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SEISMICALLY RETROFITTING AND UPGRADING RC-MRF BY USING EXPANDED METAL PANELS

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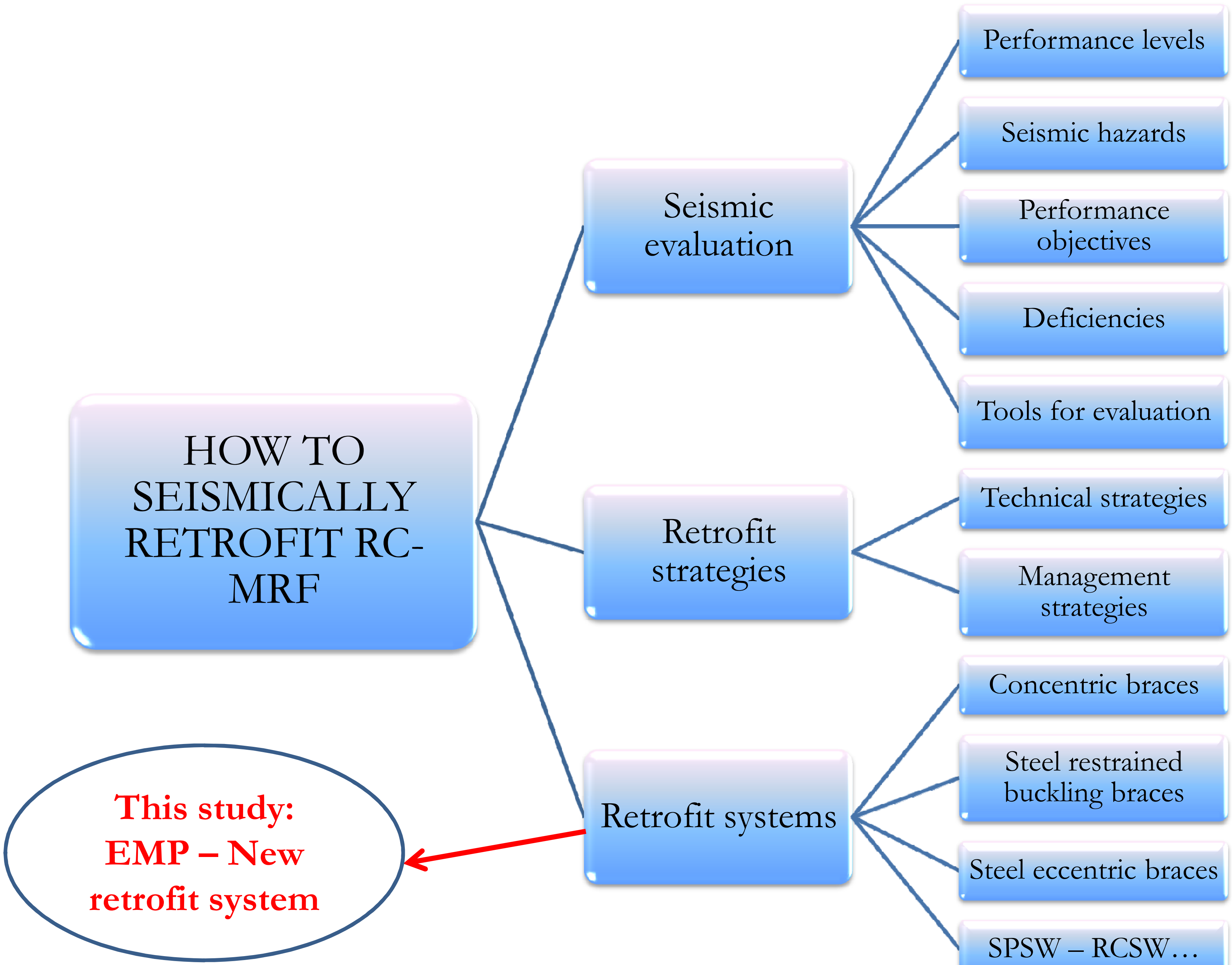
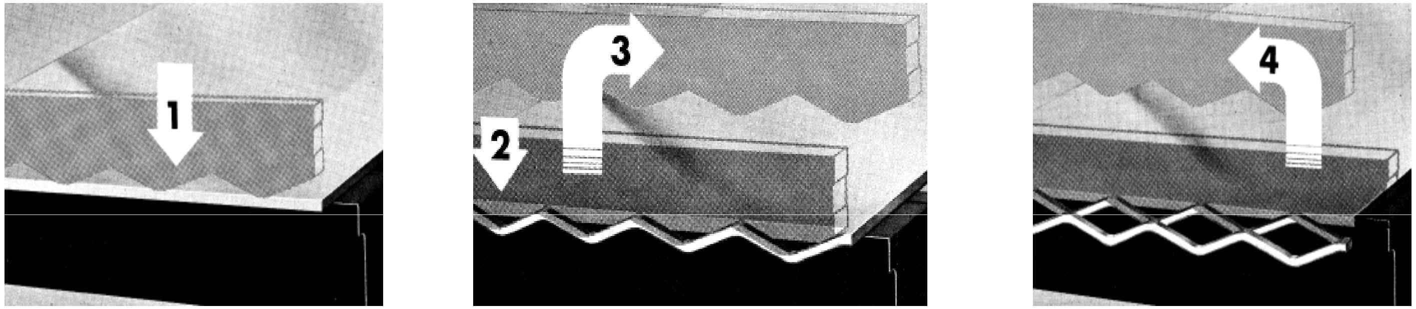
Outline

1. Overview of procedures of seismic retrofit of reinforced concrete moment resisting frames
2. Expanded Metal Materials and Panels (EMP)
3. Experimental studies on EMP
4. Numerical studies on EMP
5. Application of EMP to seismically retrofit RC-MRF

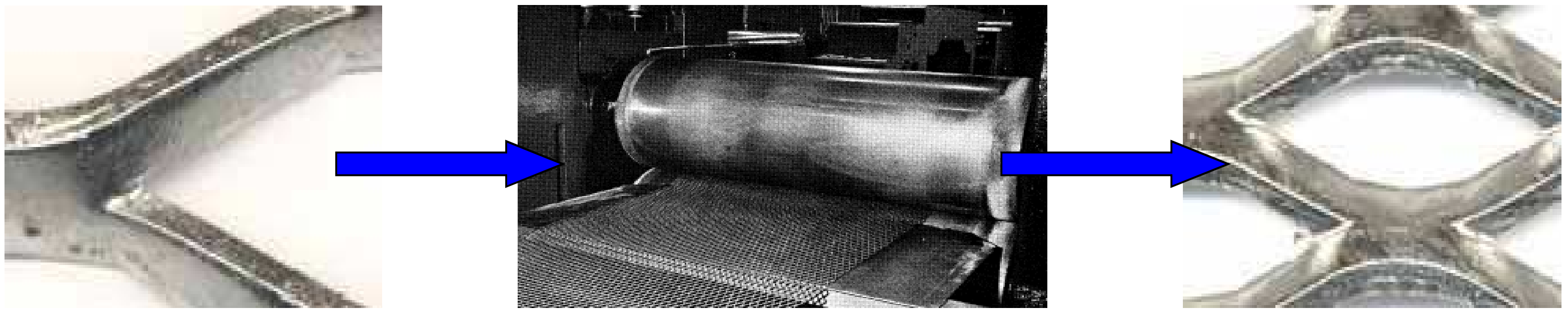

HOW TO SEISMICALLY RETROFIT RC-MRF
Seismic evaluation
Performance levels
Seismic hazards
Performance objectives
Deficiencies
Tools for evaluation
Retrofit strategies
Technical strategies
Management strategies
Retrofit systems
Concentric braces
Steel restrained buckling braces
Steel eccentric braces
SPSW – RCSW…
This study: EMP – New retrofit system

EXPANDED METAL PANELS – Introduction

- Expanded Metal Material (EM): steel or different alloys and adhesive materials
- Expanded Metal Panels (EMP): Panels formed by expansively pressing and simultaneously slitting a plate made of EM to obtain 3D rhomb-shape stitch sheets;



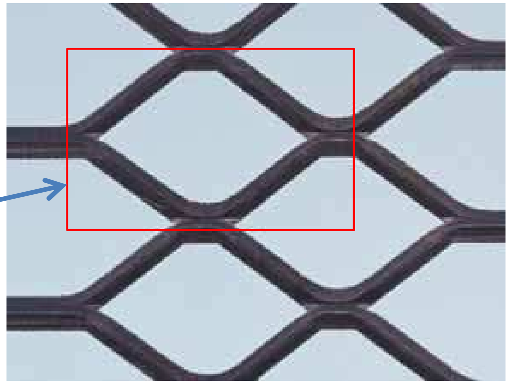
3D stitch sheets can be cut by the dimensions of ±1,250 x ±2,500m or can be flattened by passing through a cold-roll reducing mill and then cutting with the dimensions of ±1,250 x ±2,500m

