Progettazione sismica di facciate Vetrate: Strategie e casi di applicazione

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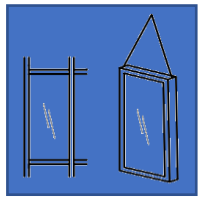
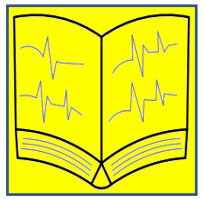
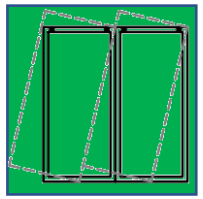
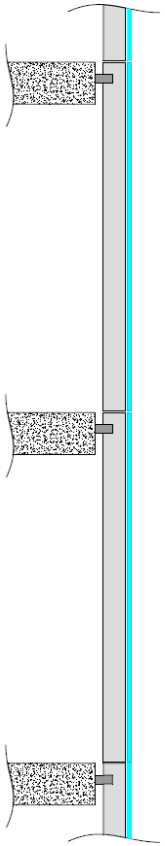
- La facciata continua: MT vs Cellule
- Analisi sismica: quadro normativo
- Analisi spostamenti imposti
- Casi studio


FACCIATE CONTINUE (CURTAIN WALL)

Definizione (1/3):
parte dell'involucro edilizio realizzata da profili orizzontali e verticali connessi tra loro e ancorati alla struttura principale dell'edificio e contenente tamponamenti (pannelli vetrati)
(EN 13830)



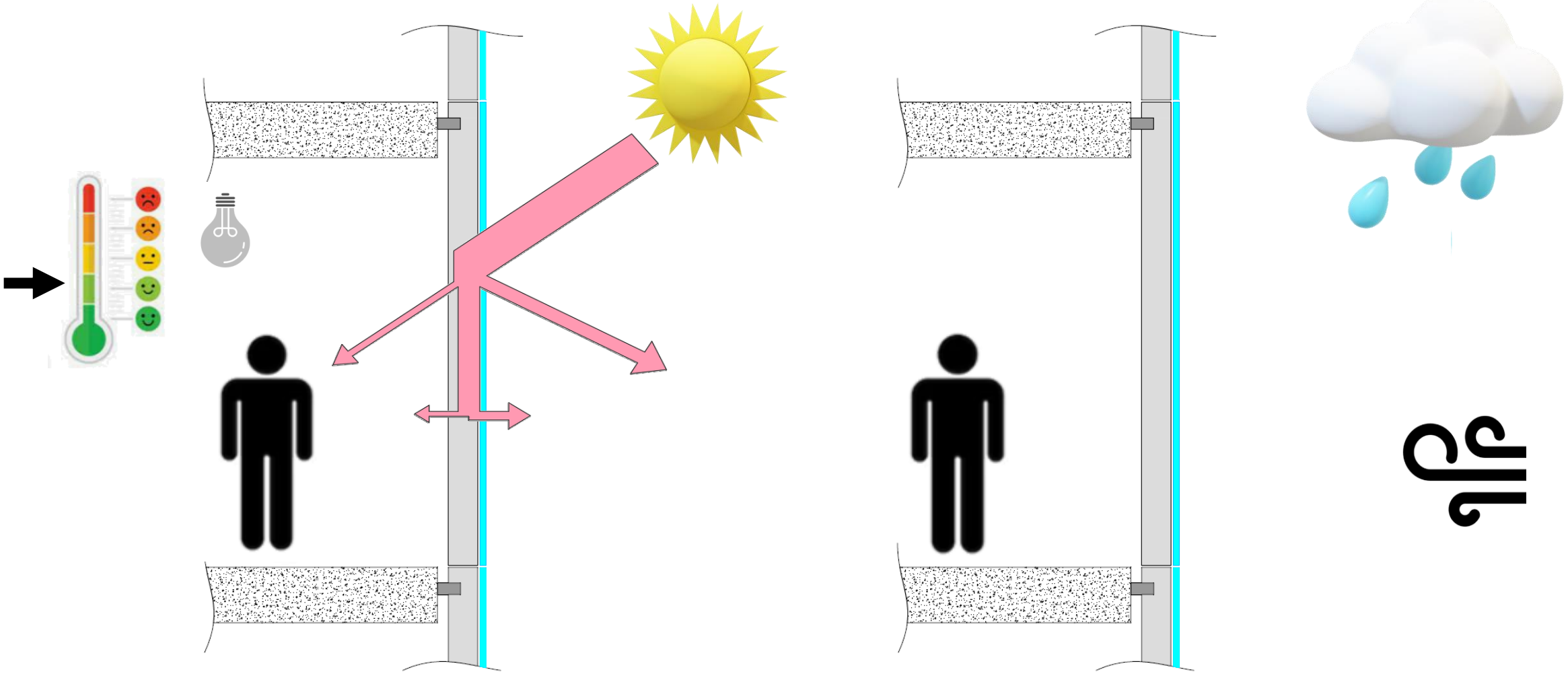
Seagram Building | Ludwig Mies van der Rohe
New York | 1958

Imperial College | Allies And Morrison
London | 2016

«L*a facciata è libera e così le finestre possono correre da un bordo all'altro ininterrotte*»
Le Corbusier

FACCIATE CONTINUE (CURTAIN WALL)

Definizione (2/3):
Garantiscono resistenza agli agenti atmosferici, sicurezza d'uso, risparmio energetico e ritenzione del calore **(EN 13830)**

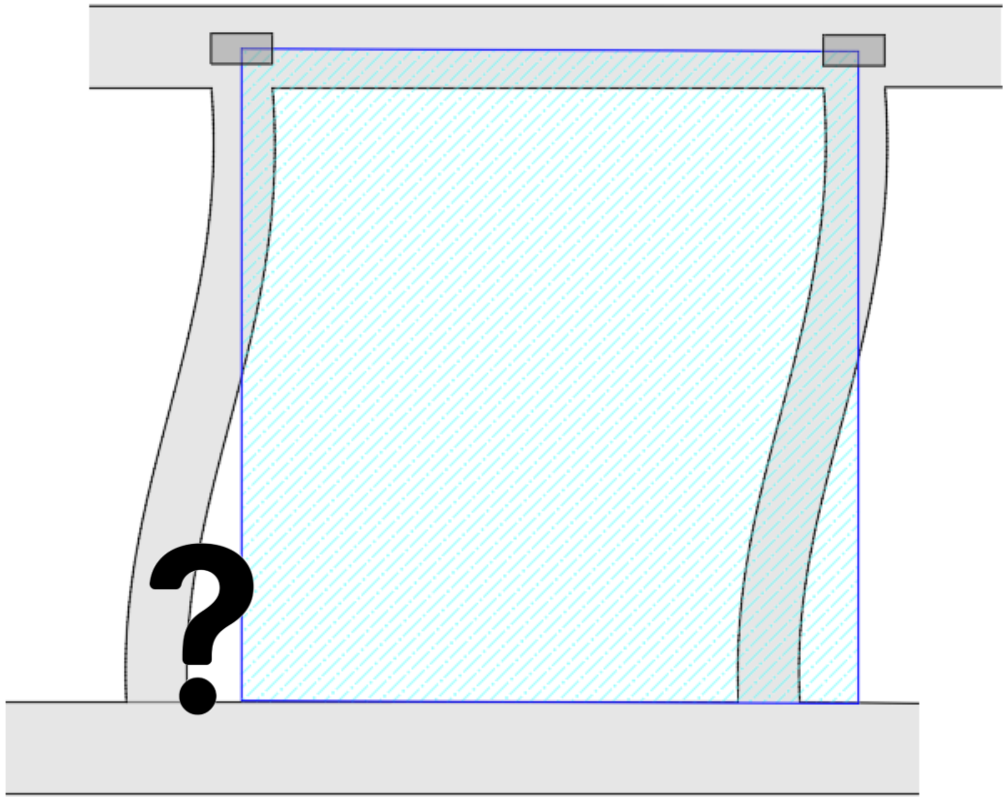


FACCIATE CONTINUE (CURTAIN WALL)

Definizione (3/3):
Non concorrono alla capacità portante dell'edificio, non sopportano altri carichi oltre al peso proprio e alle forze ambientali che agiscono su di esse
(EN 13830 - CWCT)

Trasmette alla struttura dell'edificio principale:
- carichi propri
- carico ambientale (vento, neve, ecc.)
- spinta delle persone
- carico sismico

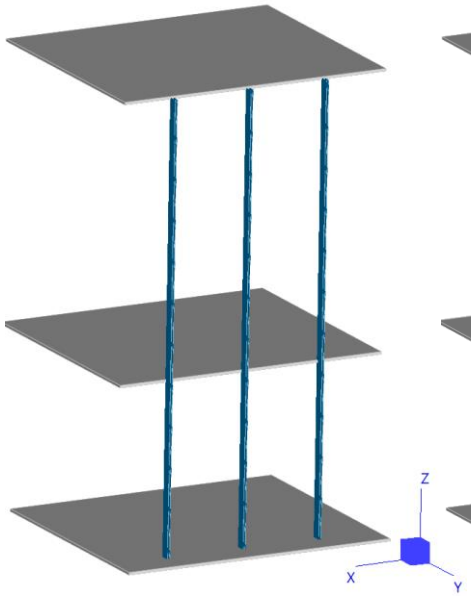
Elemento secondario non strutturale



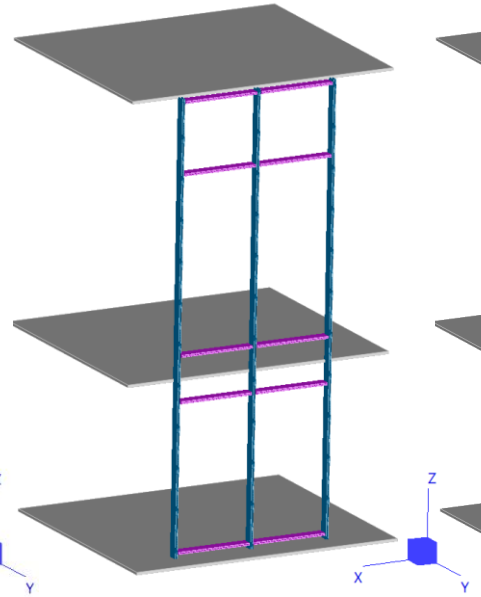
MONTANTI E TRAVERSI (STICK SYSTEM)

Kö Bogen II | Ingenhoven Architects
Düsseldorf | 2018

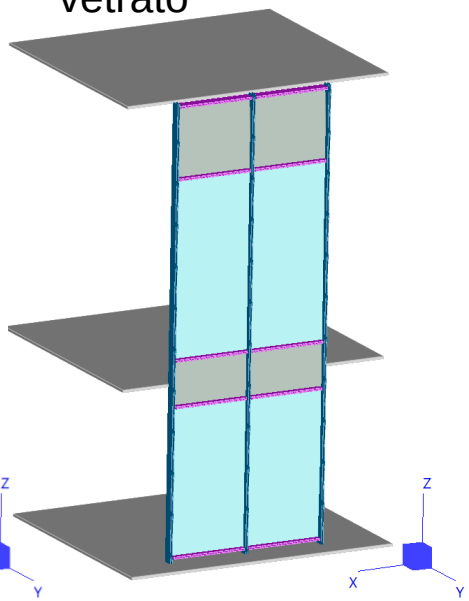
Montanti

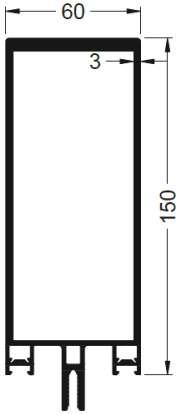


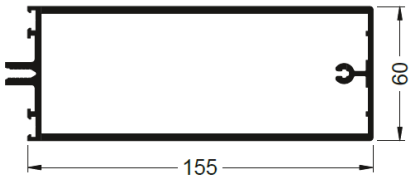
Traversi

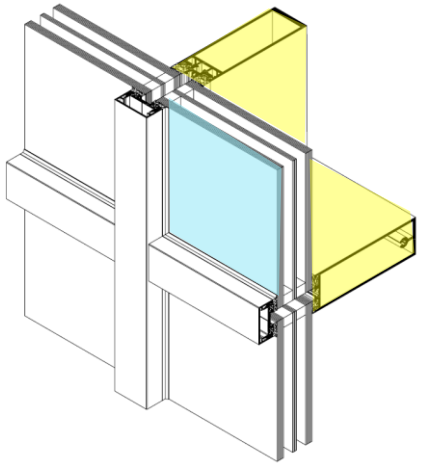


Pannello vetrato









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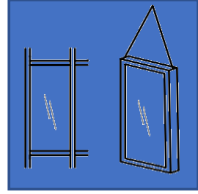
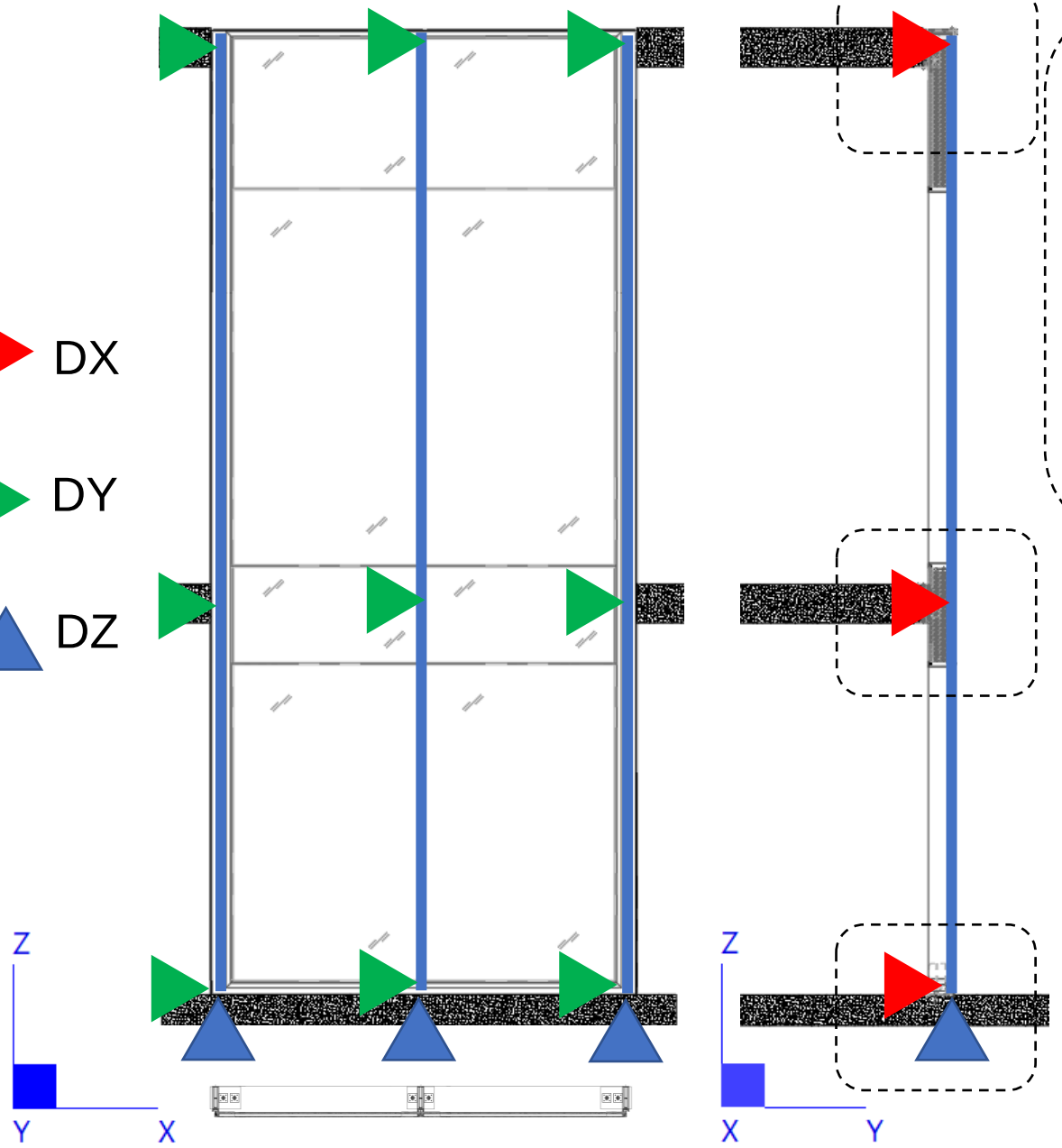
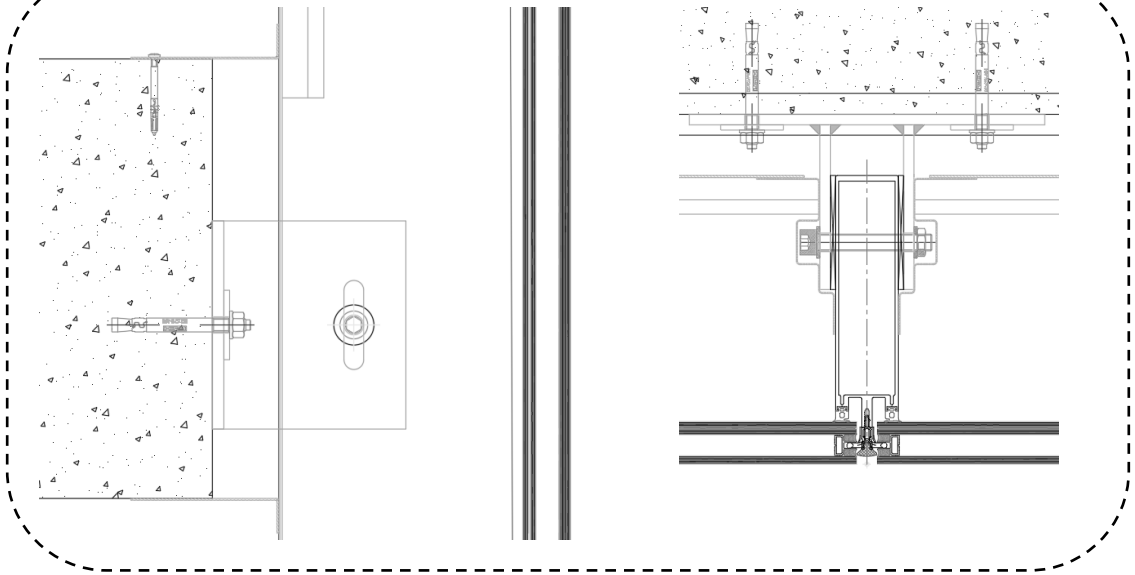


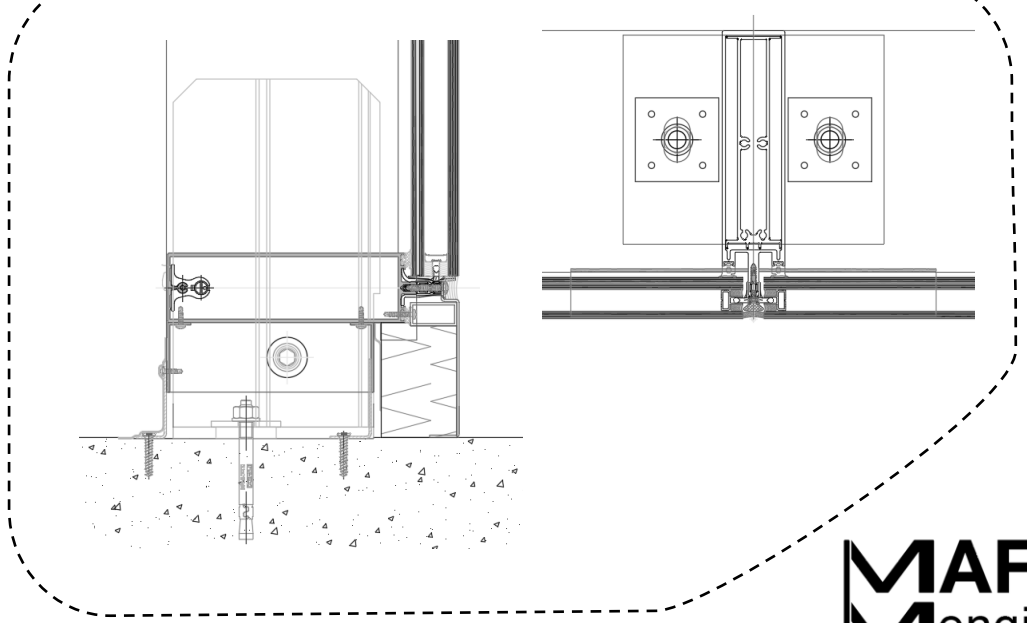
DX

DY

DZ

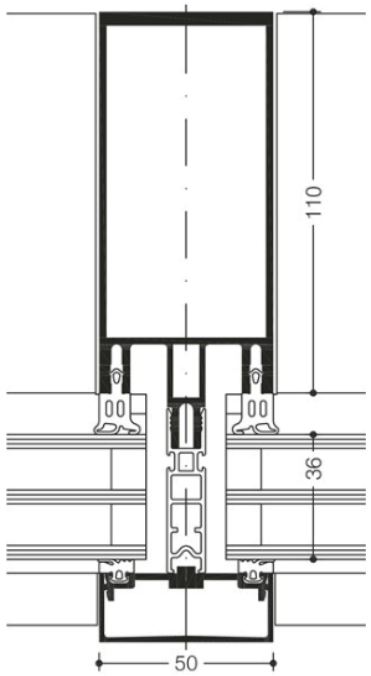






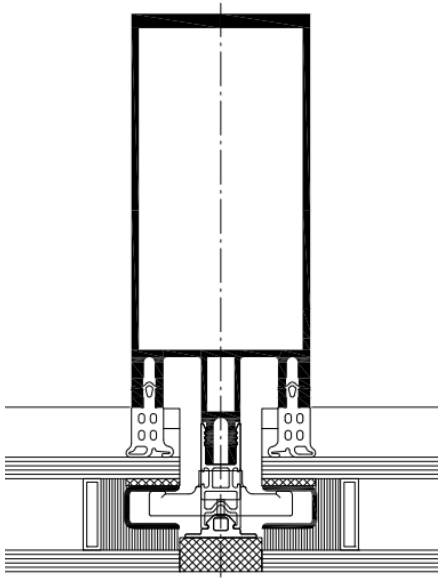
MONTANTI E TRAVERSI (STICK SYSTEM)

Pressore



Gap tra montante e vetro 4-7 mm

Toggle



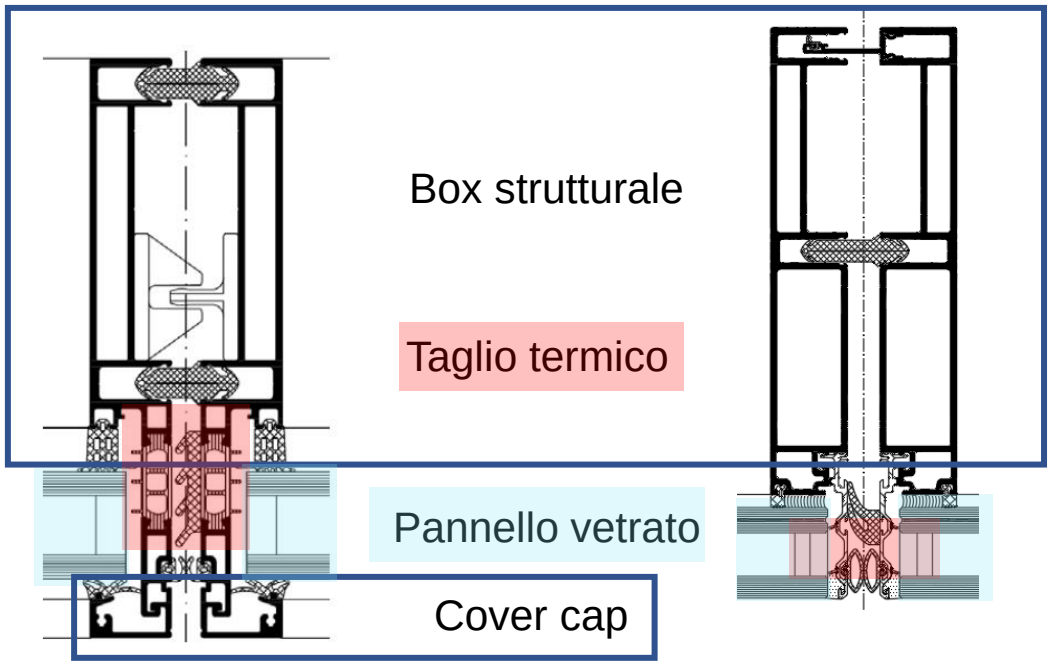
Gap tra montante e vetro 1-4 mm

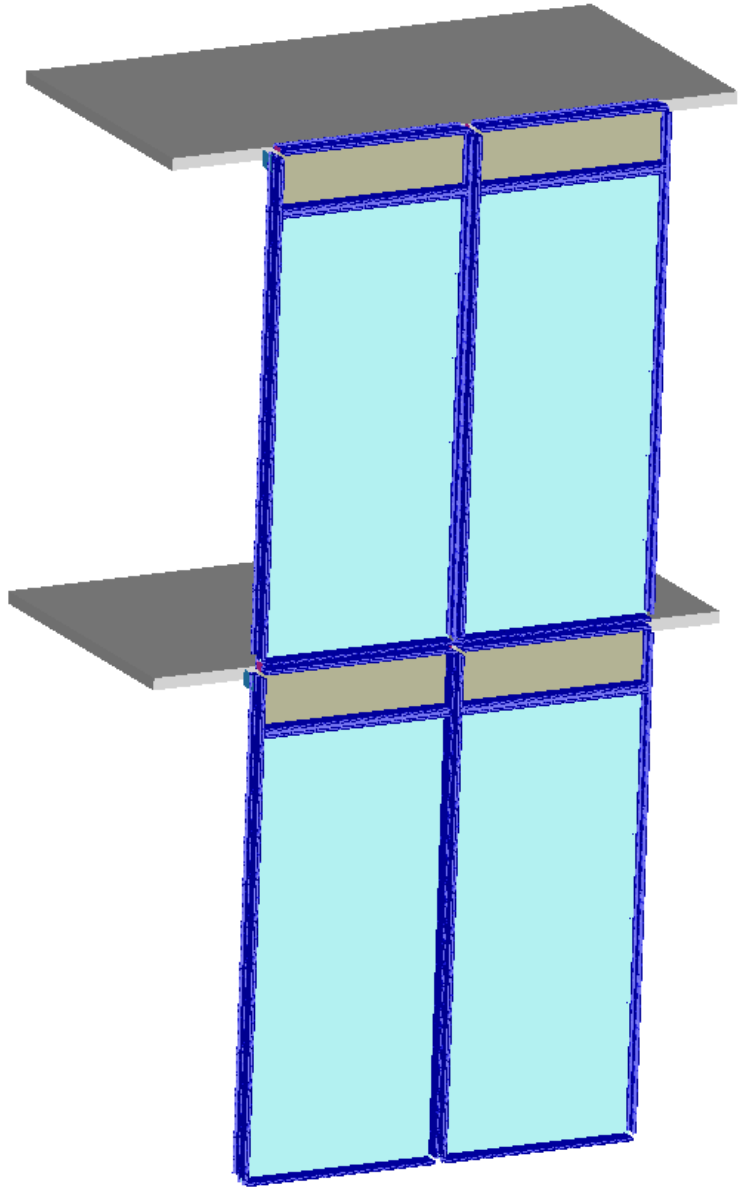
CELLULE (UNITIZED SYSTEM)

