4ο Πανελλήνιο συνέδριο
ΑΝΤΙΣΕΙΣΜΙΚΗΣ ΜΗΧΑΝΙΚΗΣ
ΤΕΧΝΙΚΗΣ ΣΕΙΣΜΟΛΟΓΙΑΣ
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Ενίσχυση Φορέων ΟΣ με Τοιχοπληρώσεις ΟΣ

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DEPARTMENT OF CIVIL ENGINEERING AND GEOMATICS

Cyprus University of Technology

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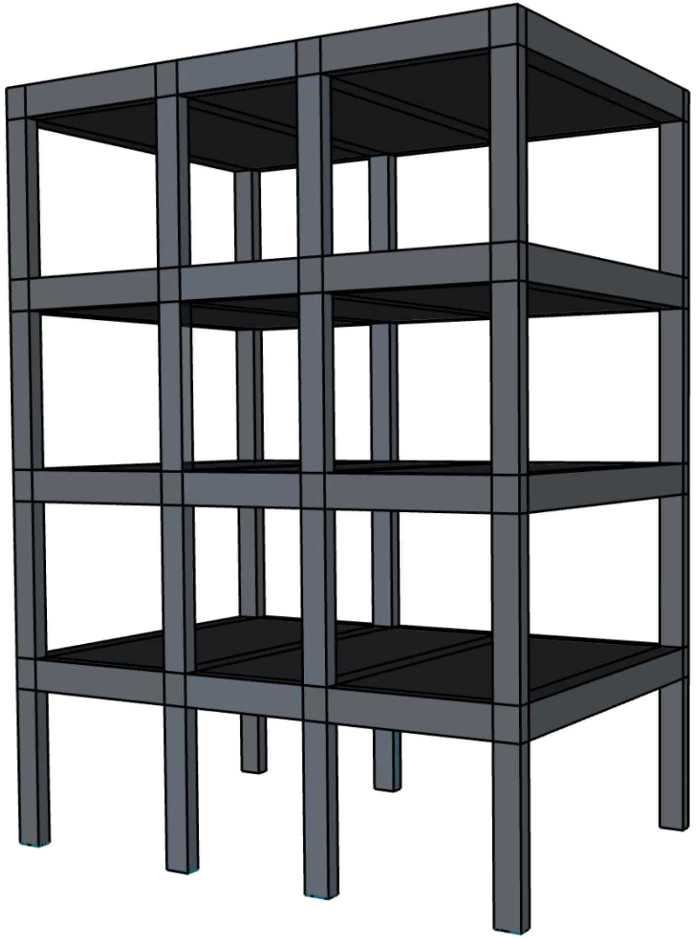
- The co-authors Elpida Georgiou and Nicholas Kyriakides

Research Scope

Strengthening of existing multi-storey multi-bay RC structures by the conversion of selected bays into new infilled RC walls

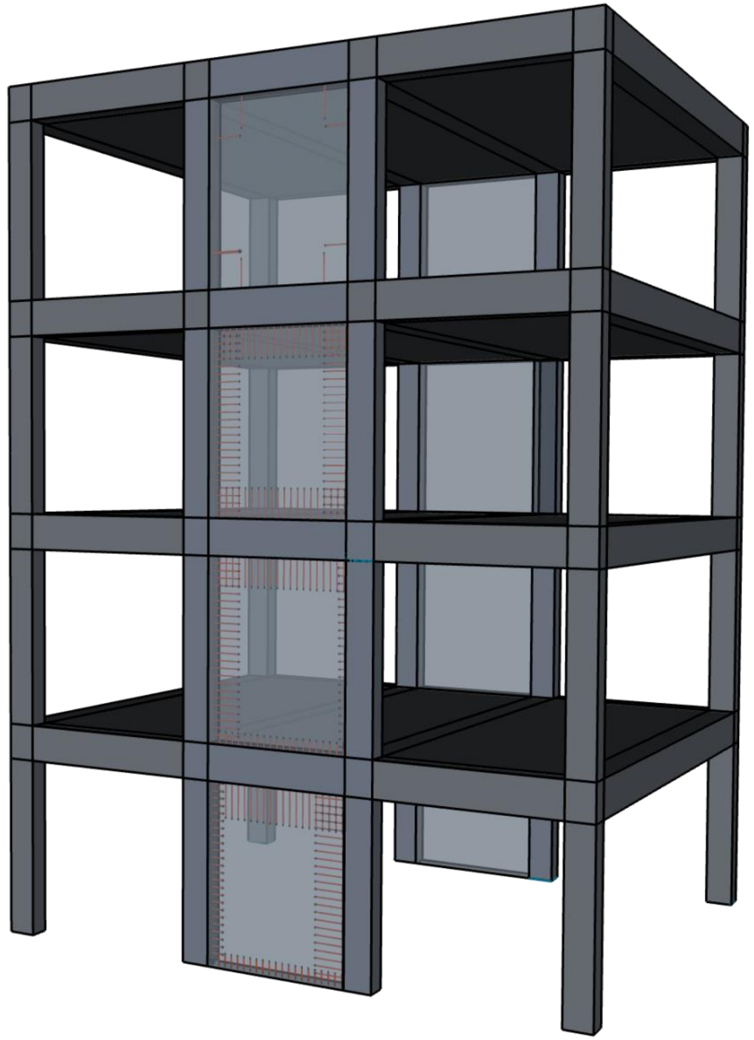


Large number of structures designed without seismic design provisions

Multi-storey reinforced concrete buildings can be most effectively and economically retrofitted by the construction of new walls

Connection details of such walls to bounding frame need to be investigated to facilitate their design

Parametric study of the contribution of dowels is necessary to complement the experimental results



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Research Procedure

Experimental specimen

- Full-scale testing of a specimen

Numerical simulation

- FEM of the infilled frame with nonlinear hysteretic behaviour
- Calibration with experimental results

Parametric study of dowels

- Numerical experiments by changing the number of dowels

Experimental Case Study - SERFIN

- SERIES, Framework Programme 7, SERFIN project
- Full-scale test
- European Laboratory of Structural Assessment (ELSA) of the JRC in Ispra

Partners

Cyprus University of Technology (Coordinator)

University of Nantes

University of Cyprus

DENCO Design & Engineering Consultants

Cyprus University of Technology

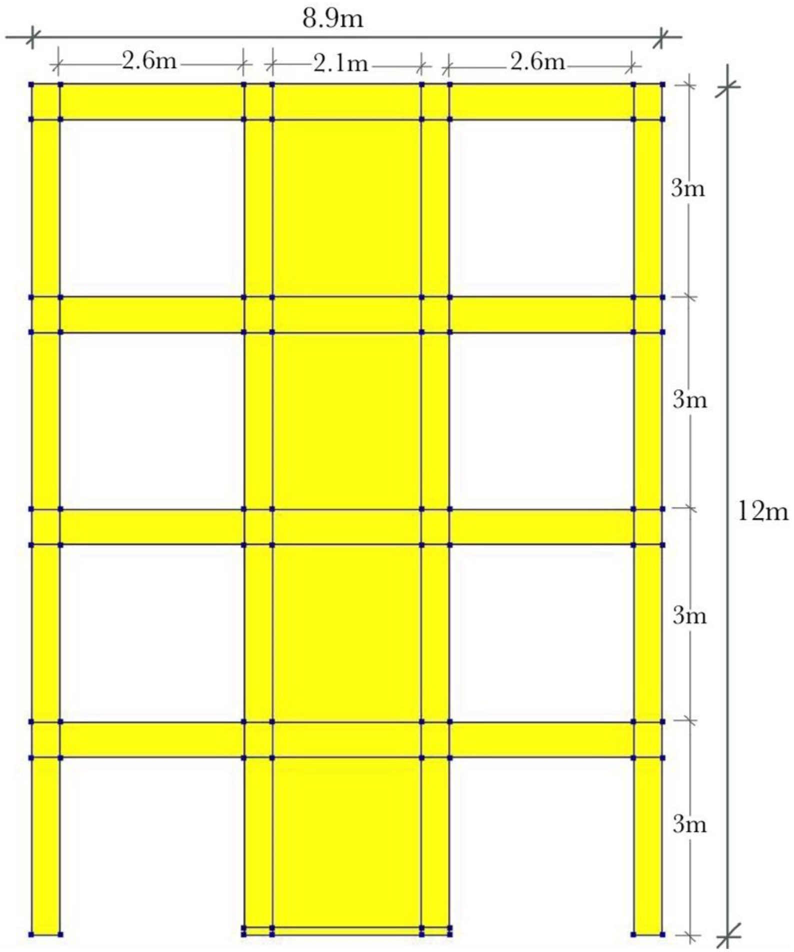
UNIVERSITÉ DE NANTES

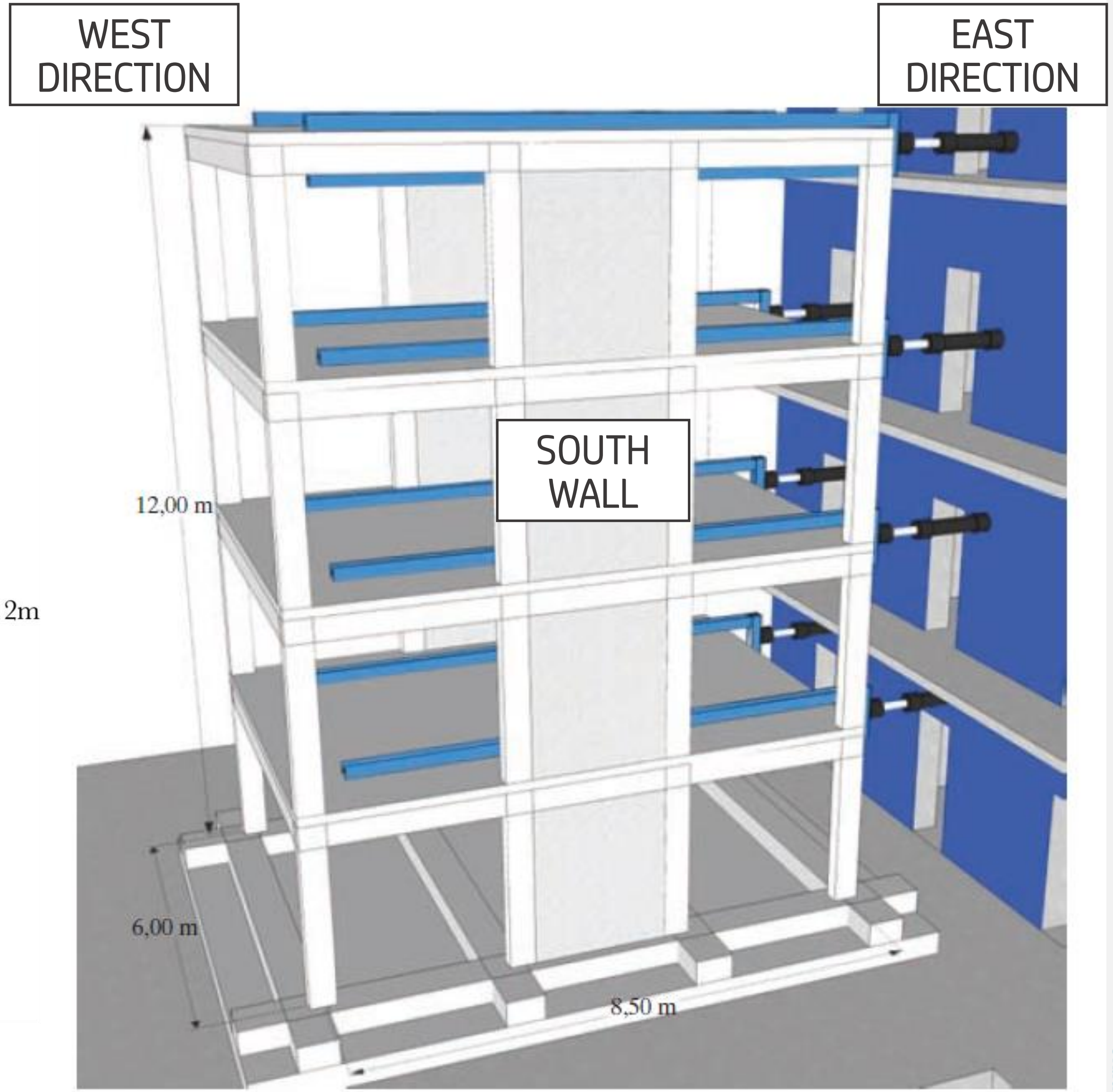
University of Cyprus

DENCO Structural Engineering

Experimental Case Study – Specimen Geometry

- 4 – story with 3 bays
- Central bay infilled with RC wall
- RC infill walls had the same thickness with the frame members – 25cm
- Columns 25x40cm
- Beams 25x50cm
- Slab 15 cm thick





Experimental Case Study – Specimen Design

Design standard

Typical building in the 70's-80's in Cyprus

CP110:1972, BS8110:1983

No provisions for earthquake load

Loads

Gravity loads only (vertically loaded)

Dead load: $3kN/m^2$

Live load: $1.5kN/m^2$

Materials

Concrete

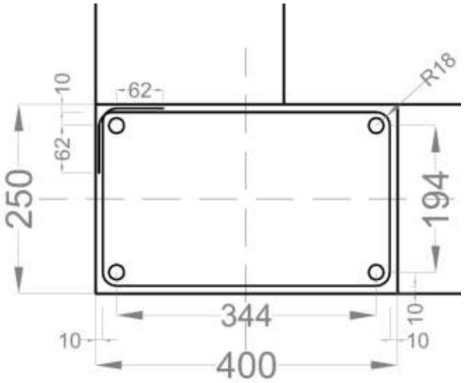
- C20/25
- Unit weight $25kN/m^3$
- E=30GPa

Reinforcement steel

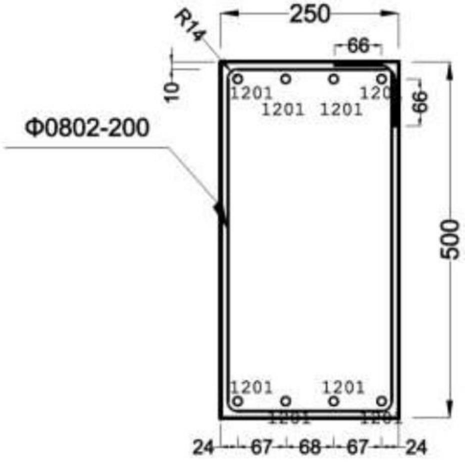
- fyk: 400MPa – existing structure
- fyk:450MPa – RC infill dowels

Experimental Case Study – Specimen Design Details

Reinforcement detail for columns

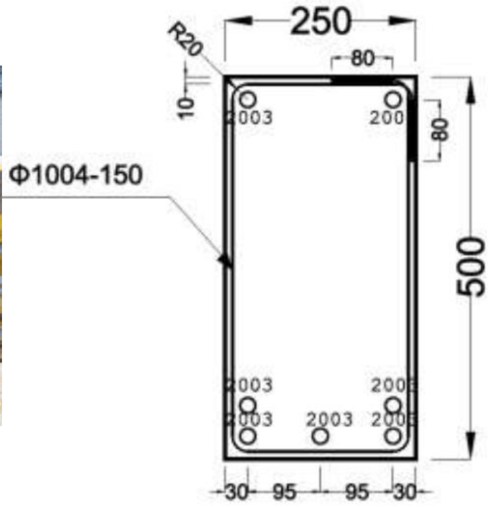


Column cross-section



Longitudinal beam cross-section

Reinforcement detail for beams



Transversal beam cross-section

Columns reinforcement

- 4Y20 longitudinal
  - Spliced right above each slab with 550mm length
- Y8/200 stirrups

