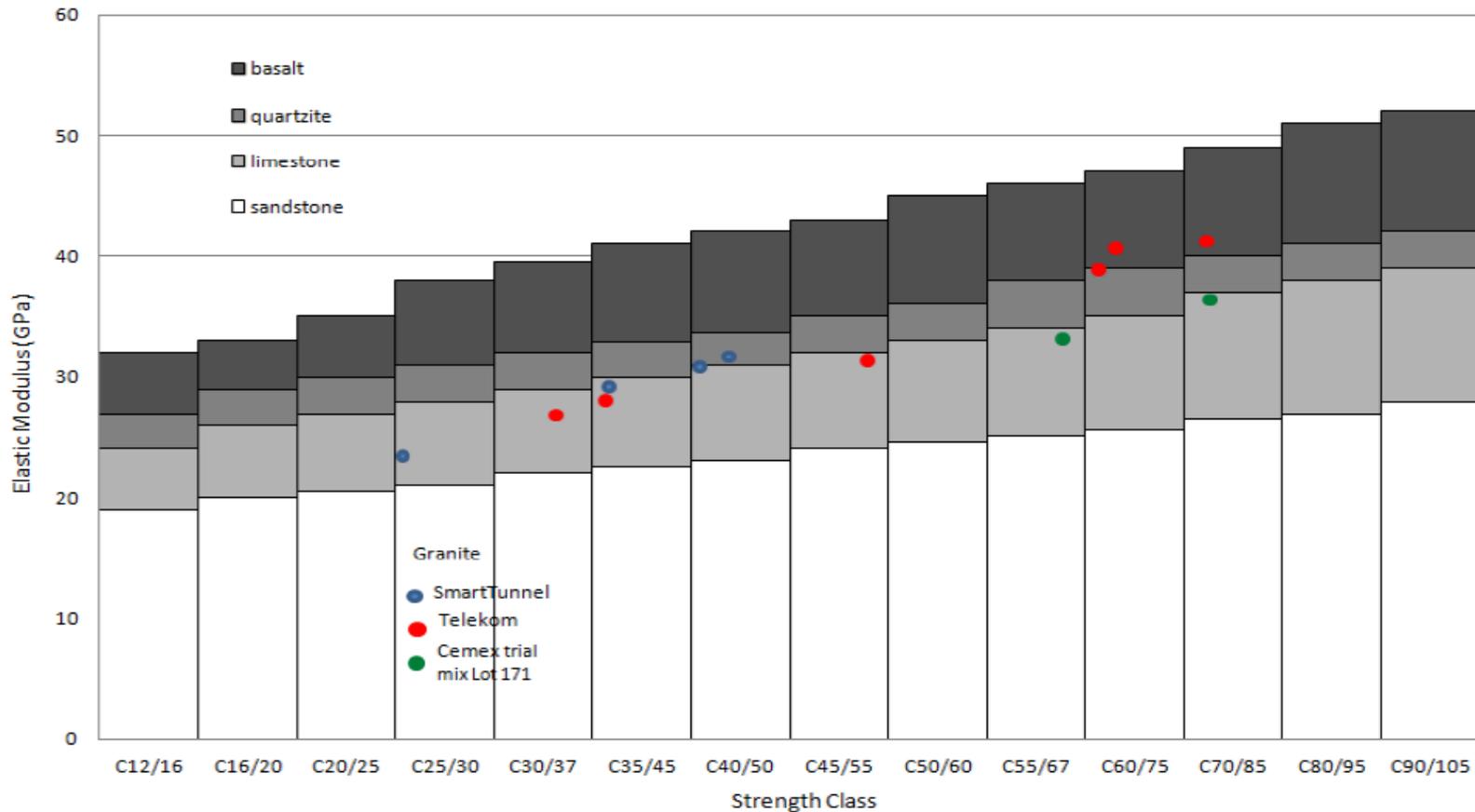
- Leggi costitutive e test sui materiali
- Leggi costitutive variano molto anche fra I codici
- Dubbi sull'applicabilità per RC ad alta resistenza
- Generalmente si interroga il concrete technologist per un database su esperienze di costruzioni precedenti nella zona e con lo stesso fornitore
- Oppure serie di test per ricavare i legami costitutivi