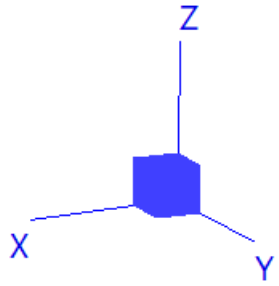
Unità prefabbricate garantiscono garanzia di performance e velocità di installazione

DTU Tower | Adrian Smith + Gordon Gill Architecture
Dubai | 2019

CELLULE (UNITIZED SYSTEM)





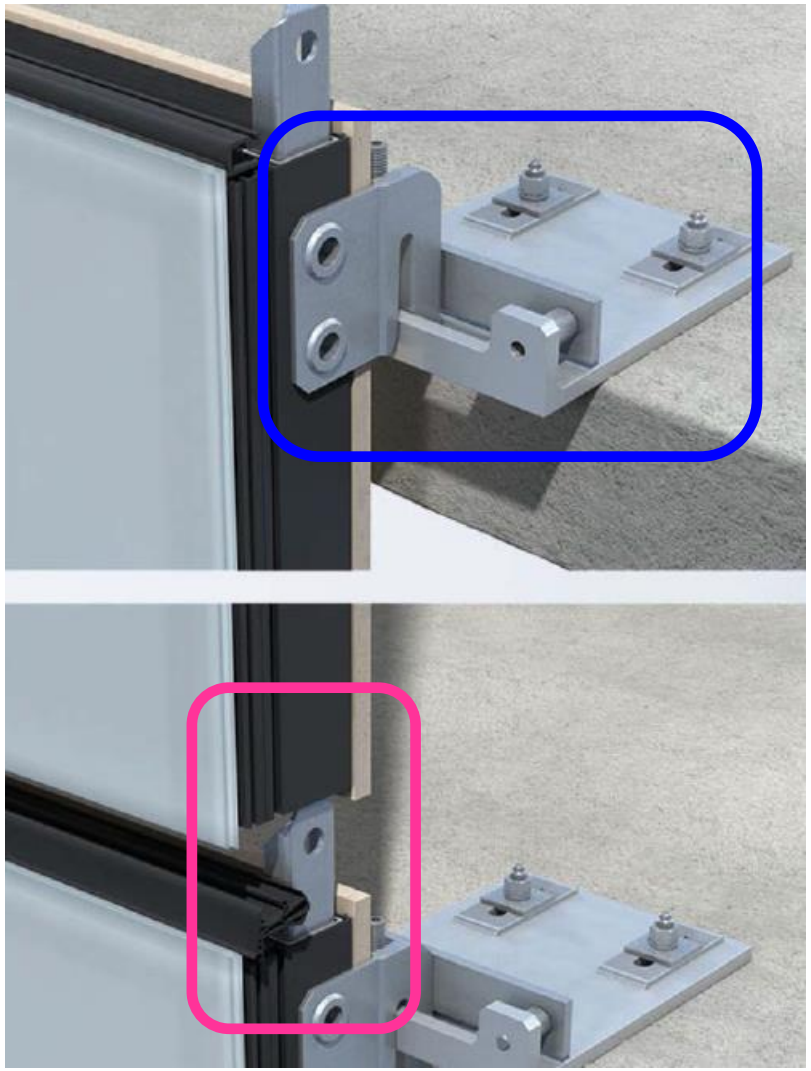


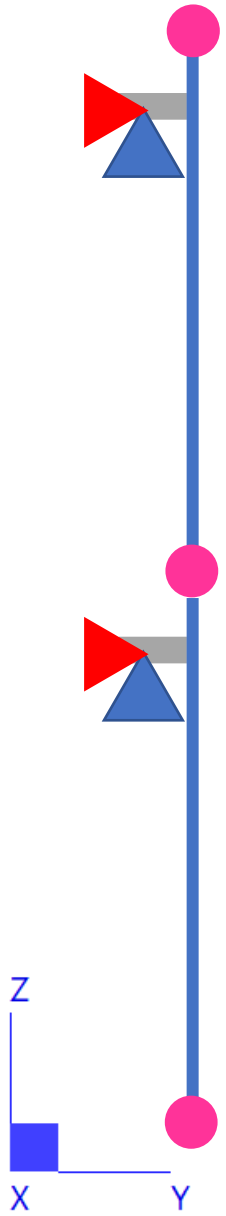
CELLULE (UNITIZED SYSTEM)

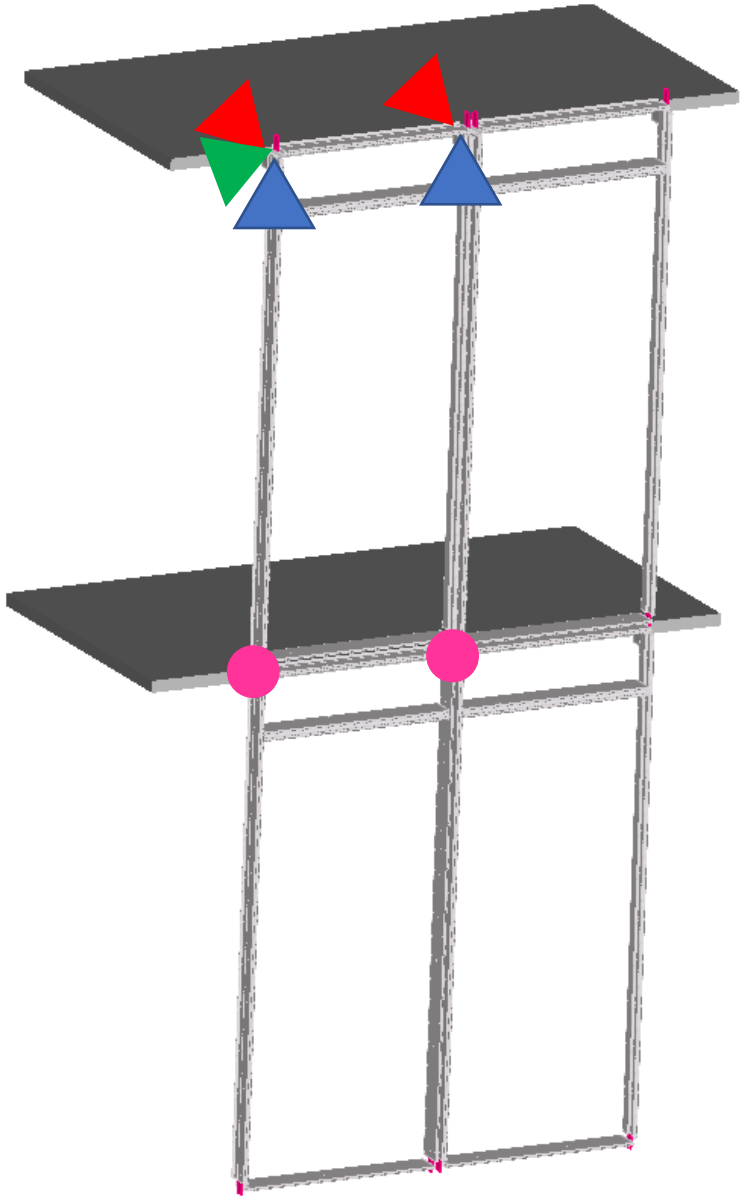
DX

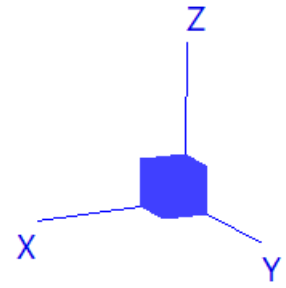
DY

DZ





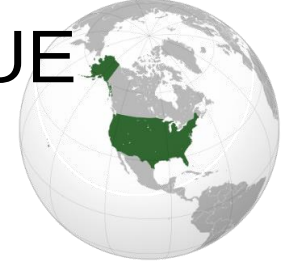




AZIONE SISMICA per FACCIATE CONTINUE

Europa

EN 1998-1



Stati Uniti

ASCE 7

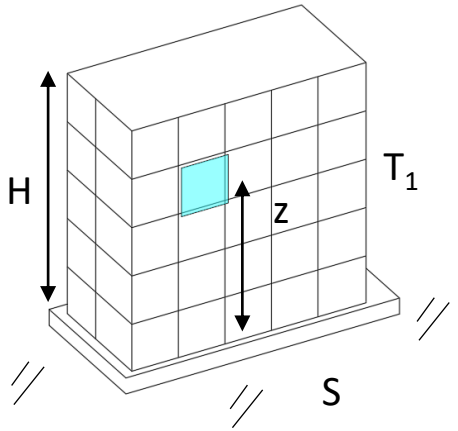
- Gli elementi non strutturali, comprese connessioni e ancoraggi, devono essere verificati nei confronti dell'azione sismica (§4.3.5)

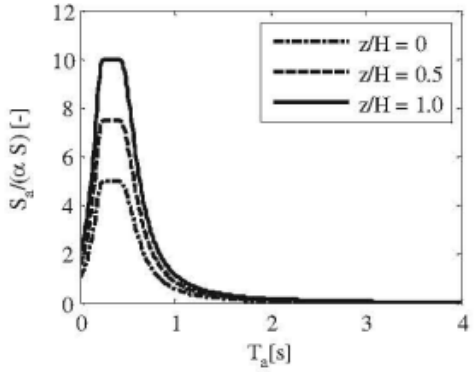
$$F_a = \frac{S_a \cdot W_a \cdot \gamma_a}{q_a}$$

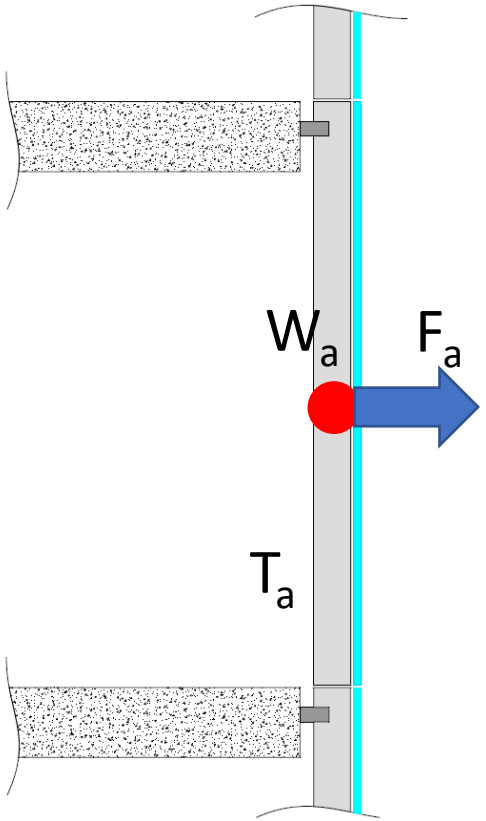
$$S_a = \alpha \cdot S \cdot \left[\frac{3 \cdot (1 + \frac{z}{H})}{1 + \left(1 - \frac{T_a}{T_1}\right)^2} - 0.5 \right]$$

Table 4.4: Values of q_a for non-structural elements

Type of non-structural element	q_a
Cantilevering parapets or ornamentations	1,0
Signs and billboards	
Chimneys, masts and tanks on legs acting as unbraced cantilevers along more than one half of their total height	
Exterior and interior walls	2,0
Partitions and facades	
Chimneys, masts and tanks on legs acting as unbraced cantilevers along less than one half of their total height, or braced or guyed to the structure at or above their centre of mass	
Anchorage elements for permanent cabinets and book stacks supported by the floor	
Anchorage elements for false (suspended) ceilings and light fixtures	







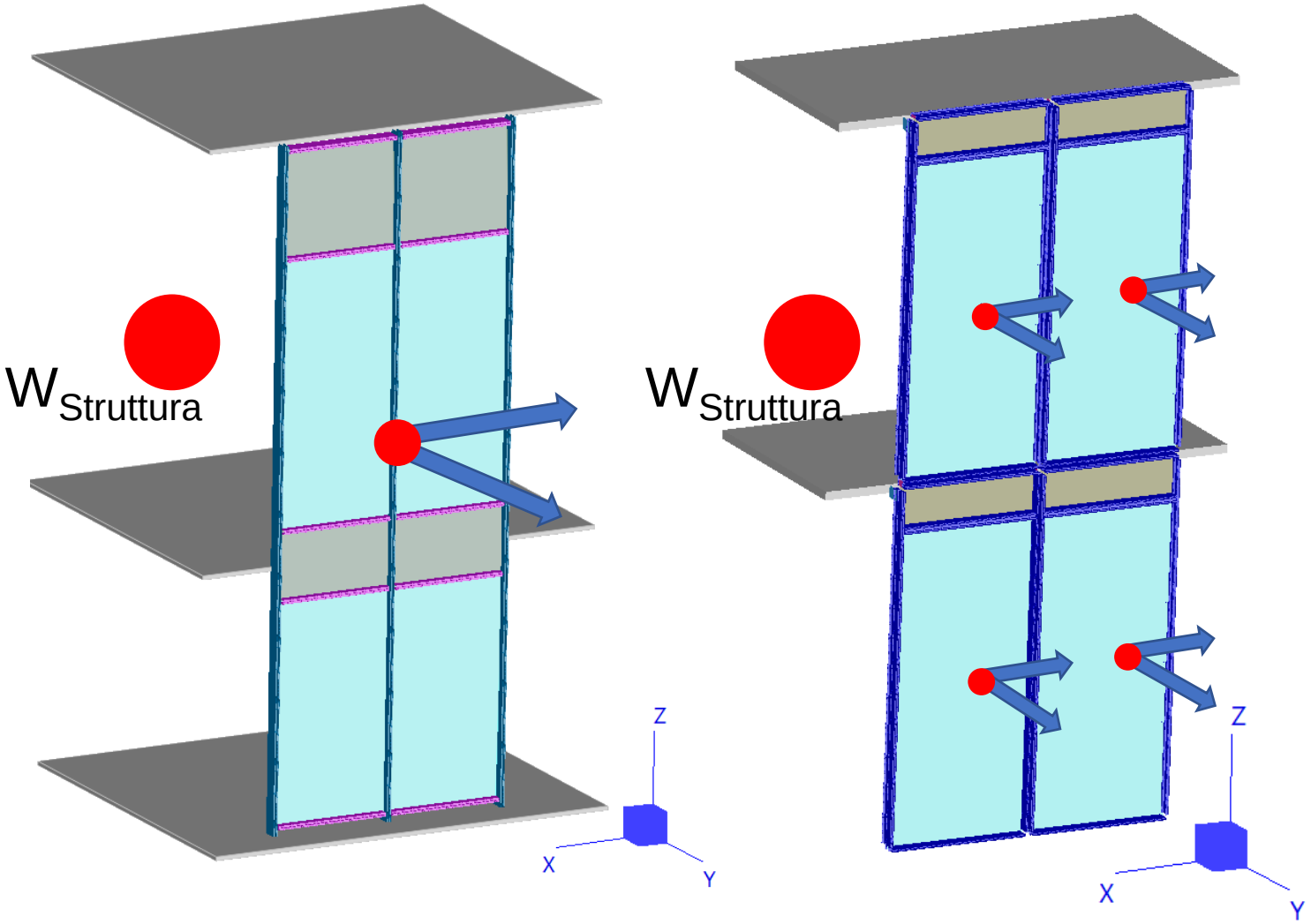
- Architectural components, and their supports and attachments (bolts, inserts, welds, and dowels, and the body of the connectors), shall satisfy against seismic action (§13.3.1 - §13.5.1 - §13.5.3)

$$F_p = \frac{0.4 \cdot a_p \cdot S_{DS} \cdot W_p}{\frac{R_p}{I_p}} (1 + 2 \cdot \frac{z}{H})$$

Table 13.5-1 Coefficients for Architectural Components

Architectural Component	a_p[a]	R_p	Ω_0[b]
Cantilever elements (braced to structural frame above its center of mass)			
Parapets	1	2½	2
Chimneys	1	2½	2
Exterior nonstructural walls[c]	1[b]	2½	2
Exterior nonstructural wall elements and connections[b]			
Wall element	1	2½	NA
Body of wall panel connections	1	2½	NA
Fasteners of the connecting system	1¼	1	1
Veneer			
Limited deformability elements and attachments	1	2½	2
Low-deformability elements and attachments	1	1½	2
Penthouses (except where framed by an extension of the building frame)	2½	3½	2
Ceilings			
All	1	2½	2

AZIONE SISMICA per FACCIATE CONTINUE



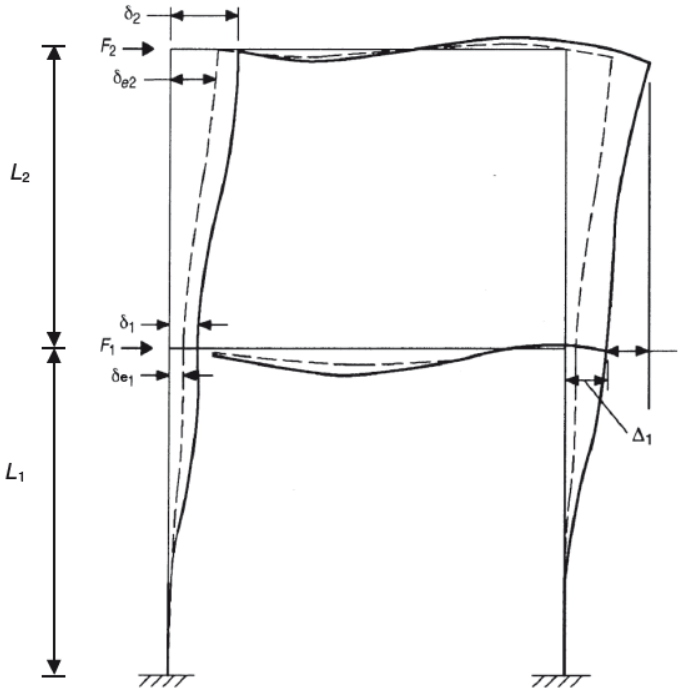
- Peso facciata vetrata tipica: 80-100 kg/m^2
- Accelerazione sismica tipica per elementi secondari (SLV): 0.3 g
- Pressione tipica del vento per facciate: 100-200 kg/m^2

Azione sismica NON dominante

Spostamenti struttura principale da accomodare

AZIONE SISMICA per FACCIATE CONTINUE

ASCE 7



Story Level 2

F_2 = strength-level design earthquake force

δ_{e2} = elastic displacement computed under strength-level design earthquake forces

δ_2 = $C_d\,\delta_{e2}/I_E$ = amplified displacement

Δ_2 = $(\delta_{e2} - \delta_{e1})\,C_d/I_E \le \Delta_a$

Story Level 1

F_1 = strength-level design earthquake force

δ_{e1} = elastic displacement computed under strength-level design earthquake forces

δ_1 = $C_d\,\delta_{e1}/I_E$ = amplified displacement

Δ_1 = $\delta_1 \le \Delta_a$

Δ_i = Story Drift

Δ_i/L_i = Story Drift Ratio

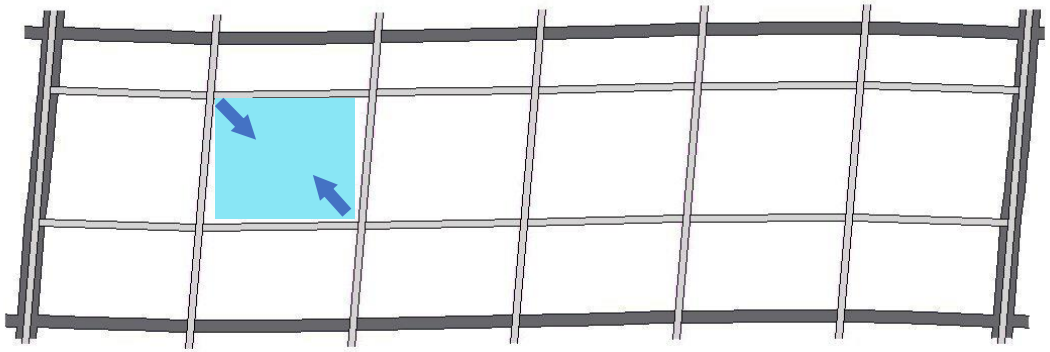
δ_2 = Total Displacement

Table 12.12-1 Allowable Story Drift, Δ_a[a,b]

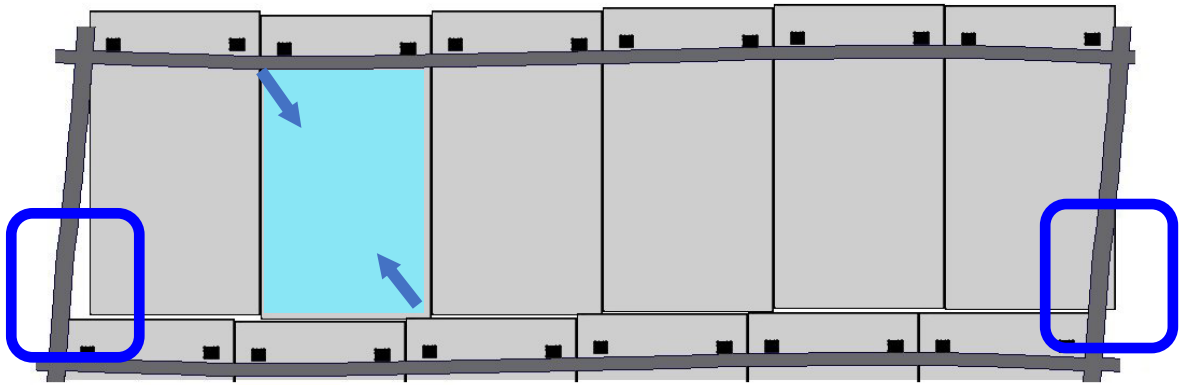
Structure	Risk Category I or II	Risk Category III	Risk Category IV
Structures, other than masonry shear wall structures, 4 stories or less above the base as defined in Section 11.2, with interior walls, partitions, ceilings, and exterior wall systems that have been designed to accommodate the story drifts.	$0.025h_{sx}$[c]	$0.020h_{sx}$	$0.015h_{sx}$
Masonry cantilever shear wall structures[d]	$0.010h_{sx}$	$0.010h_{sx}$	$0.010h_{sx}$
Other masonry shear wall structures	$0.007h_{sx}$	$0.007h_{sx}$	$0.007h_{sx}$
All other structures	$0.020h_{sx}$	$0.015h_{sx}$	$0.010h_{sx}$

[a] h_{sx} is the story height below Level x.

CWCT – BS standard



Montante e traversi – drift di piano

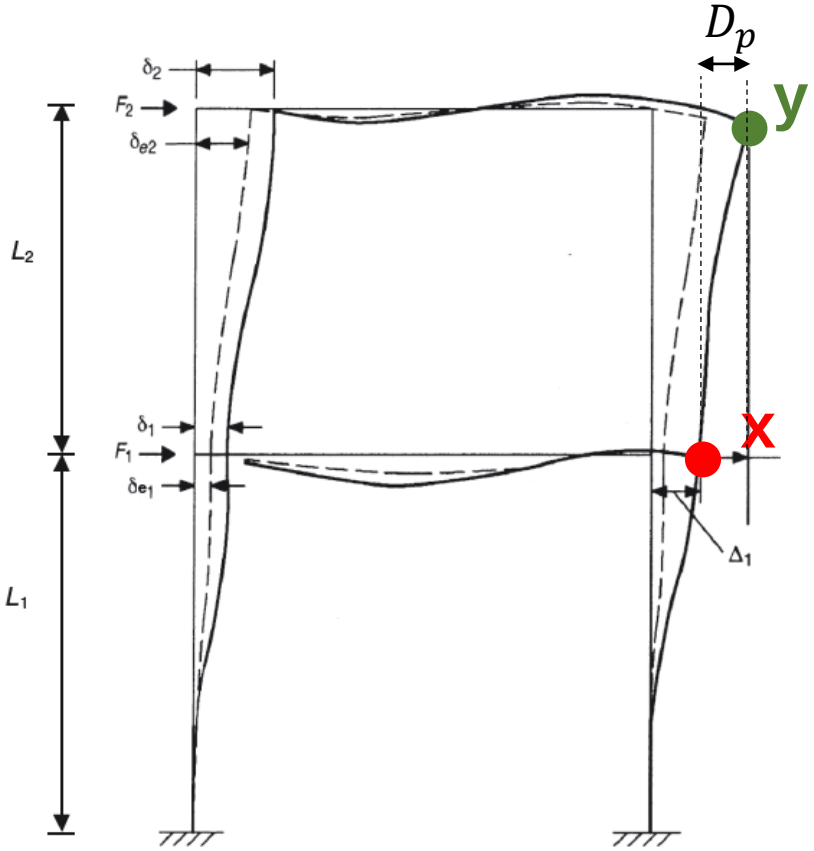


Cellule – drift di piano

AZIONE SISMICA per FACCIATE CONTINUE

ASCE 7

Spostamento relativo dovuto all'azione sismica:
$D_{pl} = D_p \cdot I_e = (\Delta_x - \Delta_y) \cdot I_e$
I_e = importance factor



Exterior Nonstructural Wall Elements and Connections (§13.5.3)

a. Connections and panel joints shall allow for the story drift caused by relative seismic displacements (D_p) determined in Section 13.3.2, or 0.5 in. (13 mm), whichever is greatest.
b. Connections to permit movement in the plane of the panel for story drift shall be sliding connections using slotted or oversize holes, connections that permit movement by bending of steel, or other connections that provide equivalent sliding or ductile capacity.
c. The connecting member itself shall have sufficient ductility and rotation capacity to preclude fracture of the concrete or brittle failures at or near welds.
d. All fasteners in the connecting system such as bolts, inserts, welds, and dowels and the body of the connectors shall be designed for the force (F_p) determined by Section 13.3.1 with values of R_p and a_p taken from Table 13.5-1 applied at the center of mass of the panel.

Glass in Glazed Curtain Walls, Glazed Storefronts, and Glazed Partitions (§13.5.9)

Glass in glazed curtain walls, glazed storefronts, and glazed partitions shall meet the relative displacement requirement of Eq. 13.5-1:

$$\Delta_{fallout} \geq 1.25 I_e D_p$$

or 0.5 in. (13 mm), whichever is greater where:

$\Delta_{fallout}$ = the relative seismic displacement (drift) at which glass fallout from the curtain wall, storefront wall, or partition occurs

$\Delta_{fallout}$, the drift causing glass fallout from the curtain wall, storefront, or partition shall be determined in accordance with **AAMA 501.6** or by engineering analysis.

Prove su mock up

AZIONE SISMICA per FACCIATE CONTINUE

Europa

EN 13830

- **Assessment of seismic serviceability limit (§D.2)**

The positive difference between the air permeability measured at maximum pressure before and after the seismic movement should not differ by more than 0,6 $m^3/h.m^2$ (0.2 $m^3/h.m$ length of joint).

- **Assessment of seismic safety limit (§D.2)**

The curtain walling shall safely withstand the seismic movement regime and shall retain its integrity in fulfilling
the following criteria:

- no parts shall fall down (except for glass) unless it has been specifically evaluated that it is safe for them to do so;
- any holing shall not occur (except for glass) unless it has been specifically evaluated that it is safe for them to do so;
- any infilling panel shall remain in its position and come off only when removed;
- any permanent deformation of curtain walling component shall be accepted.
- Specific safe brakeage criteria for glass are given in EN 12600:2002, Clause 4.