Longitudinal Beams reinforcement

- 4Y12 top + bottom
- Y8/200 stirrups

Transversal Beams reinforcement

- 2Y20 top
- 5Y20 bottom
- Y10/150 stirrups

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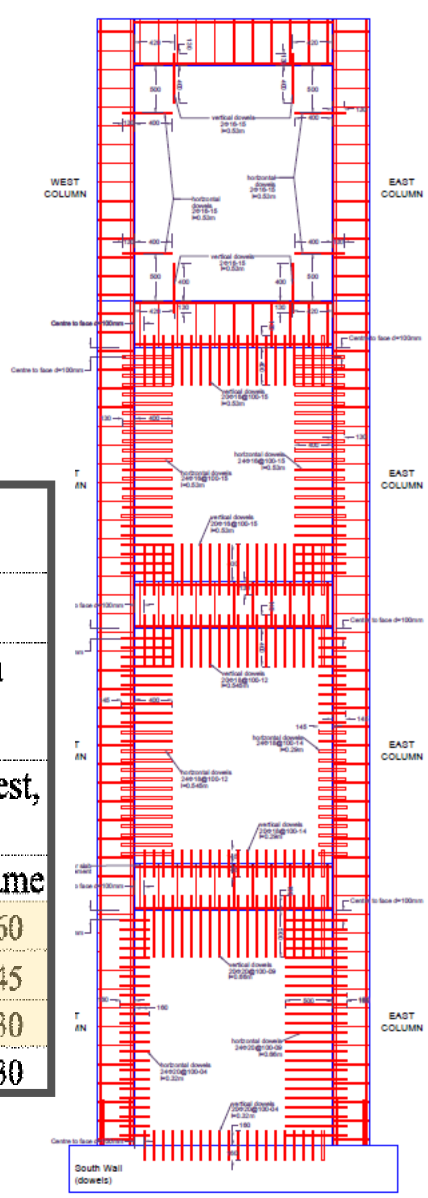
Experimental Case Study – Specimen Design Details

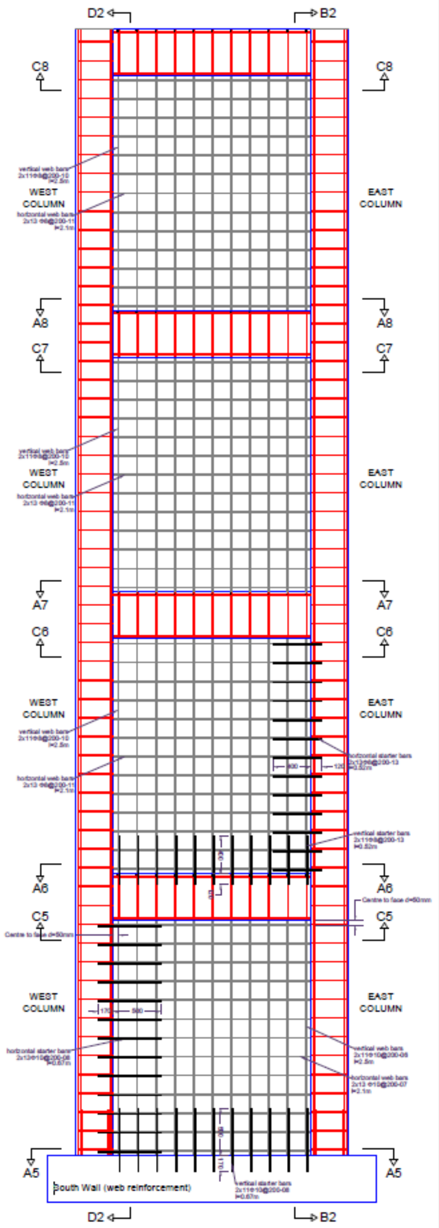
RC Infills & Dowels

- Different amounts of reinforcement for the infills
  - With the North one being the stronger of the two
- Two distinct connection details

Story	N Wall								S Wall							
	web bars	embedment of web starter bars, mm		Dowels					web bars	embedment of web starter bars, mm		dowels				
				Φ mm	embedment, mm							Φ mm	embedment, mm			
		in wall	in frame		bottom & east in:		top&west in:			in wall	In frame		bottom & east in:		top&west, in:	
					wall	frame	wall	frame					wall	frame	wall	frame
1	Φ12@200	600	230	Φ20	160	160	600	190	Φ10@200	500	170	Φ20	160	160	500	160
2	Φ10@200	500	170	Φ20	160	160	500	160	Φ 8@200	400	120	Φ18	145	145	400	145
3	Φ8@200			Φ18	400	145	400	145	Φ8@200			Φ16	400	130	400	130
4	Φ8@200			Φ16	400	130	400	130	Φ8@200			Φ16	400	130	400	130

Wall reinforcement and connection details between the walls and the bounding frame





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Experimental Case Study
Connection Details

Connection detail 1

Starter bars

- Web bars connected with the surrounding frame through lap splicing
- Same diameter starter bars
- Epoxy grouted into the frame members

Short dowels

- Transfer the shear at the interface between the wall and the frame member

Connection detail 2

Longer dowels

- Act both as dowels and as starter bars of the web reinforcement
- These dowels are considered as lap-spliced
- The clear distance between the dowel and the nearest web bar, violated the maximum clear distance of 50mm or 4Φ between lapped bars (Specified in Eurocode 2 (CEN, 2004))

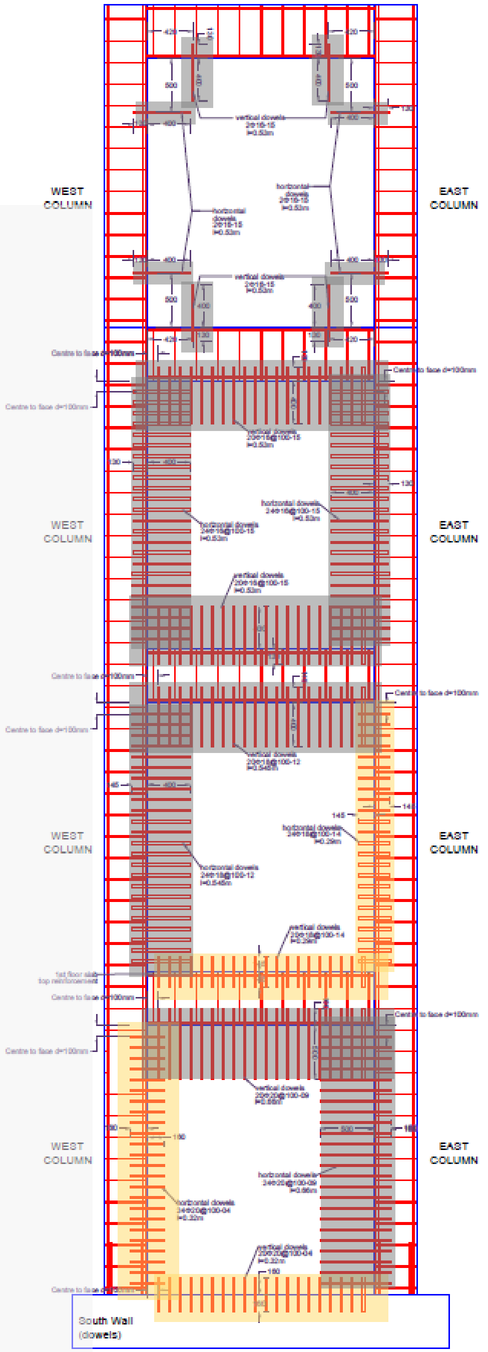

Short dowels

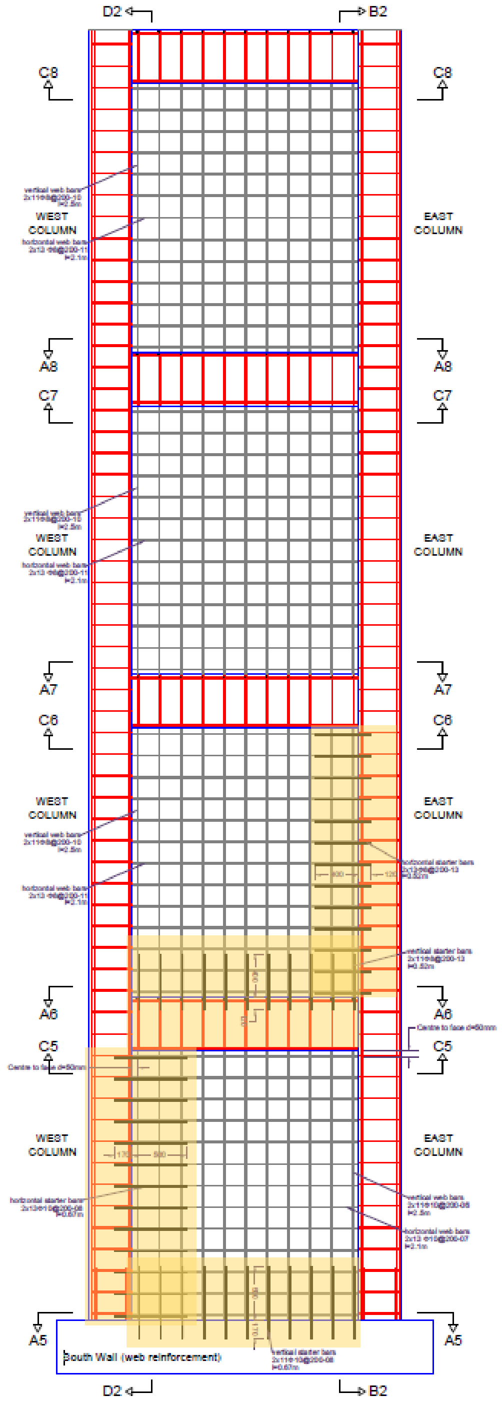

Dowels and starter bars


Dowels, starter bars and web reinforcement


Dowels


Dowels and web reinforcement





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Experimental Case Study – Dowel Details

Connection detail 1

Connection detail 2

Experimental Case Study – Dowel Details

Experimental Case Study – Dowels and web reinf.

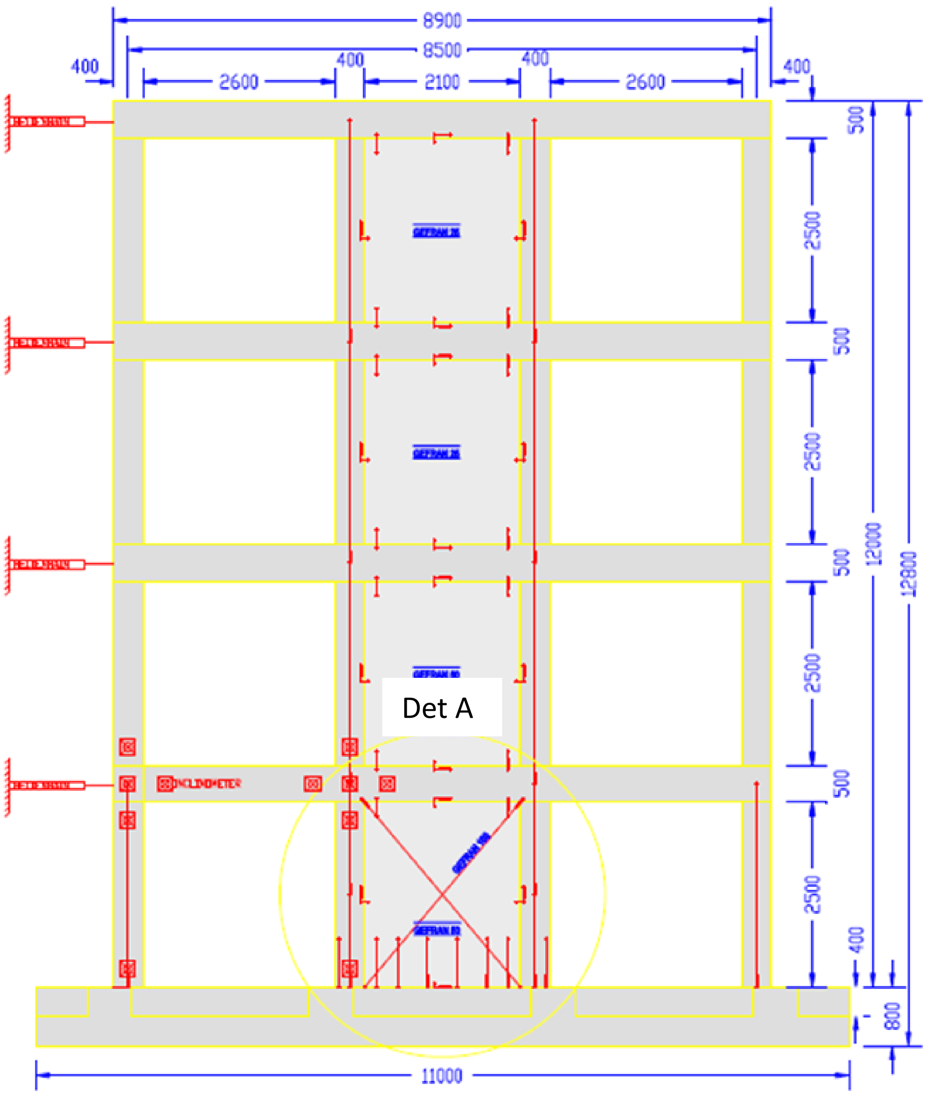
Experimental Case Study – Specimen Design

3-sided CFRP reinforcement jackets to reinforce the edges of the wall

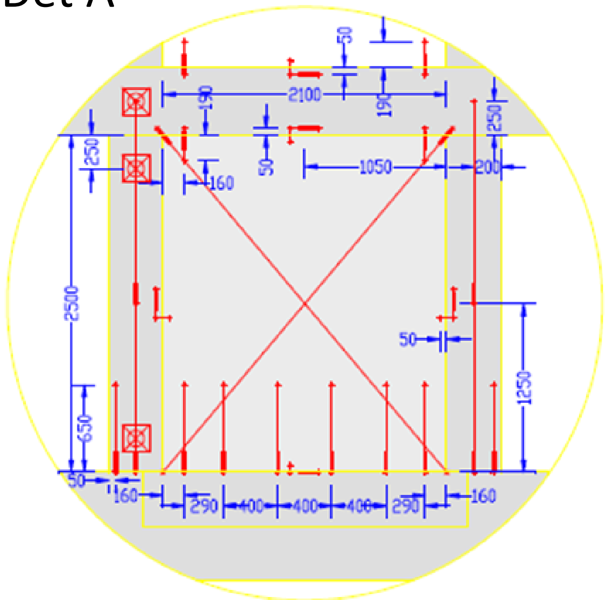
Additional retrofit on the lap length to avoid premature tensile lap-splice failure