CIs – Cambiamento delle proprietà



Cls – Variabilità delle proprietà

Elastic Modulus in relation to strength class and aggregate type and local data from Smart tunnel Project, Telecom Tower and Cemex Trial Mix Lot 171



CIs – Validazione delle proprietà

ACI Code

$$E_c = 33w_c^{1.5} \sqrt{f'_c} \quad \text{lb/in}^2 \text{ in USCS units}$$

$$= 0.043w_c^{1.5} \sqrt{f'_c} \quad \text{MPa in SI units}$$

With normal-weight, normal-density concrete these two relations can be simplified to

$$E_c = 57,000 \sqrt{f'_c} \quad \text{lb/in}^2 \text{ in USCS units}$$

$$= 4700 \sqrt{f'_c} \quad \text{MPa in SI units}$$

where E_c = modulus of elasticity of concrete, lb/in² (MPa); and f'_c = specified 28-day compressive strength of concrete, lb/in² (MPa).

AS3600

3.1.2 Modulus of elasticity

The mean modulus of elasticity of concrete at the appropriate age (E_{cm}) shall be either—

(a) taken as equal to—

- (i) $(\rho^{1.5}) \times (0.043 \sqrt{f_{cm}})$ (in megapascals) when $f_{cm} \leq 40$ MPa; or
- (ii) $(\rho^{1.5}) \times (0.024 \sqrt{f_{cm}} + 0.12)$ (in megapascals) when $f_{cm} > 40$ MPa,

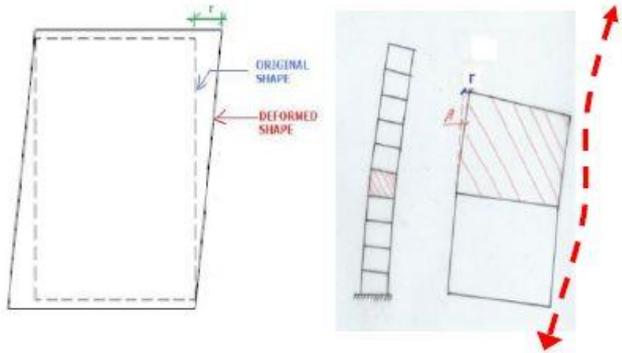
consideration being given to the fact that this value has a range of $\pm 20\%$;

Source: Civil Engineering Portal - <http://www.engineeringcivil.com/modulus-of-elasticity-of-concrete.html>

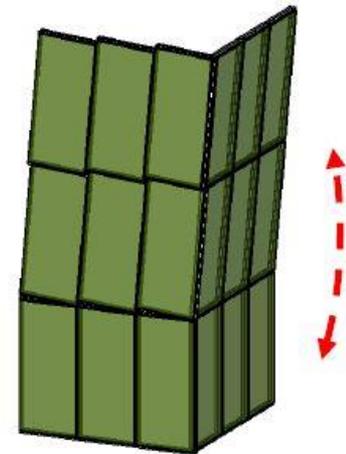
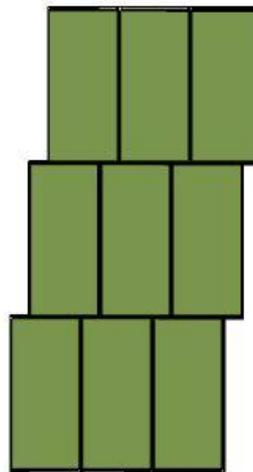
Comp Str	Mod E Measured (x 10 GPa)	US calc (modified)	AS3600 3.1.2 calc	Density (cylinder)	Measured vs Calculated
49.3	3.24	3.30	3.27	2340	0.99
50.8	3.53	3.35	3.34	2360	1.06
55	3.6	3.49	3.35	2330	1.07
69.3	3.96	3.91	3.62	2340	1.09
74.5	4.26	4.06	3.77	2370	1.13
86.3	4.37	4.37	3.98	2380 * batch rec	1.10
90.5	4.46	4.47	4.04	2380	1.10
39	3.1	2.94	3.02	2330 ENVISIA	1.03
98.3	4.2	4.66	4.29	2430 Peppertree	0.98
91	3.76	4.48	3.98	2350 Peppertree	0.95
100.5	4.16	4.71	4.37	2450 ENVISIA	0.95
68.5	3.62	3.89	3.82	2430 ENVISIA	0.95
73.8	3.86	4.04	3.93	2440 ENVISIA	0.98
44.5	3.4	3.14	3.31	2410 ENVISIA	1.03
48.5	3.4	3.27	3.42	2420 ENVISIA	0.99