Stati Uniti

FEMA 450

- **Glass in glazed curtain walls, glazed storefronts, and glazed partitions (§6.3.7)**

Glass performance in earthquakes can fall into one of four categories:
(Serviceability)

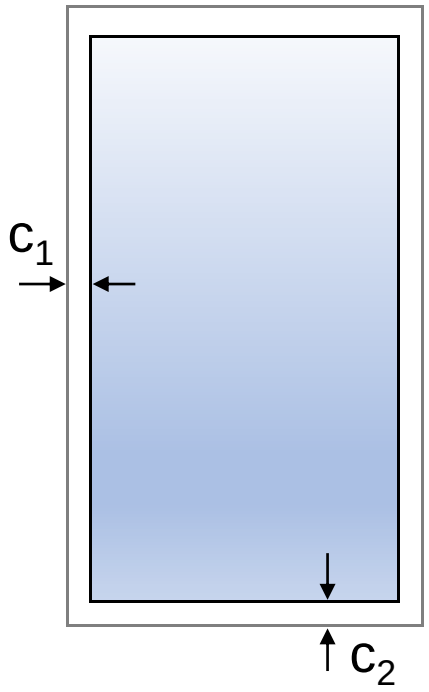
1. The glass remains unbroken in its frame or anchorage.
2. The glass cracks but remains in its frame or anchorage while continuing to provide a weather barrier, and to be otherwise serviceable.

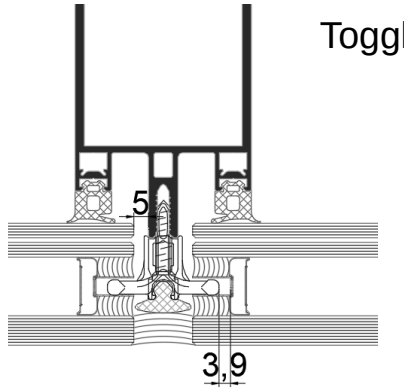
(Safety)

3. The glass shatters but remains in its frame or anchorage in a precarious condition, likely to fall out at any time.
4. The glass falls out of its frame or anchorage, either in fragments, shards, or whole panels.

MONTANTI E TRAVERSI vs CELLULE

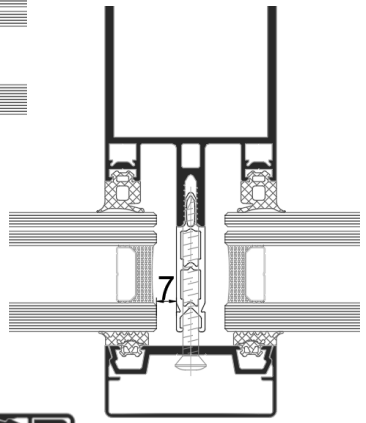
Comportamento laterale della facciata è influenzato:
- Connessioni tra i profili e grado di incastro
- Geometria del vetro e spazio libero con la struttura di supporto
- Interazione con elementi vicini (cellule)

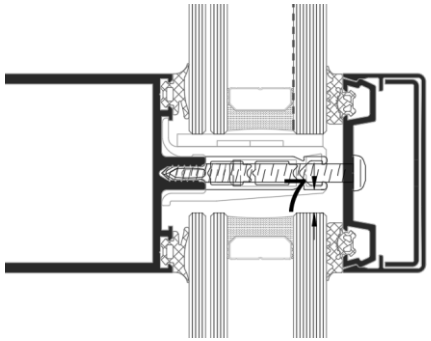




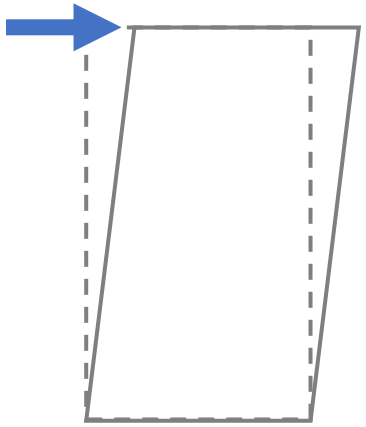
Toggle

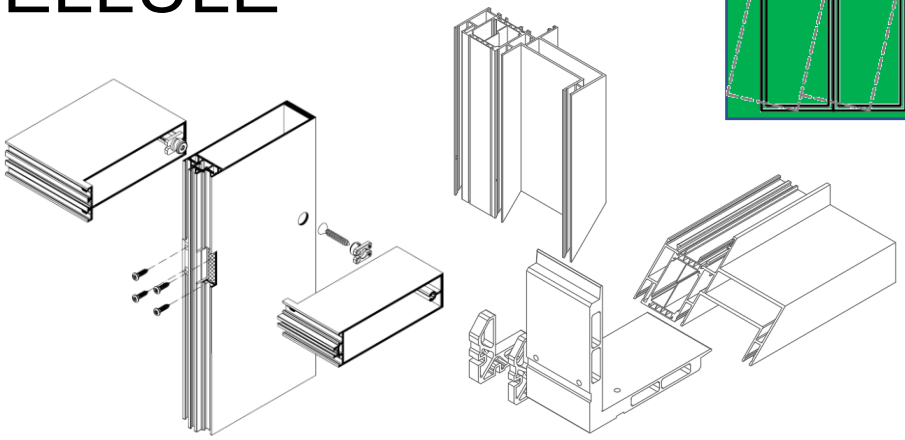
Pressore





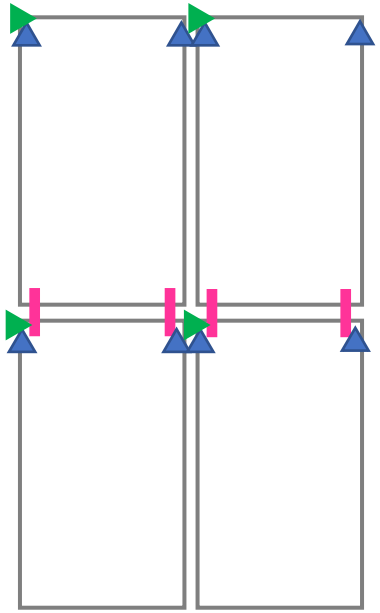
Supporto vetro

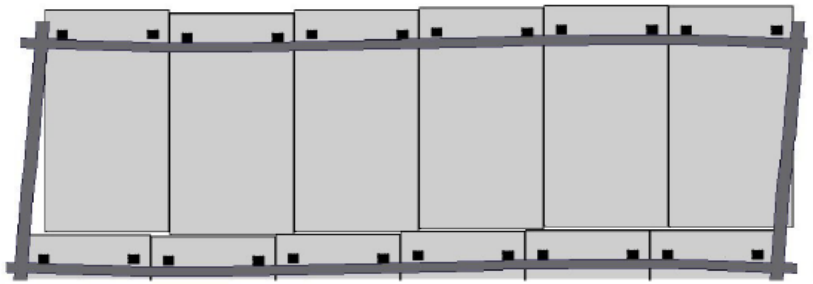


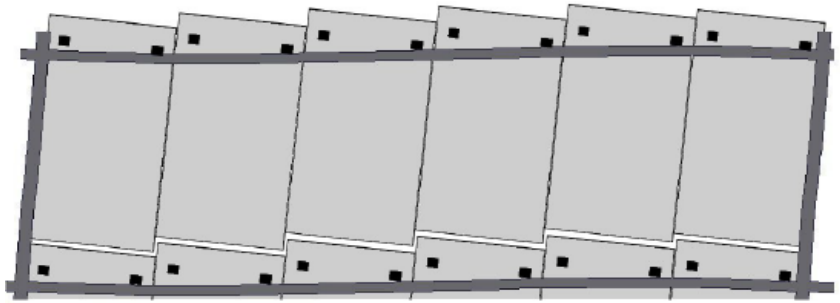


MT

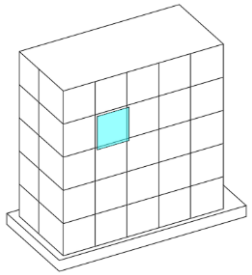
Cellule

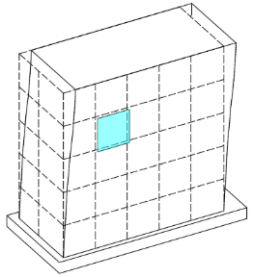


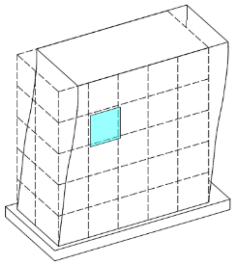


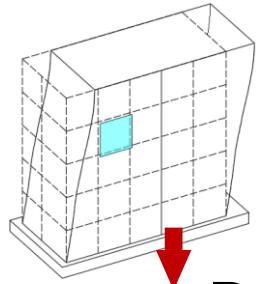


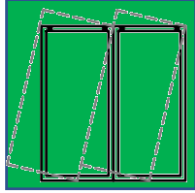
MONTANTI E TRAVERSI - MOVIMENTI

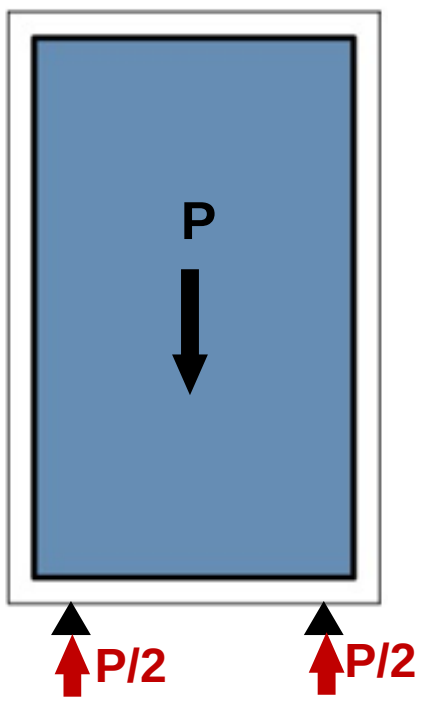




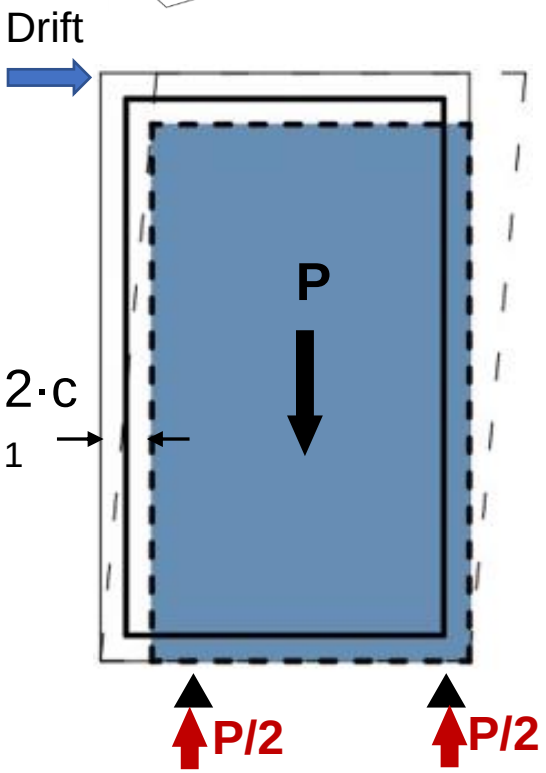




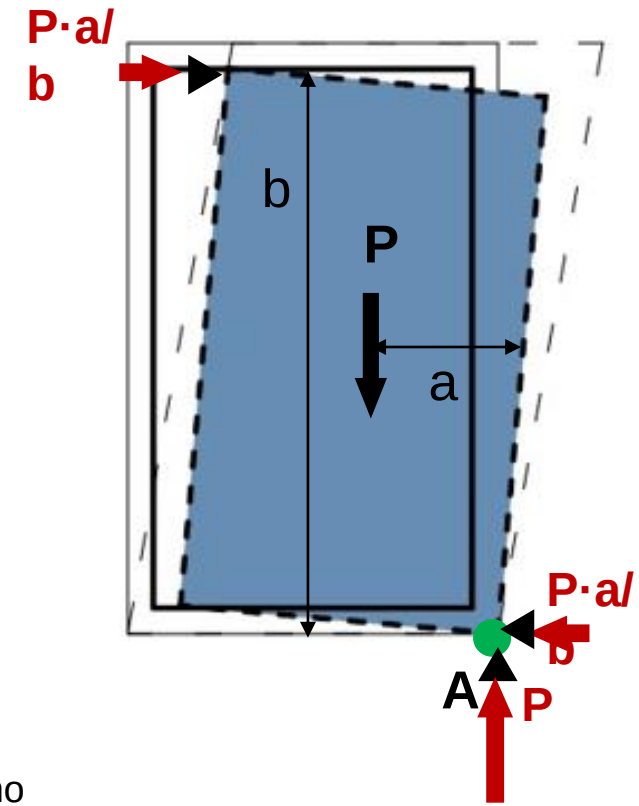




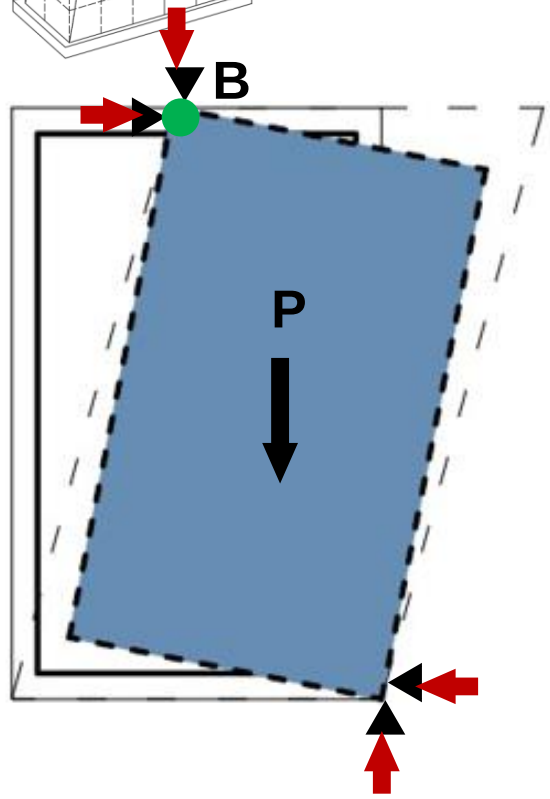
1) Condizioni nominali



2) I profili si deformano assecondando il drift di piano. Fino ad uno spostamento di $2 \cdot c_1$ il vetro non ruota.

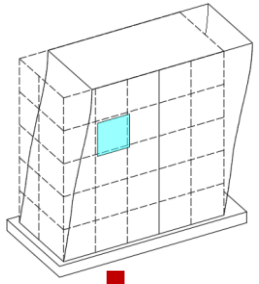


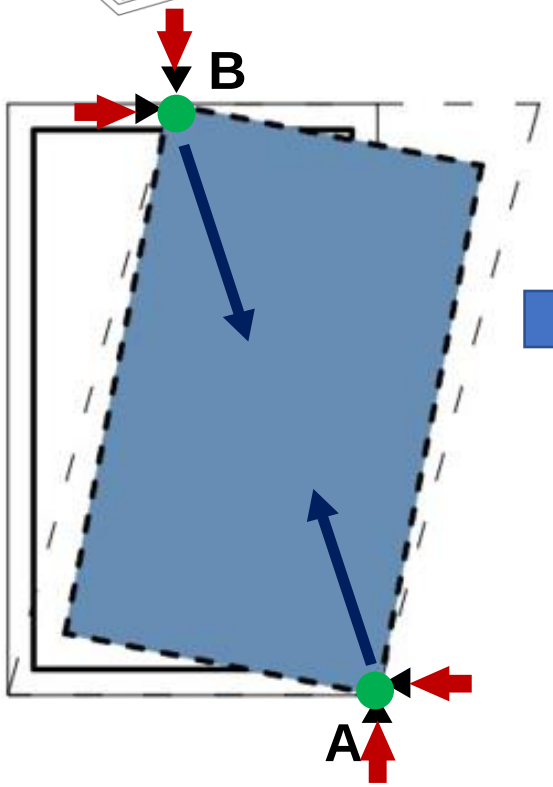
3) I profili continuano a deformarsi. Il vetro inizia a ruotare attorno al punto A.



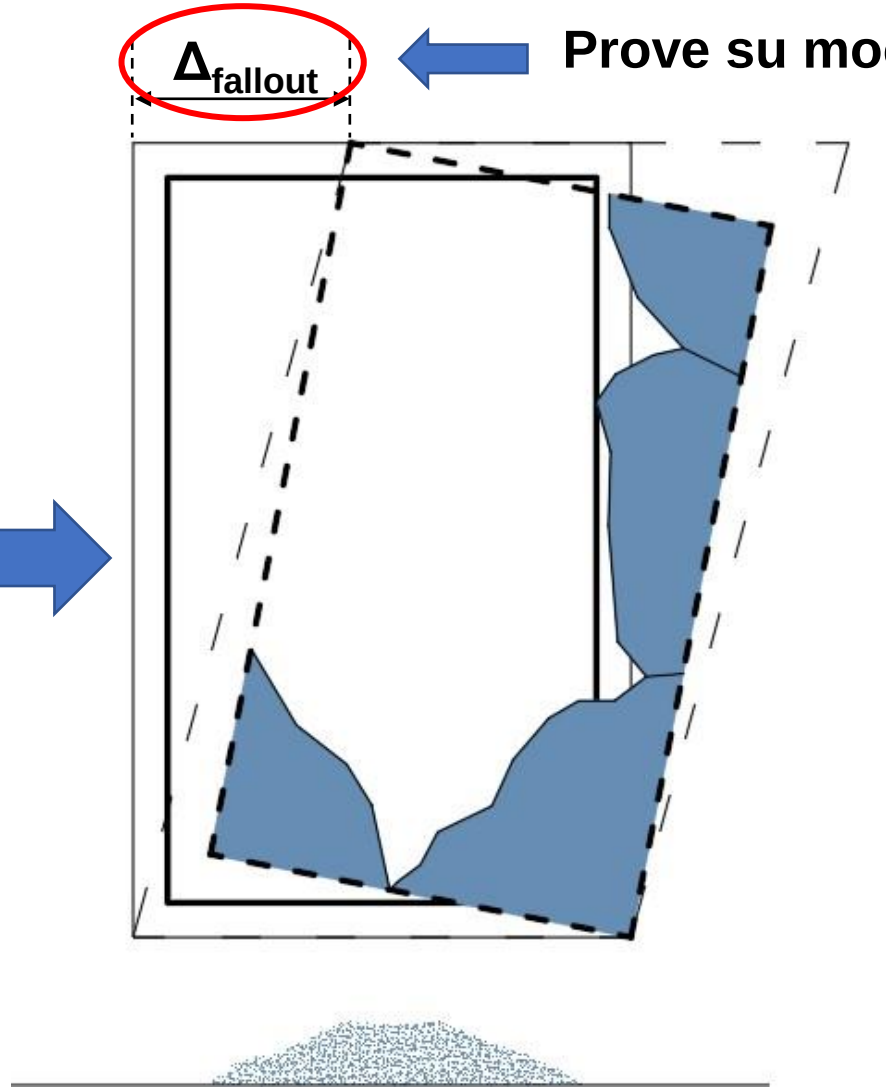
4) L'angolo superiore del vetro tocca l'angolo del telaio (punto B). Nessun ulteriore spostamento o rotazione è possibile.

MONTANTI E TRAVERSI - MOVIMENTI

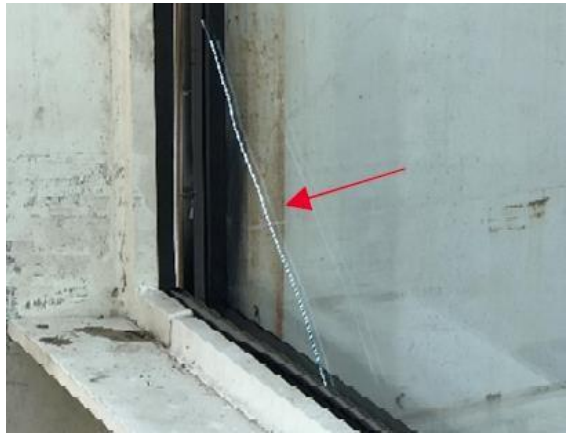




5) Per spostamenti della struttura maggiori del punto 4), si genera puntone nel vetro



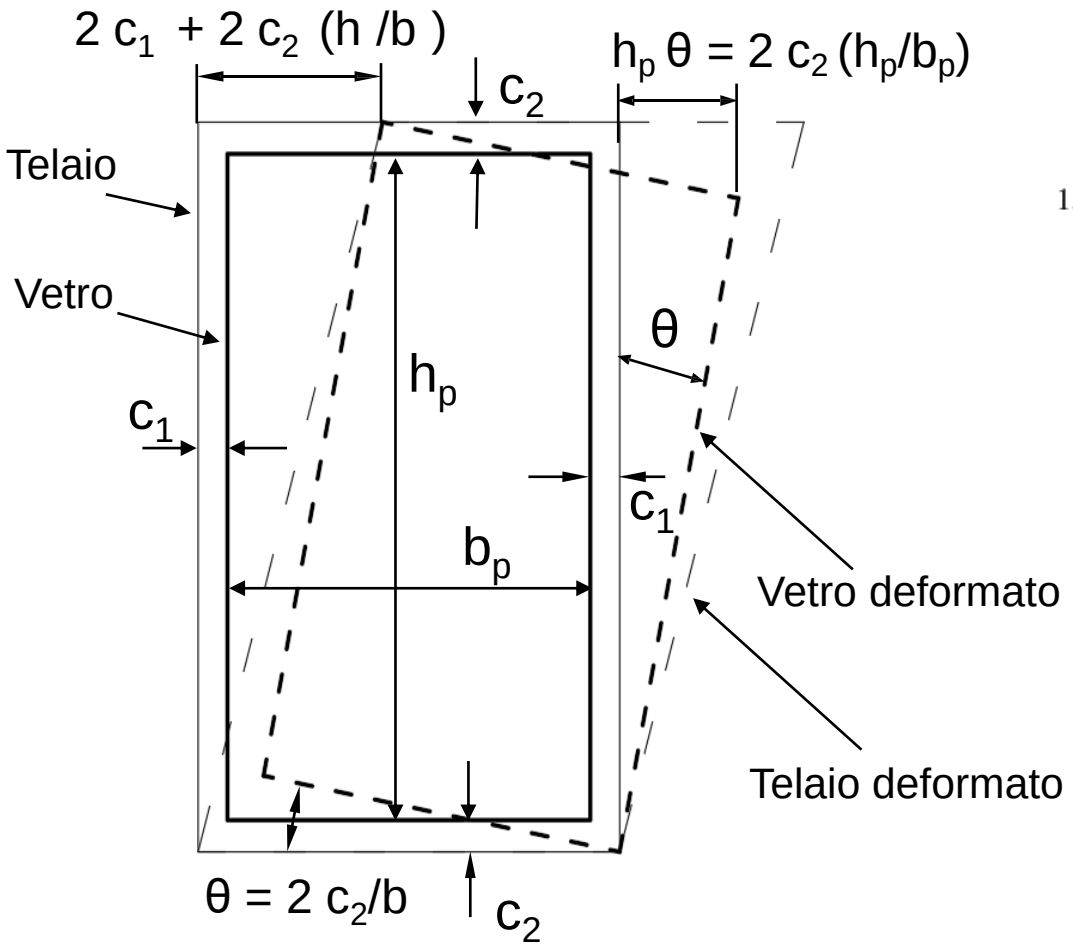
Prove su mock up!



Rottura del vetro!

MONTANTI E TRAVERSI - MOVIMENTI

ASCE 7



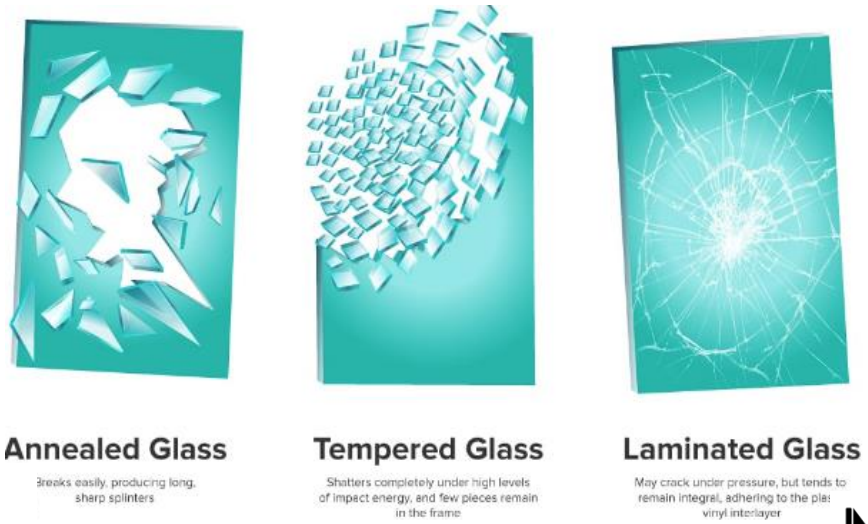
$$D_{clear} = 2 \cdot c_1 \cdot \left(1 - \frac{h_p \cdot c_2}{b_p \cdot c_1}\right)$$

EXCEPTION:

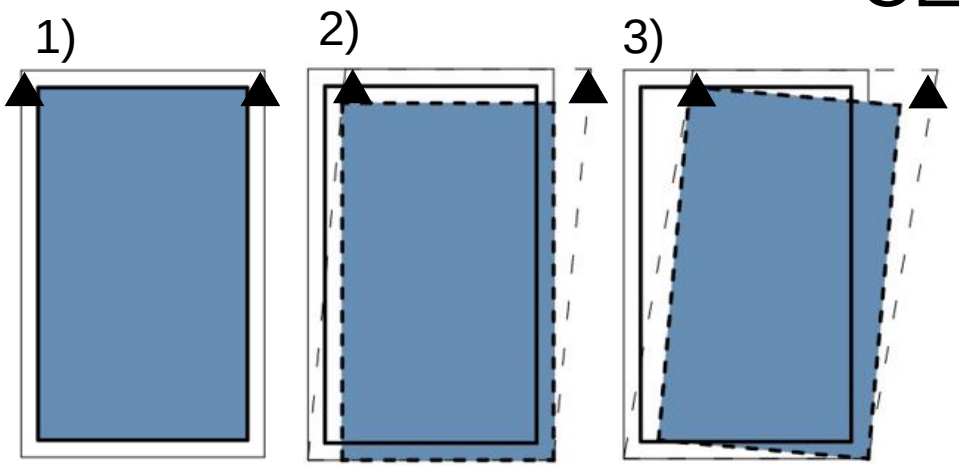
1. Glass with sufficient clearances from its frame such that physical contact between the glass and frame will not occur at the design drift, as demonstrated by Eq. 13.5-2, need not comply with this requirement:

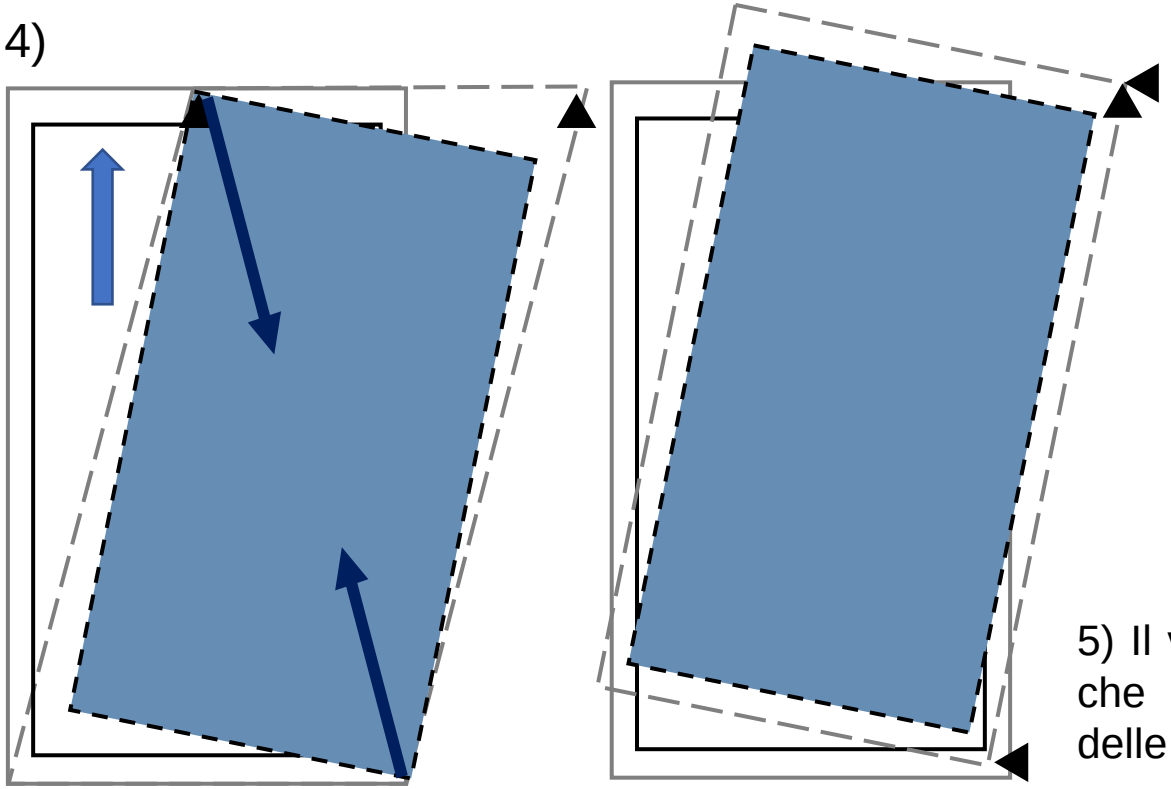
$$D_{clear} \geq 1.25 D_p$$

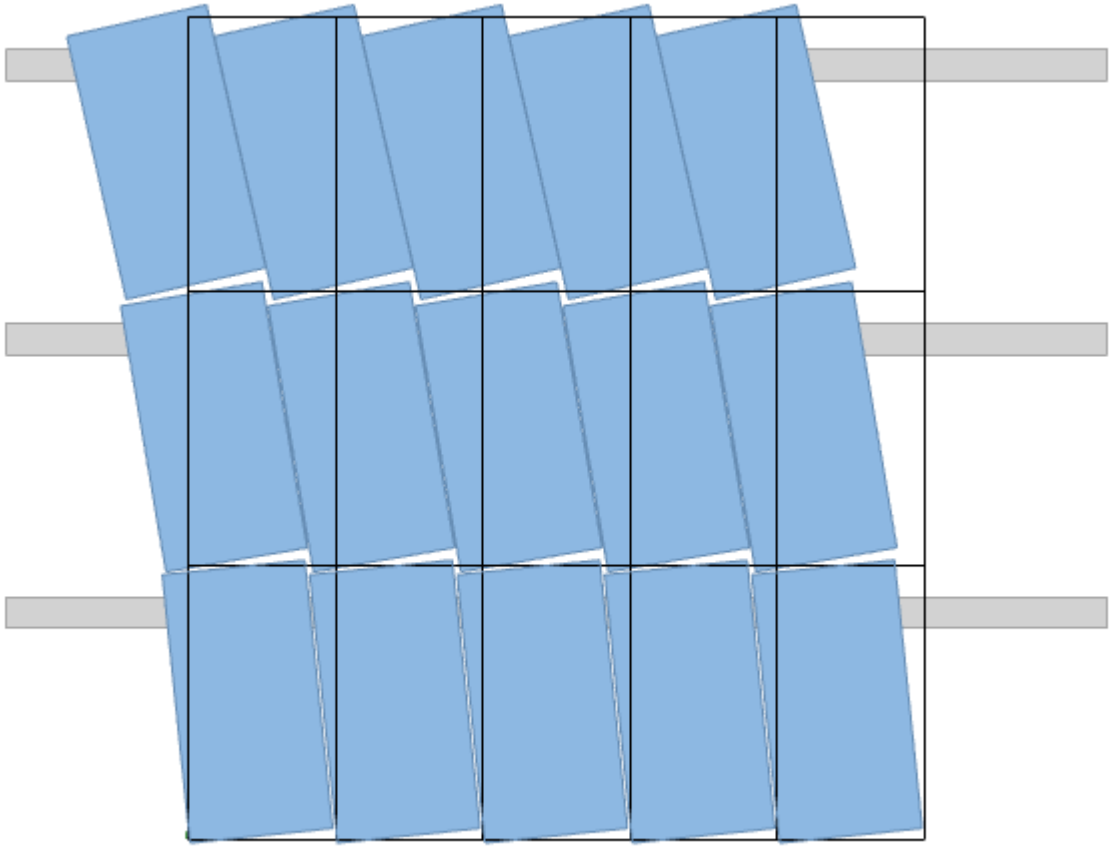
2. Fully tempered monolithic glass in Risk Categories I, II, and III located no more than 10 ft (3 m) above a walking surface need not comply with this requirement.
3. Annealed or heat-strengthened laminated glass in single thickness with interlayer no less than 0.030 in. (0.76 mm) that is captured mechanically in a wall system glazing pocket, and whose perimeter is secured to the frame by a wet glazed gunable curing elastomeric sealant perimeter bead of 0.5 in. (13 mm) minimum glass contact width, or other approved anchorage system need not comply with this requirement.



CELLULE - MOVIMENTI







5) Il vetro solleva la cellula che ruota attorno ad una delle due staffe a peso.

TEST su FACCIATE CONTINUE

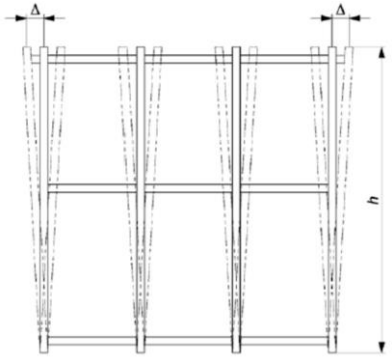
Europa

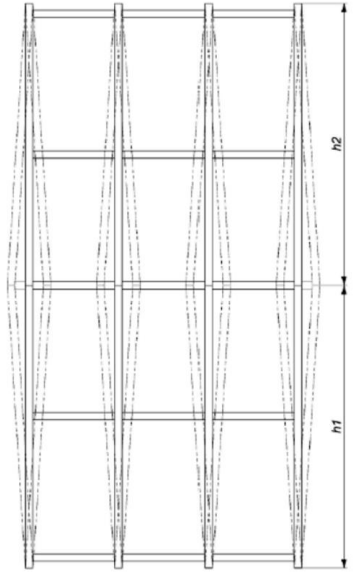
EN 13830

- **Montanti e traversi (§D.4.4)**

La prova consiste in tre cicli:
- Movimento in una posizione estrema
- Movimento nella posizione estrema opposta
- Ritorno alla posizione originale

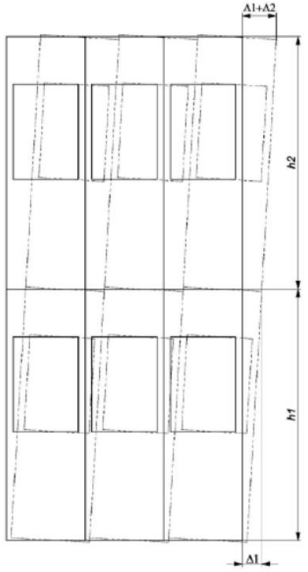
Ogni test consiste in 3 cicli completi.





- **Cellule (§D.4.4)**

Il campione deve essere costituito almeno da due pannelli in larghezza e due in altezza.



Stati Uniti

AAMA 501.4 | AAMA 501.6

AAMA 501.4-09

Recommended Static Testing Method for Evaluating Curtain Wall and Storefront Systems Subjected to Seismic an Wind Induced Interstory Drift

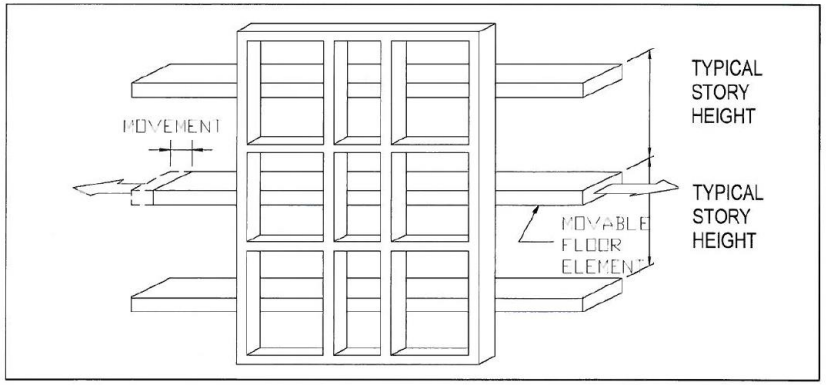


FIGURE 1: Typical Test Specimen Configuration

AAMA 501.6-09

Recommended Dynamic Test Method for Determining the Seismic Drift Causing Glass Fallout from a Wall System

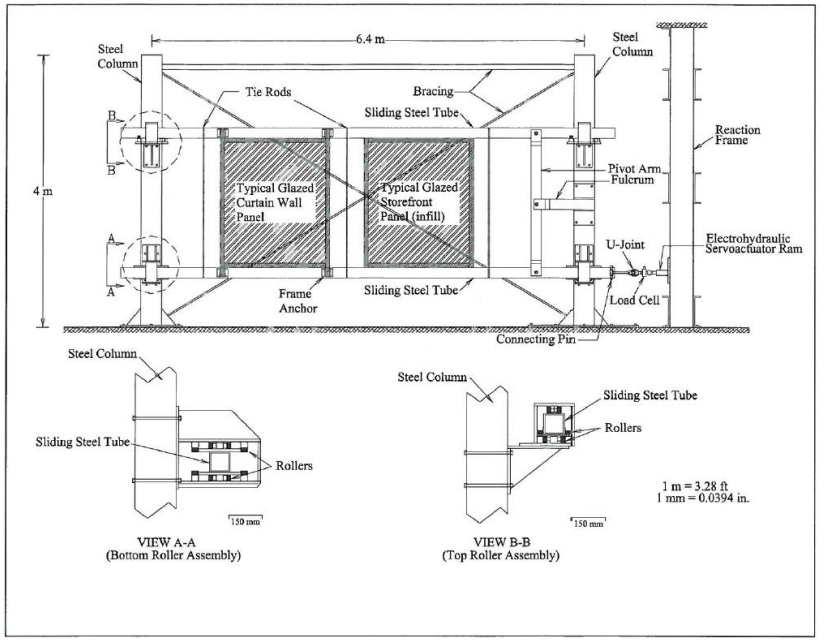


FIGURE 1: Dynamic Racking Test Facility at the Building Envelope Research Laboratory, Department of Architectural Engineering, The Pennsylvania State University, University Park, PA.

CASI STUDIO

Gilder Center | New York

Durst Headquarter | Bressanone

Forskaren | Stockholm

Oasis Mall | Doha

Museum of the Future | Dubai

Coca-Cola Arena | Dubai

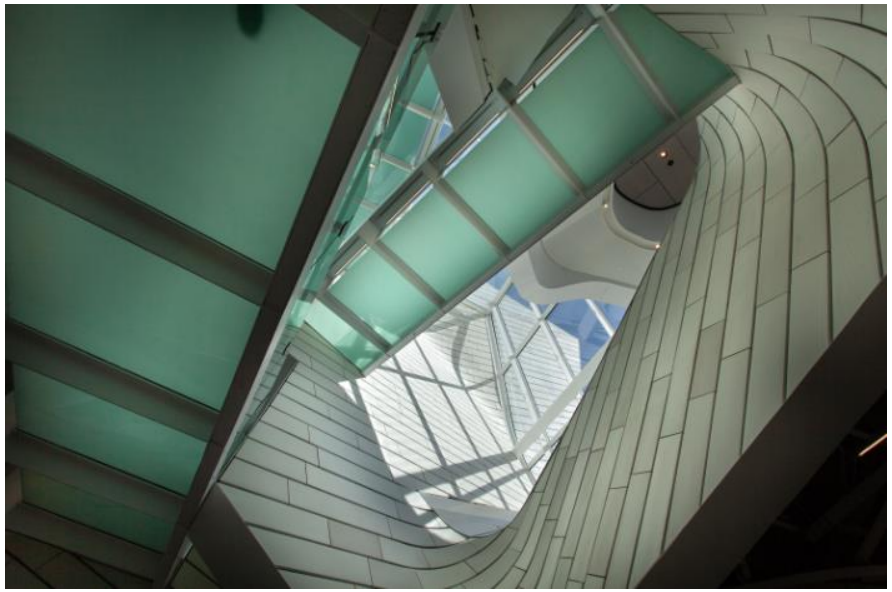
Manhattan Centre | New York

MS East Campus | Redmond

CASI STUDIO

OCMA-Orange Country Museum of Art

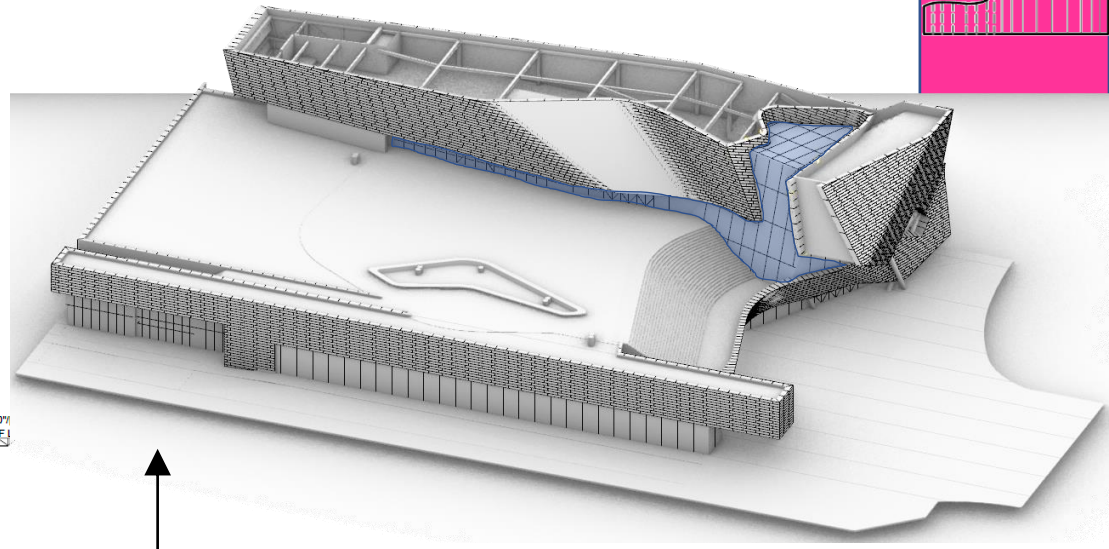
LOCATION	Costa Mesa | California
YEAR	2022
STATUS	Completed
TYPE OF BUILDING	Museum
SERVICE	Façade Engineering
FACADE CONTRACTOR	Roschmann Group
ARCHITECT	Morphosis Architects



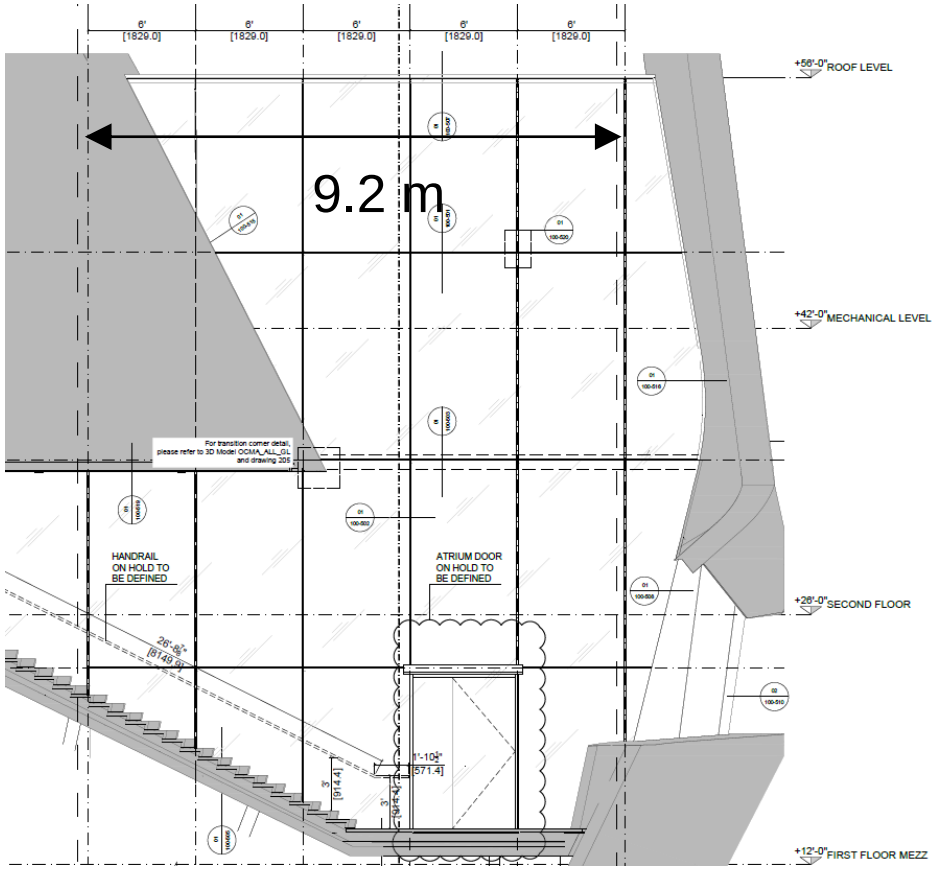
OCMA-ORANGE COUNTRY MUSEUM OF ART

Scope of work:

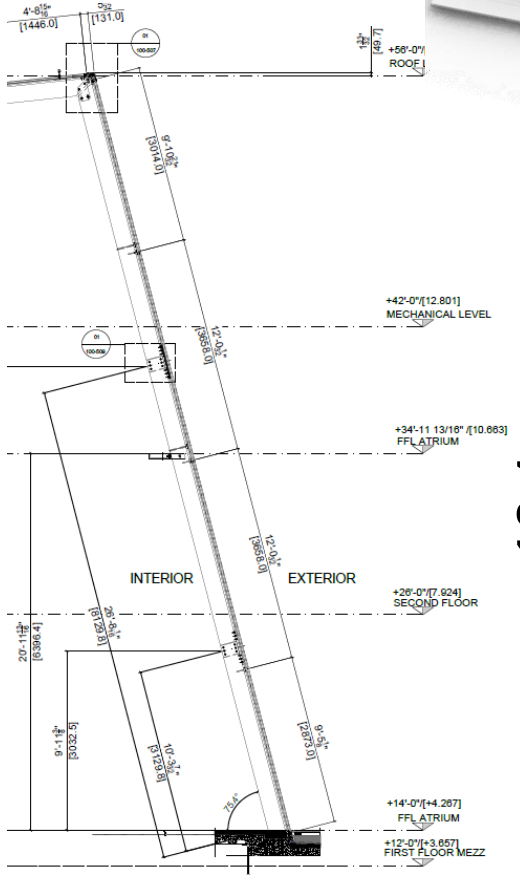
- Facciata verticale inclinata
- Copertura skylight



Prospetto di facciata:

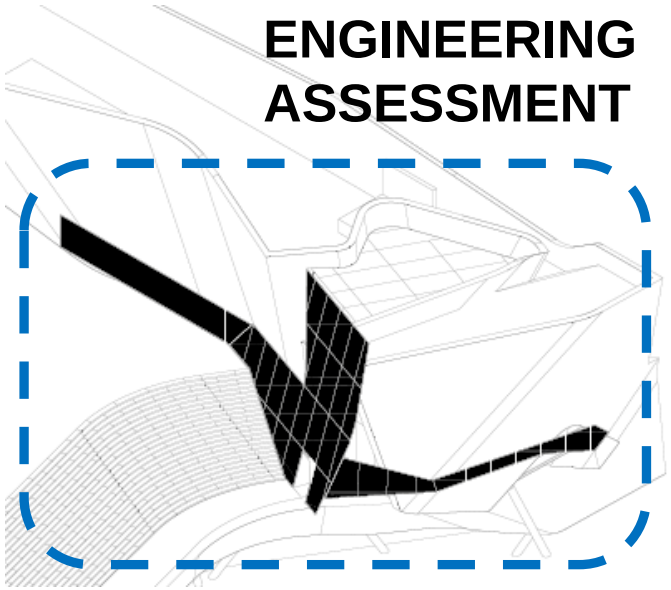


Sezione verticale:



13.4 m

ENGINEERING ASSESSMENT

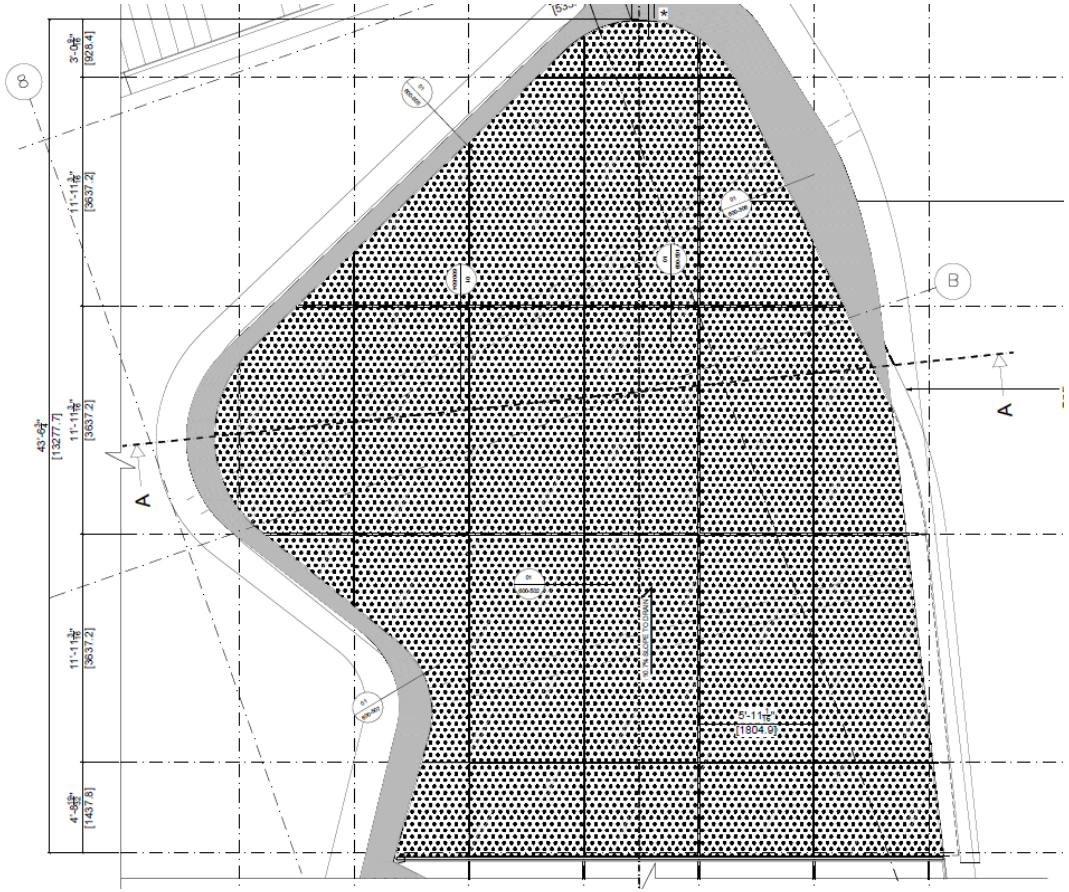


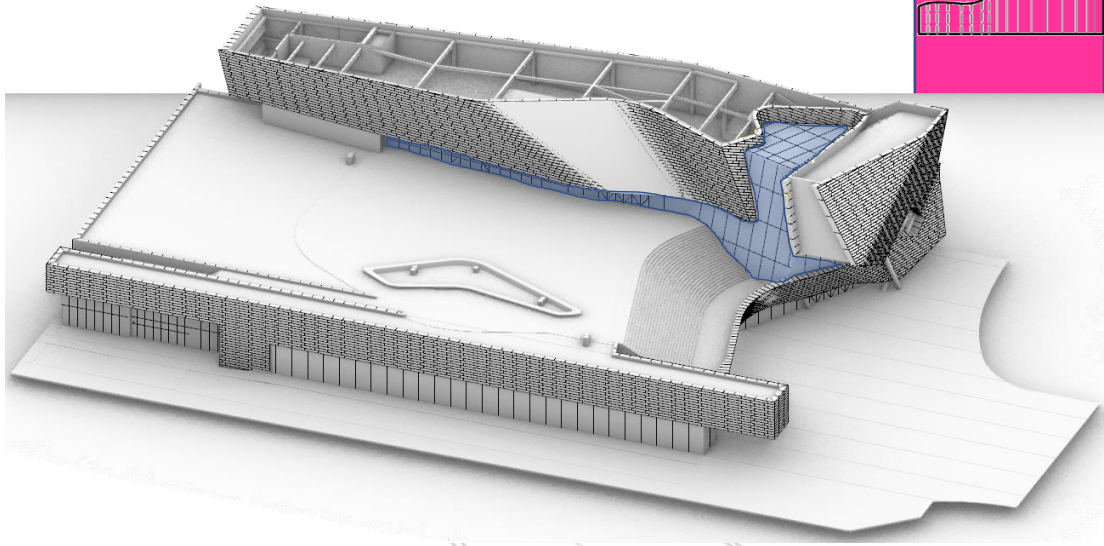
OCMA-ORANGE COUNTRY MUSEUM OF ART

Scope of work:

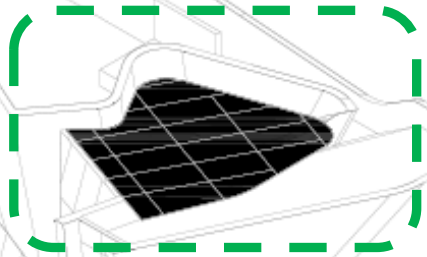
- Facciata verticale inclinata
- Copertura skylight

Pianta copertura:

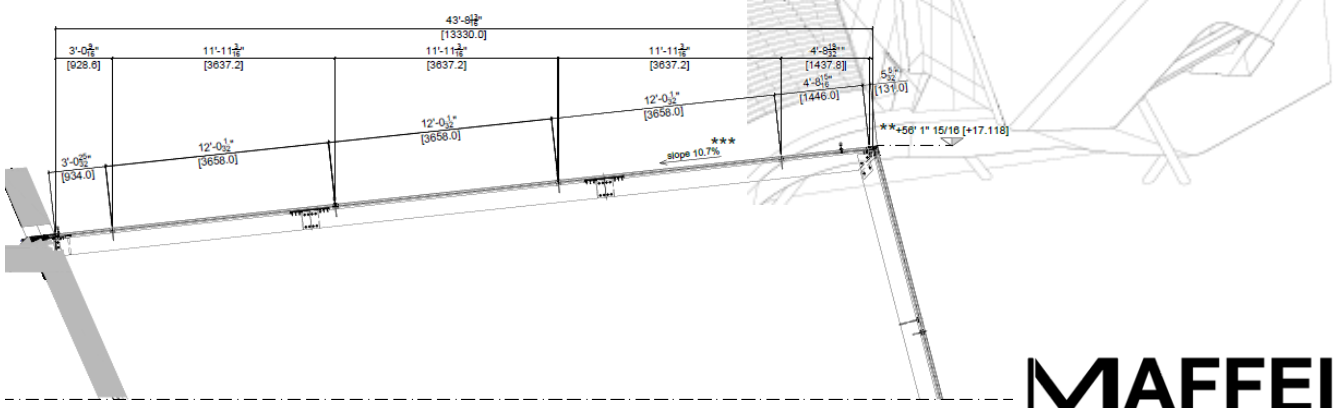




ENGINEERING ASSESSMENT

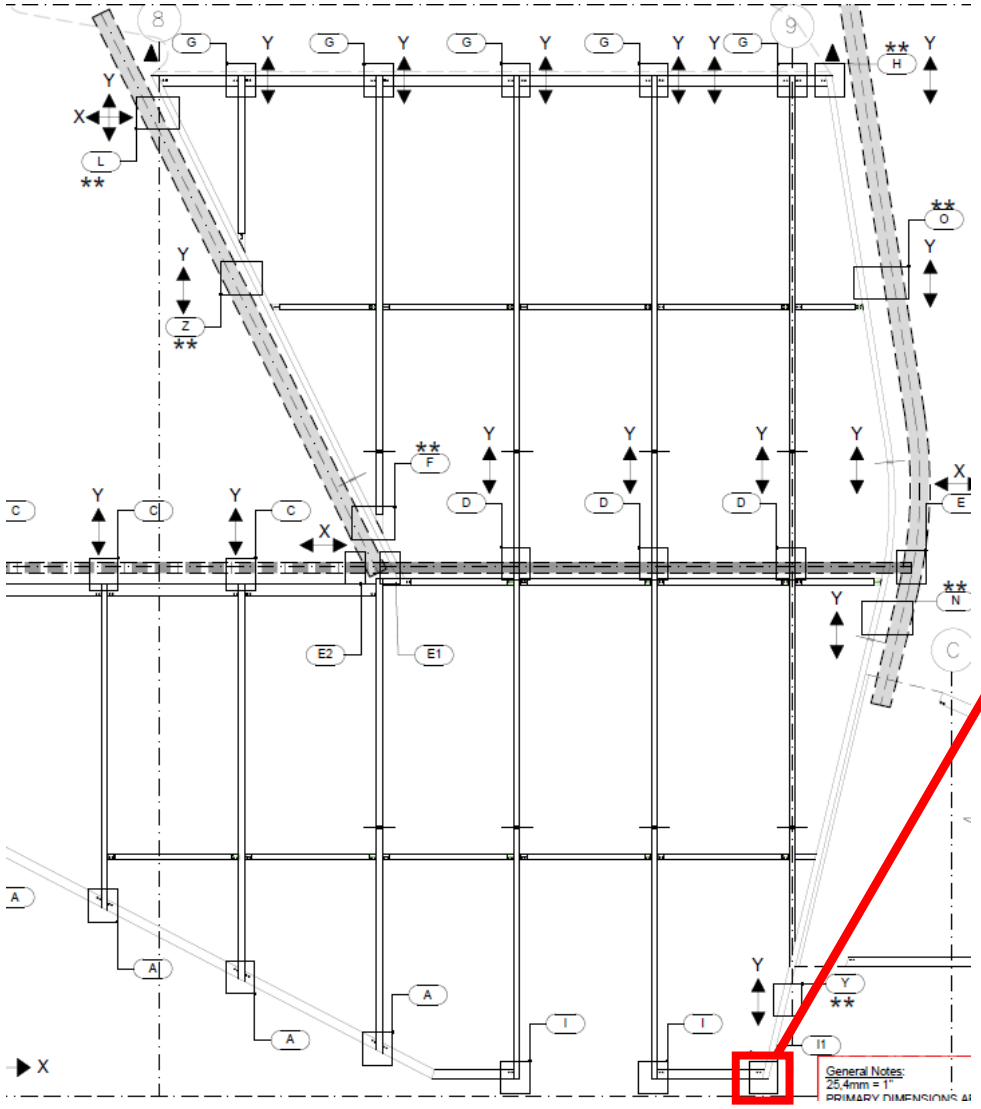


Sezione orizzontale:

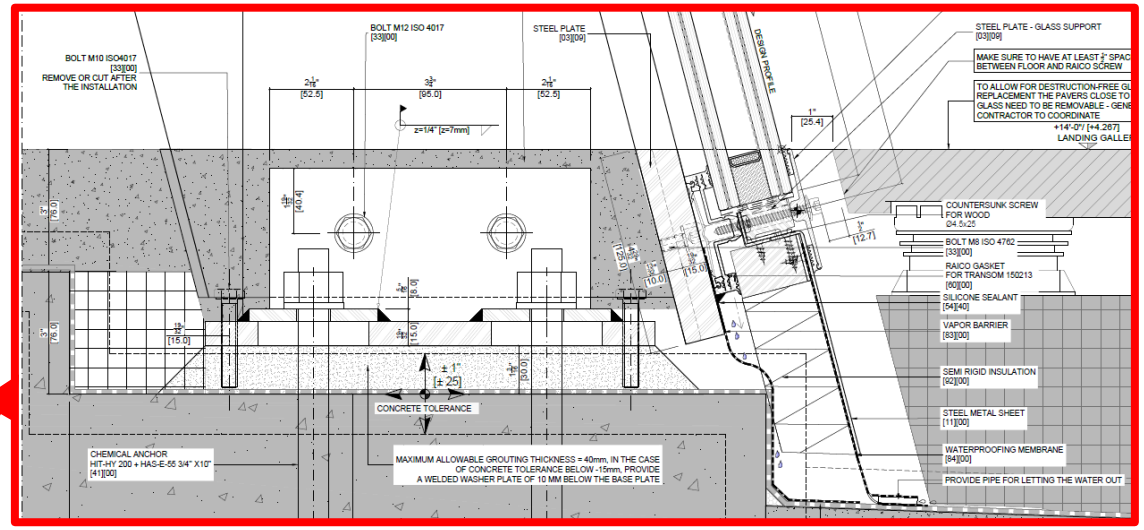


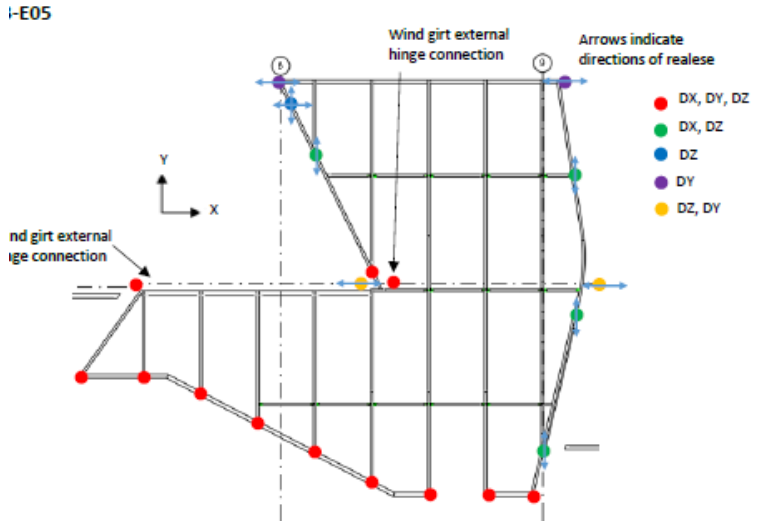
OCMA-ORANGE COUNTRY MUSEUM OF ART

Schema statico facciata



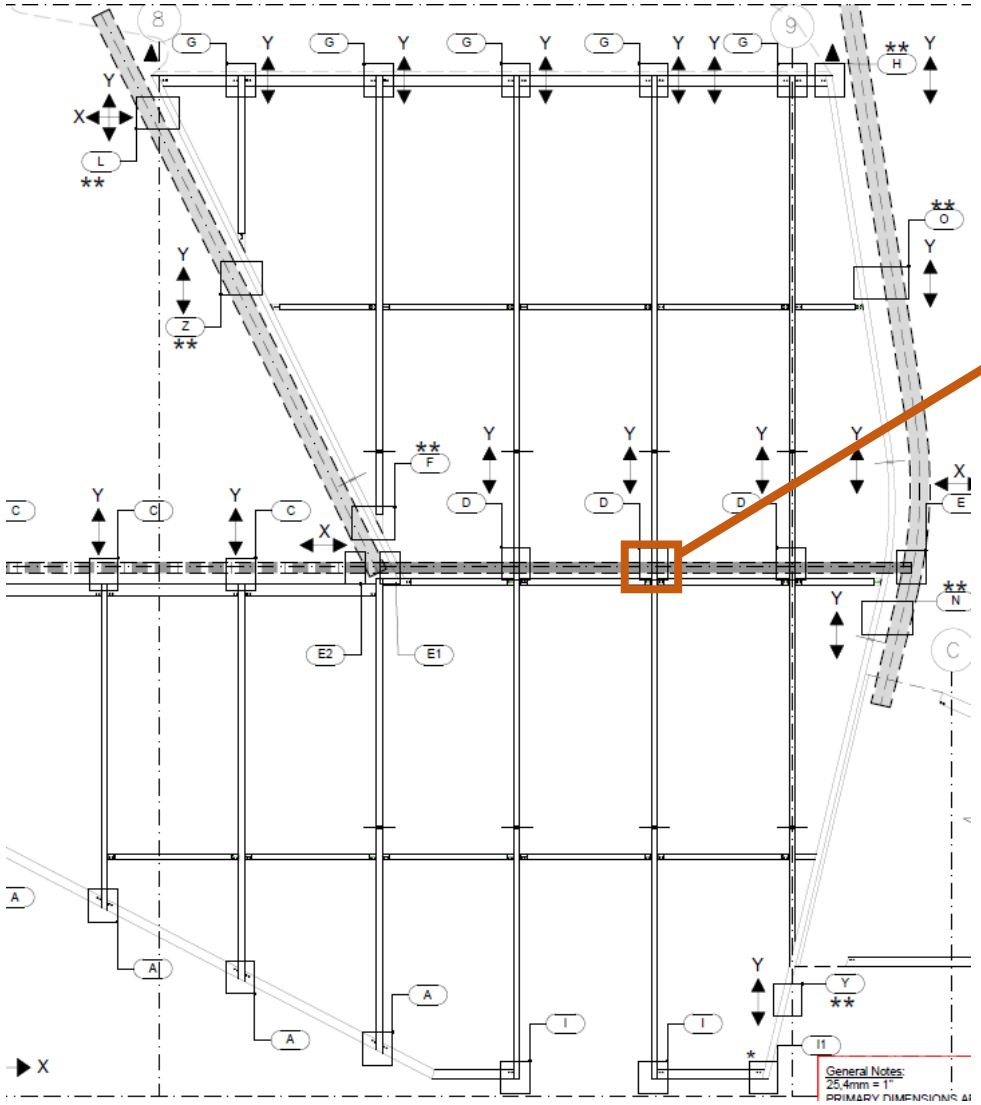
Dettaglio appoggio



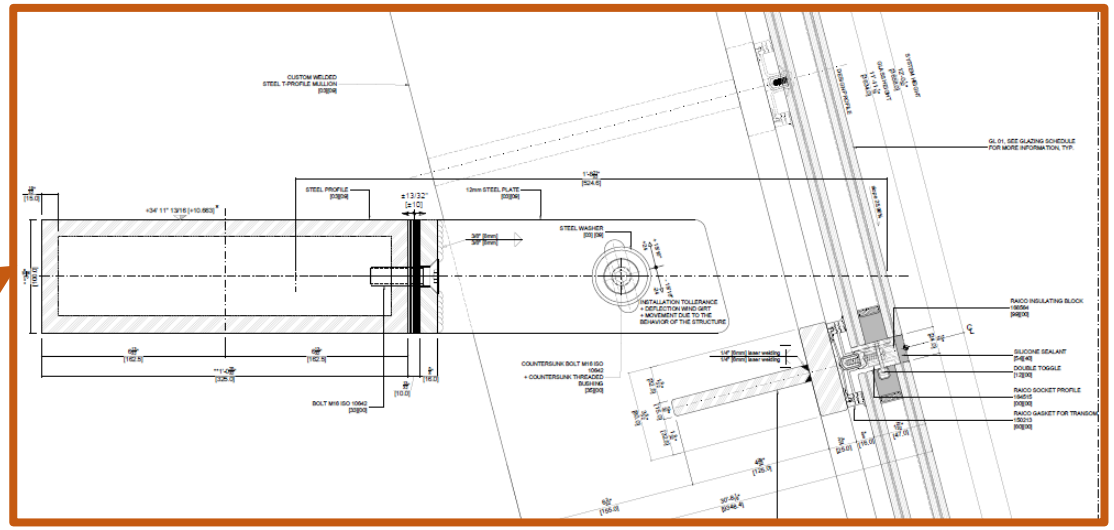


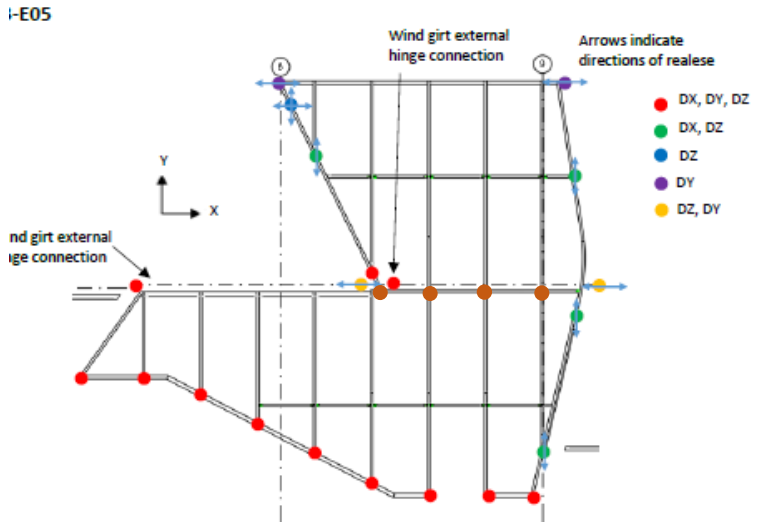
OCMA-ORANGE COUNTRY MUSEUM OF ART

Schema statico facciata



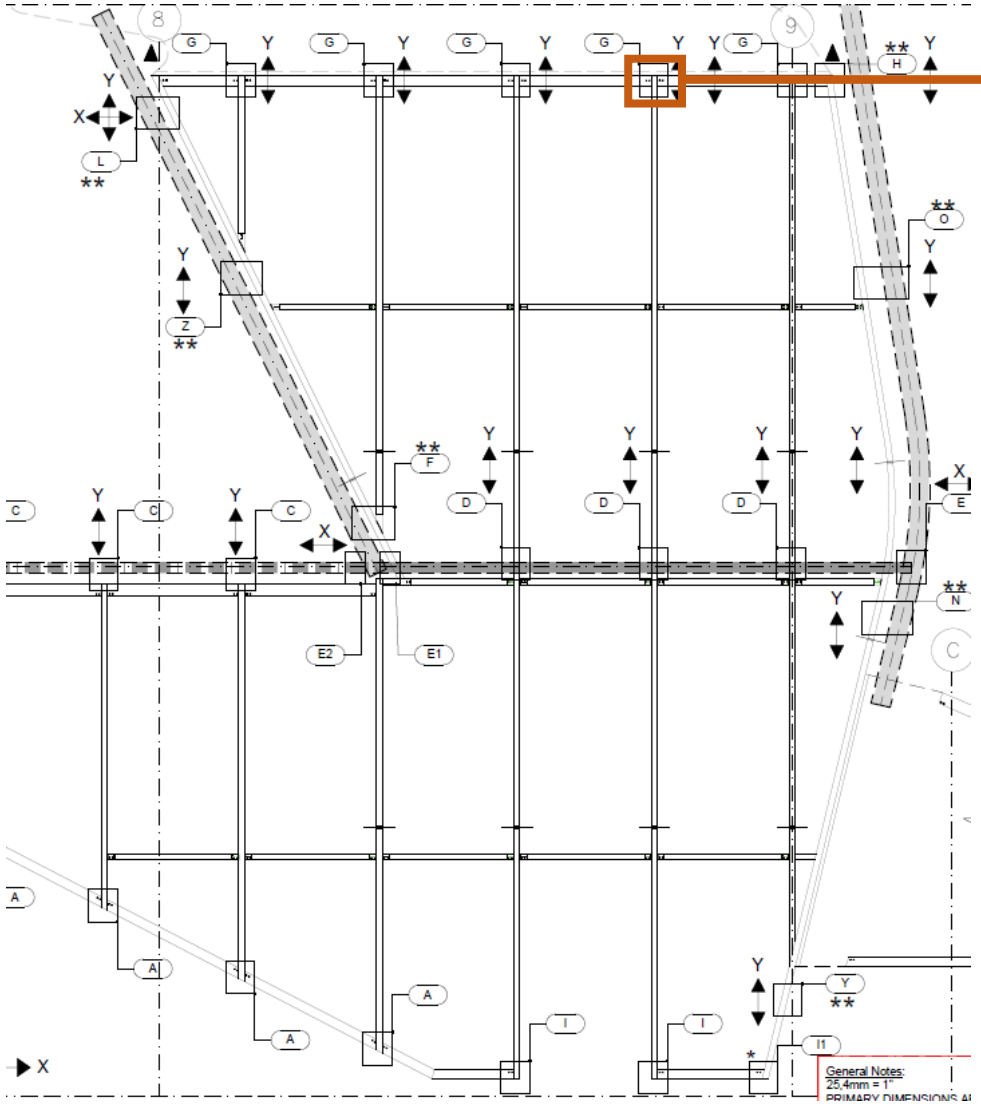
Dettaglio asola verticale

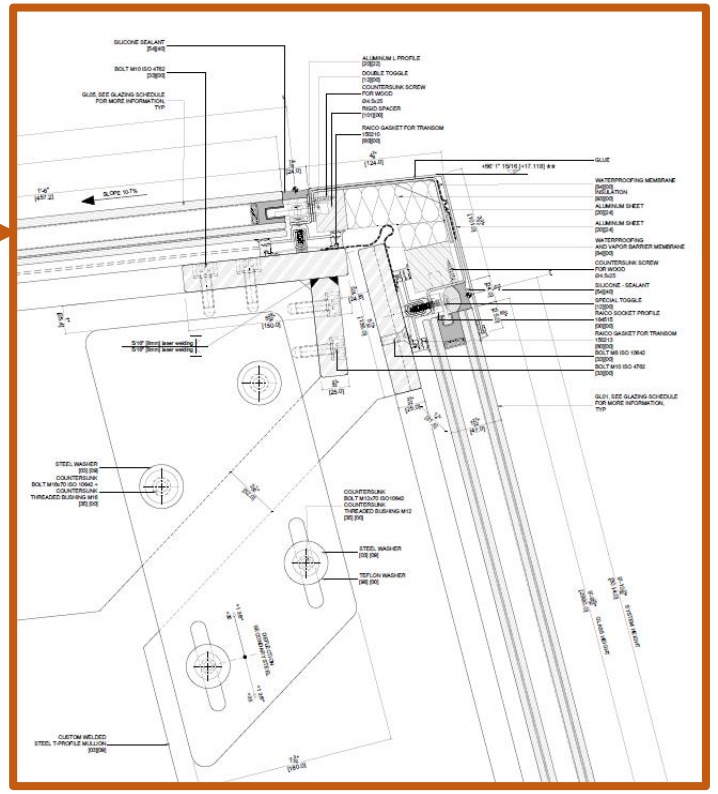




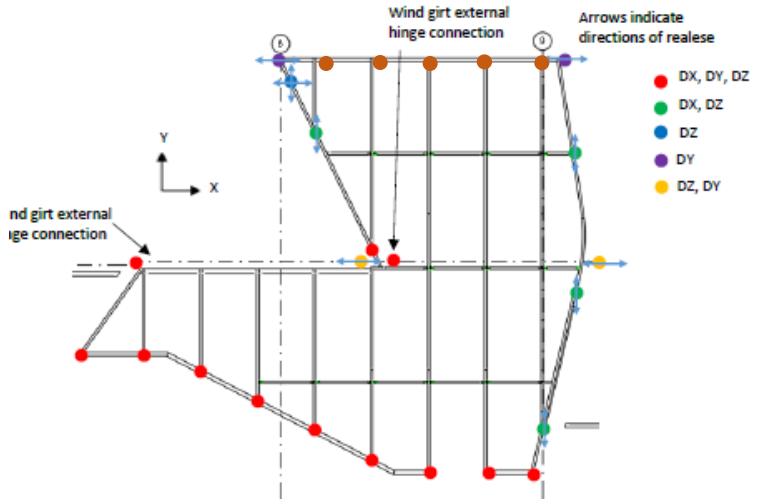
OCMA-ORANGE COUNTRY MUSEUM OF ART

Schema statico facciata



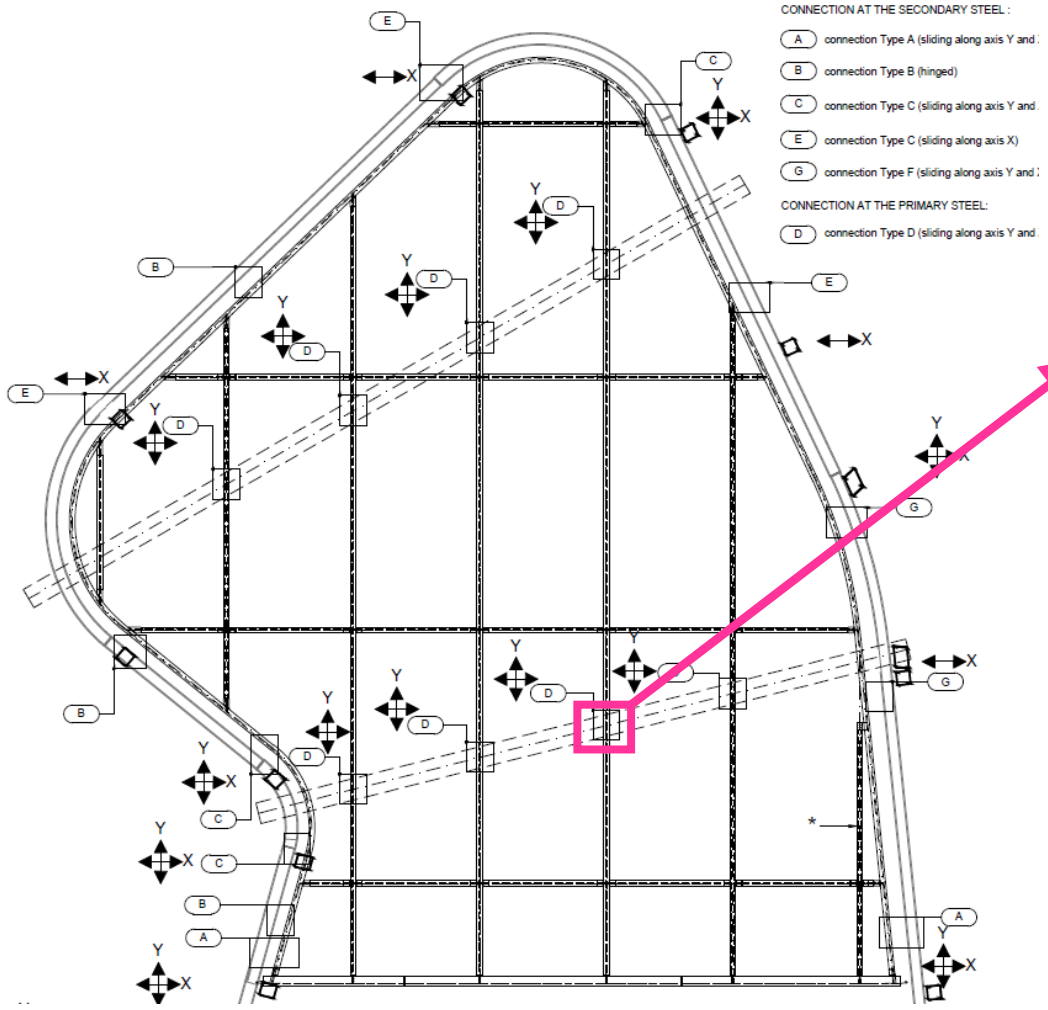


Dettaglio asola verticale in copertura

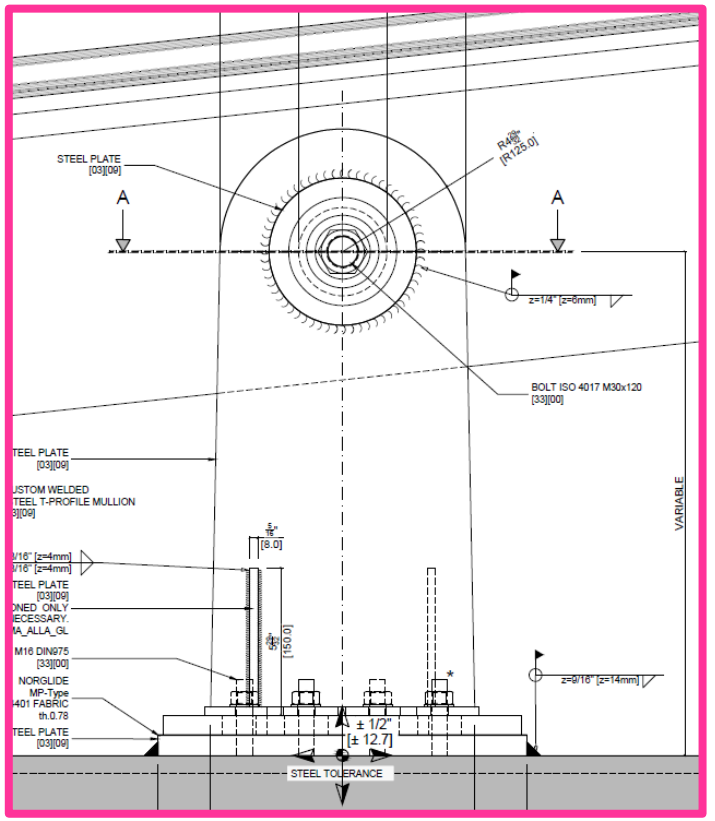


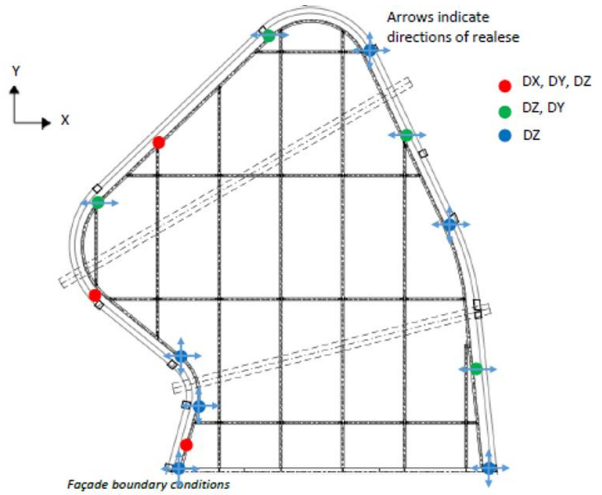
OCMA-ORANGE COUNTRY MUSEUM OF ART

Schema statico copertura



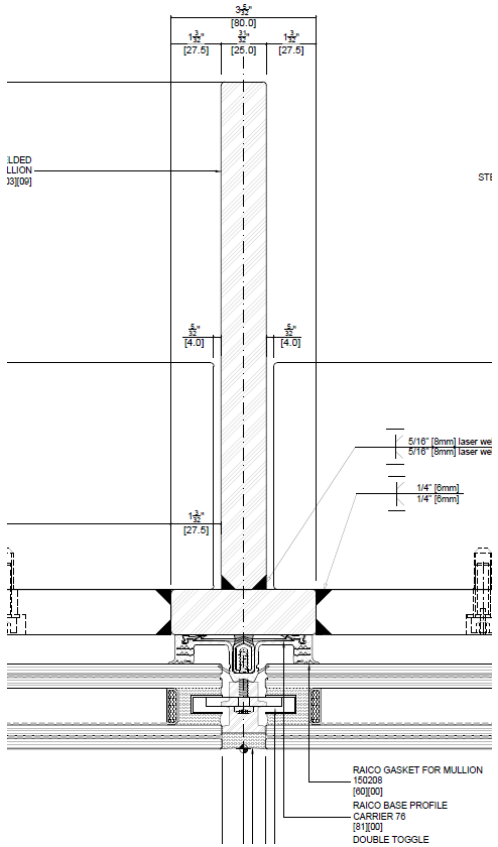
Dettaglio appoggio copertura su trave principale