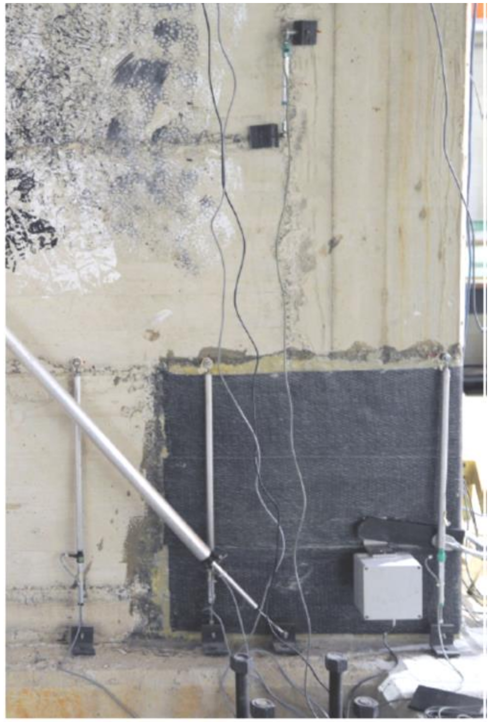
Experimental Case Study – Instrumentation

SERFIN Instrumentation



Det A





Displacement	Gefran PZ12 100	4
	Gefran PZ12 50	68
	Gefran PZ12 25	32
	Heidenhein	8
Inclination	Schaewitz AccuStar	22
Force	Piston Load Cell	8

128 channels

SERFIN Instrumentation

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Experimental Case Study - Tests

Horizontal loading

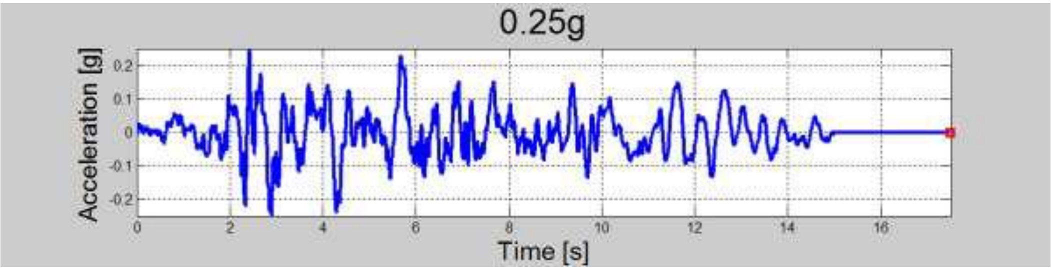
Two uni-directional pseudo-dynamic (Ps-D) tests

- 0.1g acceleration
- 0.25g acceleration

Cyclic loading

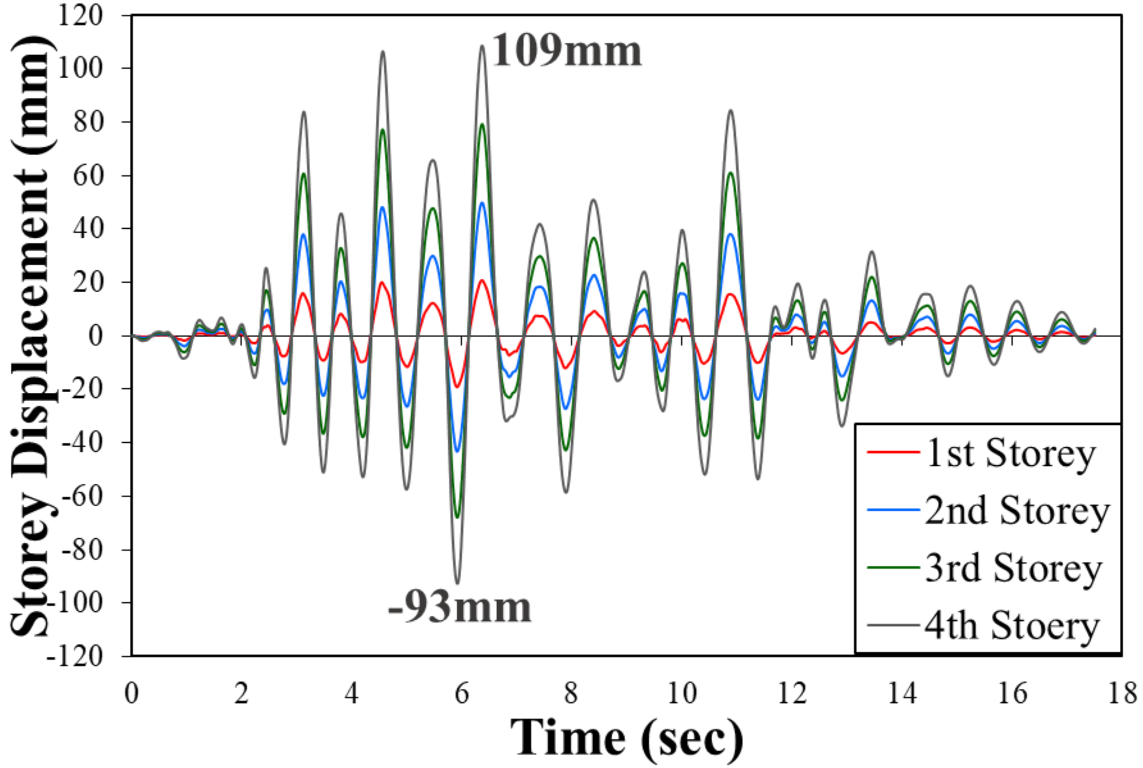
Displacement history was imposed at the top storey: 92, -92, 89, -125, 37, 0 (mm)

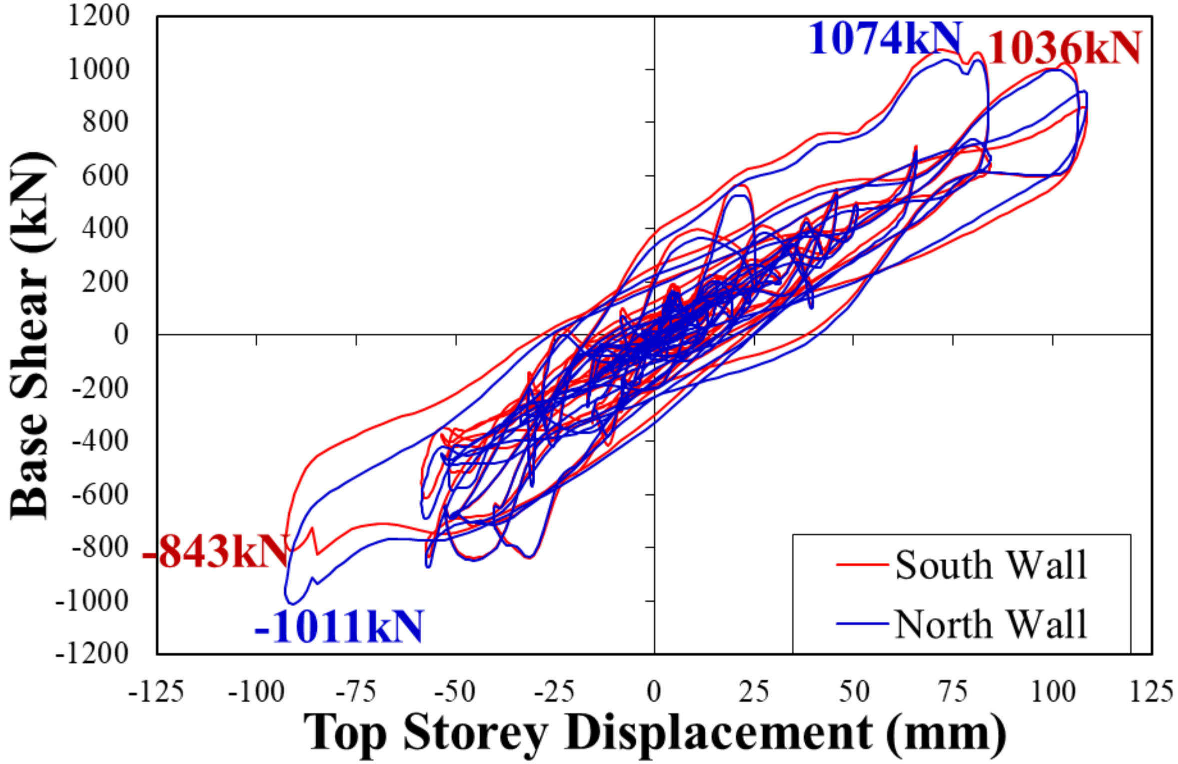
- Triangular distribution of forces was imposed



Herzeg Novi (Montenegro 1979) accelerogram scaled to 0.25g

Experimental Case Study – Global Results
0.25g acceleration test





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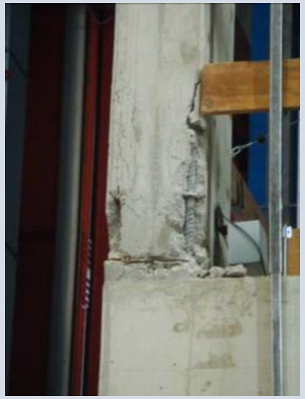
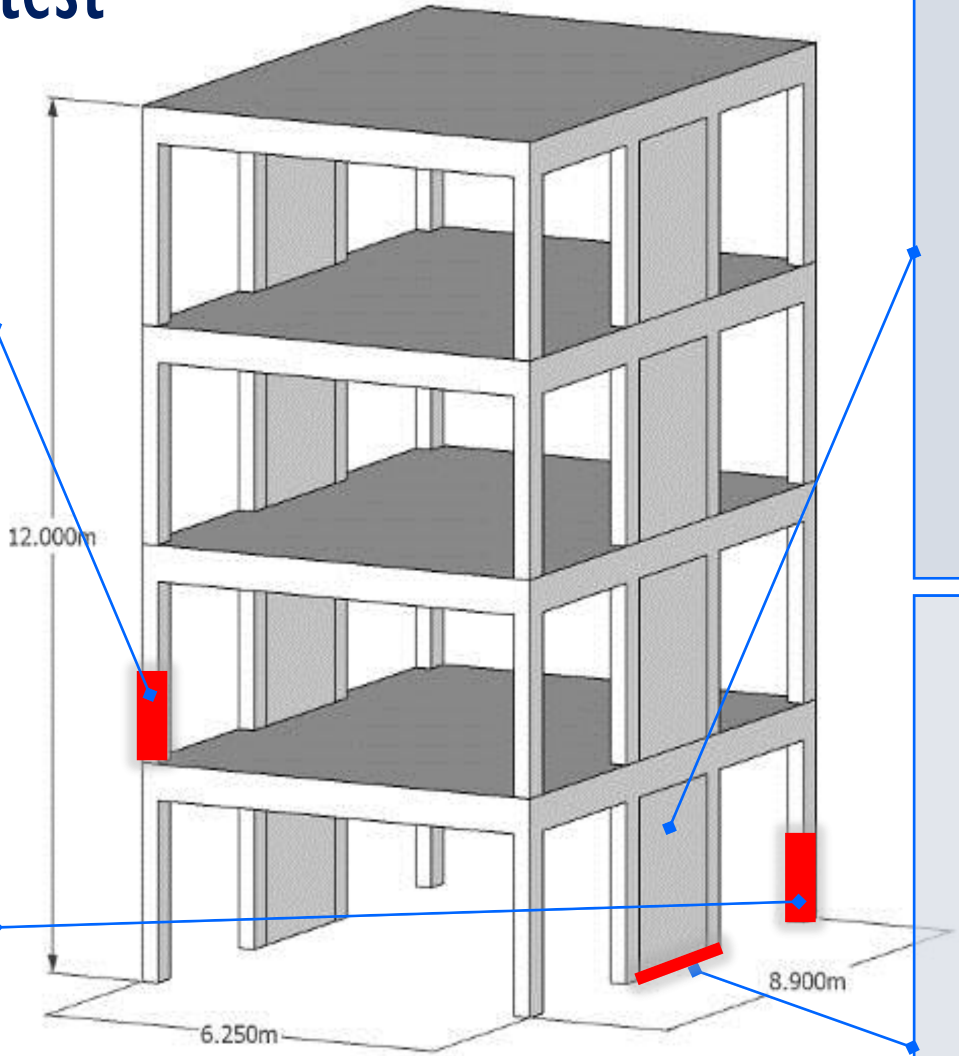
Experimental Case Study – Local Results

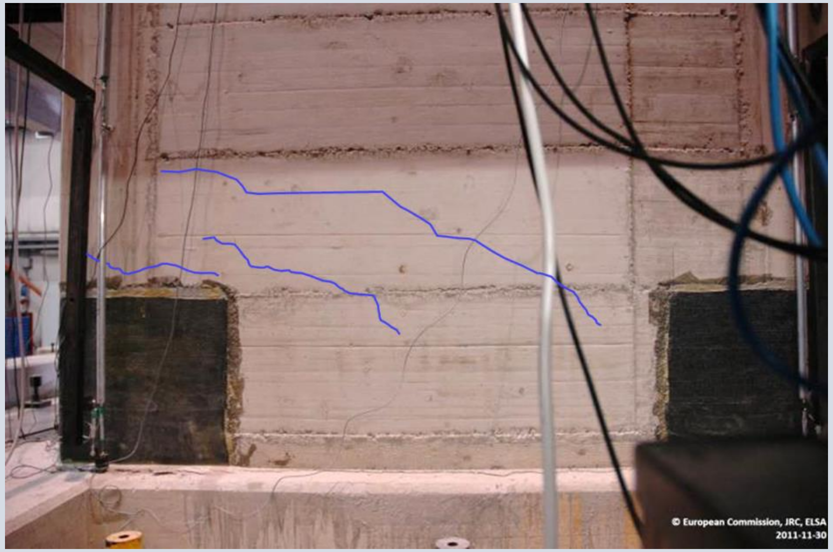
0.25g acceleration test



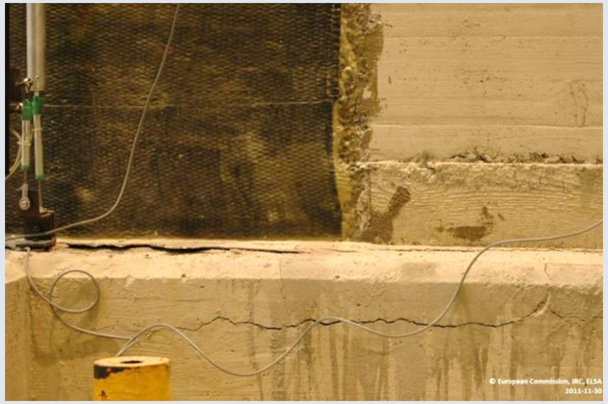
Failure of the lap splice joint
N frame

Tensile lap-splice failure of
the column at the bottom





Hairline cracks develop in the wall



Crack opens at the bottom
of the column-wall

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Conclusions from the experiment