Facciate - Racking

5. Inter Story Racking - shear deformation of floors where in plane shift of the floor slabs result in rhomboidal deformations.

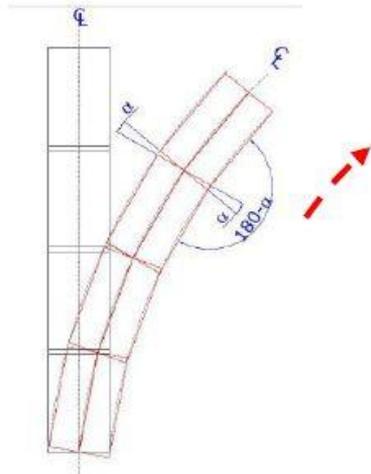


Shear deformation



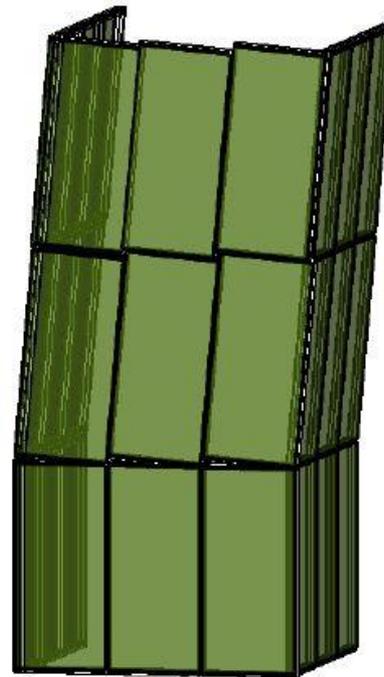
Facciate – Rotazione

- 6. Floor rotation caused by building flexural deformation due to wind load causing in plane rotation
- 7. The same deformations cause out of plane bending – Opening and closing the stack joints.



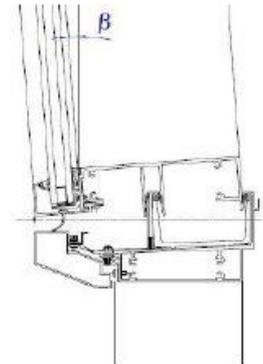
Bending deformation

Opening of stack joints



Panel Movement
Mode 2
In plane panel
Rotation

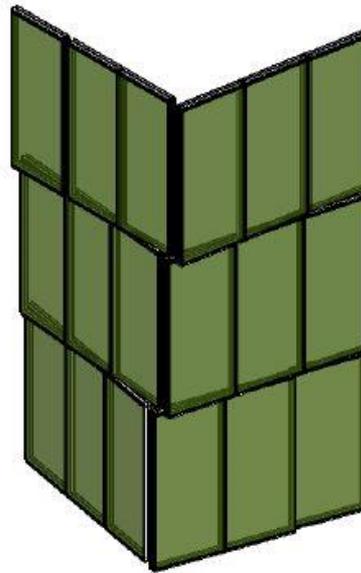
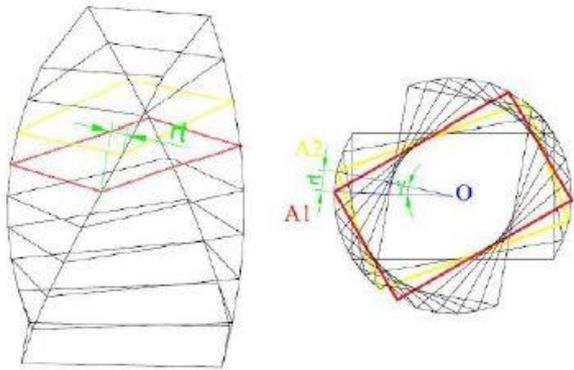
Closing of stack joints