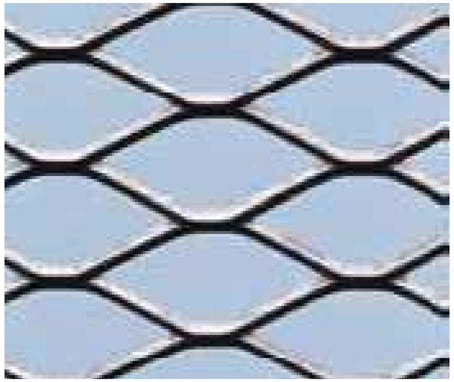


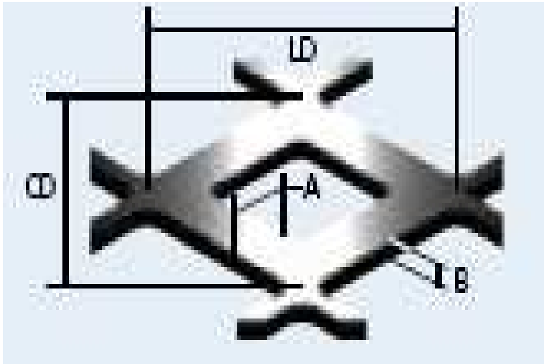
EXPANDED METAL PANELS – Introduction

⇨ Result: Rhomb shaped stitches with a lot of possible dimensions

A rhomb shape stitch







- Expanded metal → Flattened Type: without overlap between stitches

→ Normal Type: with overlaps between stitches

→ Non-constantly mechanic properties;

- Fields of application → storefront protectors, fences …

⇨ **No real structural application at the moment**

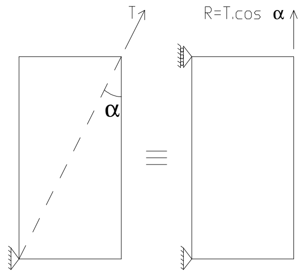
FINAL AIM OF THIS STUDY : APPLICATION OF EMP TO RETROFIT RC-MRF

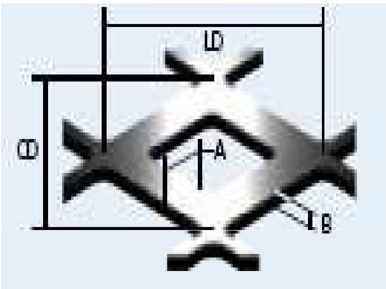
- Why could EMP be effective to seismically retrofit RC frames?
- May work as steel plate shear walls SPSW and concentric braces
- Cost of EM material is relatively low when compared with SPSW.

- My study focuses on:

1. Testing EMP loaded in shear: small to large scales to observe the behavior of EMP.
2. Numerically simulating the tests
3. Parametrically studying to propose simplified models for EMP under shear.
4. Characterizing the use of EMP in retrofitting RC frames.

EXPANDED METAL PANELS –Small scale tests





Direction 1

Direction 2

Glue connections

Spe.	LD(mm)	CD(mm)	A(mm)	B(mm)	EM type	Type of tests	Direction
1	51	27	3,5	3,0	Flatten	1-Mono 2-Cyclic	1
2	51	27	3,5	3,0	Flatten	1-Mono 2-Cyclic	2
3	86	46	4,3	3,0	Flatten	1-Mono 2-Cyclic	1
4	86	46	4,3	3,0	Flatten	1-Mono 2-Cyclic	2
5	51	23	3,2	3,0	Normal	1-Mono 2-Cyclic	1
6	51	23	3,2	3,0	Normal	1-Mono 2-Cyclic	2
7	86	40	3,2	3,0	Normal	1-Mono 2-Cyclic	1
8	86	40	3,2	3,0	Normal	1-Mono 2-Cyclic	2

EXPANDED METAL PANELS – Large scale tests

- Experimental Procedures:

→ Monotonic tests: Shear up to complete failure of sheets

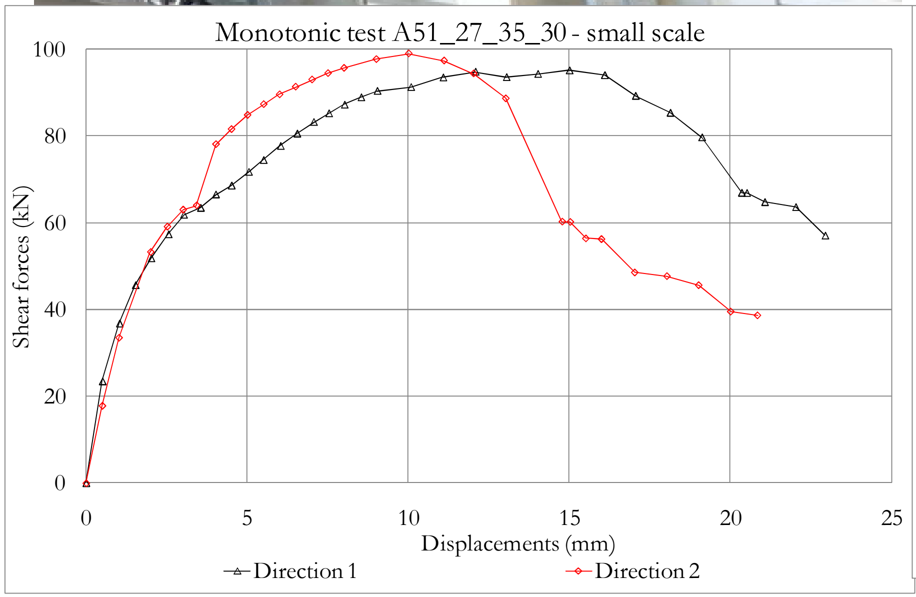
⇒ Preparing the data for cyclic tests

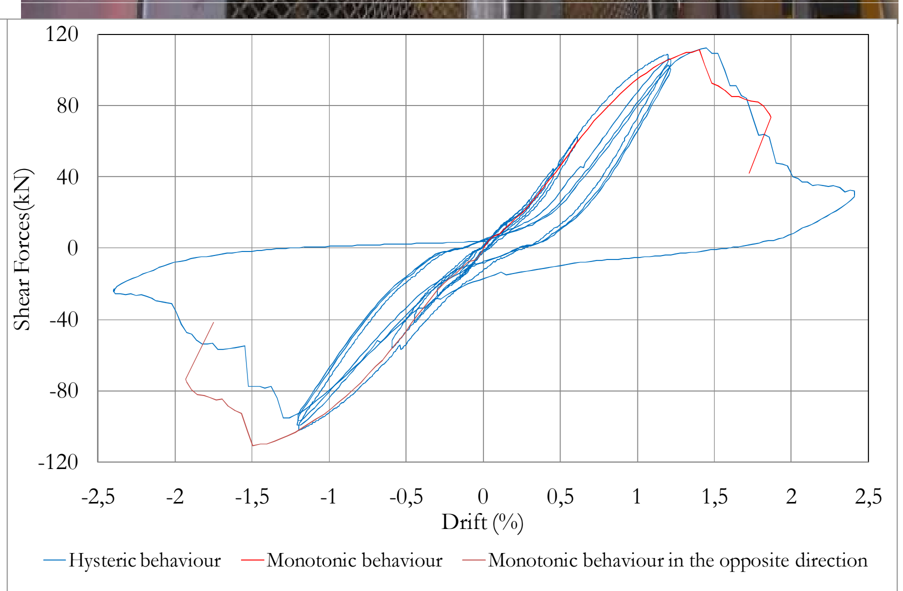
→ Cyclic tests: ECCS 1996

Large scale specimens (dimensions in mm)

Specimens	LD	CD	A	B	Type of EM	Type of tests	Dimensions(mm)
1-Mono	51	27	3,5	3,0	Flatten	Monotonic	2590x2630
2-Mono	86	46	4,3	3,0	Flatten	Monotonic	2590x2630
3-Cyclic	51	27	3,5	3,0	Flatten	Cyclic	2590x2630
4-Cyclic	86	46	4,3	3,0	Flatten	Cyclic	2590x2630

EXPANDED METAL PANELS – Test Results





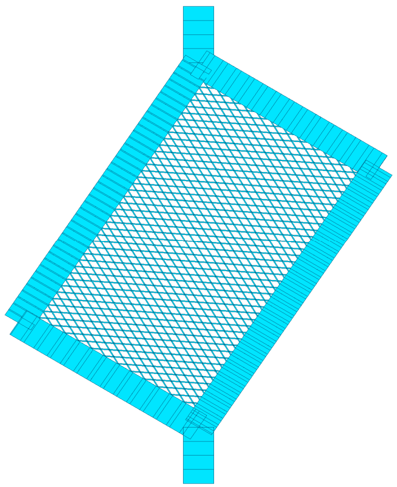
EXPANDED METAL PANELS – Simulations of tests

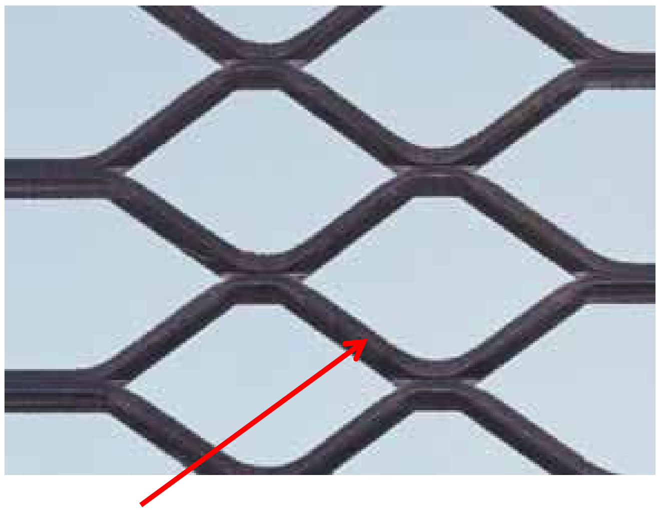
- Modeling: FINELG code

➢ Material: Material properties of EMP are exploited from tensile tests of bars: steel multi-linear relationship with softening and hardening taken into account

Yield strength (MPa)	Ultimate strength (MPa)	Yield deformation	Maximum deformation	Elastic modulus (MPa)	Strain-hardening modulus (MPa)
337	393	0,0024	0,0290	134000	2139

➢ Elements: Each bar of a rhomb shape stitch is modeled as a 3D inelastic beam. Buckling of an individual bar is neglected.