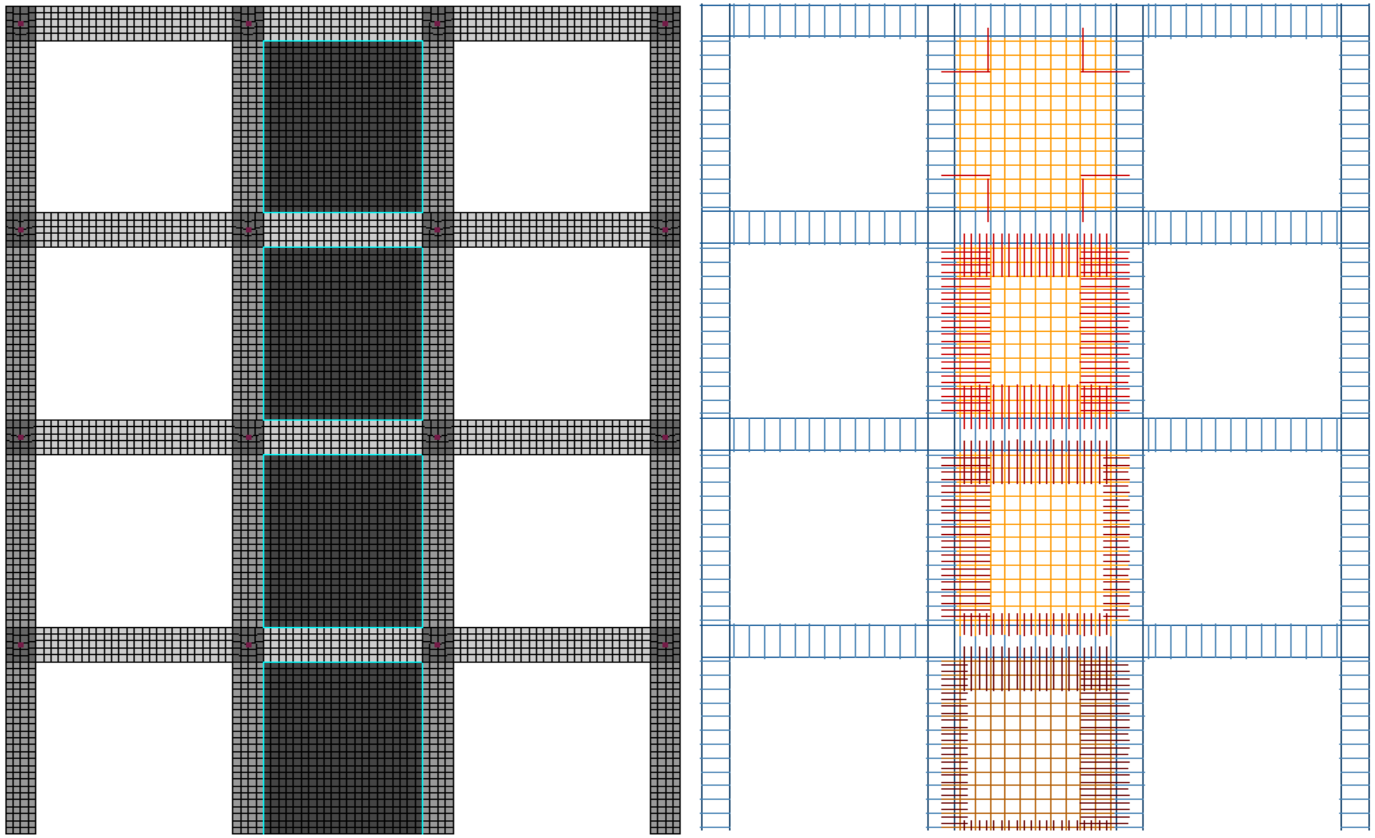
- The structure managed to sustain an earthquake of 0.25g without significant damage (5-fold increase compared to the bare frame)
- Some column lap-splices failed with concrete spalling, but the structure continued to carry load
- The 3-sided FRPs protected the wall bounding columns at the 1st floor and prevented lap-splice failure
- The “weak” frame behaved equally well as the “strong” frame

Conclusions from the experiment

- There has not been visible movement at the interface between the wall and the bounding frame
- The behaviour of the wall was mainly flexural, although on the south-frame wall some diagonal cracks appeared
- Some vertical cracks appeared at the connection of the beams to both the exterior column and the wall columns
- A horizontal crack appeared at the ground beam of the walls, and it was the main reason for loss of strength of the south frame
- The proposed system seems to behave in a satisfactory manner

Construction – Testing – Demolition

Finite Element model



	1st FE Model	2nd FE Model
Dowels take shear forces	-	✓
Dowels take axial forces	-	✓
Gap criterion between bounding frame and infill wall (non monolithic)	Monolithic behavior	✓

DIANA FEA was used

Assumptions:

- Rigid foundation
- 2D - modeling of the south frame
- CFRPs were not considered

Geometry definition: same with SERFIN specimen in a 2D model

- Half of the slab and transverse beams weight was added to the joints

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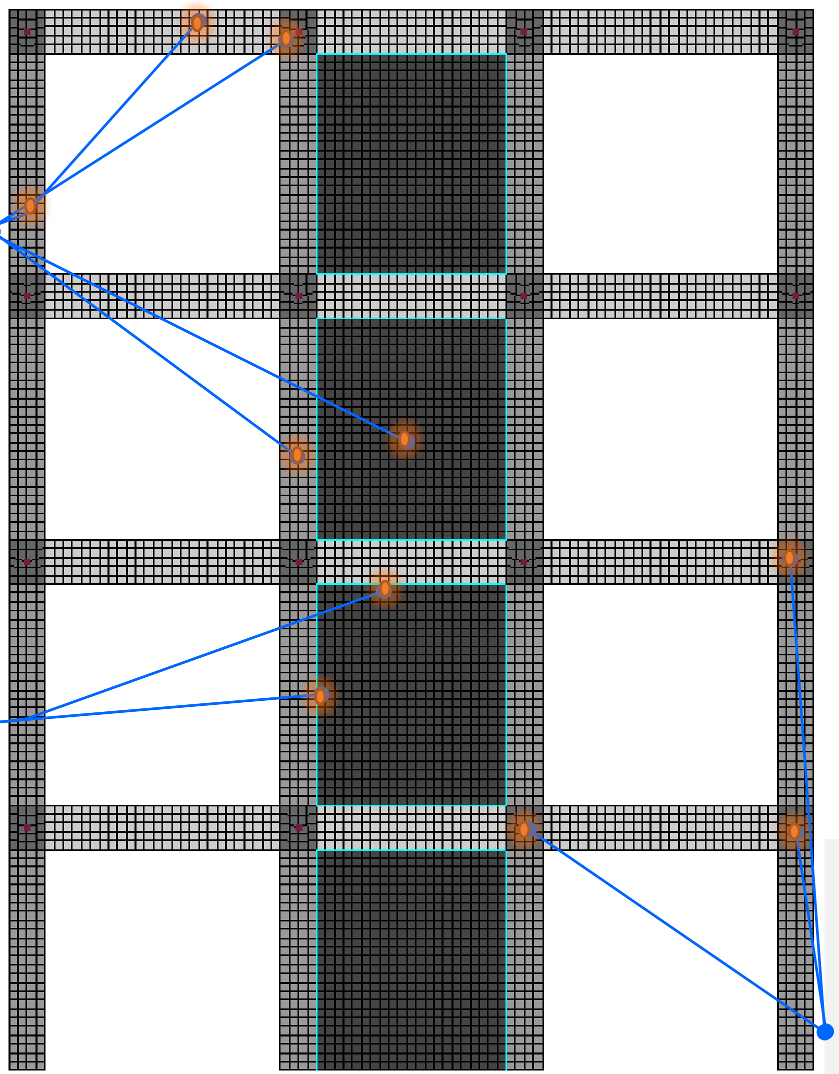
Finite Element model – elements & mesh

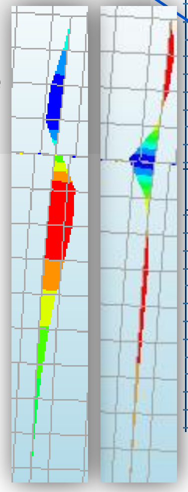
Plane stress elements CQ16M Quadrilateral – 8 nodes
Thickness 250mm
5480 elements
100x100mm

2D line interface elements CL12I
Thickness 250mm (width)
16 elements

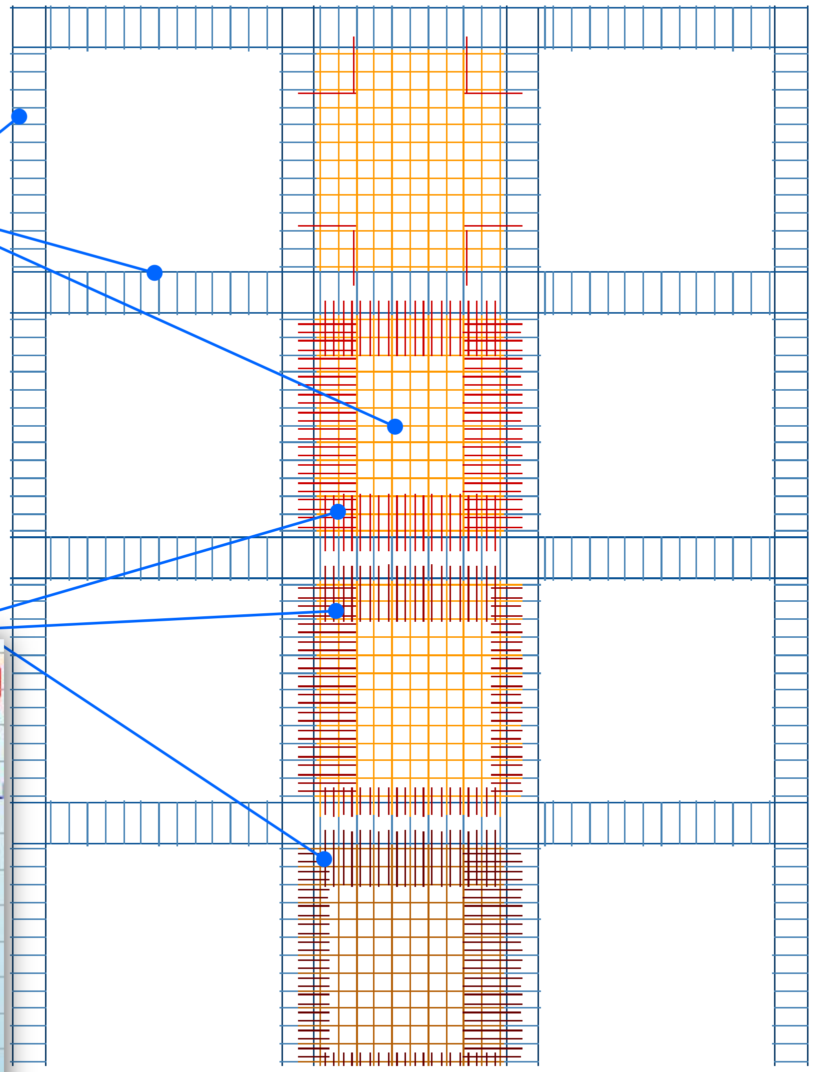


Embedded bar reinforcement in plane stress elements
Cross section-area of bars
(Y8, Y10, Y12, Y20)

Bond-slip reinforcement with Beam elements BAR LINE, INTERF BEAM
Diameter of circle
(Y16, Y18, Y20)



Point mass elements PT3T
1 node
16 elements
Half weight of building frames



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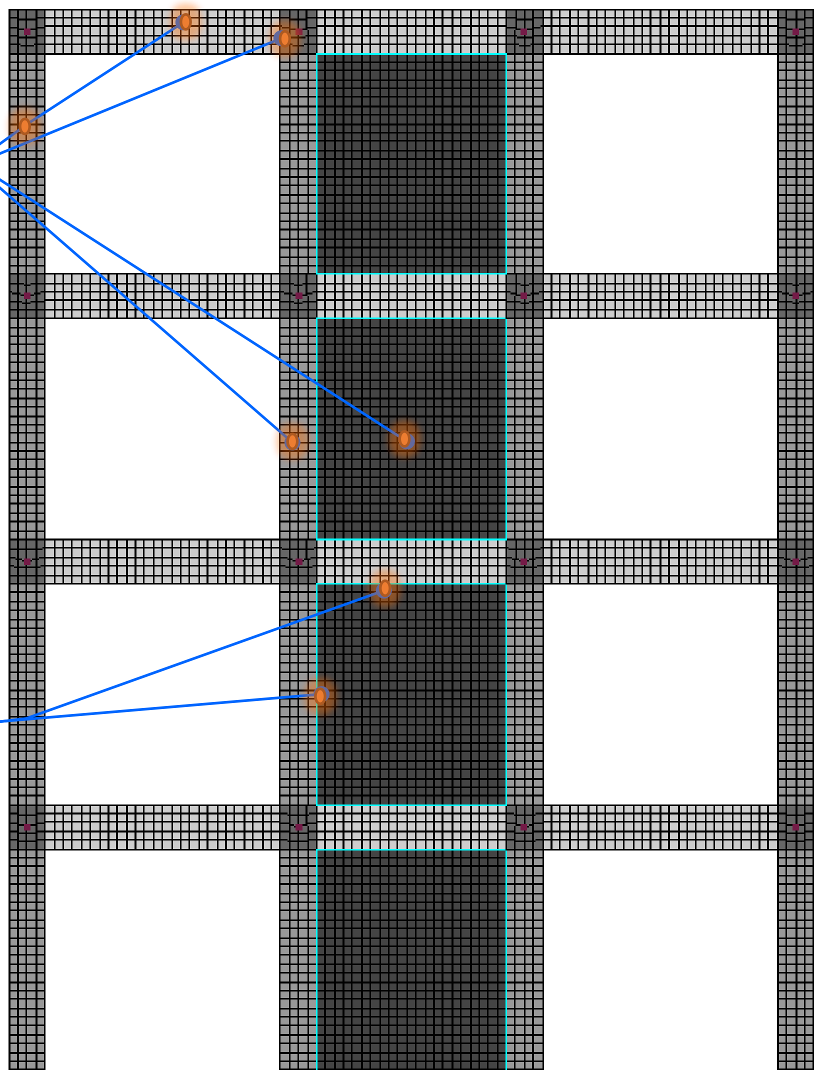
Finite Element model – material models

Total strain based cracked model for **Concrete**

Coulomb friction with Brittle Gapping model for **Interface**



Linear material properties

- Young's modulus (15GPa), reduced
- Poisson's ratio (0.2)
- Mass density (2500kg/m³)

Total strain based cracked model

- Rotating crack orientation
- Crack bandwidth specification (Rots)

Tensile behavior

- Tensile curve (fib Model Code for Concrete Structures 2010)
  - Tensile strength (2.6MPa))
  - Mode-I tensile fracture energy

Compressive behavior

- Compressive curve (Maekawa cracked concrete curves)
  - Compressive strength (33MPa)
  - Stress confinement (No increase)