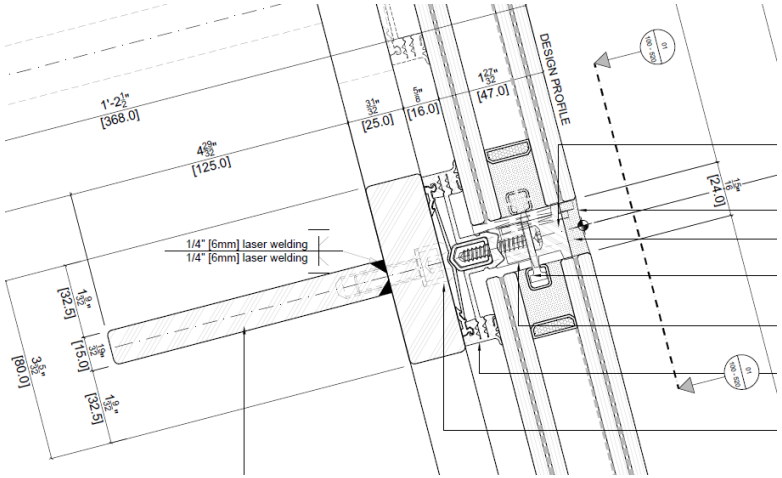


OCMA-ORANGE COUNTRY MUSEUM OF ART

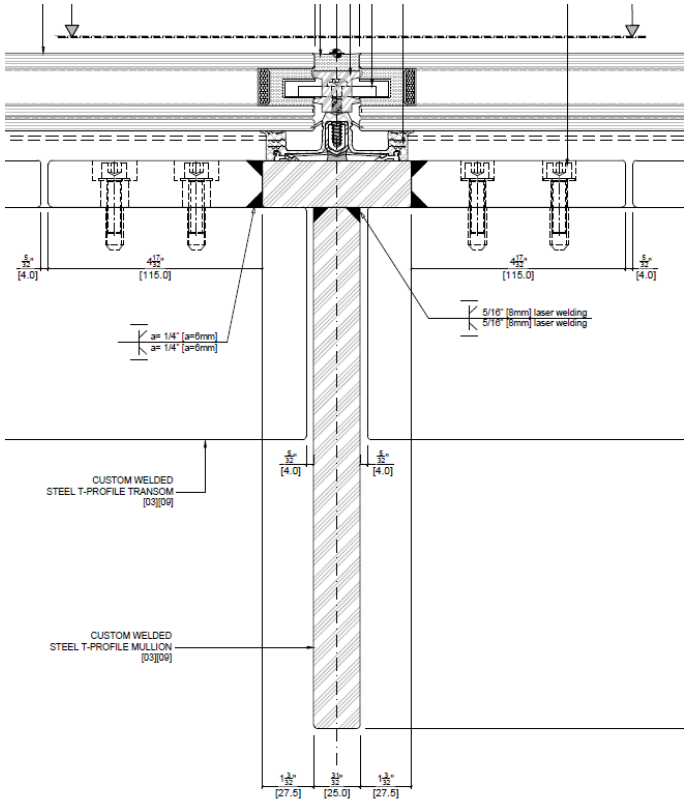
Tipi di profili utilizzati



Montanti facciata



Traversi facciata



Profili copertura

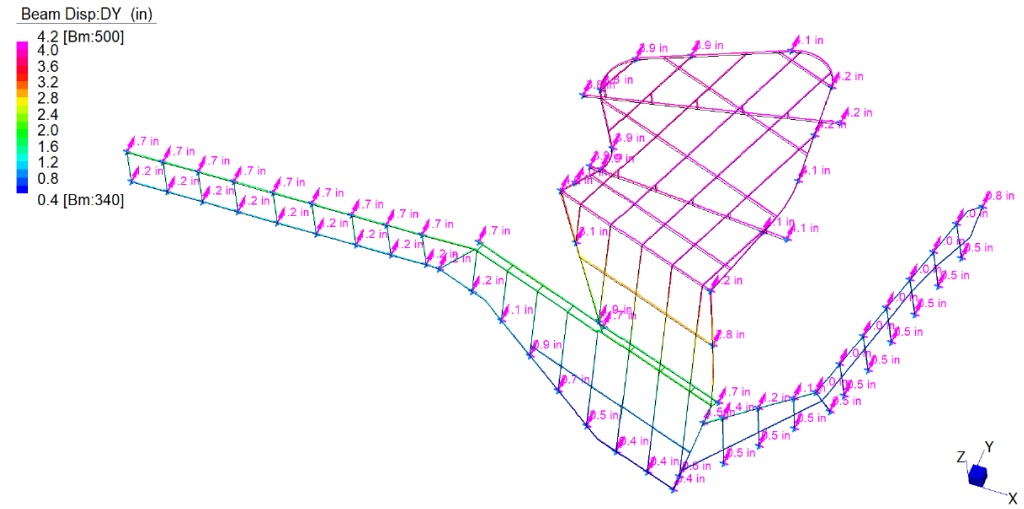
OCMA-ORANGE COUNTRY MUSEUM OF ART

Modellazione FE struttura: analisi degli spostamenti

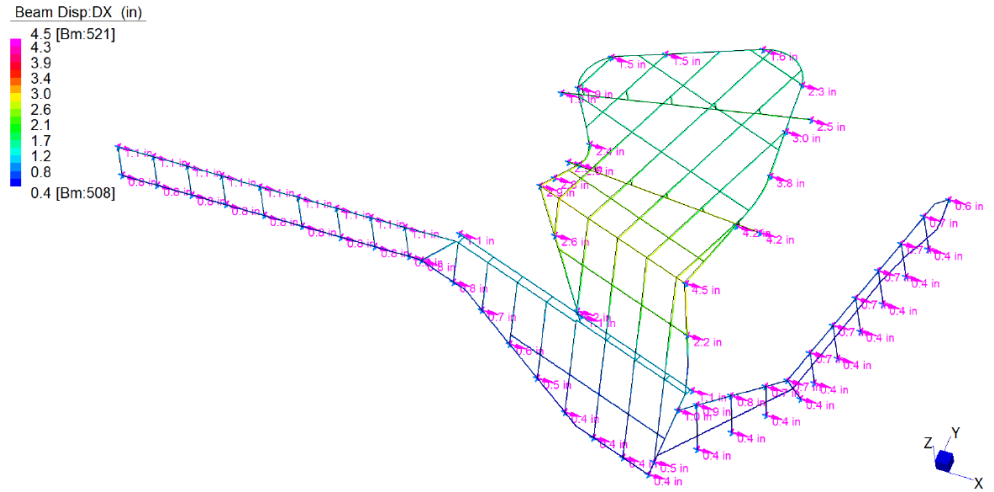
BUILDING LATERAL DISPLACEMENT

CENTER OF MASS SEISMIC LATERAL DISPLACEMENT (INCHES)				
LEVEL	EAST- WEST		NORTH - SOUTH	
	δ_{xe}	δ_x	δ_{xe}	δ_x
LOUVER ROOF	1.8	4.4	1.8	4.4
MECH FLOOR	0.6	2.3	0.4	1.5
LEVEL 2	0.3	1.2	0.2	0.8
LEVEL 1 MEZZ	0.1	0.3	0.1	0.3

NOTES:
δ_{xe} = ELASTIC DEFLECTION AT LEVEL x
δ_x = INELASTIC DEFLECTION AT LEVEL x



Contour of imposed inelastic displacements:

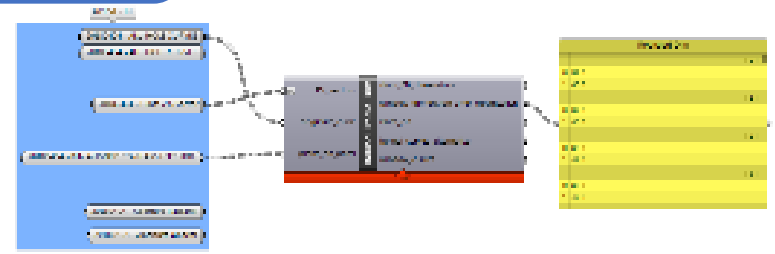


OCMA-ORANGE COUNTRY MUSEUM OF ART

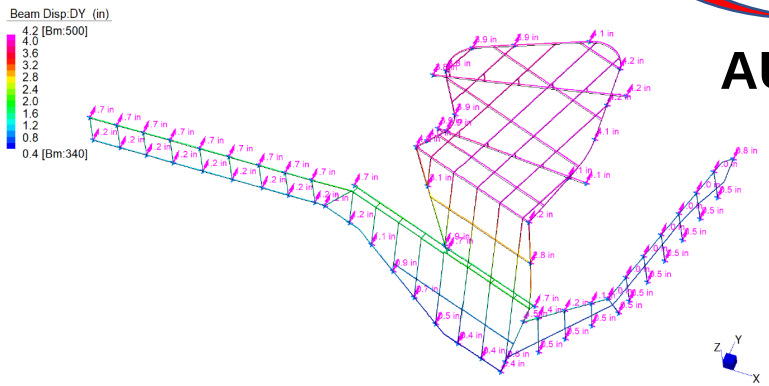
Modellazione FE struttura: analisi degli spostamenti

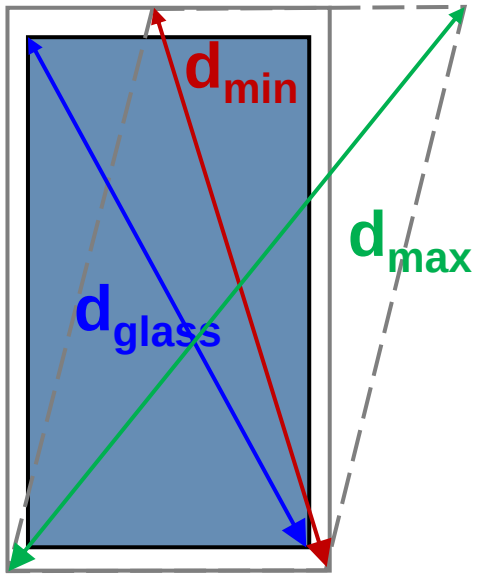
Analisi deformate: controllo diagonali (RACKING)

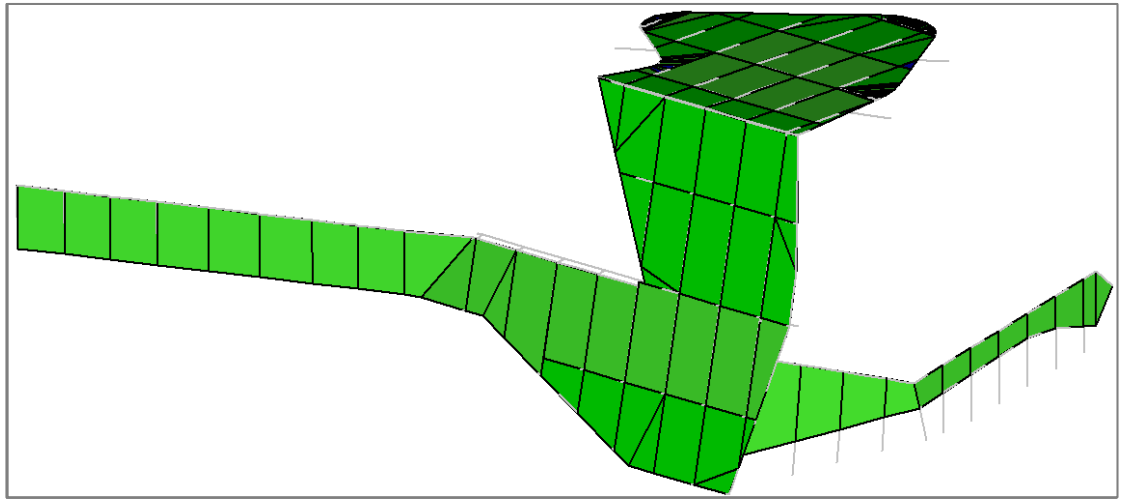
Design finale

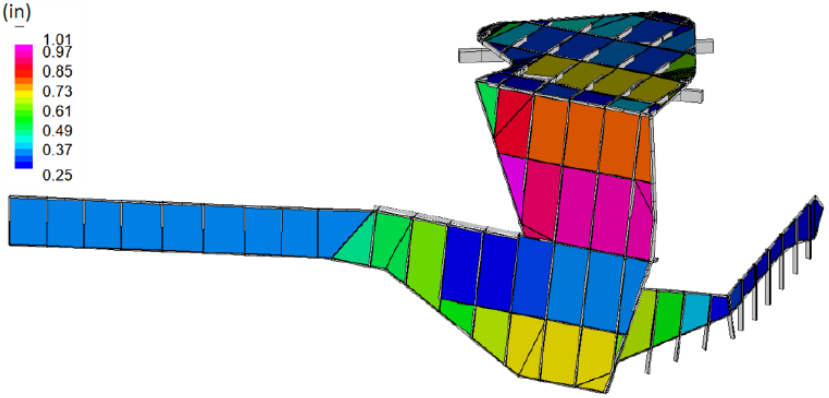


AUTOMATIZZAZIONE DEL PROCESSO





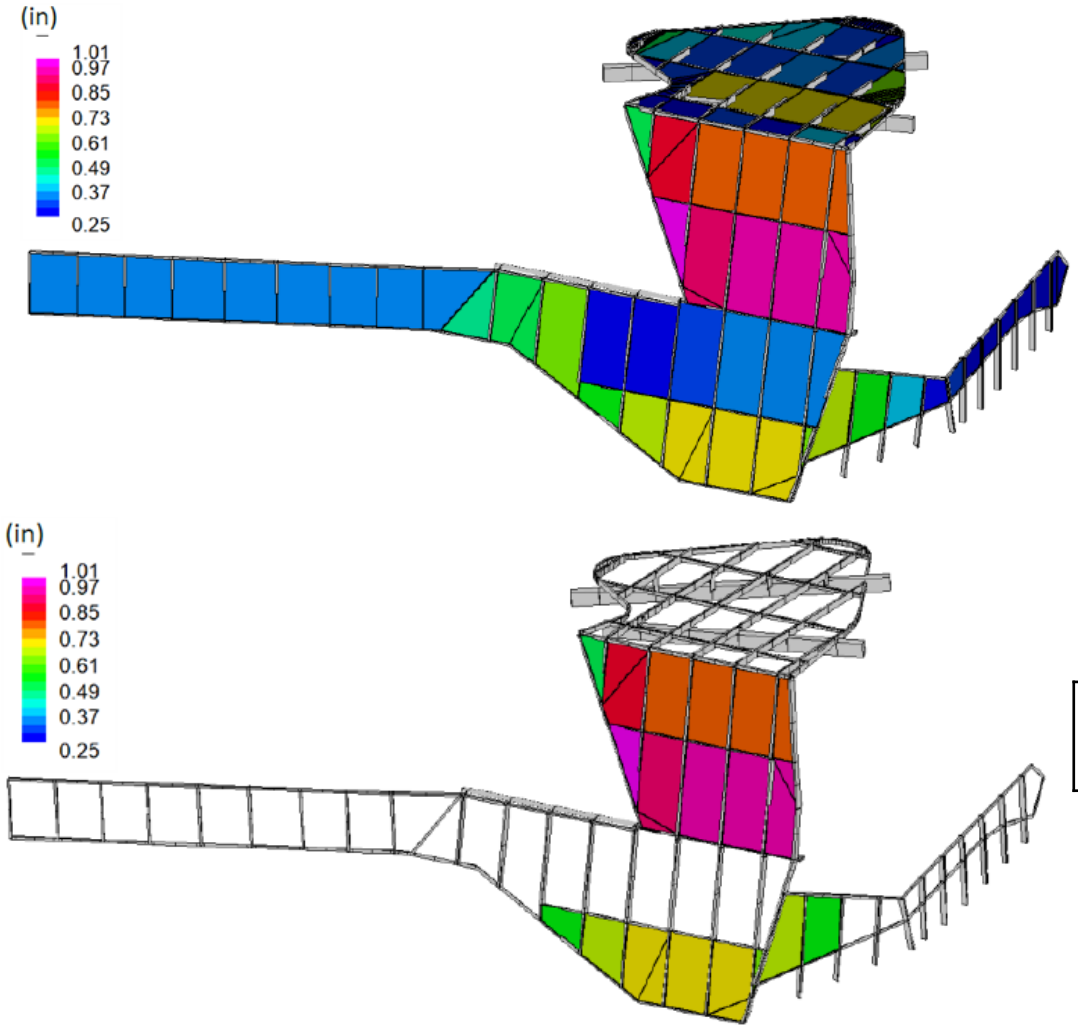


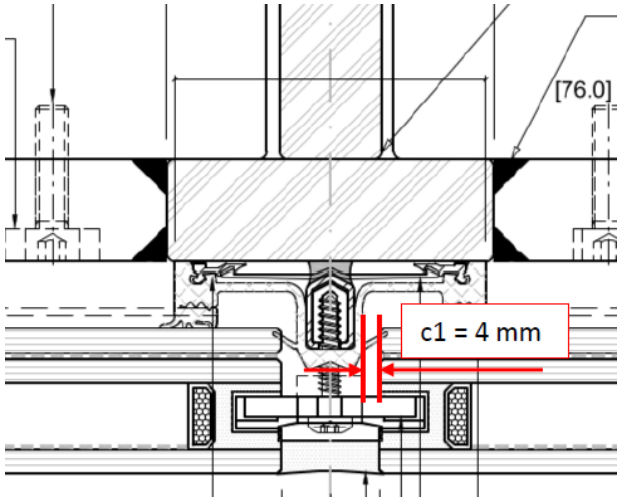


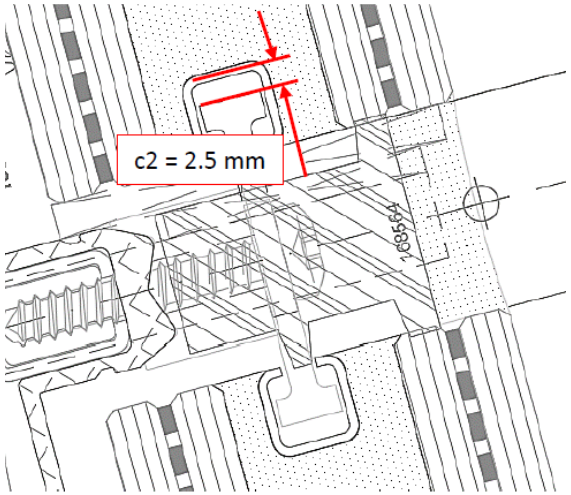
$d_{glass} < d_{min}$?		
	NO	Re-design
	SI	Design APPROVATO

OCMA-ORANGE COUNTRY MUSEUM OF ART

Analisi deformate: controllo diagonali (RACKING)



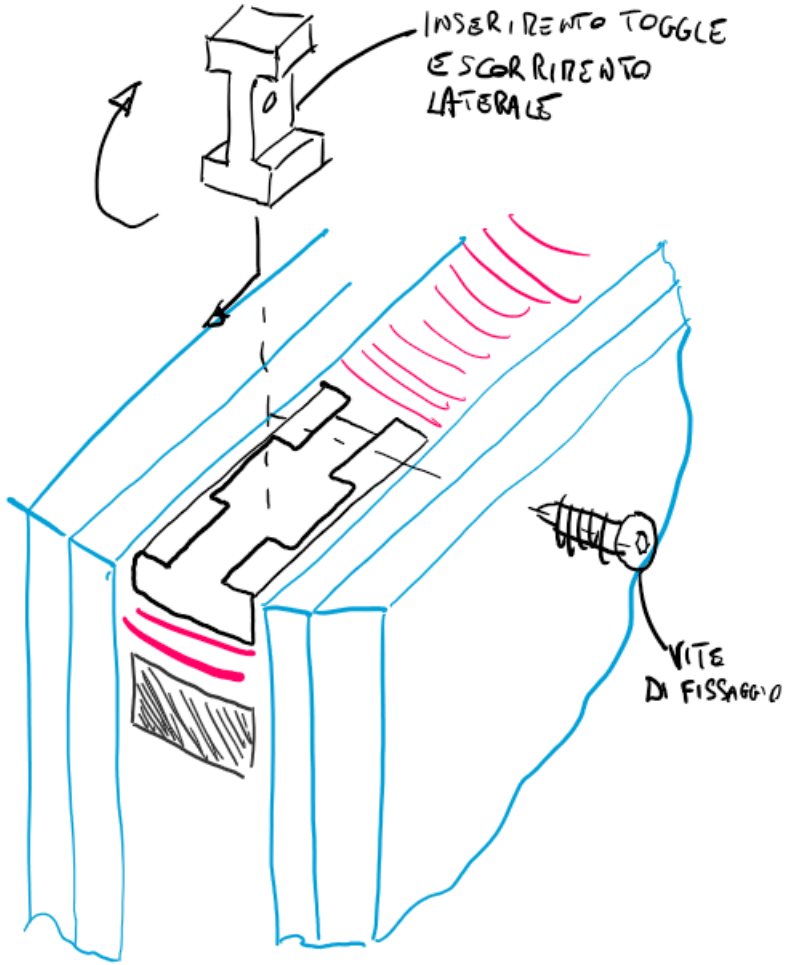


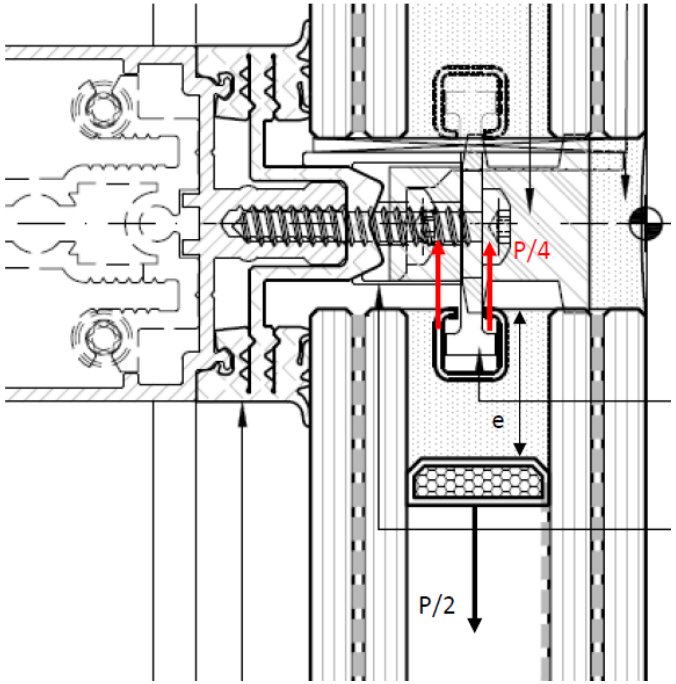


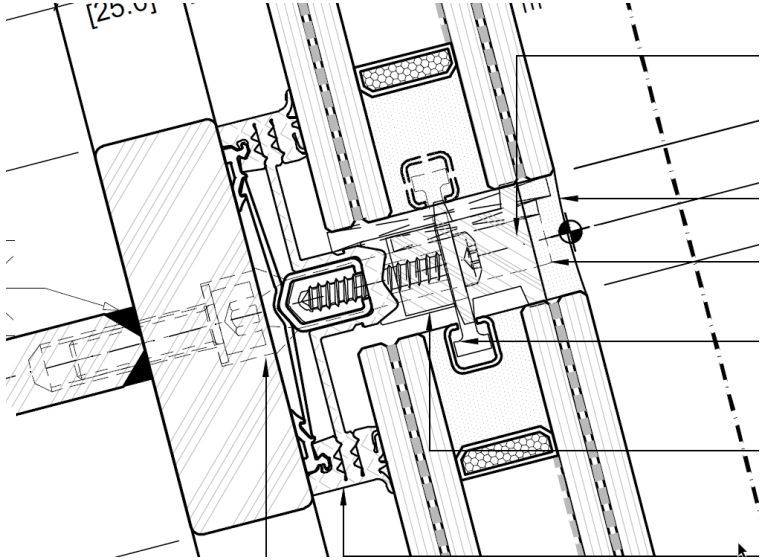
$d_{glass} < d_{min}$?	NO	Test secondo AAMA 501.6

OCMA-ORANGE COUNTRY MUSEUM OF ART

Toggle customizzato





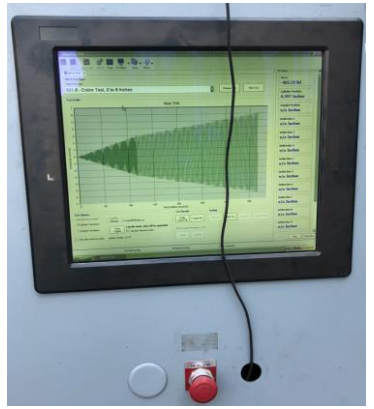


P = 1057 lbf	maximum self-weight (worst scenario)
t = 0.039 in	channel thickness
F_y = 29 ksi	yield strength AISI 316 (1.4401)
L = 1.969 in	length of single channel
n = 2	n° of channel per glass panel
Ω_v = 1.67	safety factor for ASD

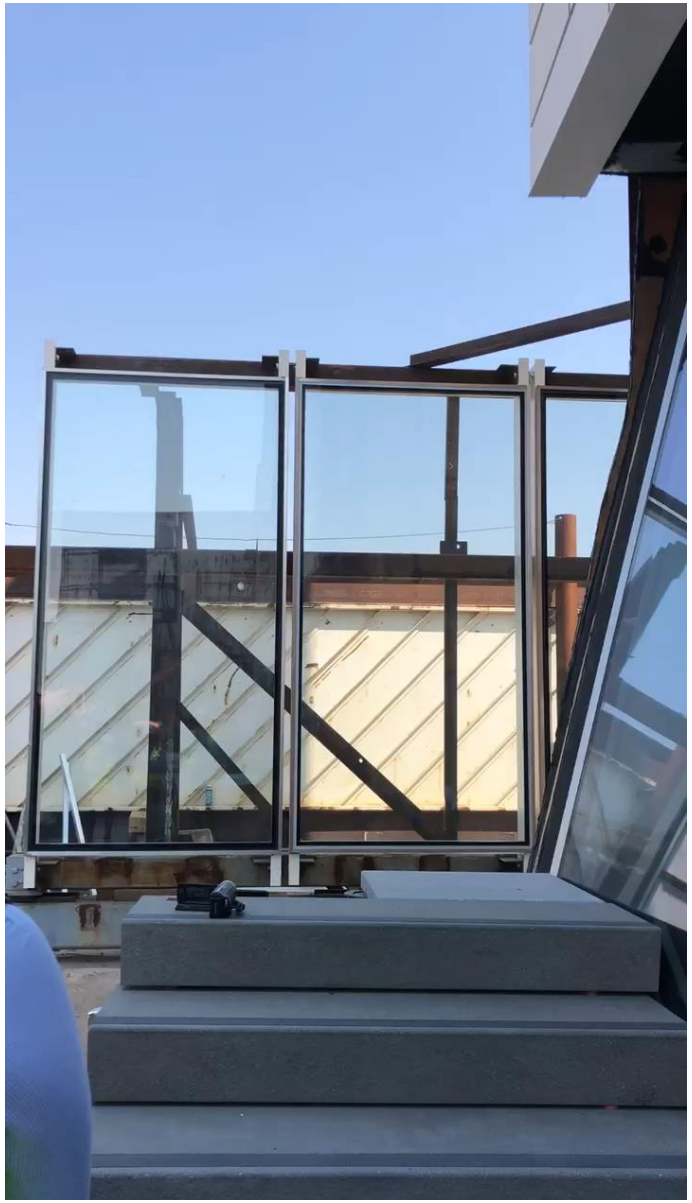
The wall of channel needs to be verified against the shear force produced by P/2