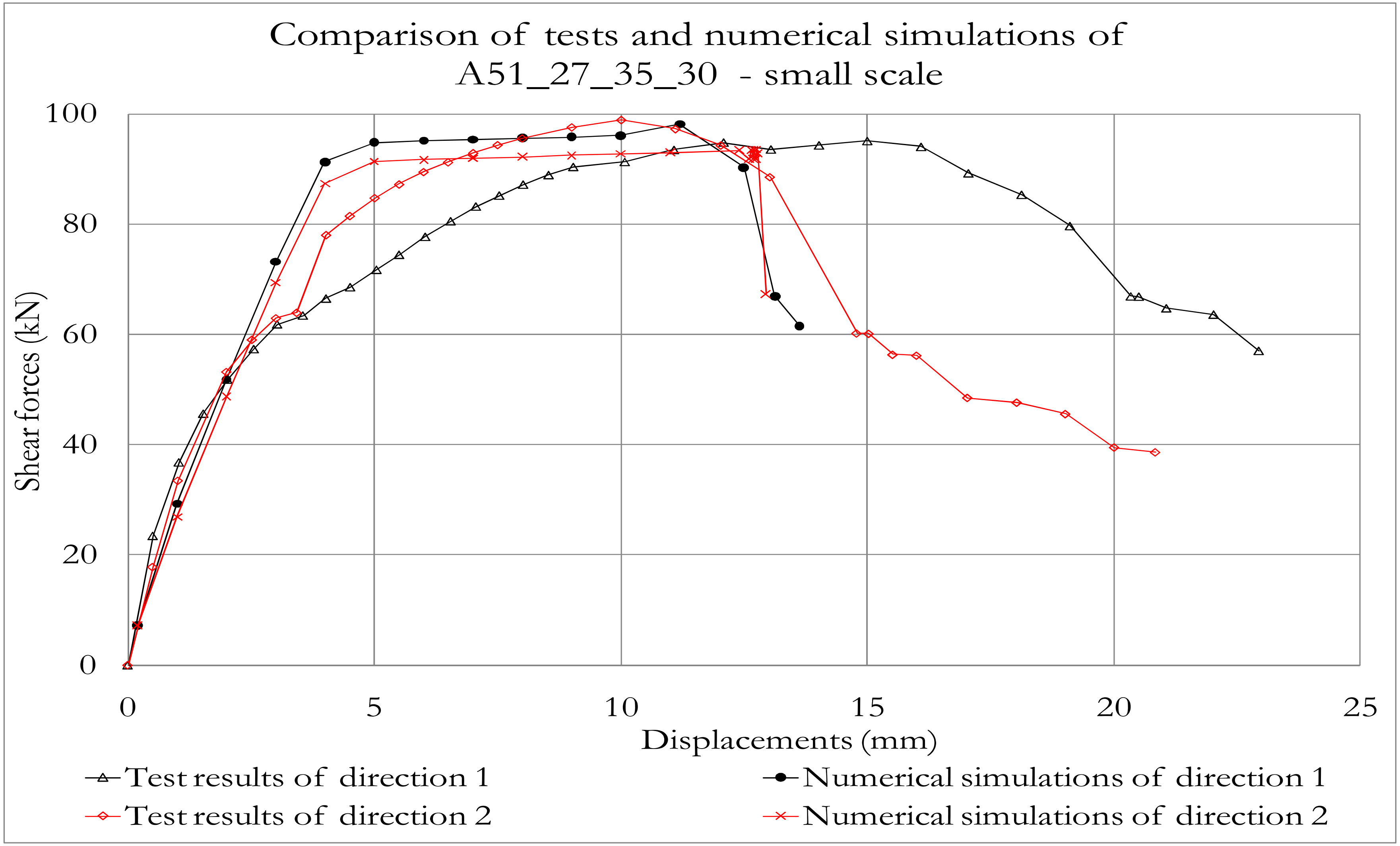




3D inelastic beam

EXPANDED METAL PANELS –Tests ⇔ Model

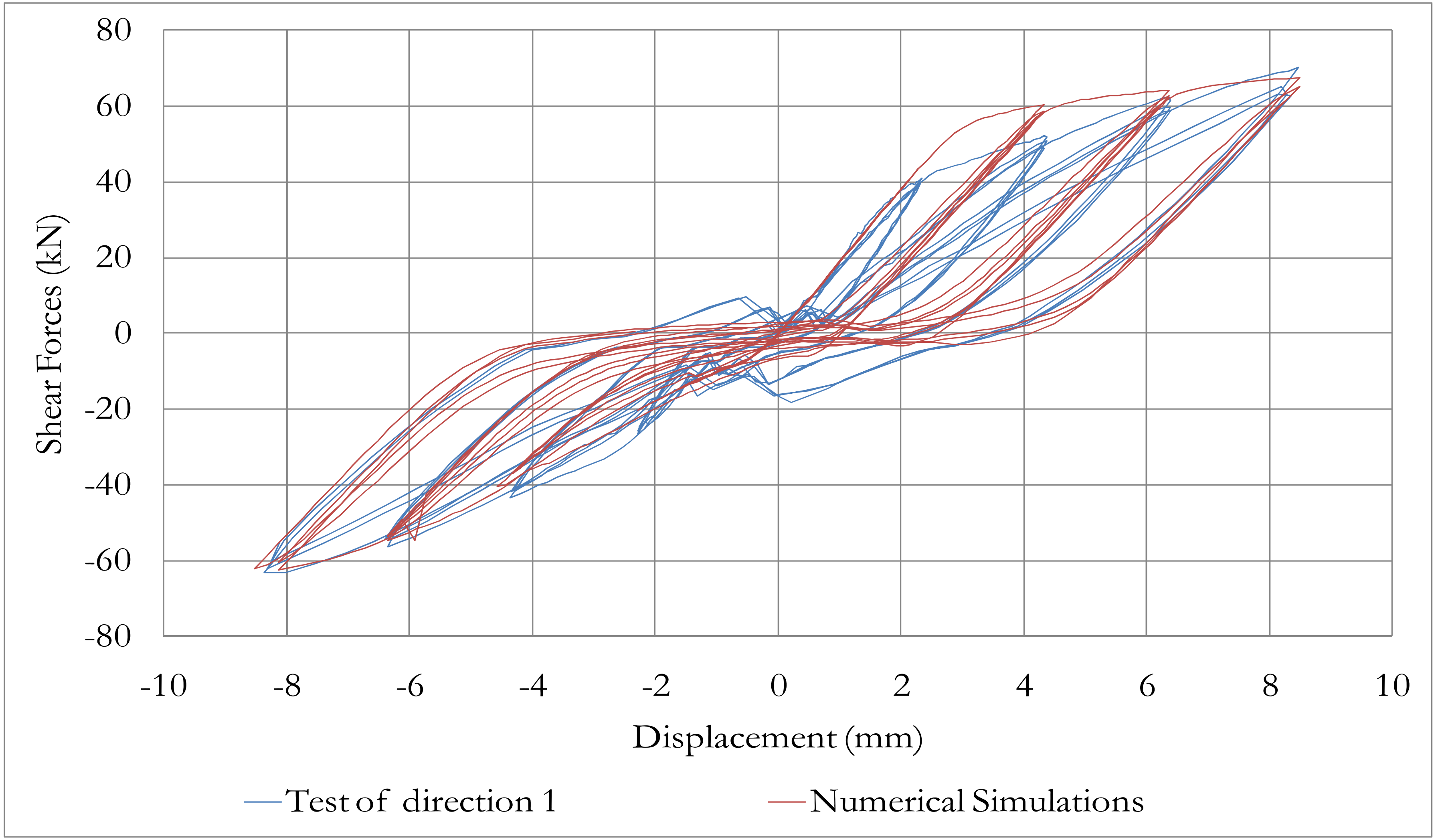
➢ Monotonic loading



EXPANDED METAL PANELS – Tests ⇔ Model

- Cyclic loading

A51_27_35_30 direction 1



EXPANDED METAL PANELS – Parametric studies – Monotonic shear loading

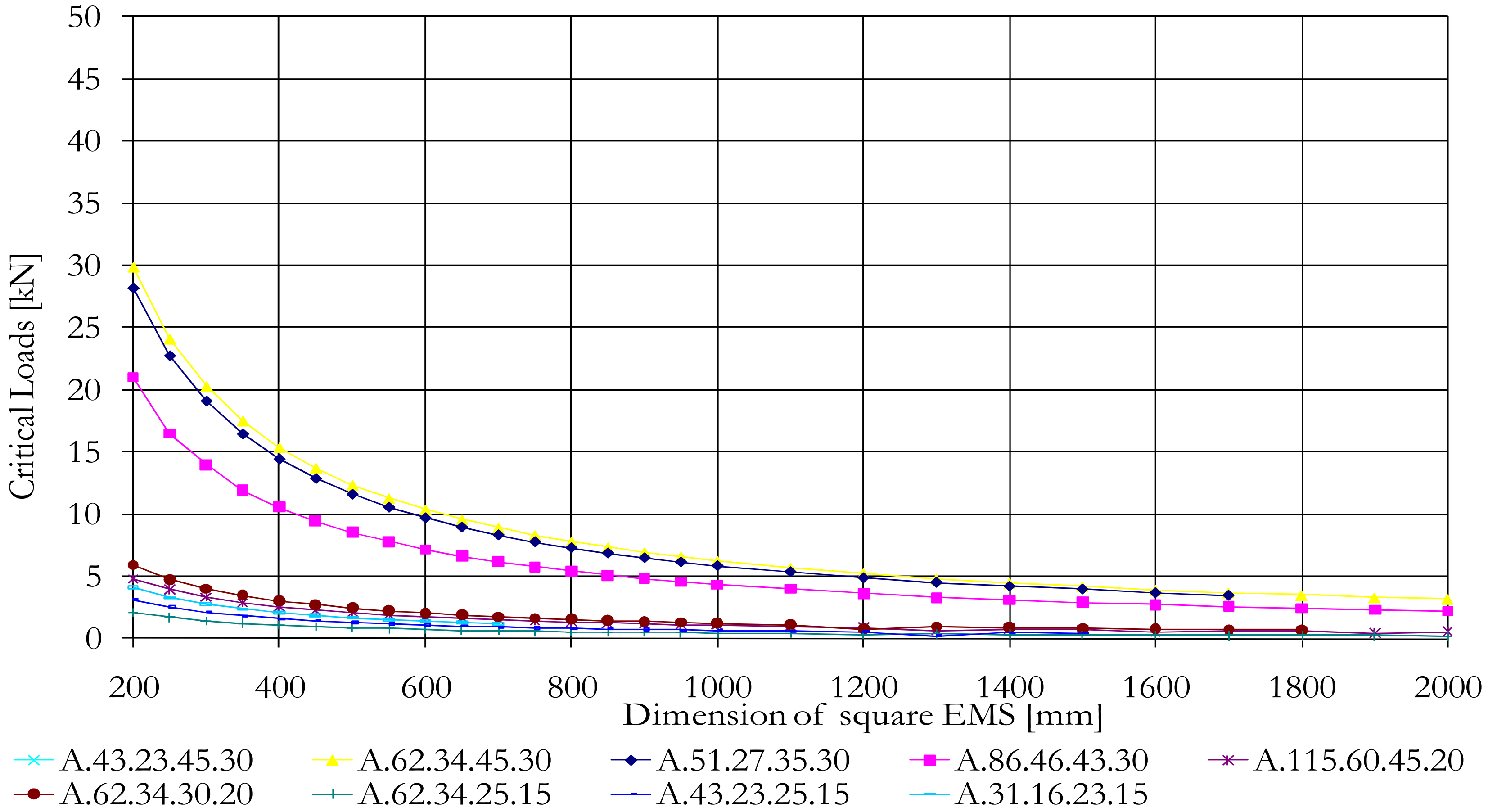
- ➢ Conclusion: FINELG describe properly the specimens' behavior

⇒ Use of FINELG in parametric studies to define a simplified model of the shear resistance of EMP

- ➢ Models in parametric studies