Finite Element model – material models

Linear elasticity
- Young's modulus 20GPa

Menegotto-Pinto
- Yield stress 450MPa for walls, 400MPa for frame members

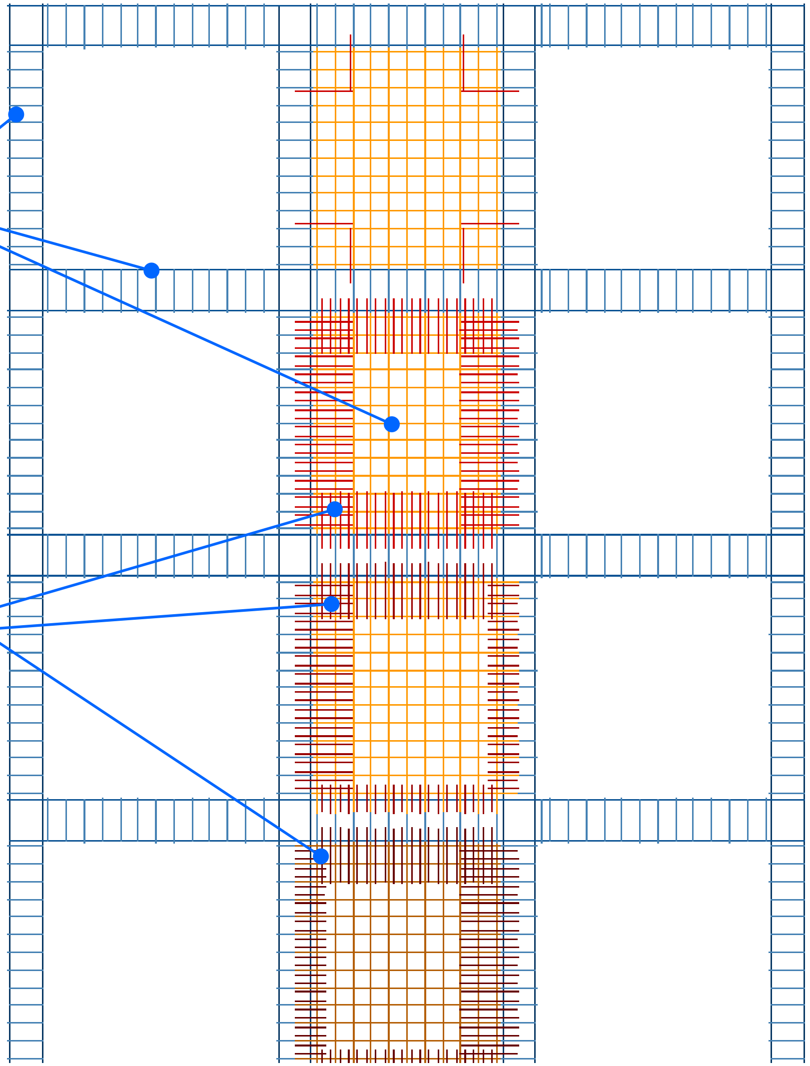
Menegotto-Pinto model for **Reinforcement steel**

Reinforcement bar
- Young's modulus 200GPa
- Mass density 7800kg/m³
- Plasticity model: von Mises plasticity

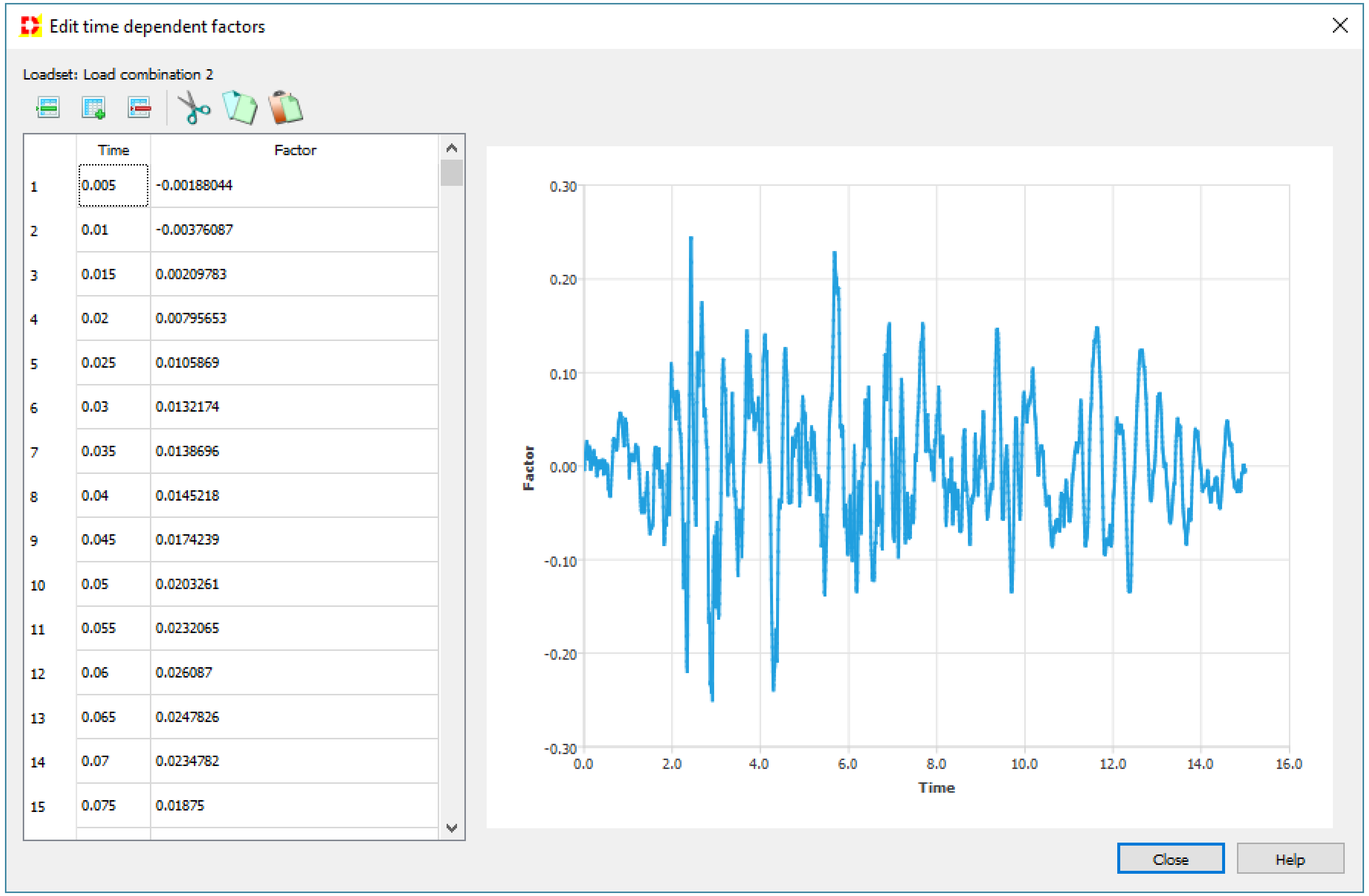
Von Mises parameters
- Hardening function (no hardening)
- Yield stress (450MPa)

Von Mises plasticity model for **Dowels**

Bond-slip interface
- Normal stiffness modulus
- Shear stiffness modulus
- Bond-slip interface failure model (Shima bondslip function)
  - Compression strength 33MPa

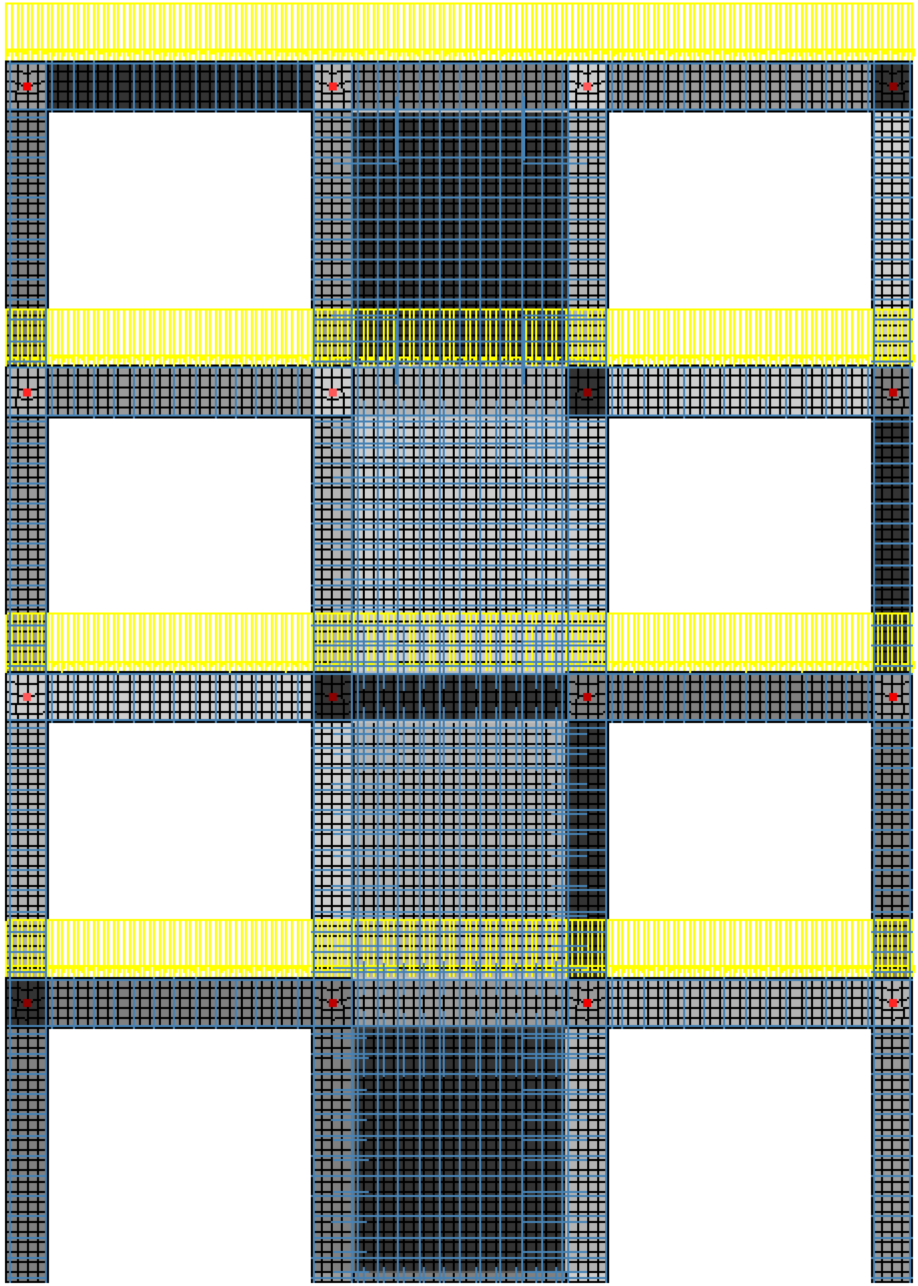


Finite Element model – loading



	Time	Factor
1	0.005	-0.00188044
2	0.01	-0.00376087
3	0.015	0.00209783
4	0.02	0.00795653
5	0.025	0.0105869
6	0.03	0.0132174
7	0.035	0.0138696
8	0.04	0.0145218
9	0.045	0.0174239
10	0.05	0.0203261
11	0.055	0.0232065
12	0.06	0.026087
13	0.065	0.0247826
14	0.07	0.0234782
15	0.075	0.01875

Herzeg Novi (Montenegro 1979) accelerogram scaled to 0.25g



Gravity vertically loads

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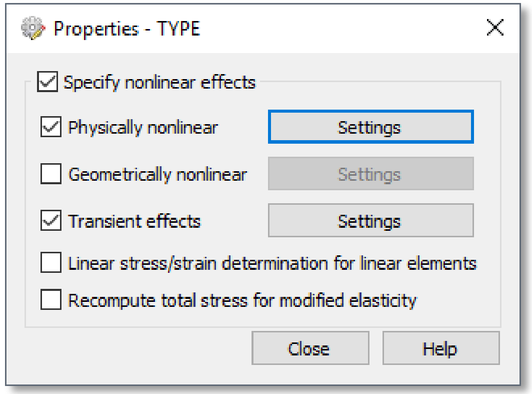
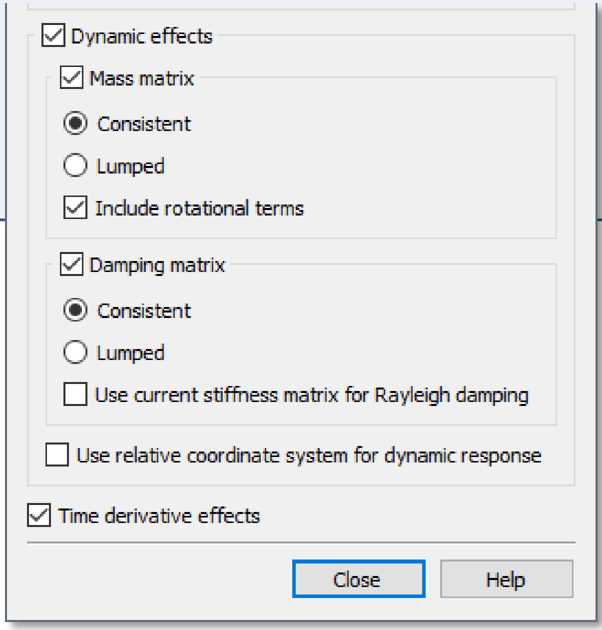
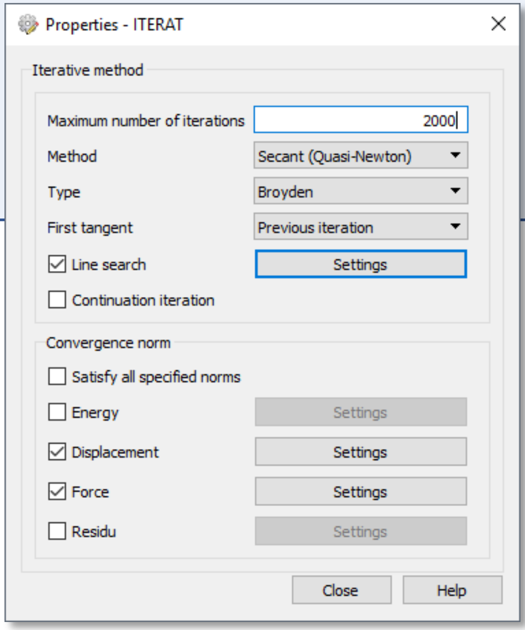
Finite Element model – Structural nonlinear analysis

Nonlinear effects	Equilibrium iteration Iterative method	Convergence norm
– Physically nonlinear	– Secant (Quasi-Newton)	– Force (0.01 Model1, 0.005 Model2)
– Transient effects	– Line search	– Displacement (0.01 Model1, 0.005 Model2)
– Executive steps (time steps)		
– 0.005 (3000 steps) – Model1		
– 0.002 (7500 steps) – Model2		