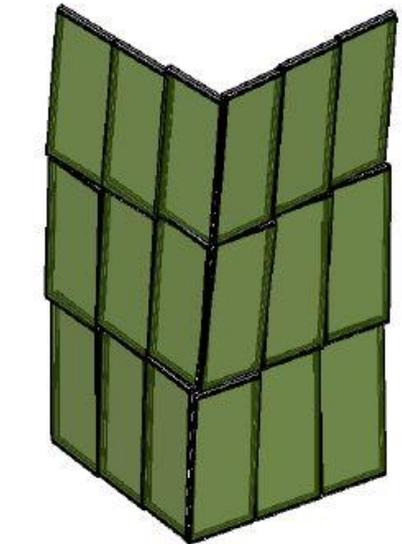
Panel Movement
Mode 3
Out of plane panel
Rotation

Facciate - Torsione

8. Building Twist

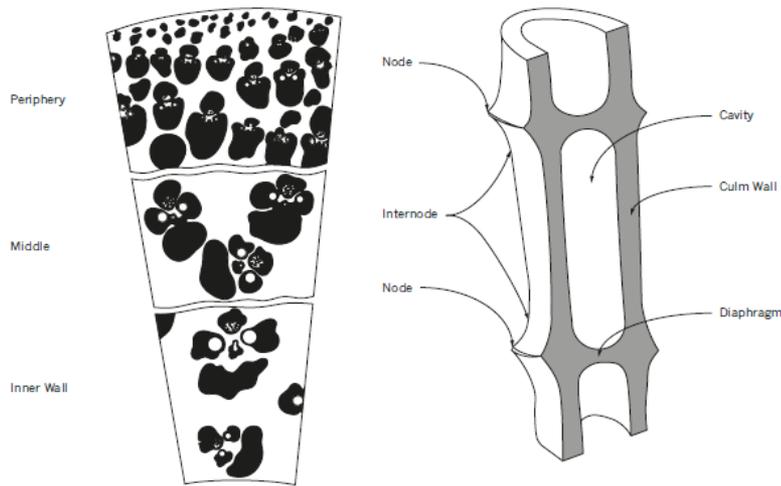


Building twisted
(shown without panel
rotation)



Panel Movement
Mode 2+3
In Plane rotation and
Out of plane panel
Rotation

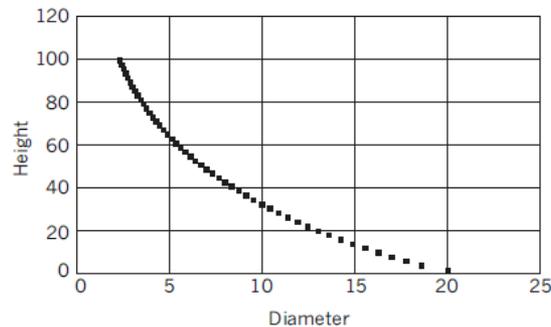
Sviluppi futuri – Natura come ispirazione



Cross Section - Segment of Bamboo Stem (Culm)