- ▪ Dimensions from small (100mm) to large values (2000mm)
- ▪ Different ratios between widths and heights of panels
- ▪ Initial deformations: 1/250 of the largest dimensions
- ▪ Steps to analyze EMP: linear elastic analysis
  critical behavior
  fully nonlinear analysis

EXPANDED METAL PANELS – Parametric studies – Monotonic shear loading

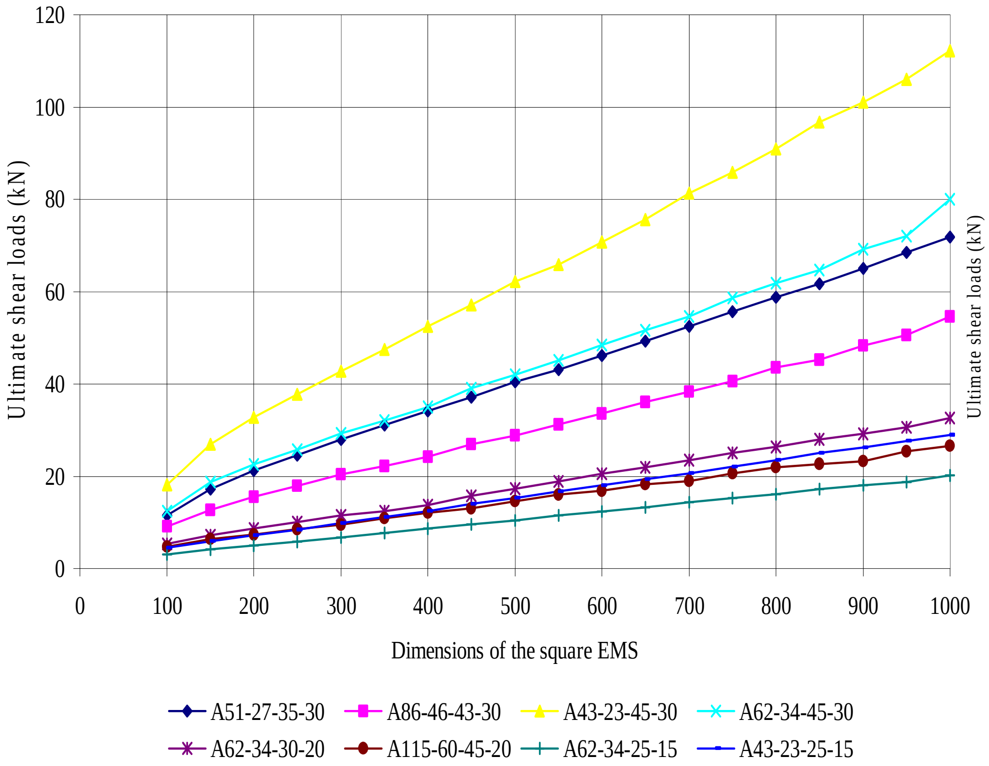
- Prior-to-buckling shear resistance of EMP

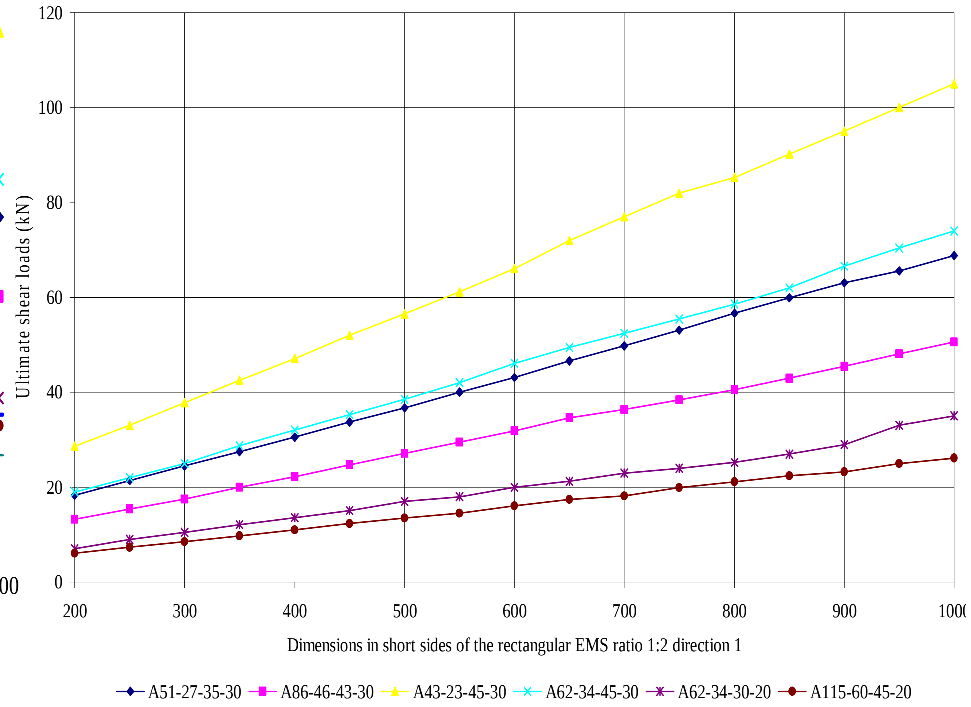


Critical loads of different square EMP with different profiles subjected to shear.