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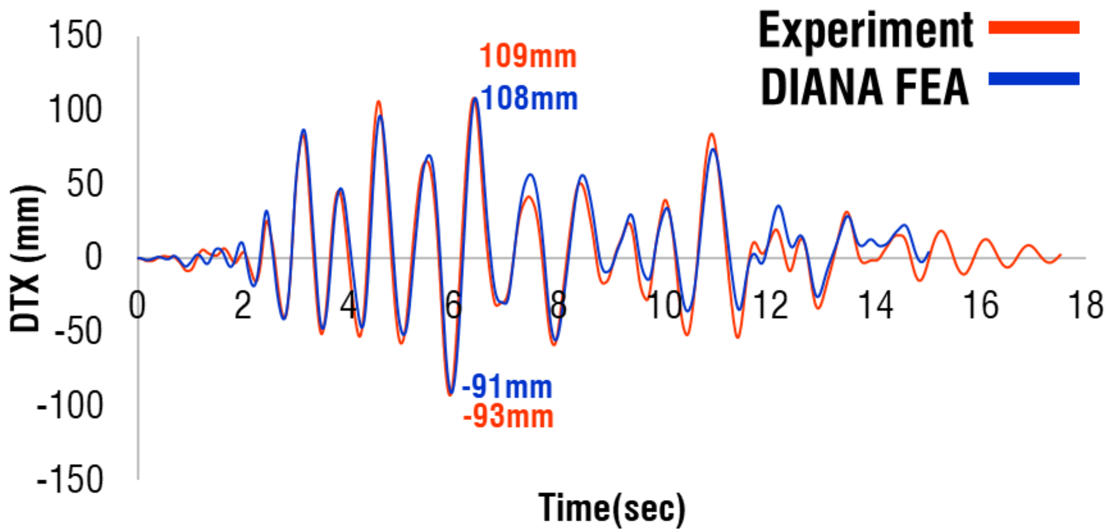
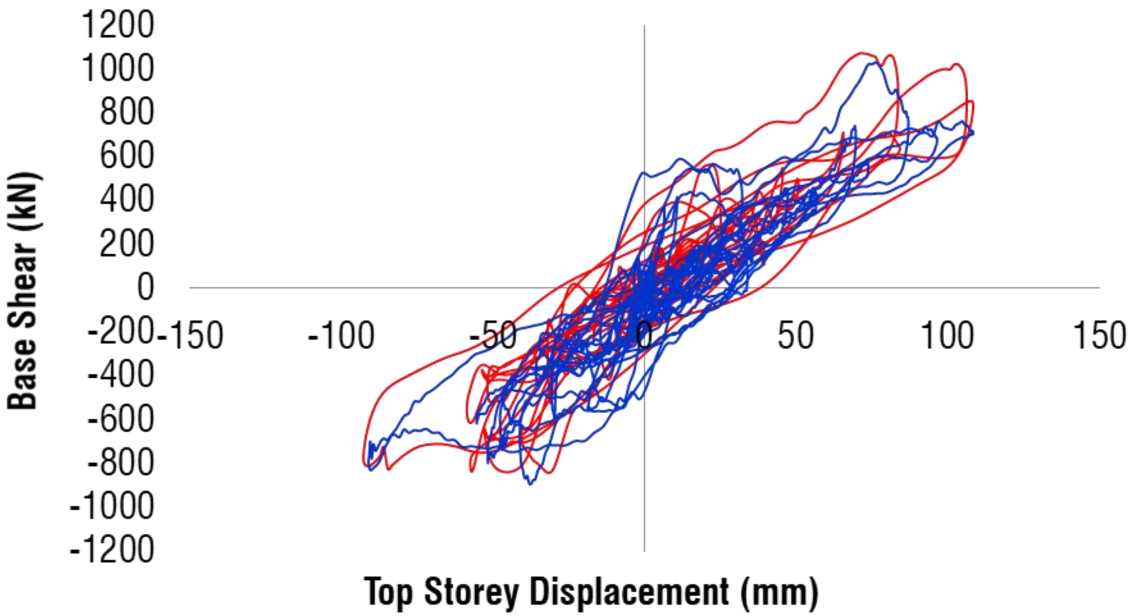
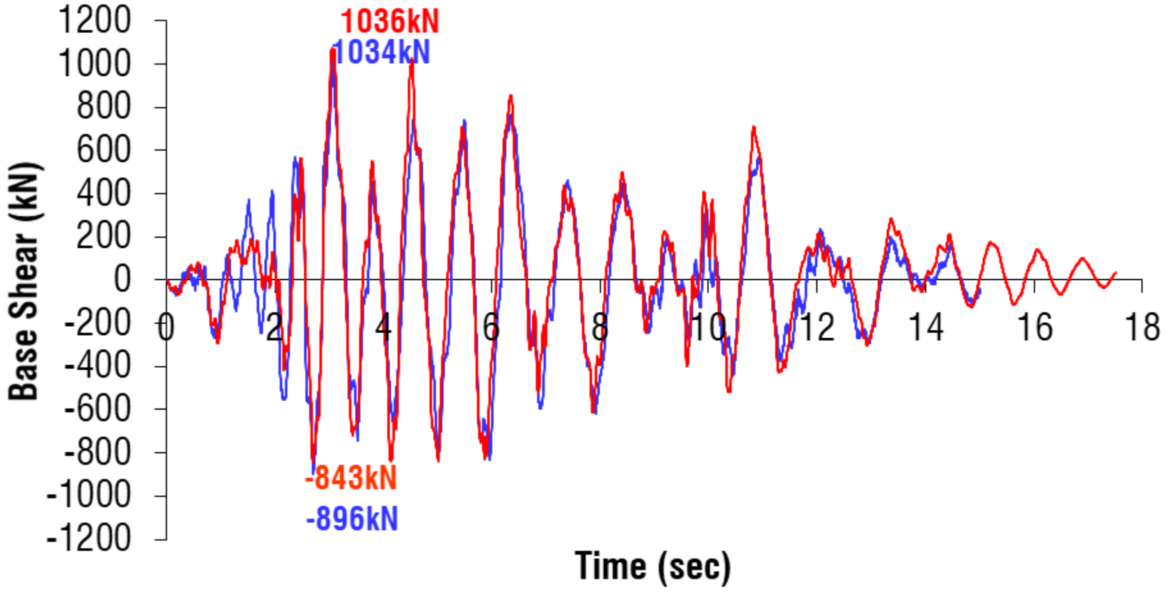
Finite Element Results – Global results comparison – ModelI

4th floor displacements



Base shear vs displacement



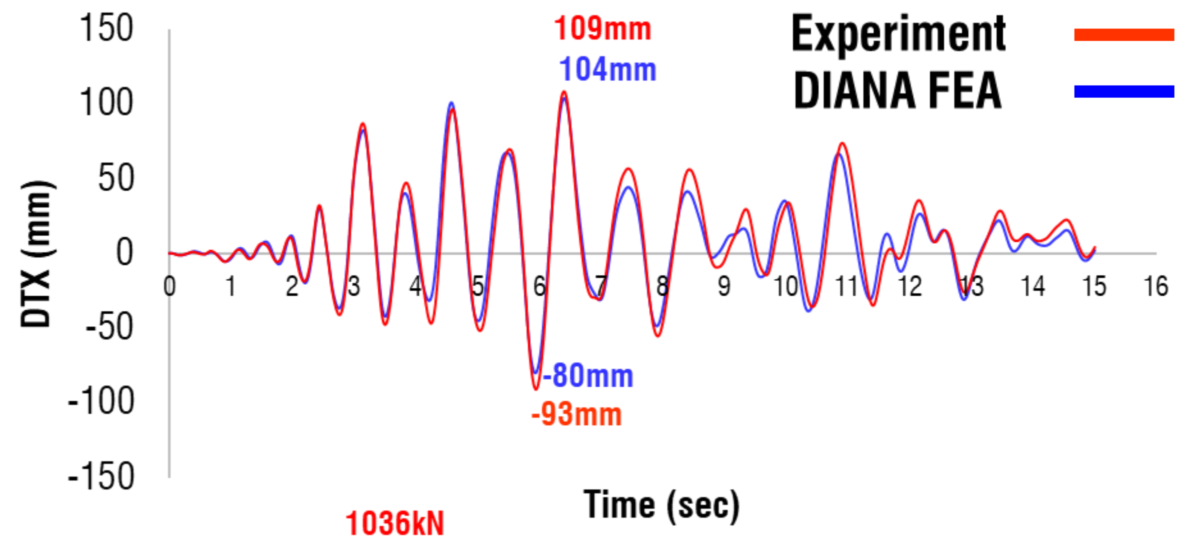


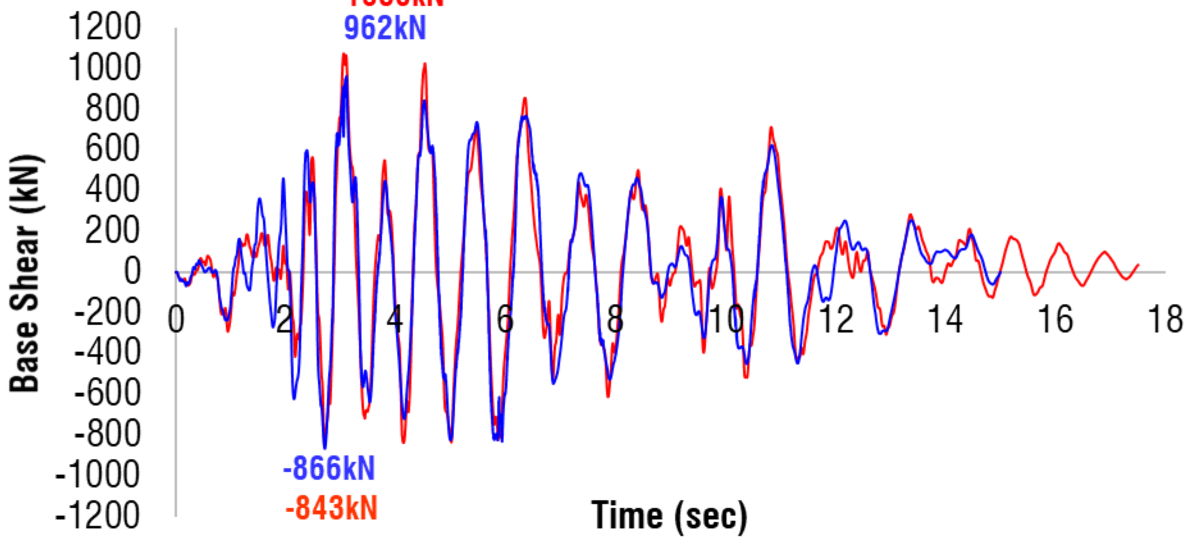
Base shear force

1st FE Model
• Dowels modeled as embedded reinforcement bars (can't take shear forces or moments) • No interface line elements between the bounding frame and the infill wall (monolithic)

Finite Element Results – Global results comparison – Model2

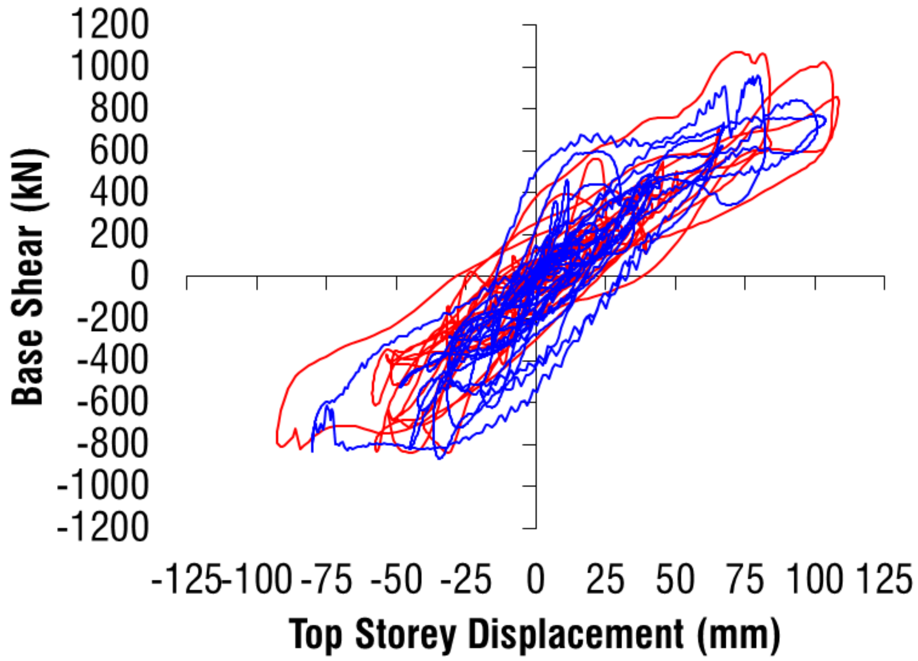
4th floor displacements





Base shear force

Base shear vs displacement



2nd FE Model
• Dowels modeled as circular beam bond-slip reinforcement (can take shear forces and moments) • With interface line elements between the bounding frame and the infill wall (with gap criterion and Coulomb friction model)

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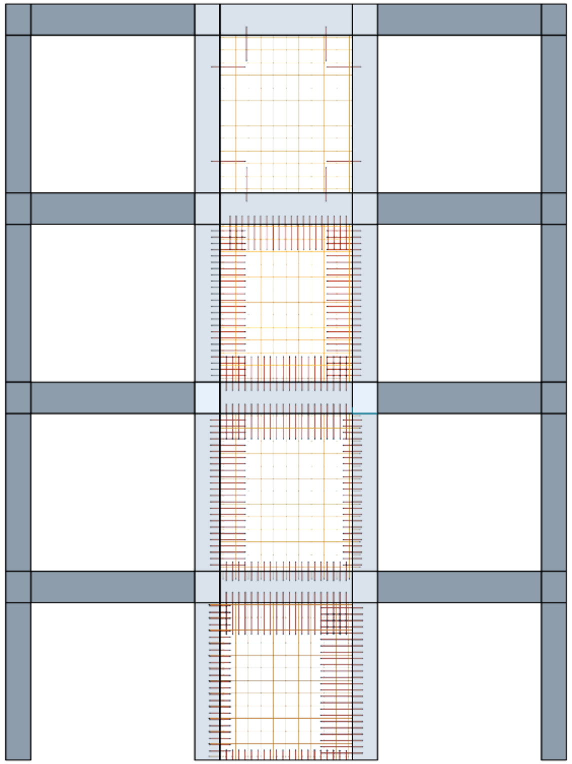
Parametric Case Scenarios – Numerical Simulations

Dowels connecting the wall to the bounding frame	Case 1 Validated model	Case 2 10 Dowels	Case 3 6 Dowels	Case 4 4 Dowels	Case 5 2 Dowels	Case 6 2 Dowels only on beams
Ground Floor Columns	24Y20/100	10Y20/250	6Y20/460	4Y20/760	2Y20/2300	2Y20/2300
Ground Floor Beams	20Y20/100	10Y20/210	6Y20/380	4Y20/630	2Y20/1900	2Y20/1900
1st Floor Columns	24Y18/100	10Y18/250	6Y18/460	4Y18/760	2Y18/2300	2Y18/2300
1st Floor Beams	20Y18/100	10Y18/210	6Y18/380	4Y18/630	2Y18/1900	2Y18/1900
2nd Floor Columns	24Y16/100	10Y16/250	6Y16/460	4Y16/760	2Y16/2300	2Y16/2300
2nd Floor Beams	20Y16/100	10Y16/210	6Y16/380	4Y16/630	2Y16/1900	2Y16/1900
3rd Floor Columns & Beams	2Y16	2Y16	2Y16	2Y16	2Y16	2Y16