Bamboo Cross Section

Bamboo Culm



Bamboo Node Diameter vs. Height

Internode number

$$x_n = n^* \frac{100}{N}$$

Internode length

$$y_{n1} = 25.13 + 4.8080x_n - 0.0774x_n^2 \text{ (below mid-height)}$$

$$y_{n2} = 178.84 - 2.3927x_n + 0.0068x_n^2 \text{ (above mid-height)}$$

Internode diameter

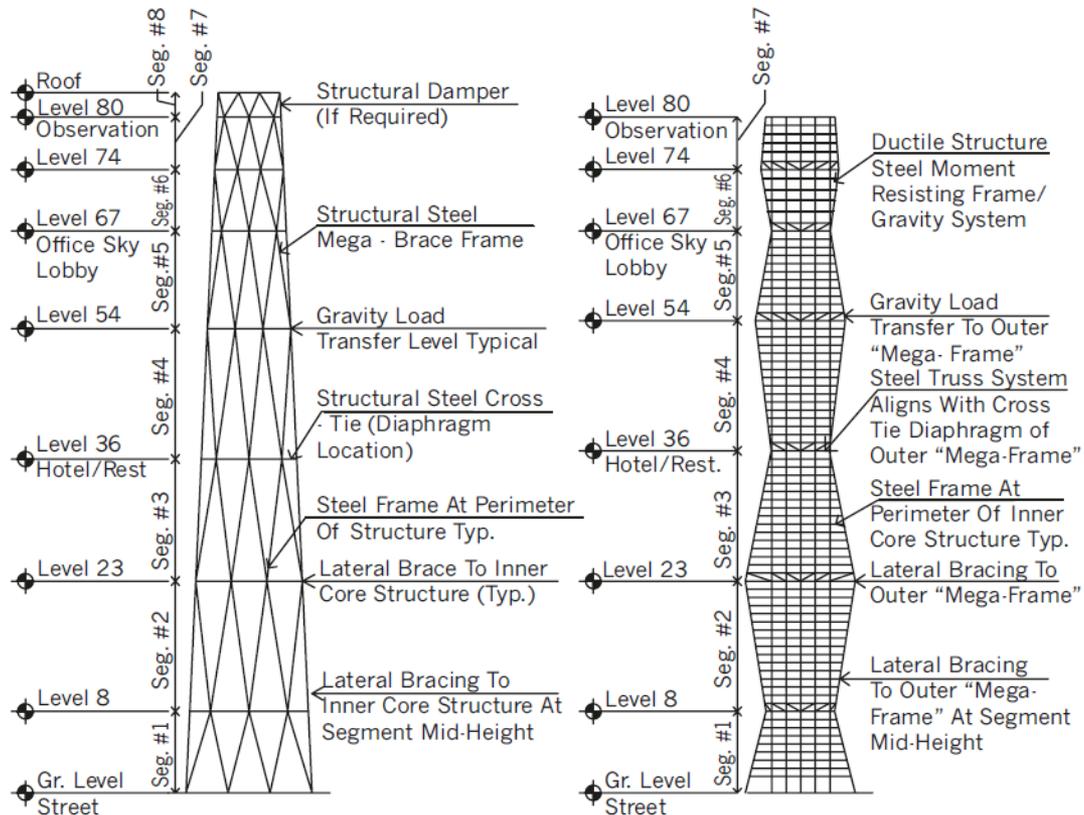
$$d_{n1} = 97.5 - 0.212x_n + 0.016x_n^2 \text{ (below mid-height)}$$

$$d_{n2} = 178.84 - 2.3927x_n + 0.0068x_n^2 \text{ (above mid-height)}$$

Wall thickness

$$t = 35 + 0.0181(x_n - 35)^{1.9}$$

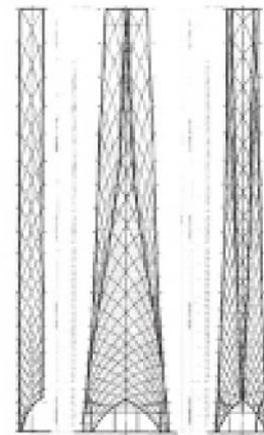
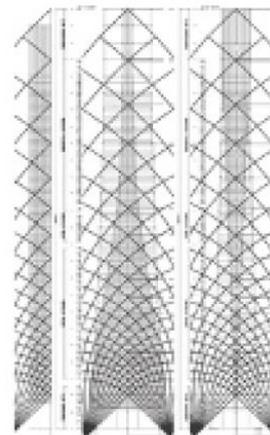
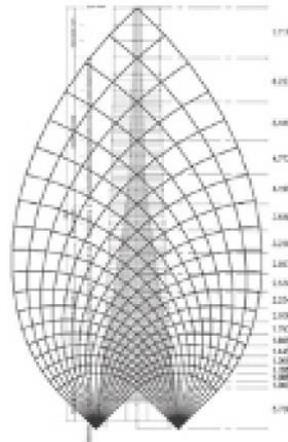
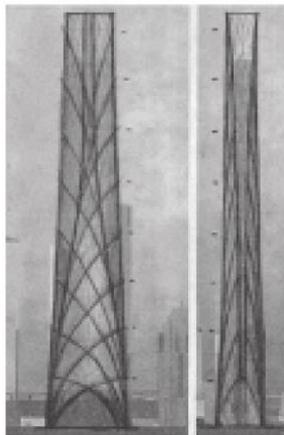
Natura come ispirazione