EXPANDED METAL PANELS – Parametric studies – Monotonic shear loading

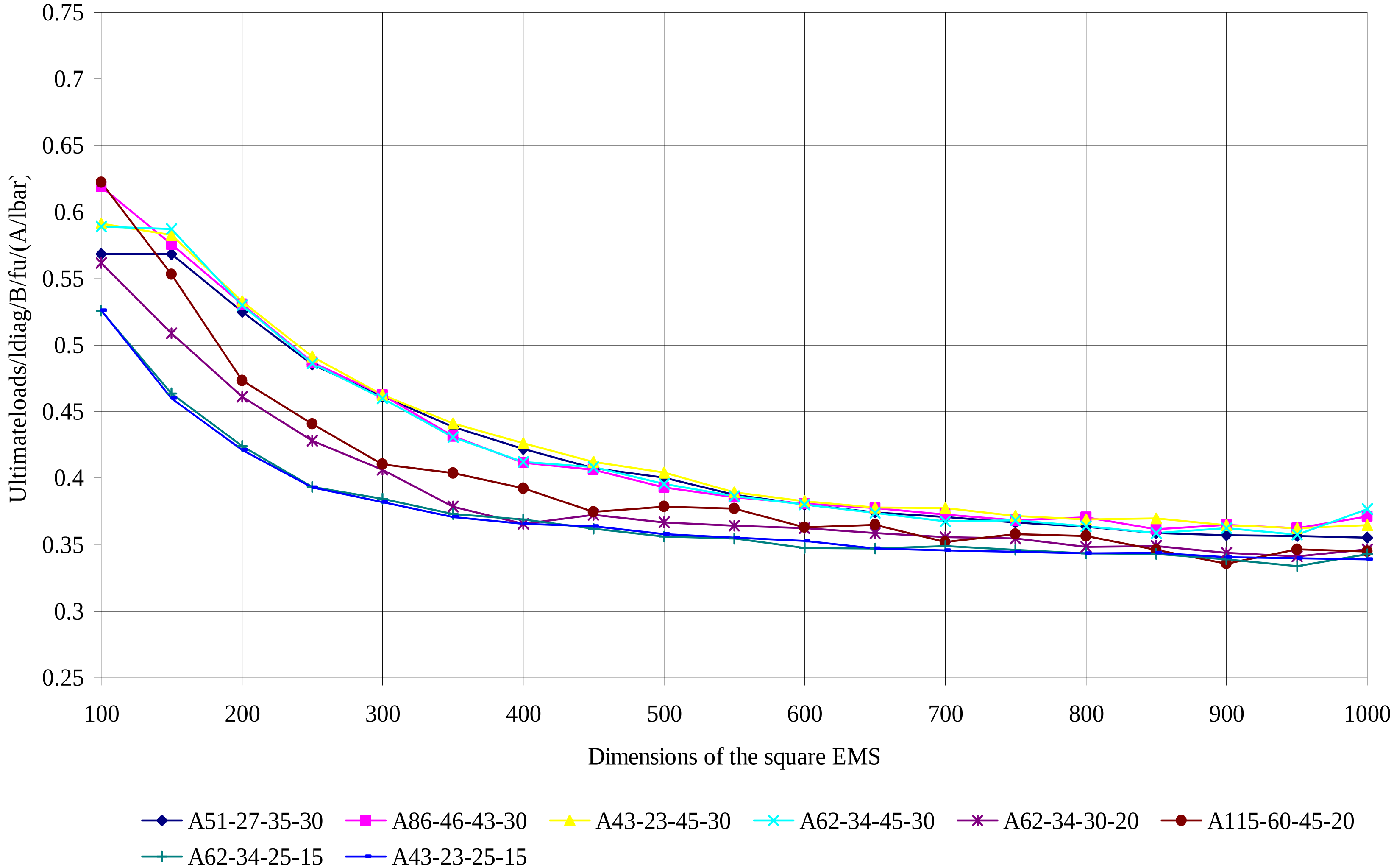
- Post-buckling shear resistance





Ultimate load in function of the dimensions of square and rectangular EMP

EXPANDED METAL PANELS – Parametric studies – Monotonic shear loading



Ultimate load in function of the dimensions of square EMP

EXPANDED METAL PANELS – Parametric studies – Monotonic shear loading

- Monotonic ultimate resistance of EMP – Simplified model: the panels work as one diagonal tension band.

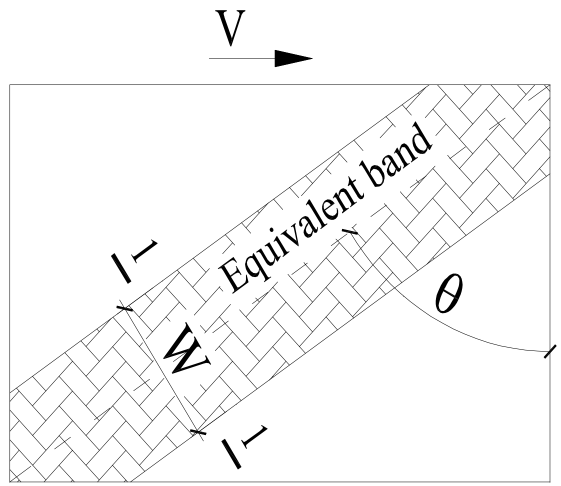
$$V = W \,.\, B \,.\, f = \gamma \,.\, \alpha \,.\, l_{dia} \,.\, B \,.\, f$$

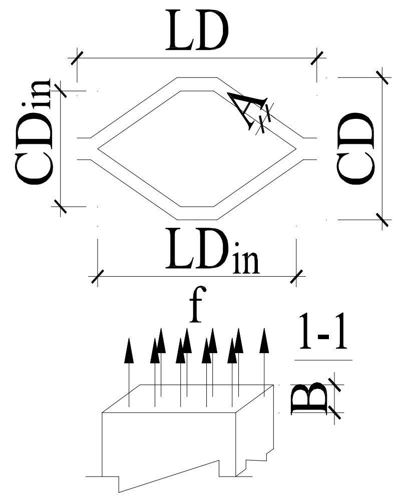
V shear resistance of the sheet; W – effective width of the equivalent band

l_{dia} diagonal length of the sheet

B thickness of the sheet

f stress generated in the equivalent band





$$\alpha = \frac{A}{l_{bar}} = \frac{A}{\sqrt{\left(\frac{LD - LD_{in}}{2}\right)^2 + \left(\frac{CD - CD_{in}}{2}\right)^2}}$$

influence of rhomb shape

γ - influence of aspect ratio of panel

0.35 square

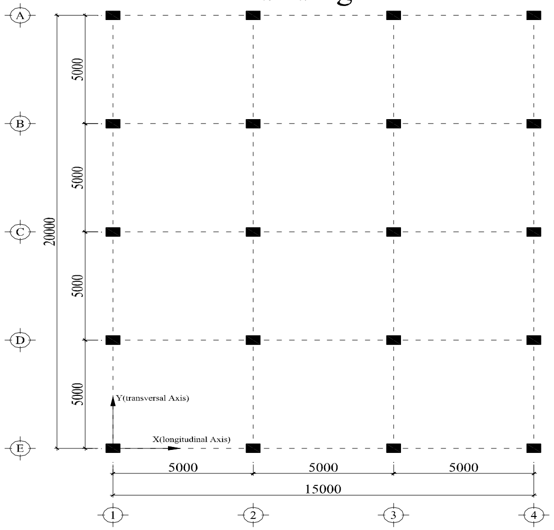
0.27 rectangular with ratio 2:1

0.18 rectangular with ratio 3:1

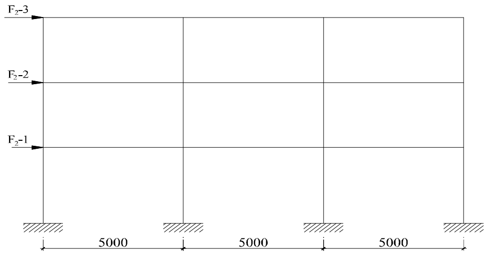
DESIGN OF RC-MRF ACCORDING TO EC2-EC8

- Four RC moment resisting frames:

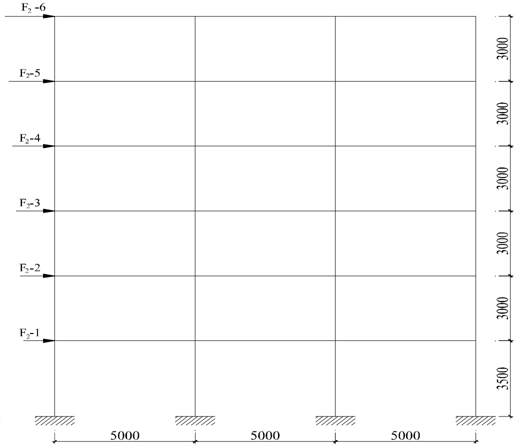
Building Plan



Frame 1 and 3 - 3 stories



Frames 2 and 4 - 6 stories



Order/No of Stories	Design Code	Layout (plan and elevation)	Span x No of Spans (m)	Story Heights (m)	Slab thickness (m)
1/3	EC2	Regular	5 m x 3	3,5 + 2x3	0,15
2/6	EC2	Regular	5 m x 3	3,5 + 5x3	0,15
3/3	EC2+EC8	Regular	5 m x 3	3,5 + 2x3	0,15
4/6	EC2+EC8	Regular	5 m x 3	3,5 + 5x3	0,15

DESIGN OF RC-MRF ACCORDING TO EC2-EC8

- Loads and Seismic Actions and Material Characteristics:

Dead loads (kN/m^2)	Live loads (floor-roof) (kN/m^2)	Wind loads (Pre-Suc) (kN/m^2)	PGA	DC Class	γ_I	f_{ck} (MPa)	f_{yk} (MPa)
5,67	3,00-2,00	0,90-0,07	0,15g	DCM	1	25	500

- Dimensions of beams and columns

Order/No of Stories	Columns (m)		Beams (m)		
	Internal	External	Width	Height	Flange
1/3	0,35 x 0,35	0,35 x 0,35	0,25	0,35	0,85
2/6	0,35 x 0,35	0,35 x 0,35	0,25	0,35	0,85
3/3	0,35 x 0,35	0,35 x 0,35	0,25	0,35	0,85
4/6	0,4 x 0,4	0,4 x 0,4	0,25	0,35	0,85