Validated model - calibrated in DIANA FEA

Same number of dowels like the SERFIN experiment

Parametric-study scenarios models

Another 5 different cases of the number of dowels in the model

Same analysis procedure with 0.25g earthquake record were used for all the parametric-study scenarios

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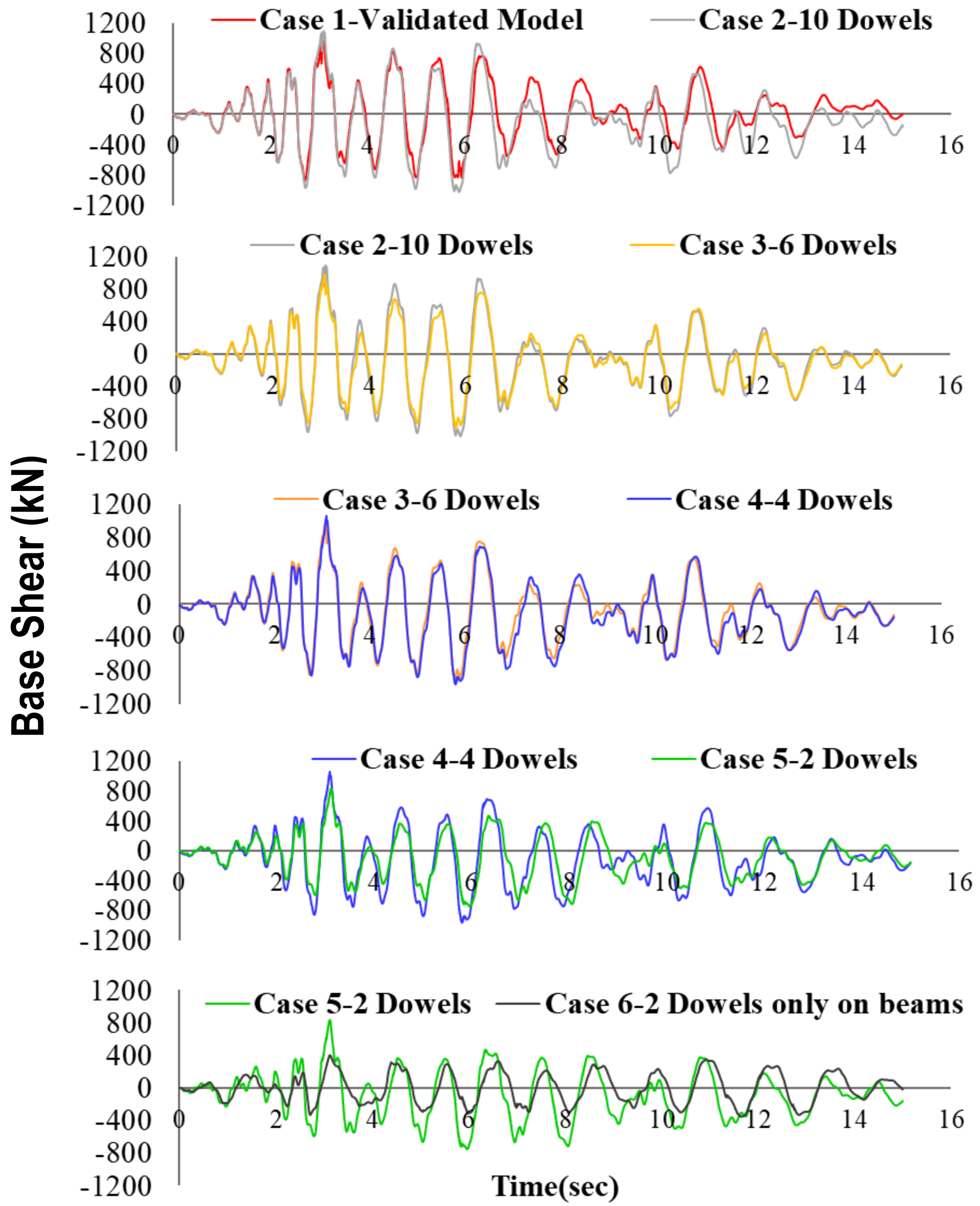
Numerical Results – Base Shear Forces

	Case 1	Validated Model
	Case 2	10 Dowels
	Case 3	6 Dowels
	Case 4	4 Dowels
	Case 5	2 Dowels
	Case 6	2 Dowels only on beams

About the same values for the first four cases

More obvious reduction of the base shear after the fifth case scenario

The lower the number of dowels, the lower the base shear-force of the building

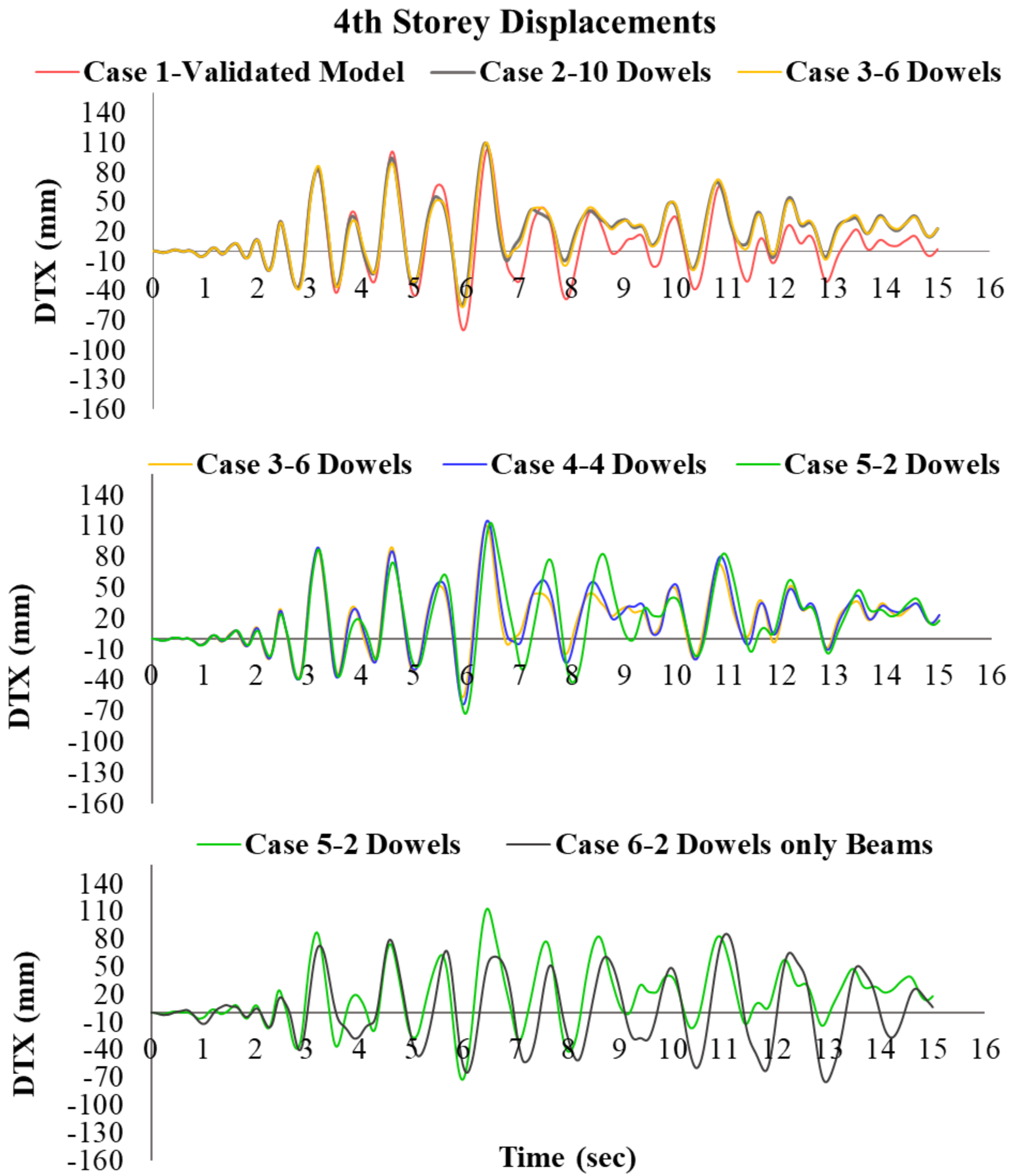


Numerical Results
Top Storey Displacements

Red	Case 1	Validated Model
Grey	Case 2	10 Dowels
Yellow	Case 3	6 Dowels
Blue	Case 4	4 Dowels
Green	Case 5	2 Dowels
Dark grey	Case 6	2 Dowels only on beams

Indication that the building got some **permanent deformations** *(in the positive direction)*

The **elastic characteristics (reduced stiffness and fundamental frequency)** of the frame have changed with the reduction of the number of dowels *after the third case scenario*



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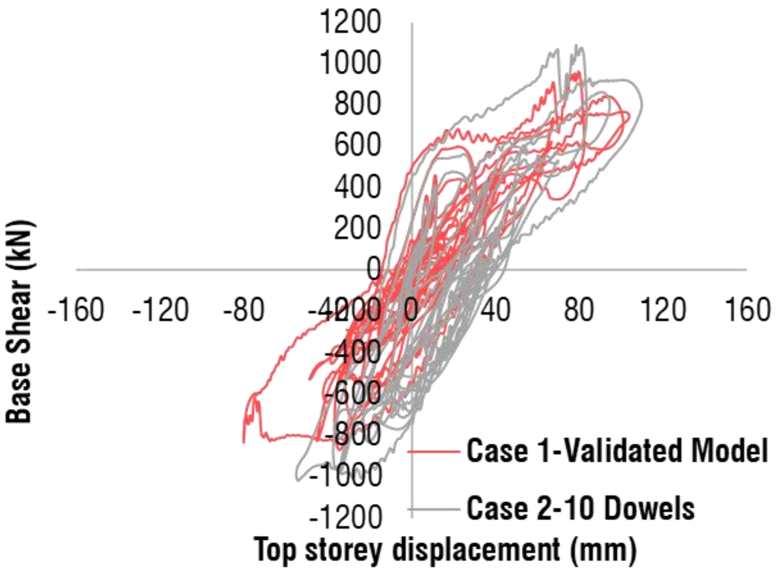
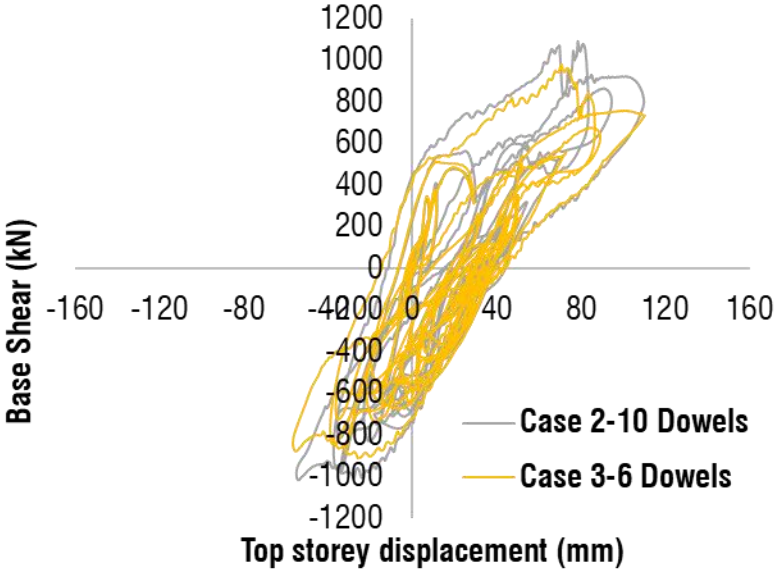
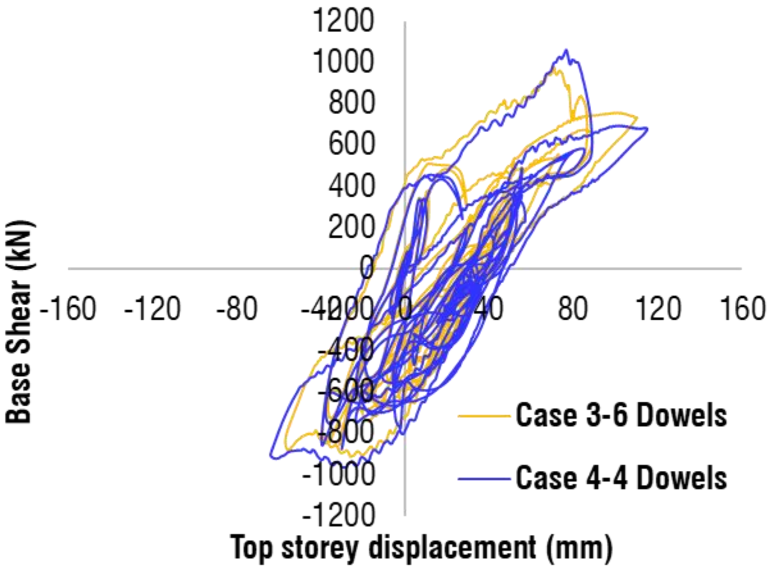
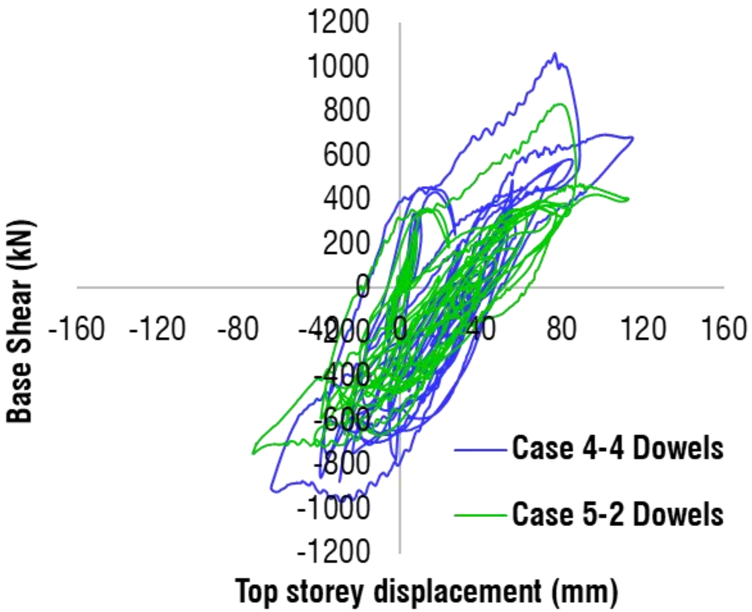
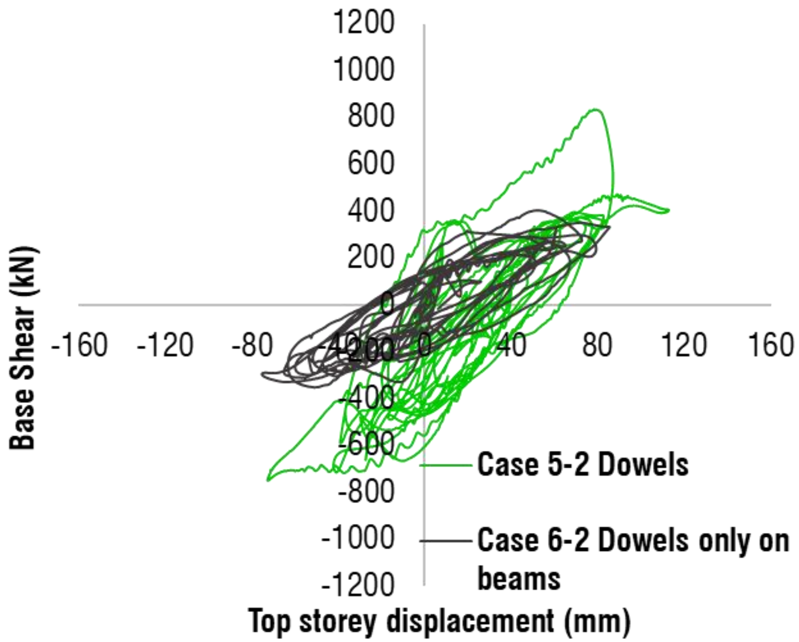
Numerical Results – Base Shear Forces Vs Top Storey Displacements











