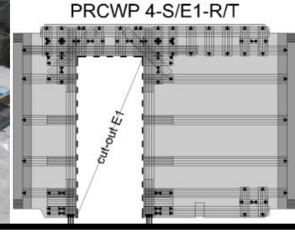
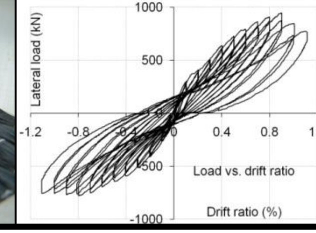








Dr.ing. DEMETER István
Dr.ing. NAGY-GYÖRGY Tamás

AN EXPERIMENTAL PROGRAM OVERVIEW

RC Wall Panels Strengthened with FRP Composites

Department of Civil Engineering and Building Services
Politehnica University of Timisoara
ROMANIA

2017

CONTENT

1. **INTRODUCTION**
2. EXPERIMENTAL PROGRAMME
3. EXPERIMENTAL ELEMENT
4. TEST SET-UP
5. LOADING STRATEGY
6. INSTRUMENTATION
7. DAMAGE ASSESSMENT AND STRENGTHENING
8. EXPERIMENTAL RESULTS
9. CONCLUSIONS

1999 Kocaeli, Turkey earthquake (EERI, Earthquake Spectra)

SIGNIFICANT EARTHQUAKES

WORLD (last 20 years)