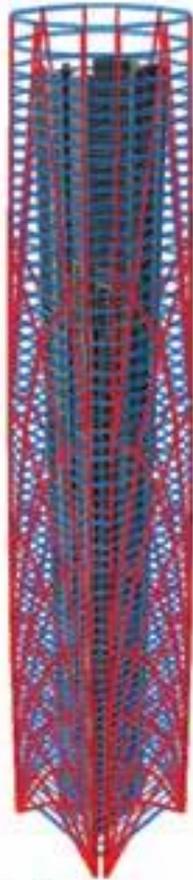
A Elevation-Outer
Mega-Brace Structural Frame

B Elevation-Inner Ductile
Moment-Resisting Frame

Natura come ispirazione



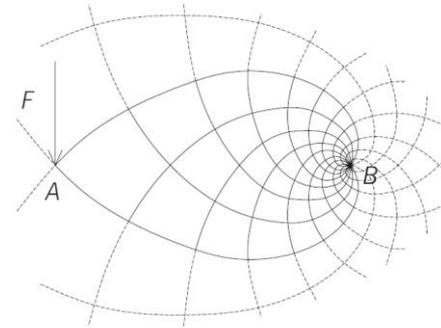
Trasferimento nella filosofia strutturale



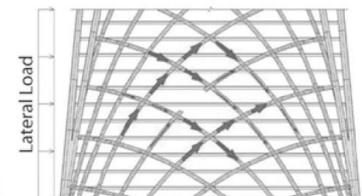
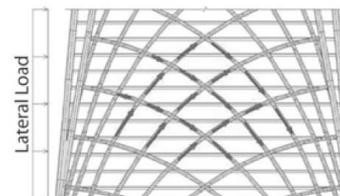
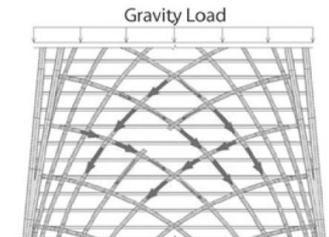
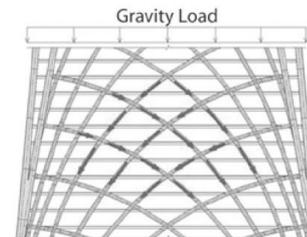
Office Tower



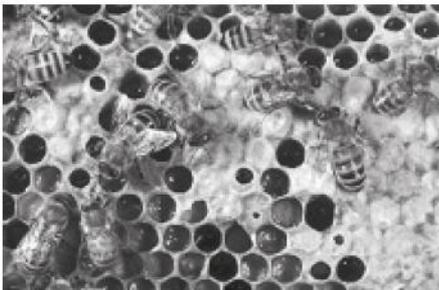
Hotel Tower



Michell Truss Diagram, A single force F is applied at A , and acting at right angles to line AB , is balanced by an equal and opposite force and a couple, of moment $F \times AB$, applied at B . The minimum frame is formed of two similar equiangular spirals having their origin at B and intersection orthogonally at A , together with all other spirals orthogonal to these and enclosed between them