DESIGN OF RC-MRF ACCORDING TO EC2-EC8

First mode periods, weight and effective mass of the original frames and design base shears of frame 3 and 4

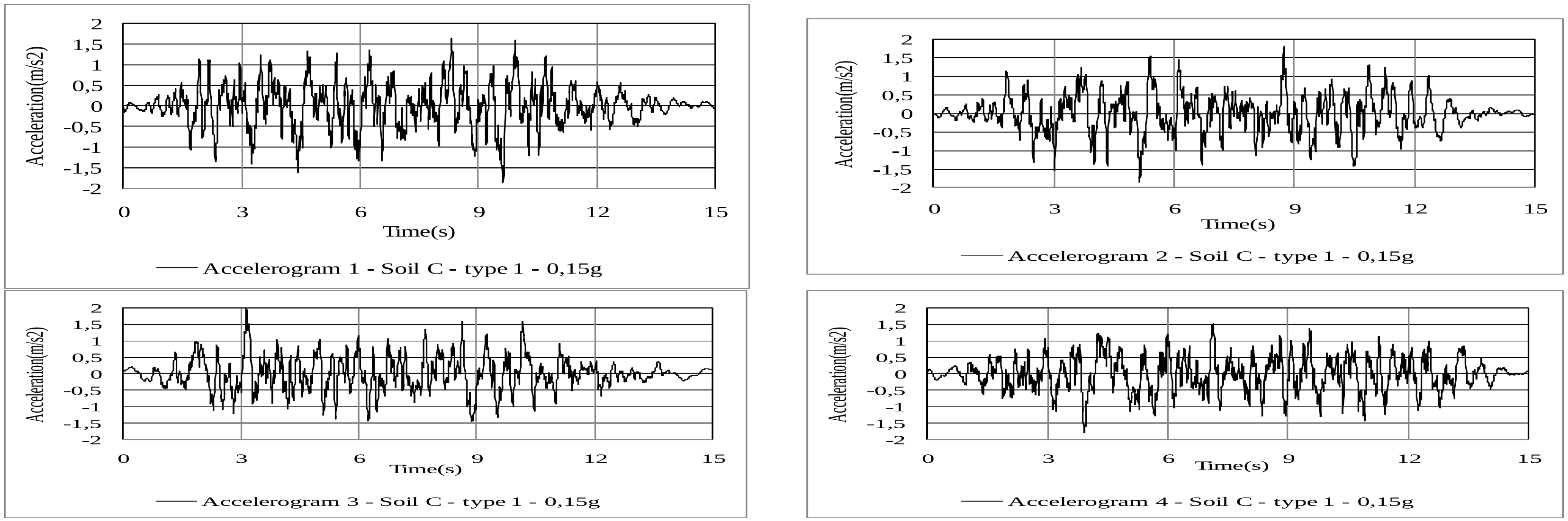
Frame/No of Stories/Design Code	1^{st} Periods of cracked frames (s)	Design base shear (kN)	Total Mass ($x10^3$ Kg)	Effective Mass
1/3/EC2	0,88	0	1722	91%
2/6/EC2	1,85	0	3486	86%
3/3/EC2+EC8	0,88	215	1722	91%
4/6/EC2+EC8	1,50	220	3536	86%

Reinforcement configuration of the four frames

Frame/Number of Stories/ Code	Beams (all stories)		Column (number of stories x rebar configuration)	
	Top	Bottom	Exterior	Interior
1/3/EC2	12Φ10+2Φ10	3Φ14	2x8Φ8+1x8Φ14	3x8Φ8
2/6/EC2	12Φ10+2Φ10	3Φ14	1x8Φ12+4x8Φ8+1x8Φ14	1x8Φ22+1x8Φ16+1x8 Φ10+3x8Φ8
3/3/EC2+EC8	12Φ10+2Φ10	3Φ16	3x8Φ20	3x8Φ20
4/6/EC2+EC8	12Φ10+2Φ10	3Φ16	6x8Φ16	1x8Φ22+5x8Φ16

SEISMIC EVALUATION OF THE ORIGINAL FRAMES

- Pushover analysis (N2 method) is first used to assess the existing frames. Then NLTH is used to check the results of pushover analysis, and to assess the real behaviour of the original structures.
- To perform nonlinear analyses of the frames, estimation of actual values of material strengths is considered, instead of the design strength in order to reflect the expected real over-strength of the structures.
- The seismic excitation is represented by a set of four artificial accelerograms, with $\gamma_I \times S \times a_{gR} = 1 \times 1{,}15 \times 0{,}15g = 0{,}1725g$



SEISMIC RESPONSE OF THE ORIGINAL FRAMES

➢ Modelling and analyses:

- Nonlinear code: SAP 2000 and SEISMOSTRUCT – a full nonlinear code
- Concrete: a uniaxial nonlinear constant confinement model (Mander et al. [1998]). Confinement : $f_{cc}/f_c = 1{,}2$ for the concrete core.
- Steel: elastic-perfectly plastic steel stress-strain diagram
- Seismic performance criteria: FEMA356 with three levels of plastic deformations of beams or columns:

  Immediate Occupancy IO, Life Safety LS and Collapse Prevention CP.
- Failure modes: (1) soft-story mechanism

  (2) local failure

  (3) the structure is 20% below the maximum strength attained.

SEISMIC RESPONSE OF THE ORIGINAL FRAMES

- Response of the original frames

Frame	Load Pattern	V_b^{1y} (kN)	Δ_b^{1y} (m)	V_b^{m} (kN)	Δ_b^{m} (m)	E (kNm)	Criteria of failure	$\Delta_t^{0,15gSC}$ (m)	$V_b^{0,15gsC}$ (kN)	Max PGA
1	'Modal'	274,9	0,112	297,1	0,148	030,1	Soft-story	0,100	261	0,22g
	'Uniform'	308,4	0,104	344,3	0,152	036,1	Soft-story	0,090	286	0,25g
2	'Modal'	147,7	0,096	219,7	0,204	028,9	Local failure	0,164	244	0,18g
	'Uniform'	170,0	0,090	256,2	0,204	034,6	Local failure	0,164	291	0,18g
3	'Modal'	347,0	0,100	505,5	0,340	133,0	Global	0,100	347	0,48g
	'Uniform'	398,5	0,100	563,7	0,290	122,0	Global	0,090	336	0,50g
4	'Modal'	158,0	0,090	265,2	0,256	047,7	Local failure	0,160	244	0,23g
	'Uniform'	183,7	0,084	318,0	0,246	054,2	Local failure	0,130	273	0,28g

Response of the original frames by pushover analyses

SEISMIC RESPONSE OF THE ORIGINAL FRAMES

- Response of the original frames

Drift of the original frames by pushover analysis (%) at PGA = 0.15g soil C

Frame 1 (Average of two load patterns)			Frame 2 (Average of two load patterns)					
Story1	Story2	Story3	Story1	Story 2	Story3	Story 4	Story 5	Story 6
1,140	1,200	1,000	0,910	1,100	0,832	1,100	0,970	0,890
Frame 3 (Average of two load patterns)			Frame 4 (Average of two load patterns)					
0,900	1,100	1,000	0,760	0,890	0,930	0,904	1,100	0,780

Fundamental periods and maximum base shear of the original frames from NLTH due to Earthquake type 1 with PGA of 0.15g soil C

Frame 1 (Average)		Frame 2 (Average)		Frame 3 (Average)		Frame 4 (Average)	
Period	Base shear	Period	Base shear	Period	Base shear	Period	Base shear
0,6s	184,3kN	1,1s	233,9kN	0,52s	233,3kN	1s	252,3kN