Decrease of the **base shear-force**, **stiffness** and **energy dissipation** of the frame - *when the dowels are reduced to two*

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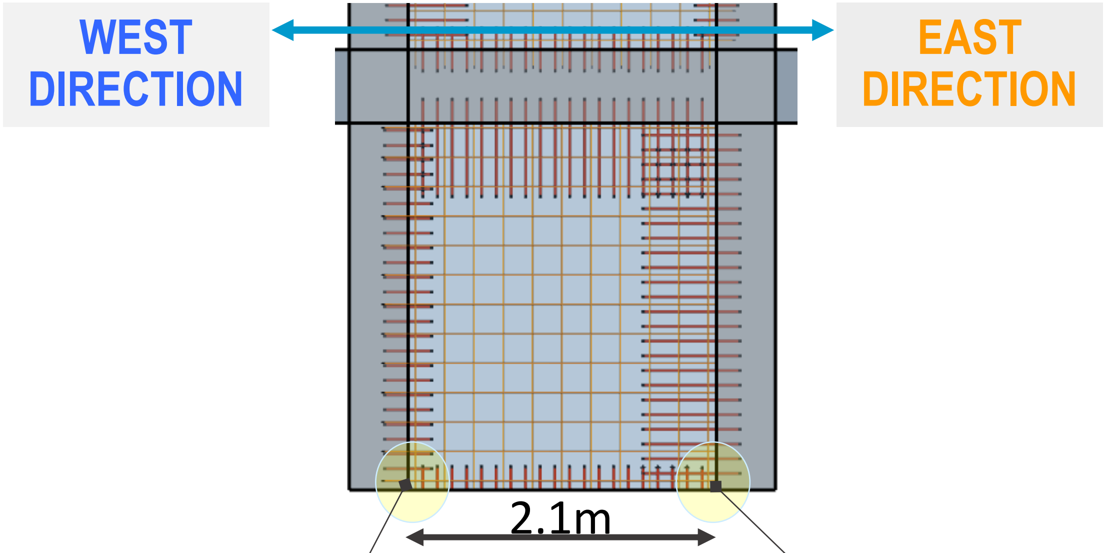
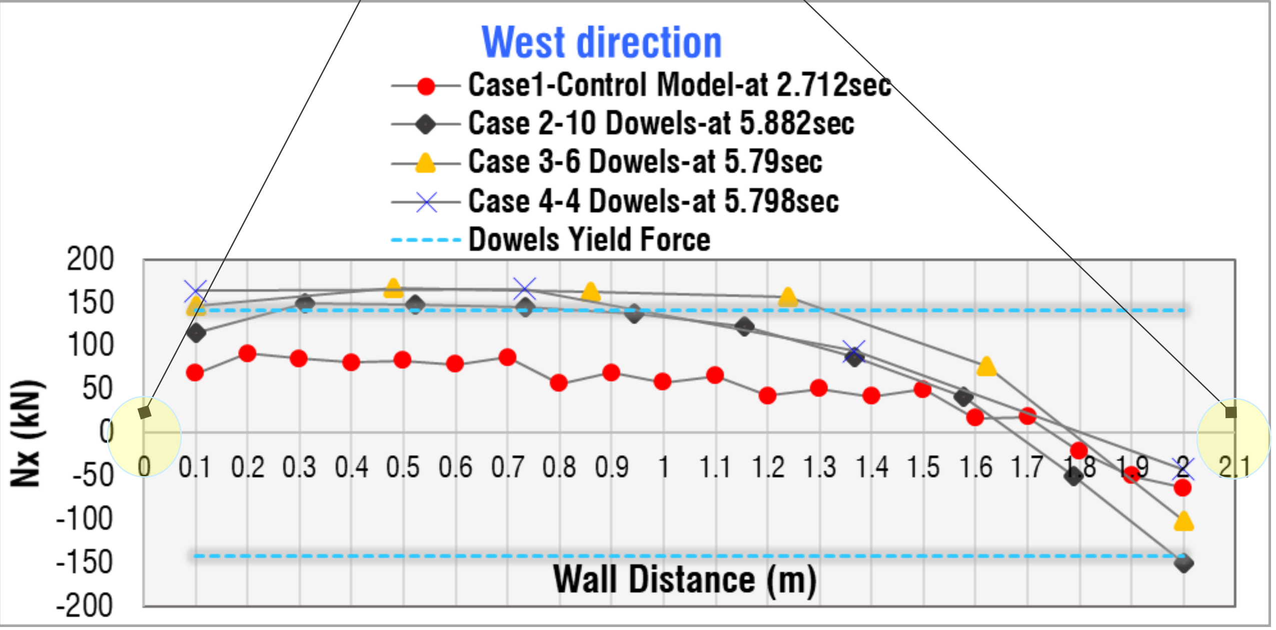
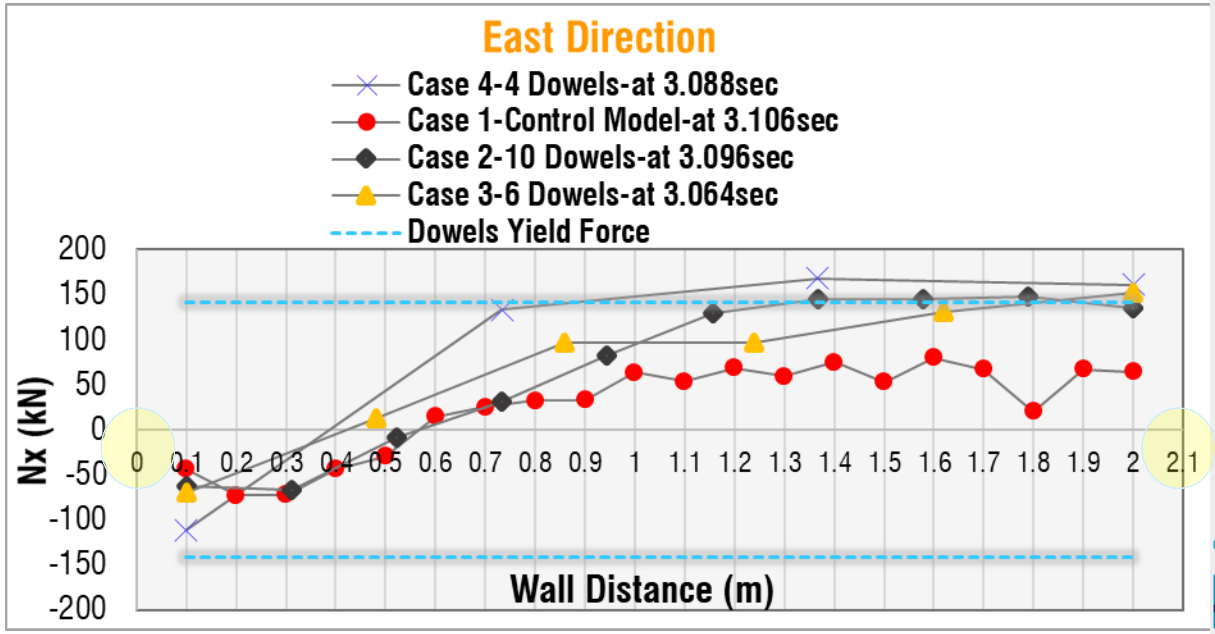
Dowels at the base

Axial forces of dowels along the length of the wall when total base shear is maximum



- The dowels of the validated model in the first case scenario take the lowest forces
- The dowels in the 2nd, 3rd and 4th scenarios take higher forces (higher than their capacity)
- More dowels reached their yield force with the reduction of the number of dowels





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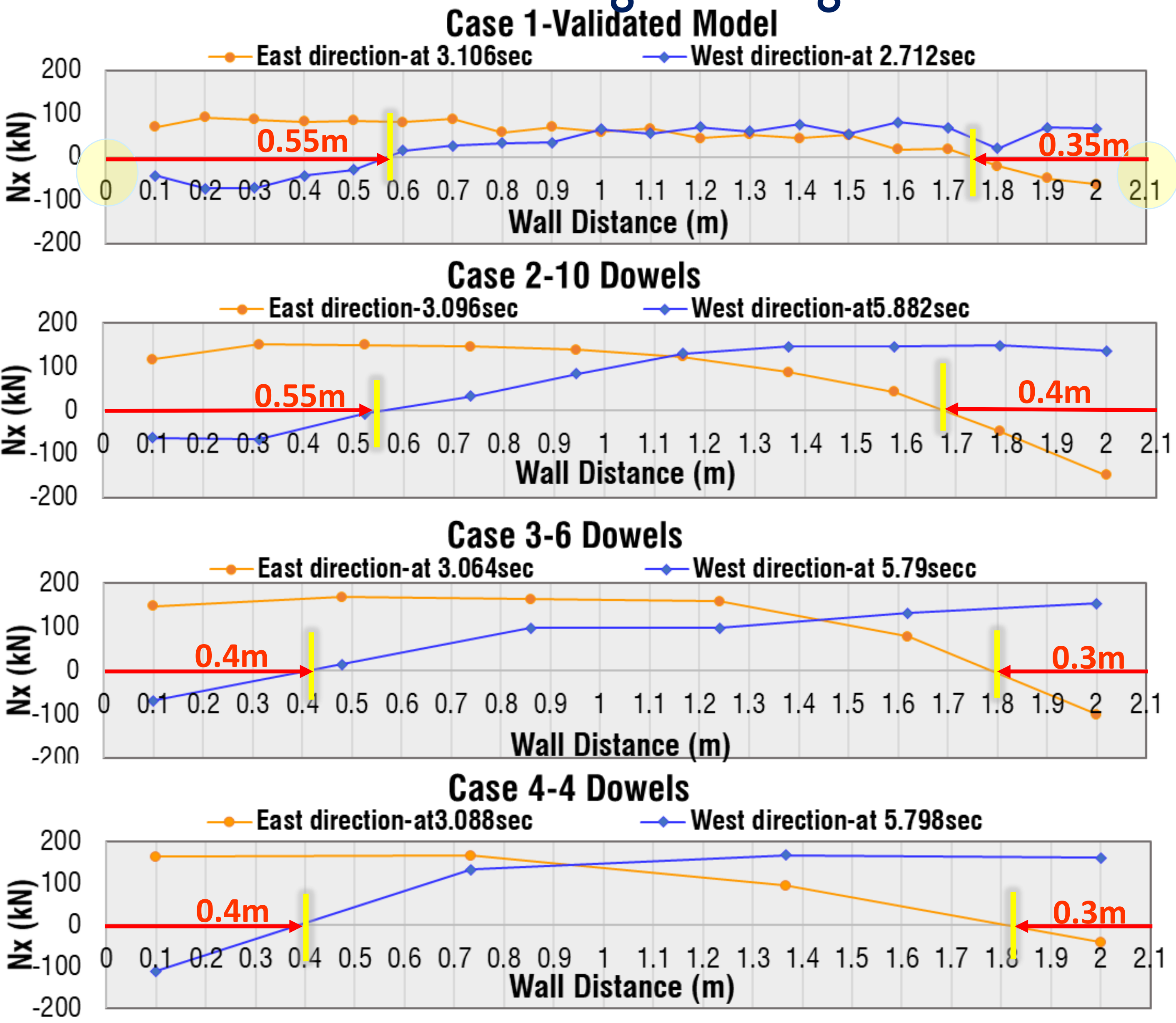
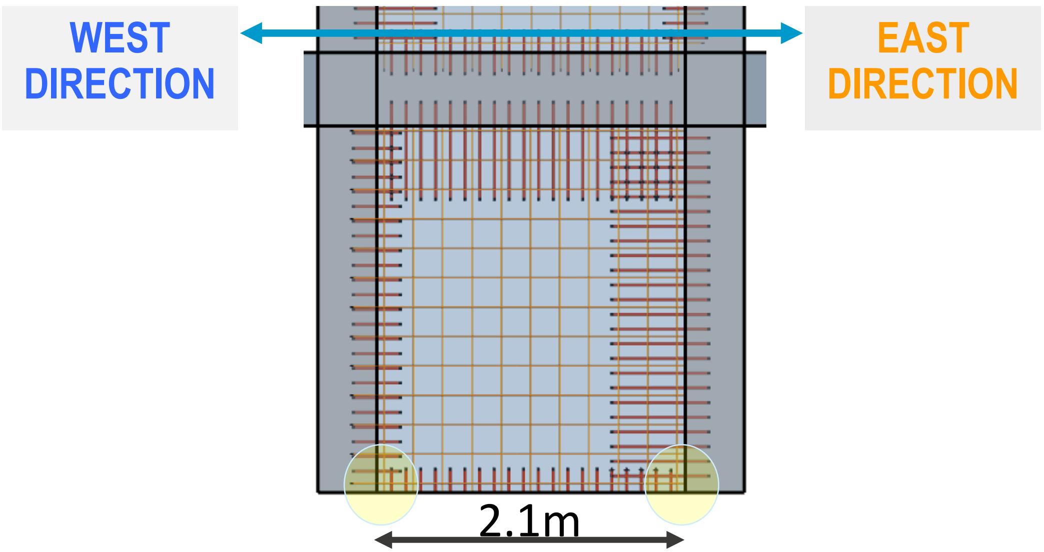
Dowels at the base

Axial forces of dowels along the length of the wall when total base shear is maximum





Larger number of dowels have yielded with the decrease of number of dowels

Conclusions from Numerical Results

Global Results

- Dowels affect the overall shear resistance capacity of the building
- The lower the number of dowels the lower the base shear-force, the stiffness and the energy absorption of the building
- The building had permanent deformations with the reduction of the number of dowels after the 3rd case scenario (dowels spacing of 380mm)
  - The fundamental characteristics of the frame changed (stiffness and fundamental frequency of the frame were reduced)

Local Results

- The dowels of the 1st case scenario (spacing of 100mm) had the lowest axial forces
- The dowels of the 2nd, 3rd and 4th case scenarios reached their yield values
- In the 3rd and 4th case scenario the position of neutral axis is moving towards the edges of the wall in both directions
  - Indicates that larger number of dowels have yielded in this case

Conclusions

- The number of dowels used in the experimental study can be reduced significantly making the use of this method more cost effective
- Further analysis of the results will provide the basis for a proposal for design guidelines for the dowels