Pattern autonomi di sviluppo – Algoritmi genetici



CLOCKWISE FROM TOP LEFT
Termite Colony

Bird Wing Skeleton Section

Honeycomb



Initial Form



Emergence Theory
Diagram

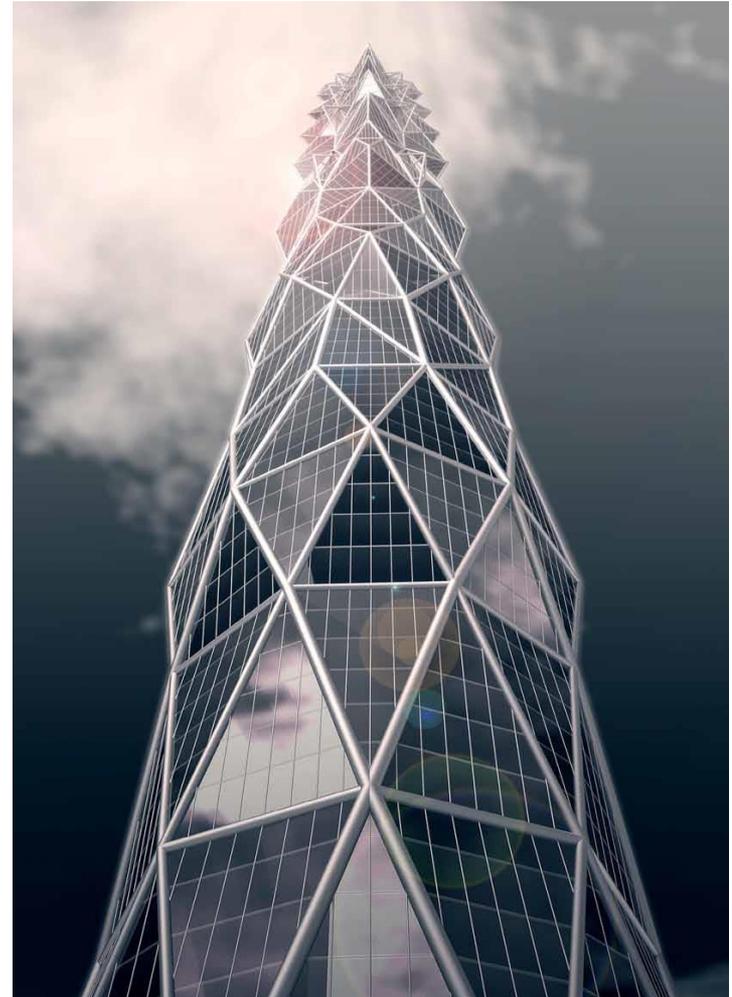
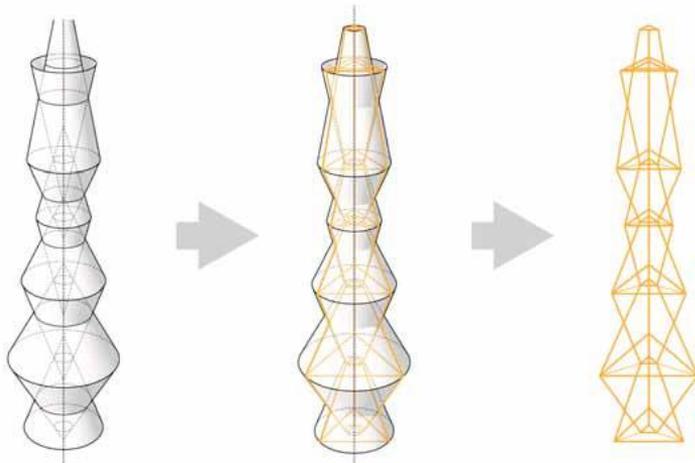
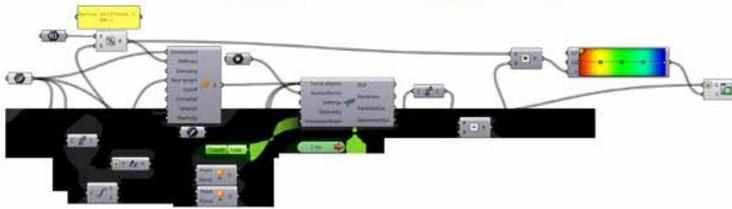
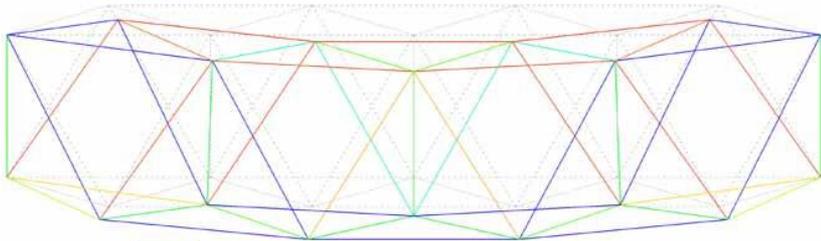