SEISMIC RESPONSE OF THE ORIGINAL FRAMES

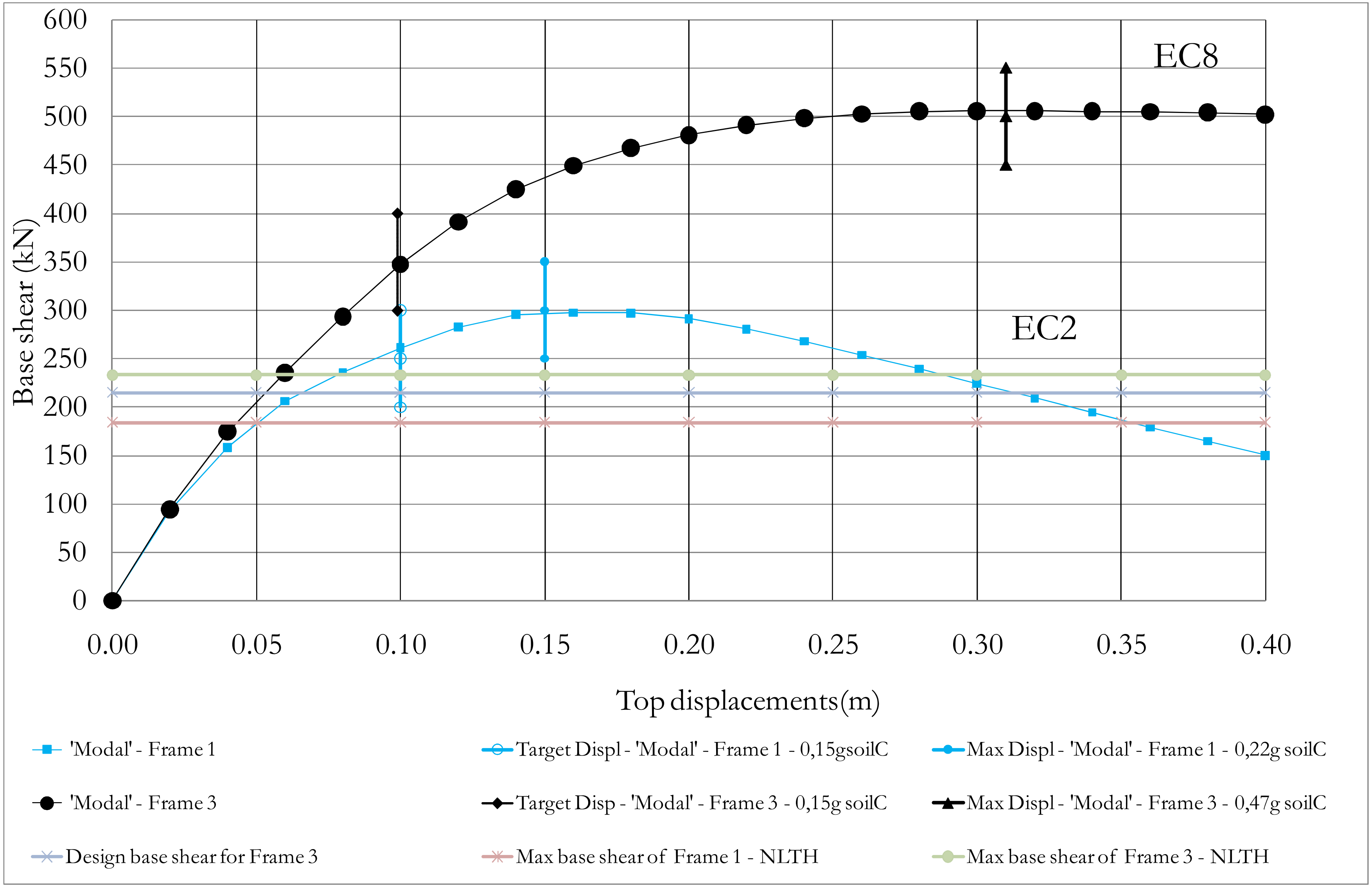
- Response of the original frames

Max story drift (%) and top displacements (m) of the original frames by NLTH due to Earthquake type 1 with PGA of 0.15g soil C

Frame 1 (Average)				Frame 2 (Average)						
Story1	Story2	Story3	Top Displ	Story1	Story2	Story3	Story4	Story5	Story6	Top Displ
0,70%	0,75%	0,71%	0,07m	0,70%	0,8%	0,8%	0,77%	0,72%	0,66%	0,124m
Frame 3 (Average)				Frame 4 (Average)						
0,51%	0,66%	0,64%	0,064m	0,63%	0,71%	0,74%	0,72%	0,69%	0,64%	0,118m

SEISMIC RESPONSE OF THE ORIGINAL FRAMES

- Response of the original frames: Pushover and target displacements of frame 1 and 3



SEISMIC RETROFIT OF RC-MRFS BY USING EMP

- Selecting the EMP to retrofit the original frames:
- Approach: Direct Displacement Based Design
- Equivalent Viscous Damping: Rules for Takeda Thin model
- EMP to carry the seismic forces. Depending on the deficiencies of the original frames, types and distribution of the EMP are selected.
- Because all frames are symmetric with three bays, EMP are put in the intermediate bay.
- In frame 1 and 3 (3-story frames), the EMPs are put in the first and second stories, while the EMP are put in the first to fourth stories in frame 2 and 4 (6-story frames). Because there is no hinge appeared at the upper stories, no EMP is put there.
- EMP is modelled as an axial tension strut with a bilinear force-displacement relationship for pushover analysis and pivot model for NLTH.

SEISMIC RETROFIT OF RC-MRFS BY USING EMP

Response of the retrofitted frames by pushover analysis

Frame	Load Pattern	V_b^{1y} (kN)	Δ_b^{1y} (m)	V_b^{m} (kN)	Δ_b^{m} (m)	E (kNm)	Criteria of failure	$\Delta_t^{0,15gSC}$ (m)	Max PGA
1	'M'	291,5	0,052	476,0	0,208	073,6	Soft-story	0,080	0,365g
	'U'	365,7	0,056	483,8	0,144	050,2	Soft-story	0,070	0,300g
2	'M'	268,1	0,090	445,4	0,253	072,2	Local failure	0,150	0,245g
	'U'	347,7	0,083	535,6	0,235	089,2	Local failure	0,120	0,265g
3	'M'	352,1	0,060	656,0	0,340	175,0	Beam-sway	0,085	0,610g
	'U'	415,0	0,060	738,3	0,300	172,0	Beam-sway	0,070	0,620g
4	'M'	288,2	0,090	444,9	0,271	088,0	Local failure	0,140	0,285g
	'U'	351,3	0,083	549,1	0,259	104,0	Local failure	0,120	0,320g

SEISMIC RETROFIT OF RC-MRFS BY USING EMP

- Comparison of behaviour between original and retrofitting frames by pushover analyses

Periods of all frames with and without EMP

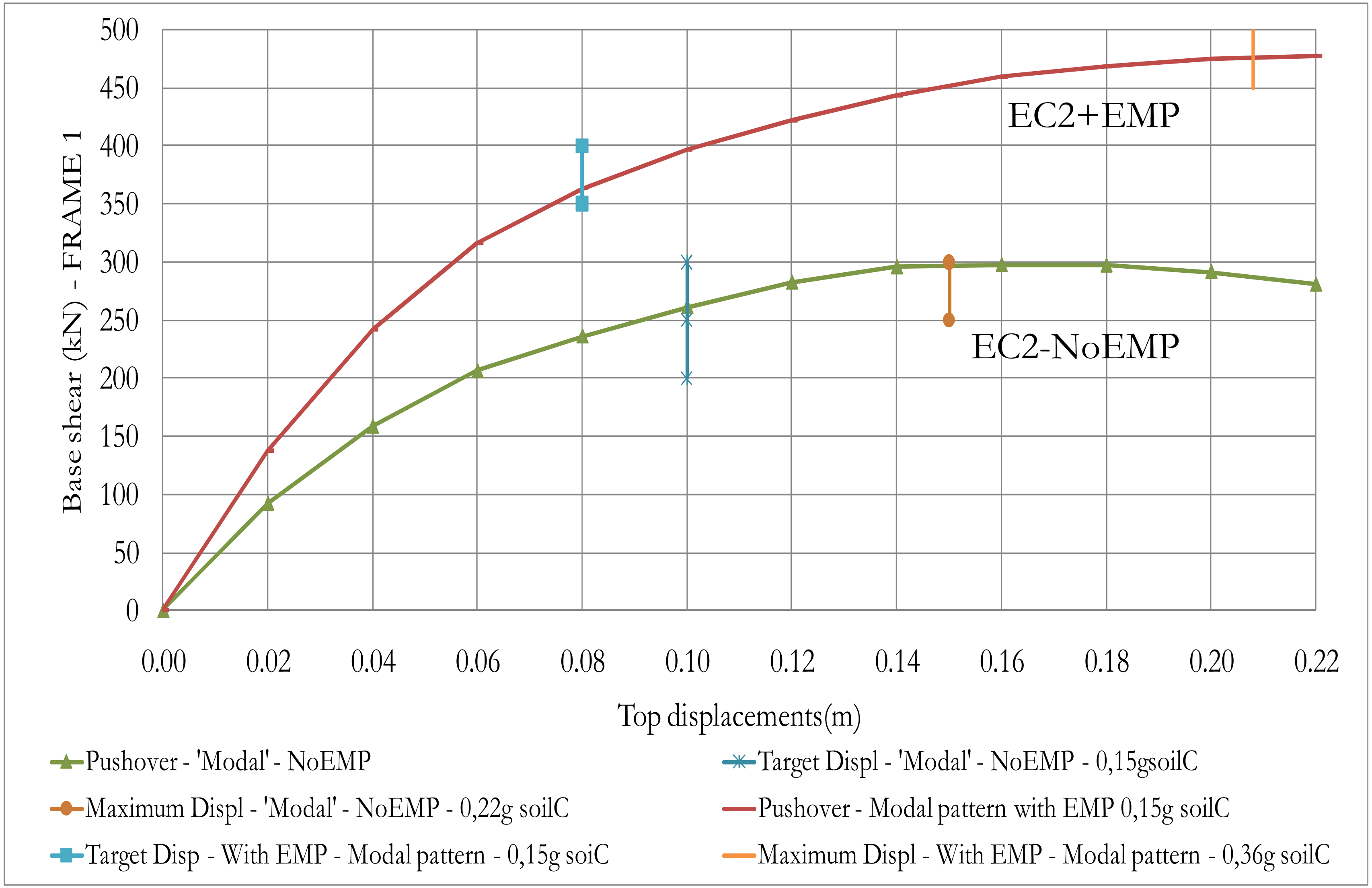
Frame 1		Frame 2		Frame 3		Frame 4	
No EMP	With EMP	No EMP	With EMP	No EMP	No EMP	No EMP	With EMP
0,85s	0,71s	1,53s	1,28s	0,85s	0,71s	1,53s	1,28s