V = P/n/2 = 265 lbf	demand of shear force per side on each channel
$V_n = (0.6F_y)*(L*t)$ = 1349 lbf	nominal shear capacity
$V_a = V_n/\Omega_v$ = 808 lbf	available shear capacity
$V/V_a = 0.33 < 1.0$ → OK	utilization factor

Setup prova dinamica (AAMA 501.6)



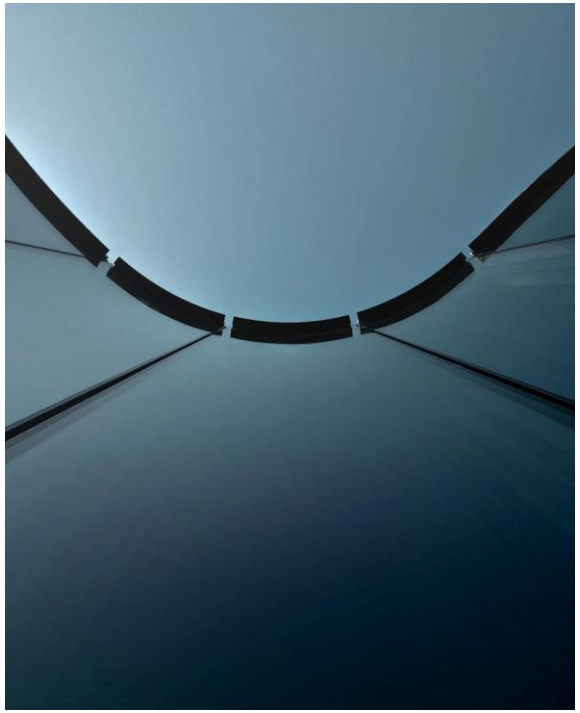
OCMA-ORANGE COUNTRY MUSEUM OF ART



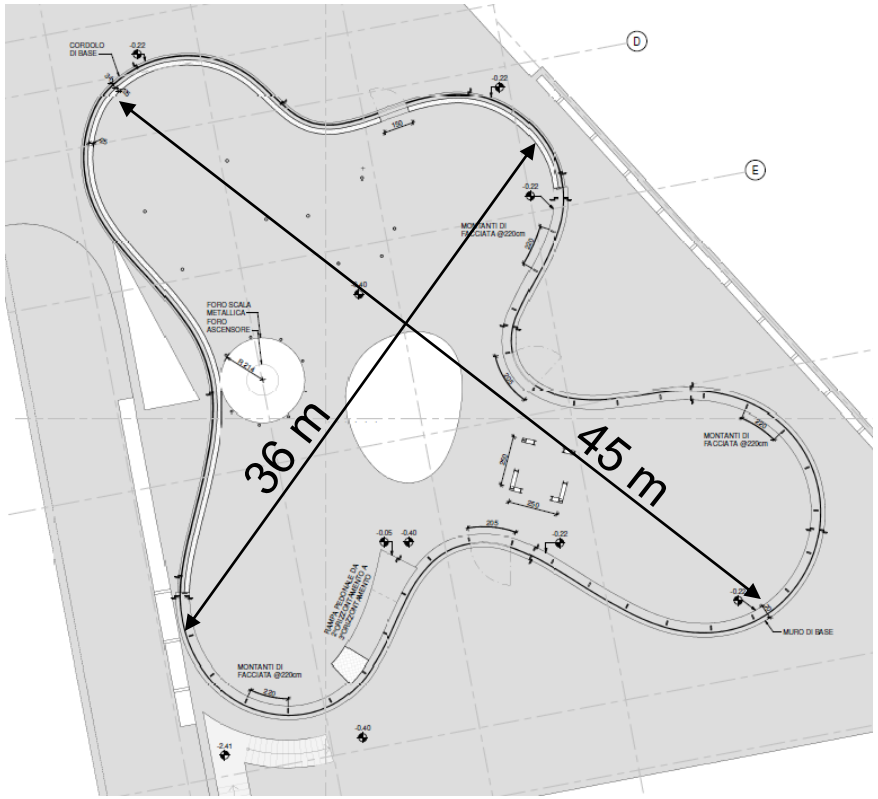
OCMA-ORANGE COUNTRY MUSEUM OF ART

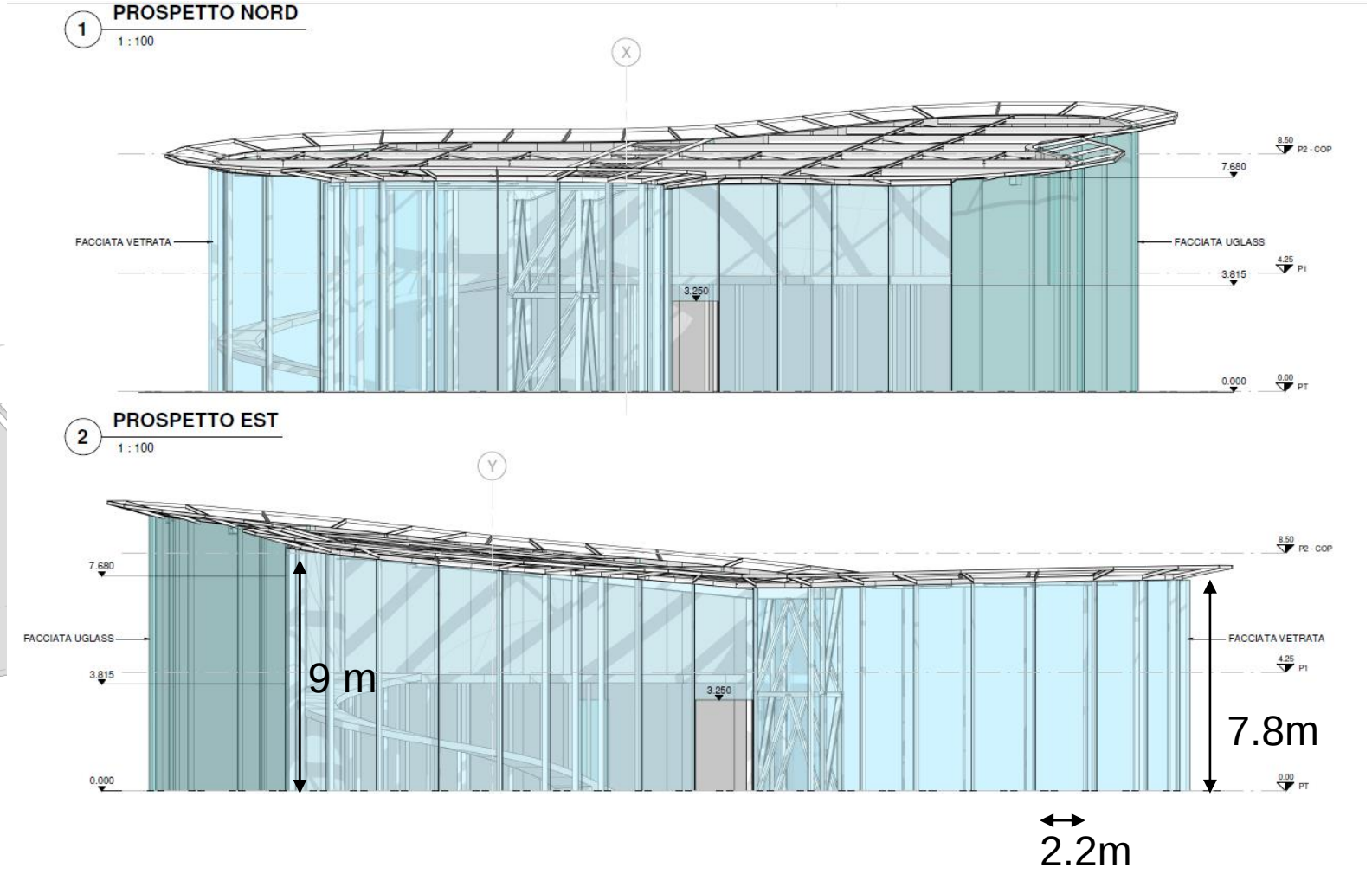
Tipografia Zardini

LOCATION	San Pietro in Cariano | Italy
YEAR	2019
STATUS	On-going September 2023
TYPE OF BUILDING	Commercial Building
SERVICE	Façade Engineering
CLIENT	Tipolitografia Zardini Srl
ARCHITECT	ACME Studio



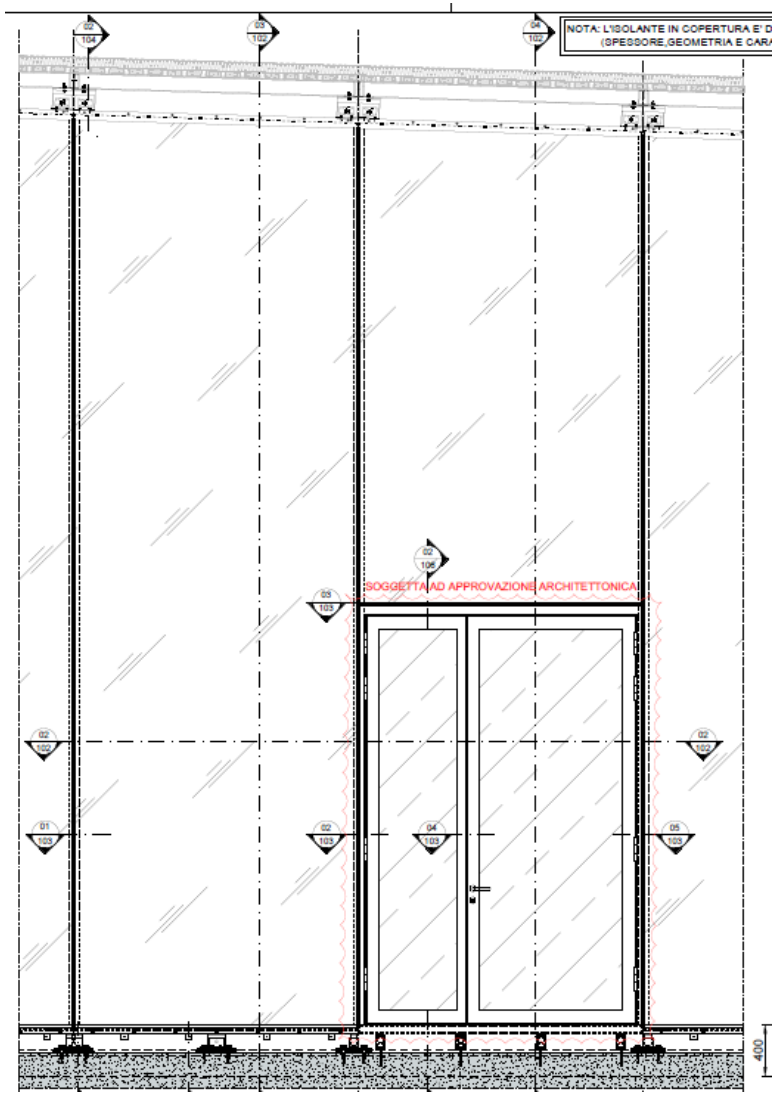
TIPOGRAFIA ZARDINI

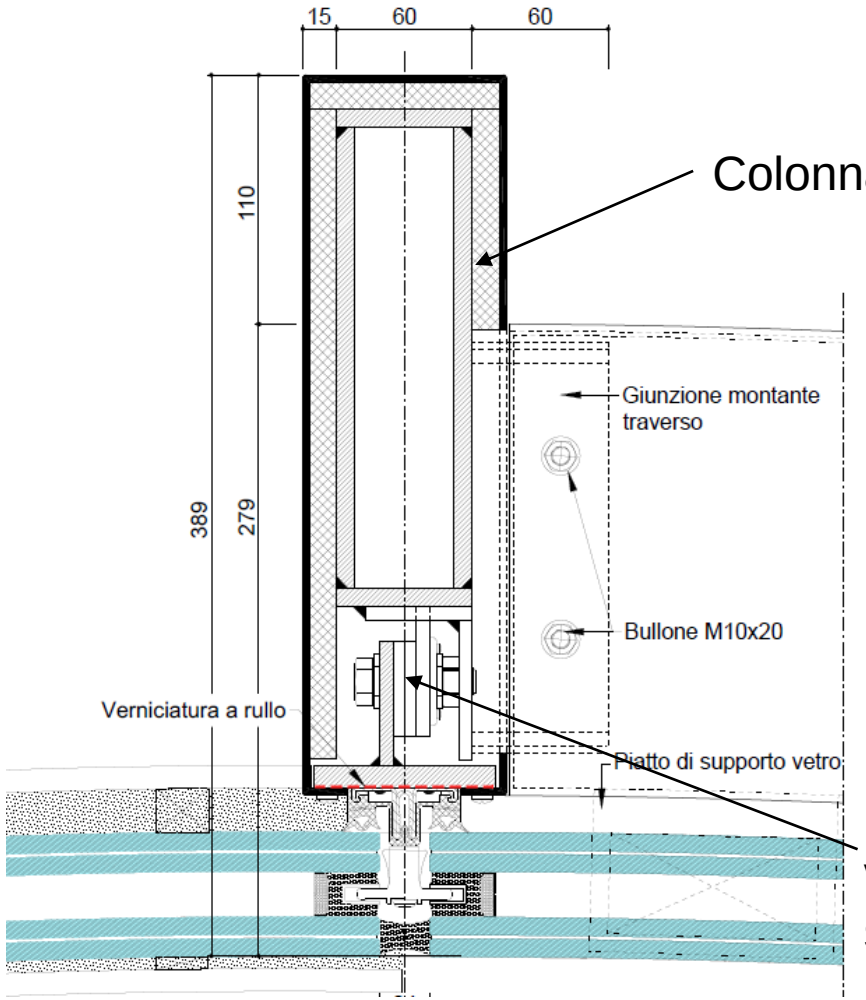




TIPOGRAFIA ZARDINI

Montante di facciata





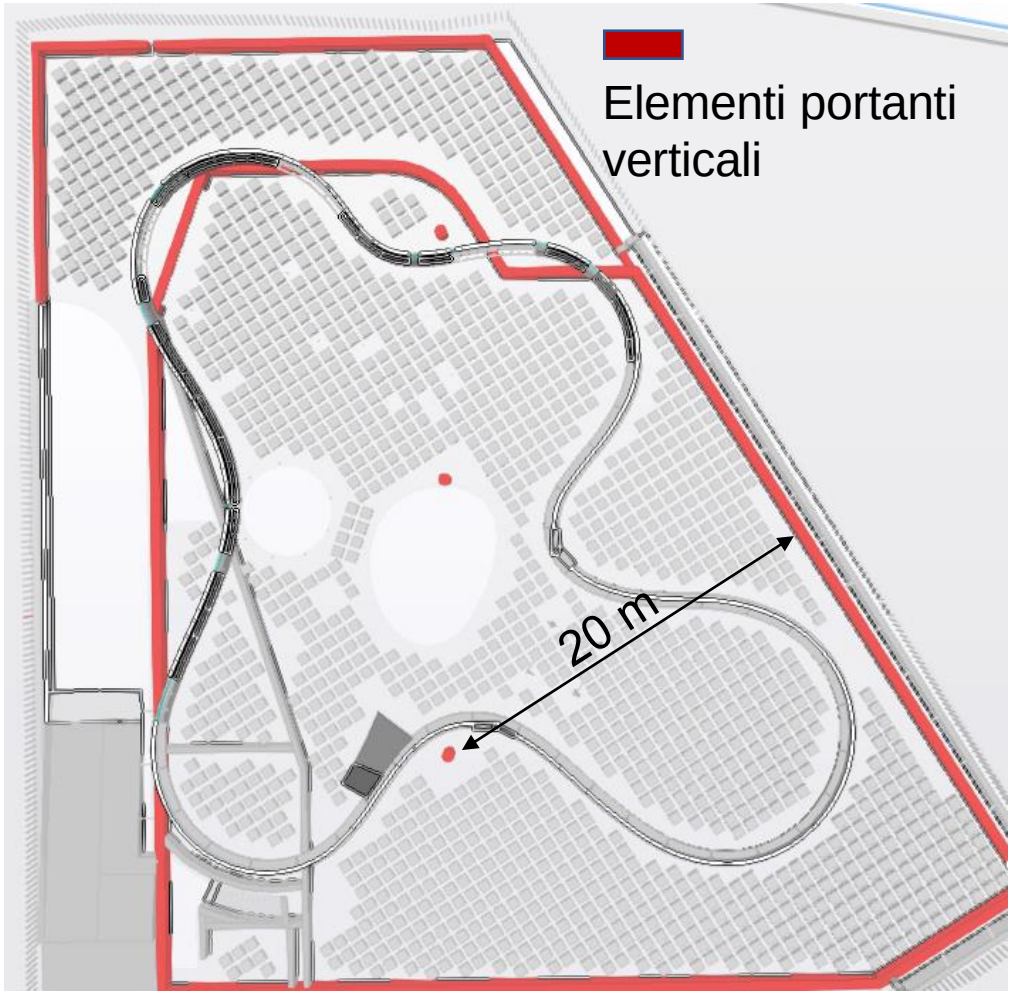
Colonna portante di copertura

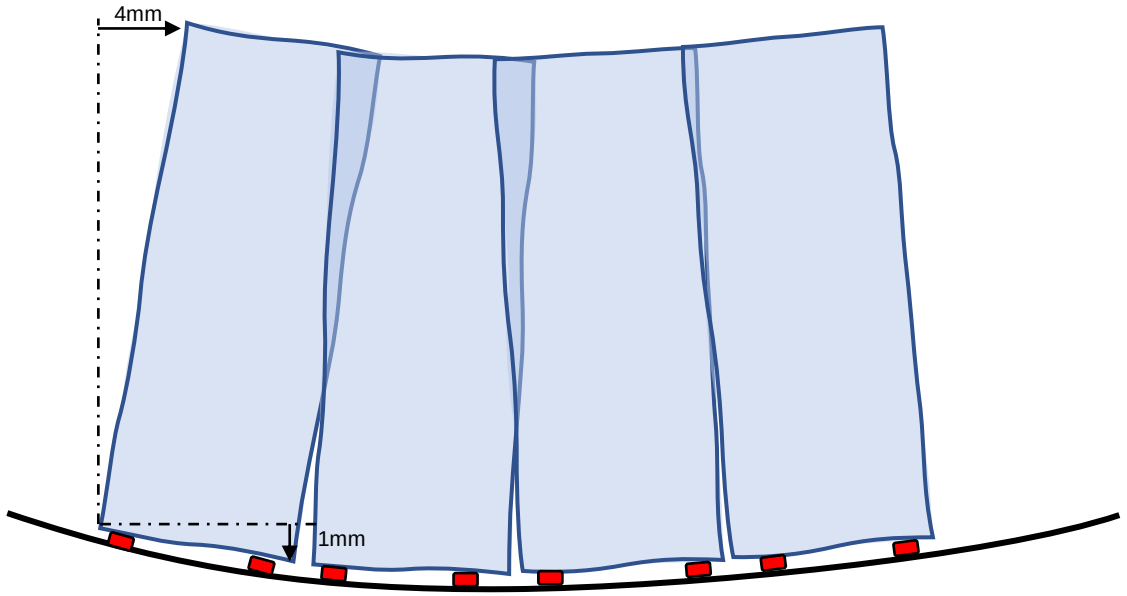
Profilo di facciata vincolato ogni metro con sistema di regolazione

TIPOGRAFIA ZARDINI

Analisi delle problematiche

Soletta portante in C.A. post teso con luce massima di 20 m.
Elevata deformabilità dei supporti del vetro → non compatibile con sistema montante traversi

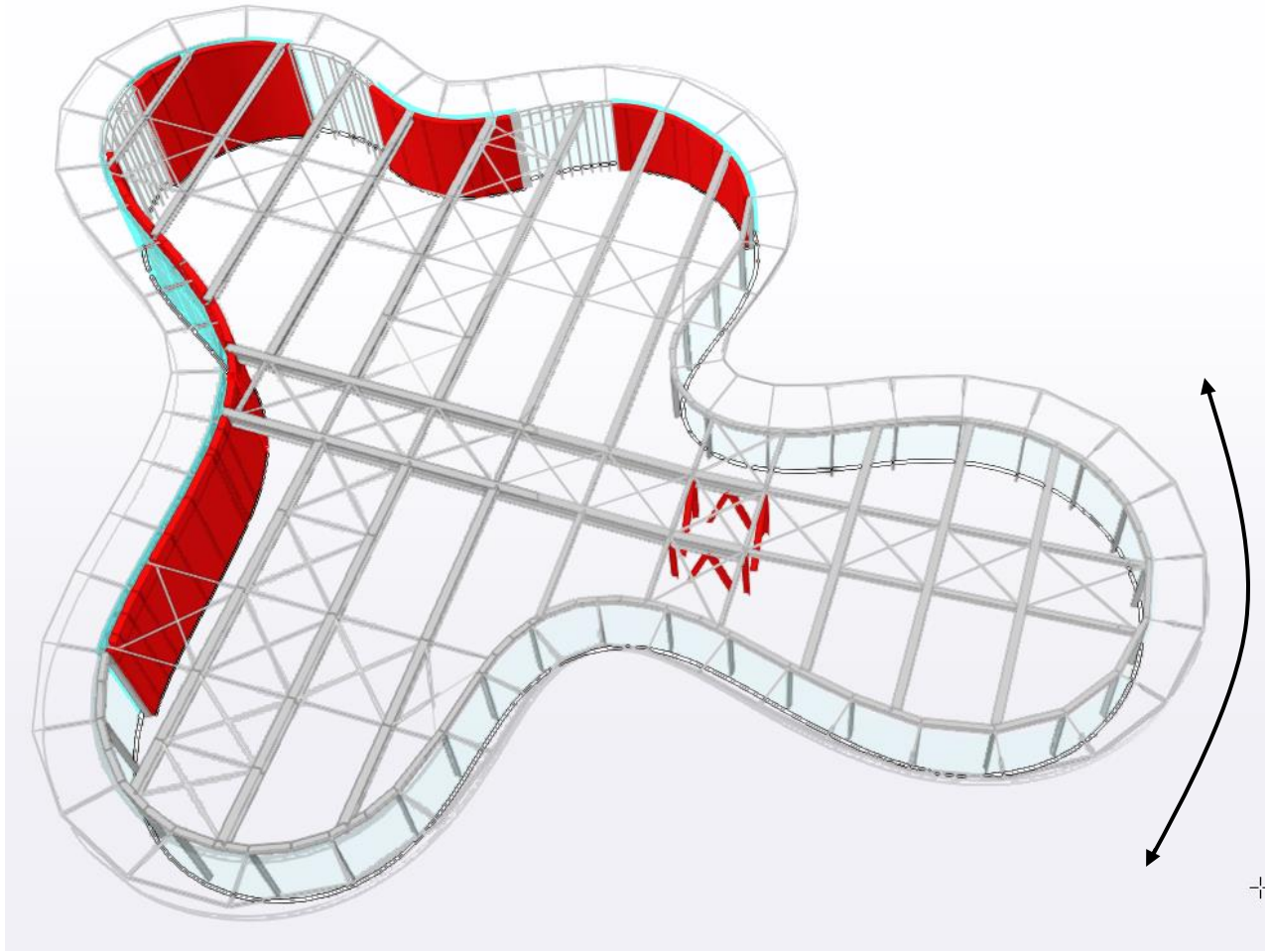




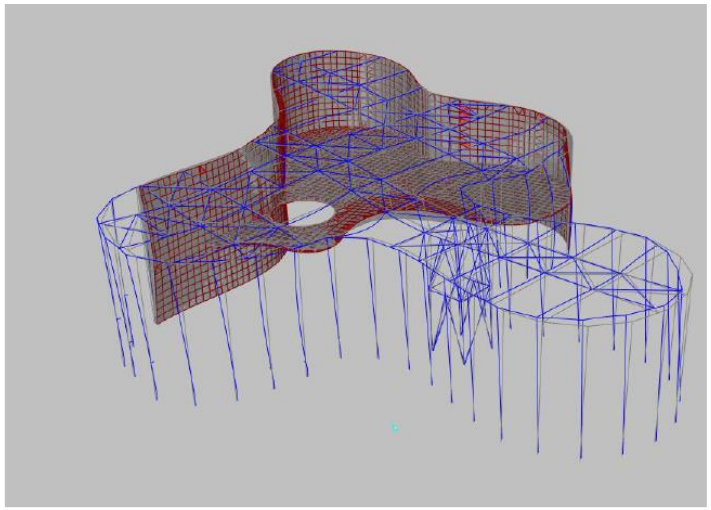
TIPOGRAFIA ZARDINI

Analisi delle problematiche

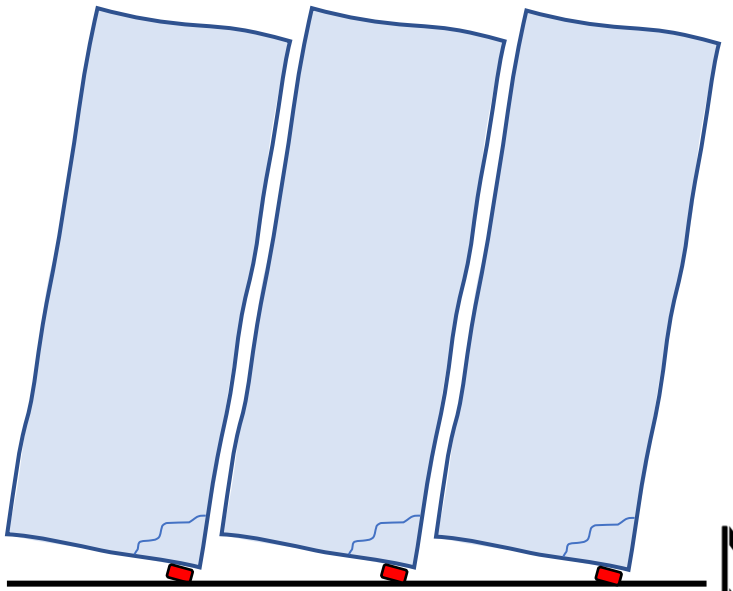
Struttura portante con comportamento torsionale→ elevati drift orizzontali che comportano sollevamento del vetro in fase di rotazione