Final Structural
Frame



Final Architectural
Elevation

Algoritmi genetici e parametric engineering



Casi di studio

- KL118



Casi di studio

- Hertsmere House



Casi di studio

Crown Sydney



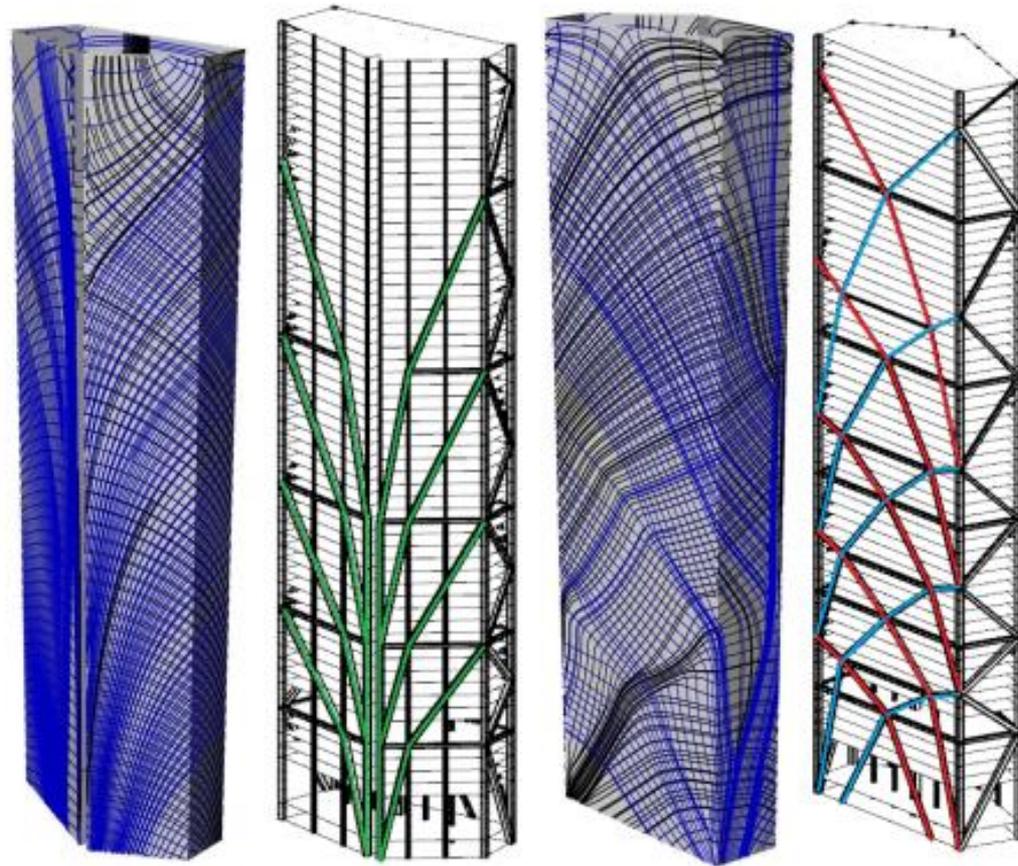
Casi di studio

ICD Brookfield place



Casi di studio

Lend Lease Circular Quay



Grazie!

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