Drift of the retrofitted frames by pushover analyses (%)

Frame 1(Average)			Frame 2(Average)					
Story1	Story2	Story3	Story1	Story2	Story3	Story4	Story5	Story6
0,74	0,77	0,79	0,66	0,76	0,78	0,79	0,78	0,73
Frame 3(Average)			Frame 4(Average)					
0,80	0,86	0,79	0,64	0,72	0,75	0,75	0,74	0,70

COMPARISON OF SEISMIC RESPONSE OF THE ORIGINAL AND RETROFITTED FRAMES

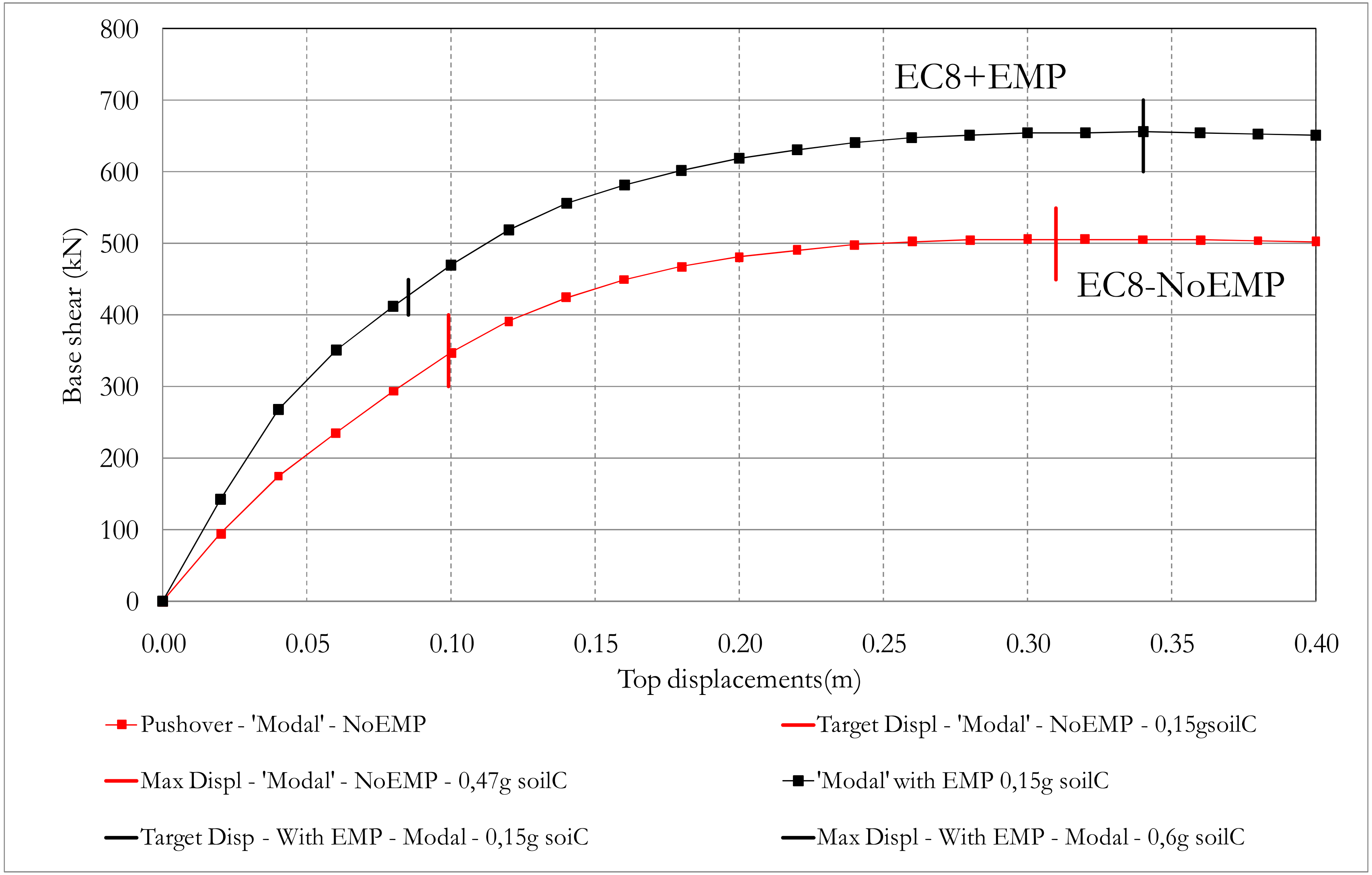
Pushover and target displacements of frame 1: before and after retrofitted



SEISMIC RETROFIT OF RC-MRFS BY USING EMP

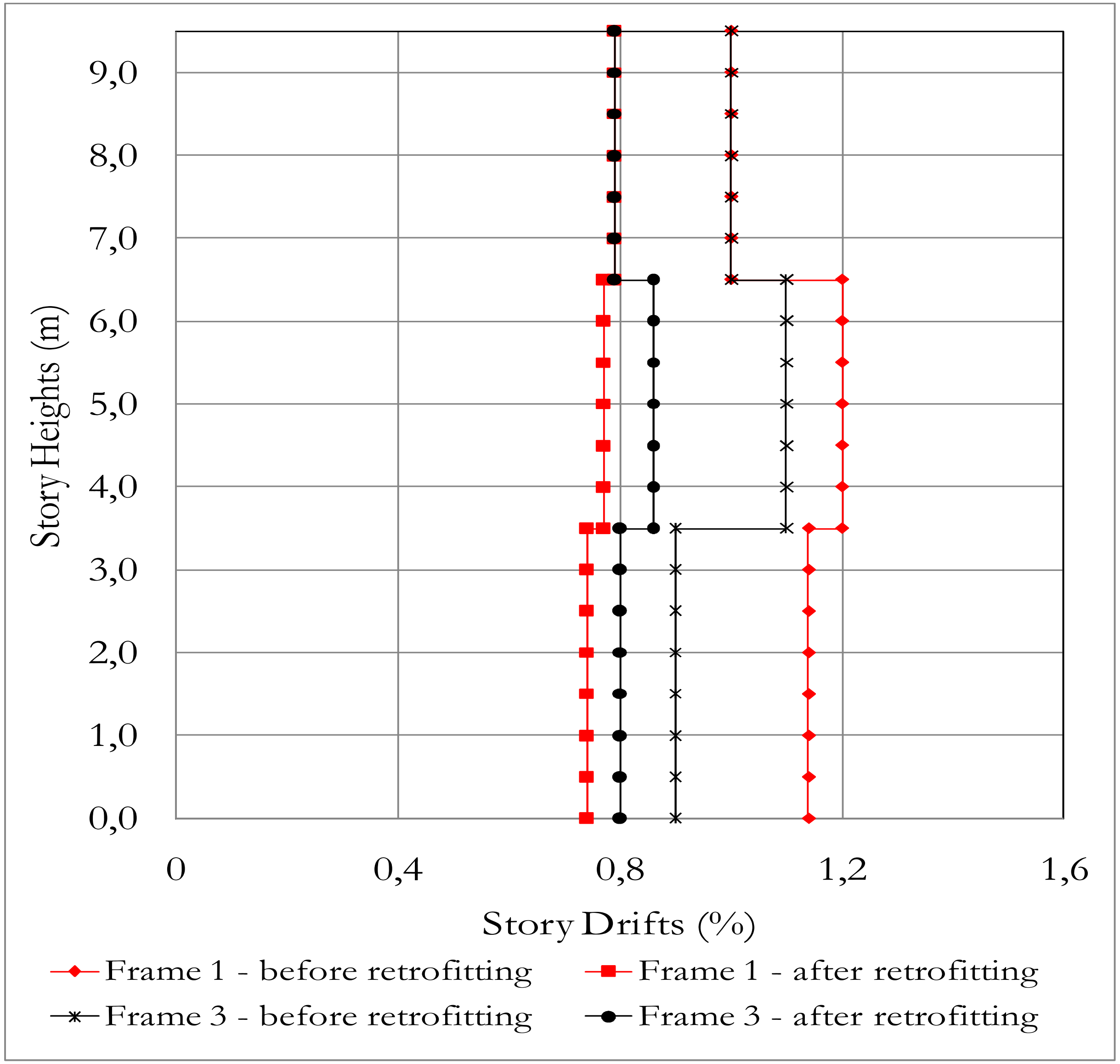
- Comparison of behaviour between original and retrofitting frames:

Capacity curves and target displacements of Frame 3 before and after retrofitting



SEISMIC RETROFIT OF RC-MRFS BY USING EMP

- Comparison of behaviour between original and retrofitting frames:



SEISMIC RETROFIT OF RC-MRFS BY USING EMP - Conclusions

- The application of the proposed retrofitting system results in an increase of strength, stiffness and ductility. The energy dissipated by EMP is considerable, reaching about 20% of the total energy.
- This results in an increase of the level of earthquake that the structures can sustain.
- Although EMP cannot change the failure mechanism of the structures, it can reduce the demand of seismic actions thanks to increases of strength and stiffness and ductility of the structures.
- NLTH points out that pushover analysis is successfully in capturing the behaviour of low and medium rise buildings.

FURTHER WORKS

- Model more different types of RC-MRF with and without EMP by both pushover and NLTH.
- Characterise the use of EMP to retrofit RC-MRF and suggest the design or retrofit procedures.
- Make suggestions for the connections between the EMP and RC-MRF.

Thank you for your attention!