Elementi portanti azioni orizzontali



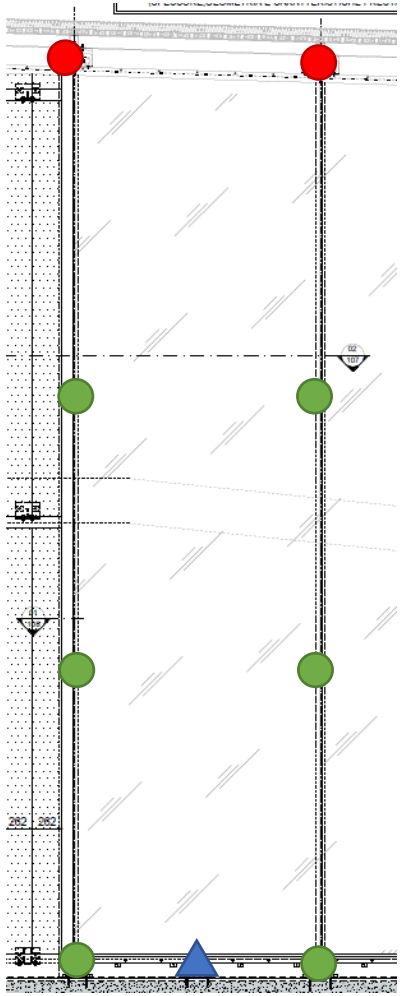
F_1=7 Hz. Deformata in punta 25 mm

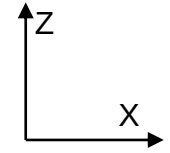


TIPOGRAFIA ZARDINI

Schema statico adottato

Sistema pivotante: vetro appoggiato al centro, vincolato fuori piano lungo il montante e nel piano in due punti in sommità

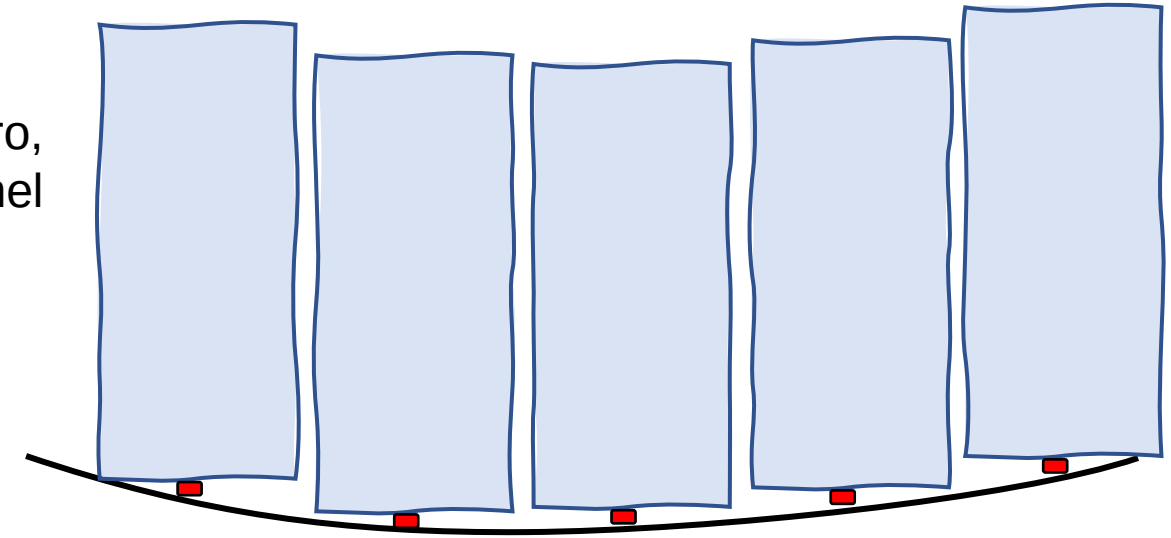




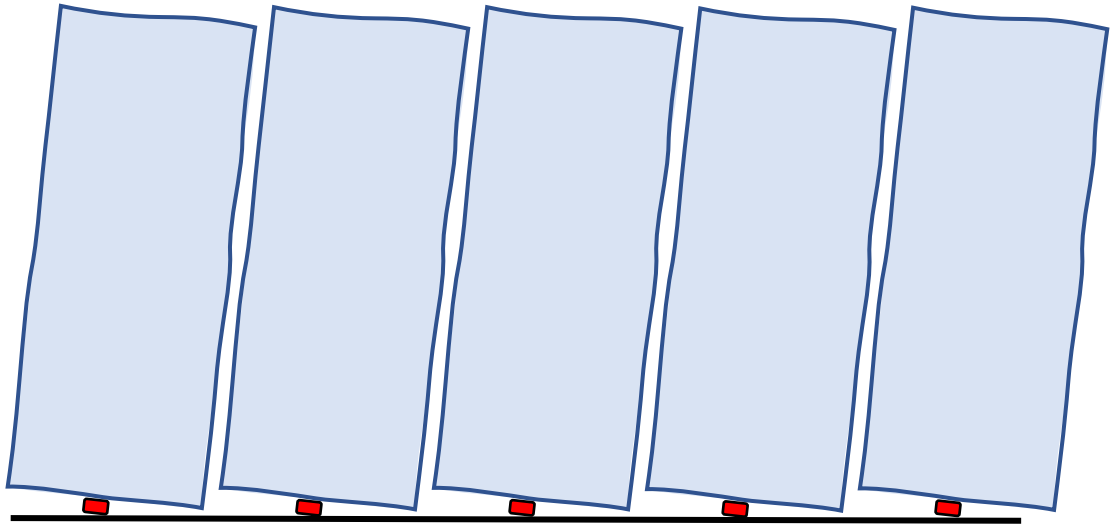
DX DY

DY

DX DY DZ

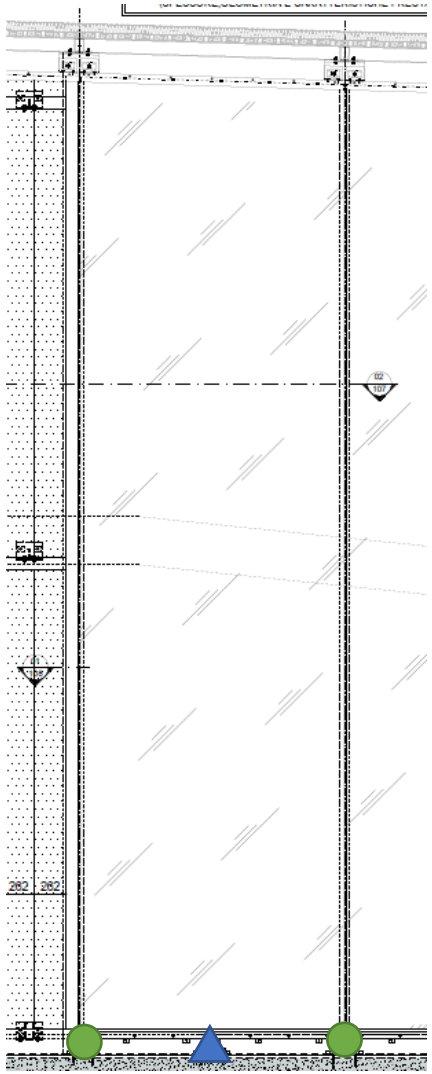


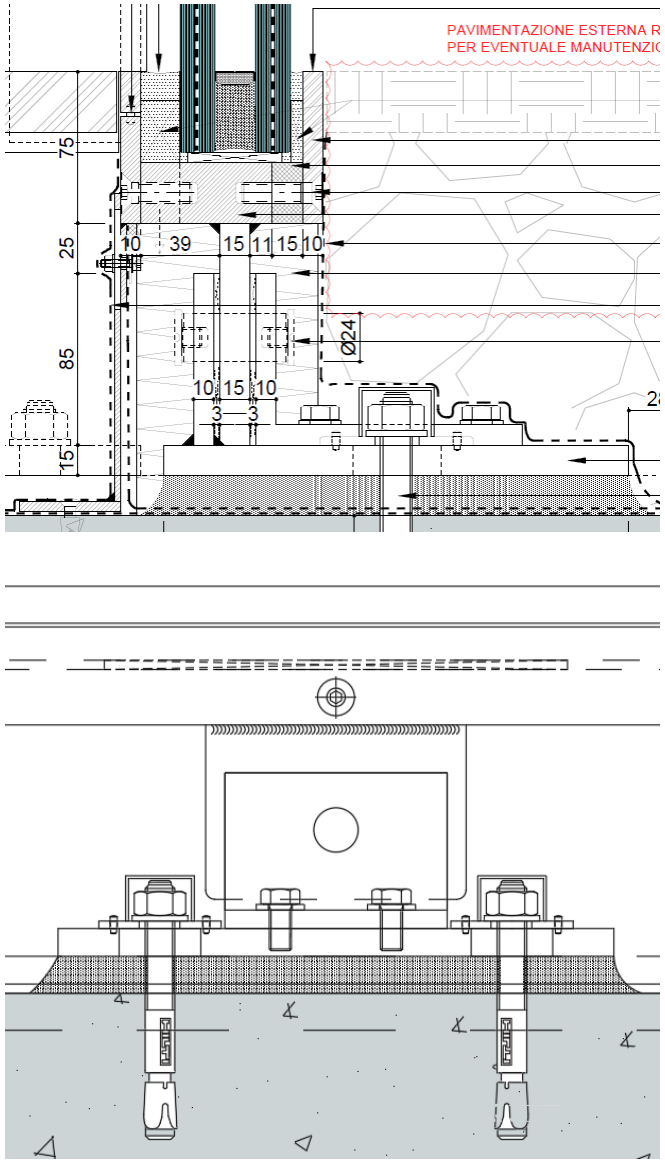
Comportamento alle deformate verticali



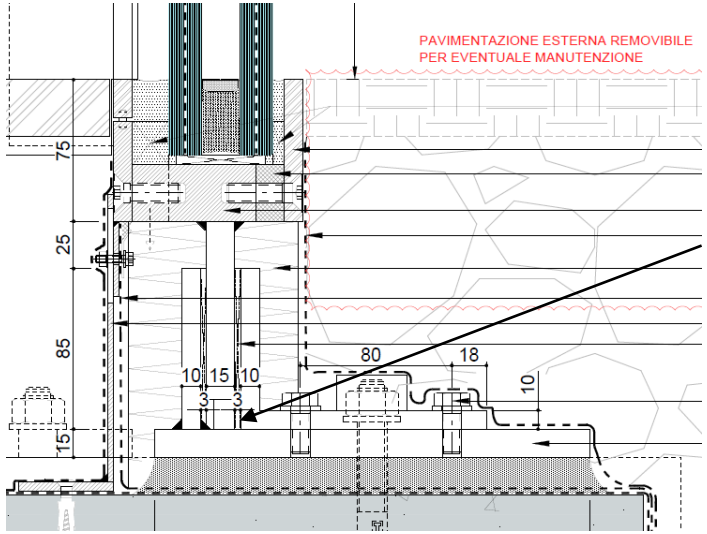
Comportamento alle deformate orizzontali

TIPOGRAFIA ZARDINI

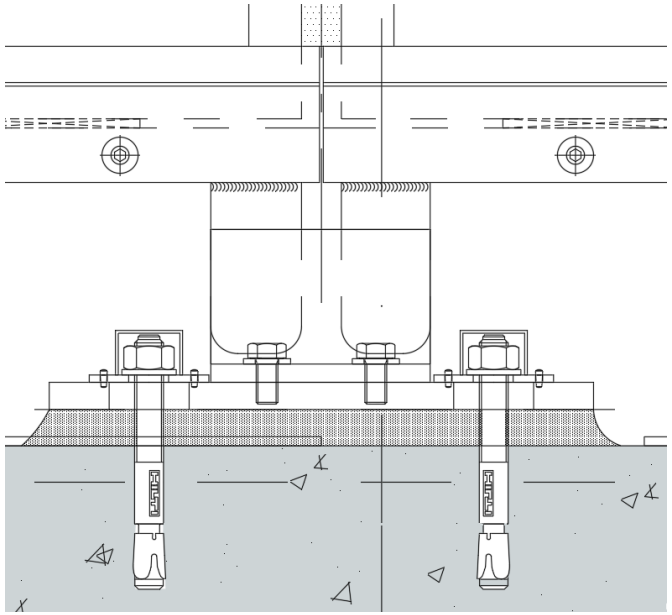




▲ Connessione pivotante

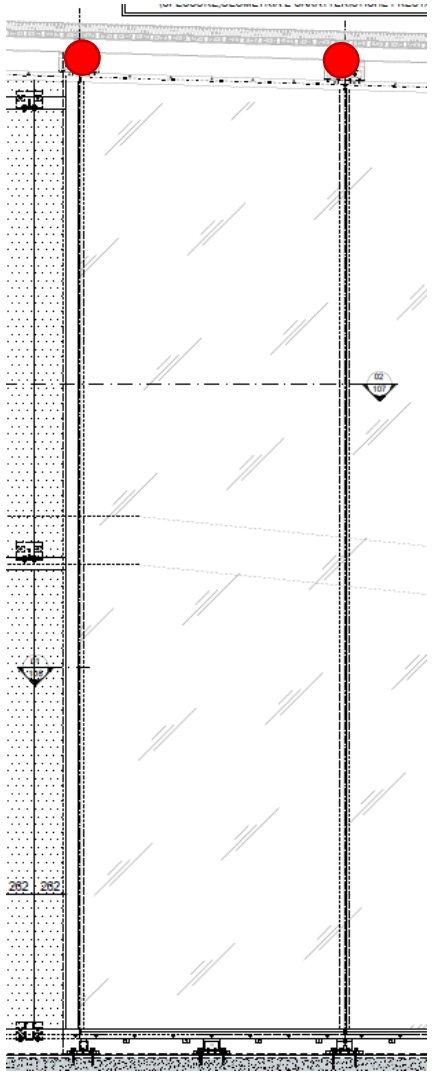


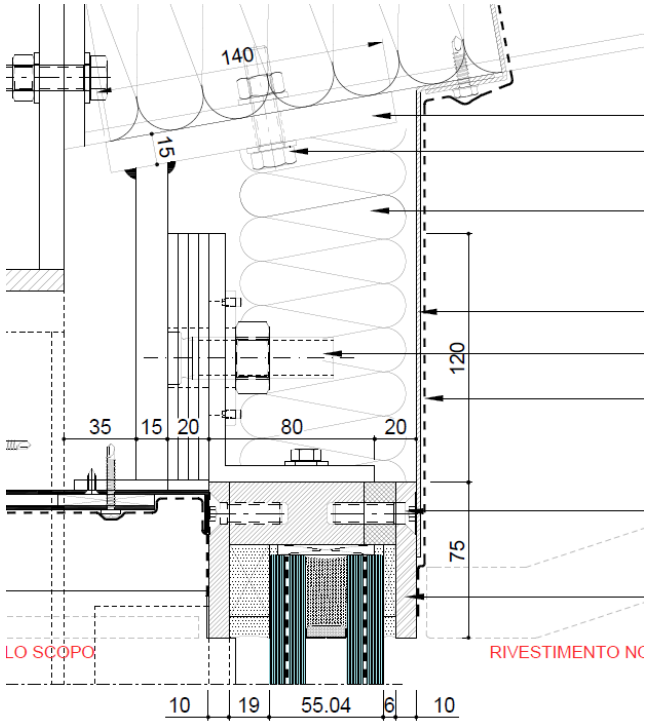
GAP da analisi spostamento

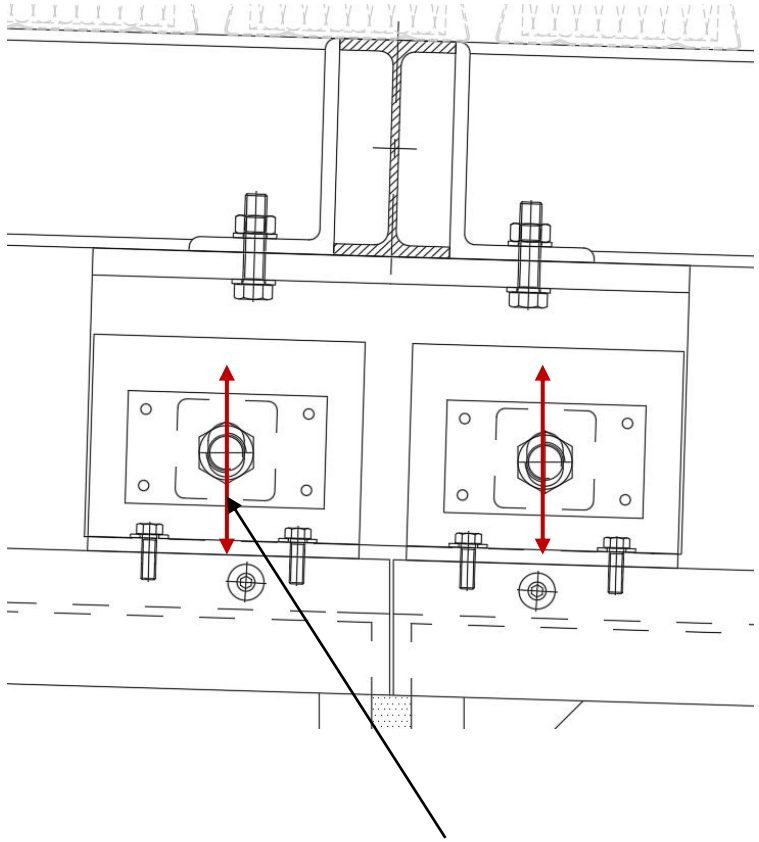


● Connessione a vento

TIPOGRAFIA ZARDINI







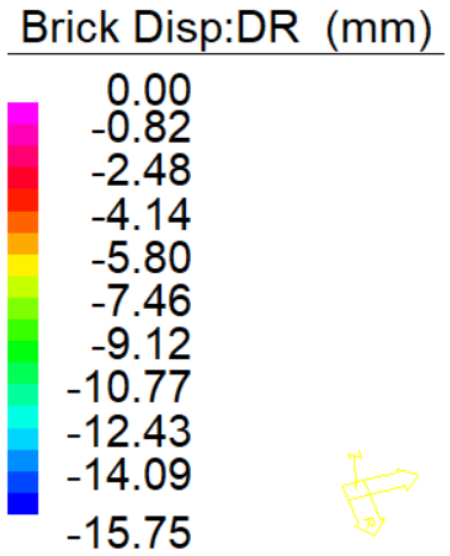
Asole verticali sulla piastrina di regolazione per permettere rotazione vetro

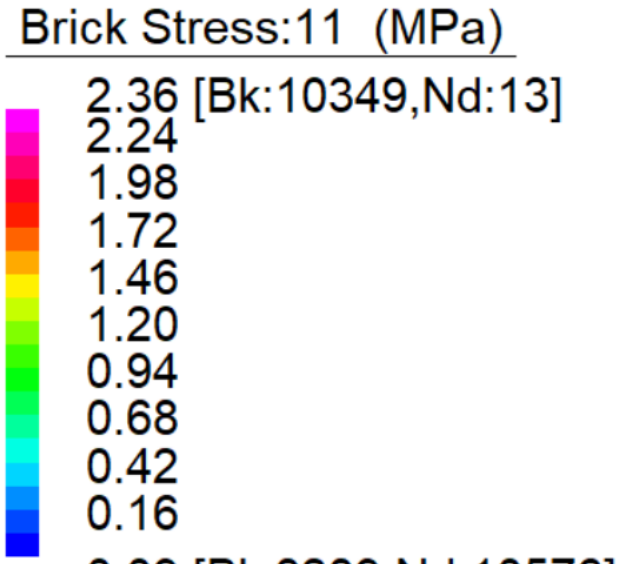
- Connessione superiore a vento e di piano

TIPOGRAFIA ZARDINI

Analisi sul vetro

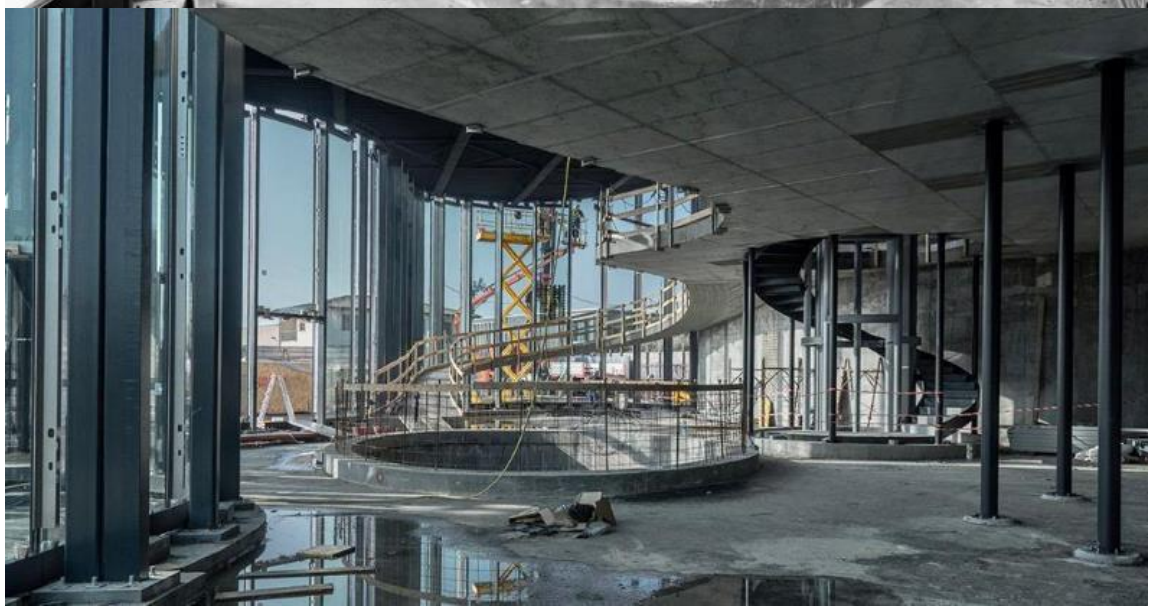
Imposizione spostamento massimo relativo tra due montanti per studio effetti sulle tensioni localizzate

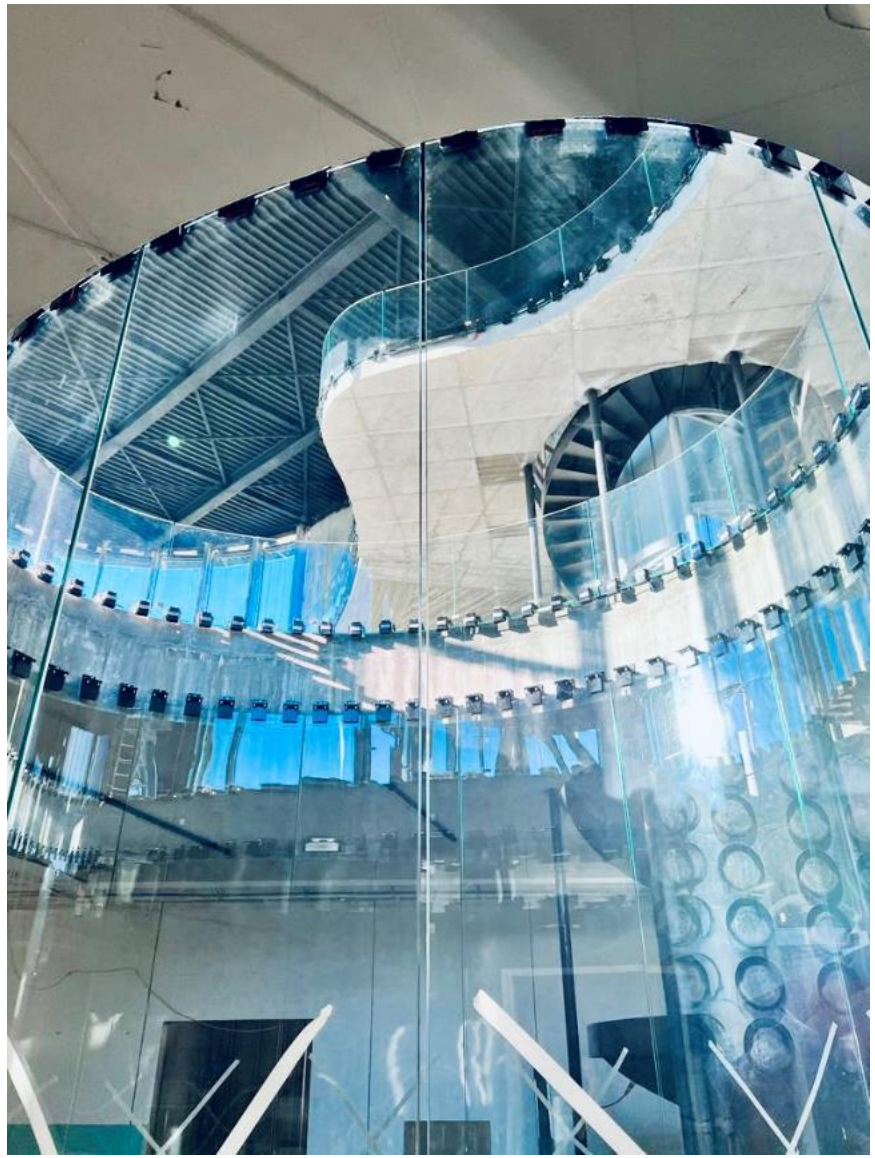




TIPOGRAFIA ZARDINI

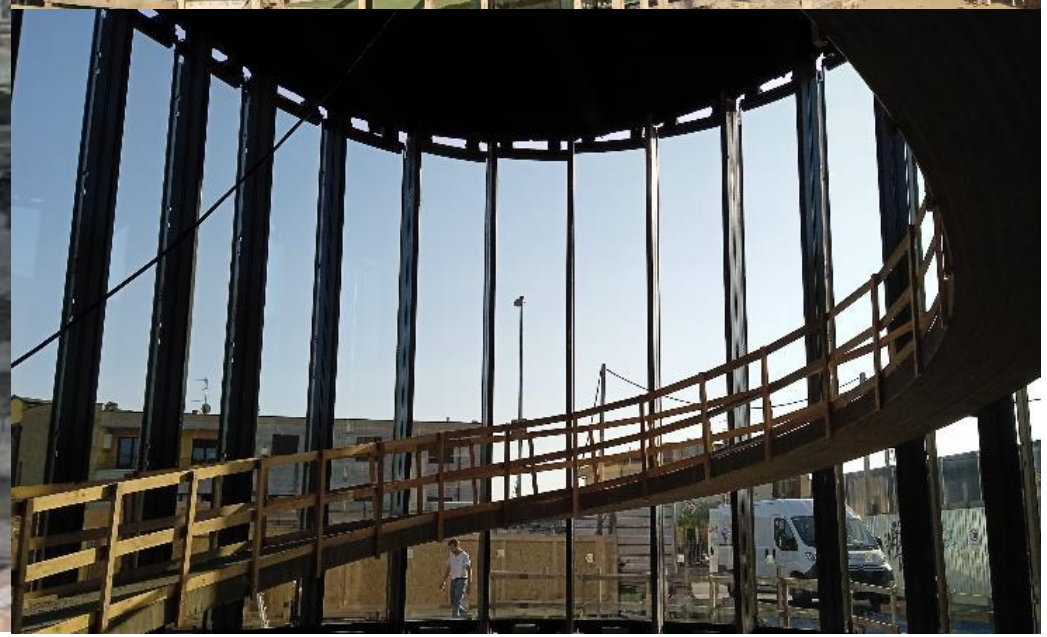
Foto cantiere





TIPOGRAFIA ZARDINI

Foto cantiere



Grazie per l’attenzione

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MAFFEIS engineering