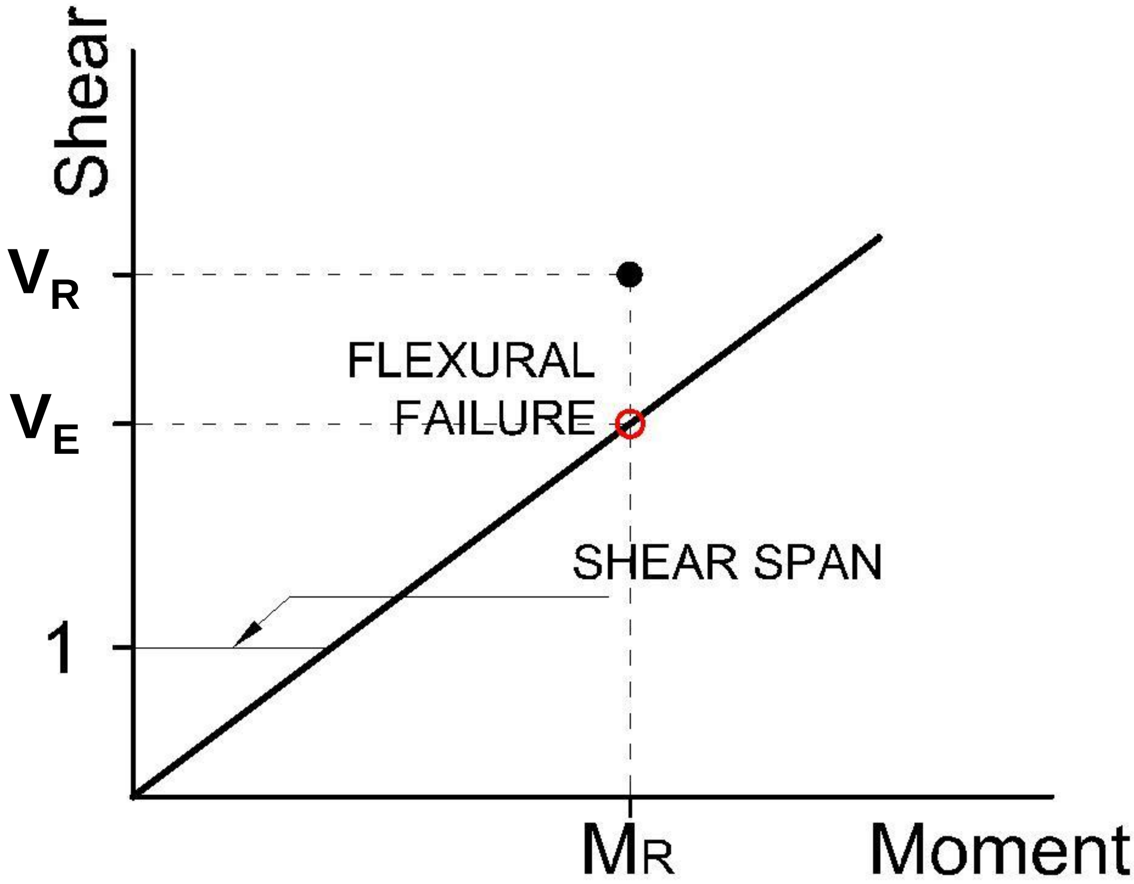
Incomplete list

1994 Northridge, USA
1995 Kobe, Japan
1999 Kocaeli, Turkey
2003 Bam, Iran
2008 Wenchuan, China
2009 L'Aquila, Italy
2010 Port au Prince, Haiti
2010 Chile
2011 Christchurch, NZ
2011 Tohoku, Japan

ROMANIA

1940, 1977, 1986, 1990

CAPACITY DESIGN RULE



FLEXURAL FAILURE
Ductile, large hysteretic loops, significant energy dissipation

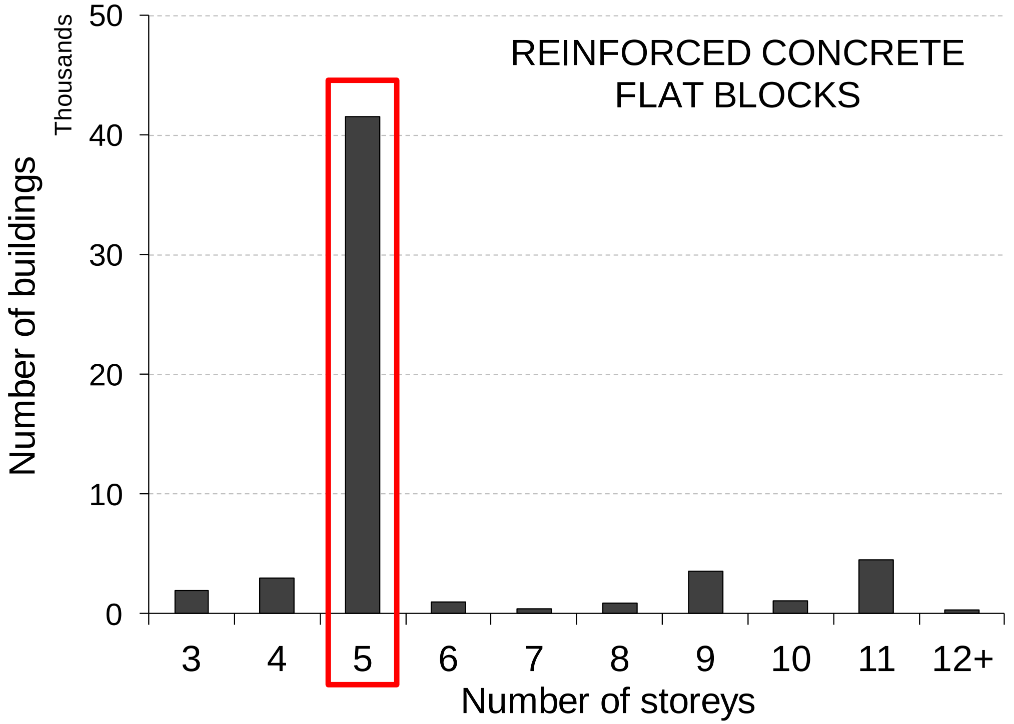
SHEAR FAILURE
Brittle, pinched hysteretic loops, reduced energy dissipation

FAILURE MODE CONTROLLED BY
Shear span ratio
Shear to flexural strength ratio

INTRODUCTION

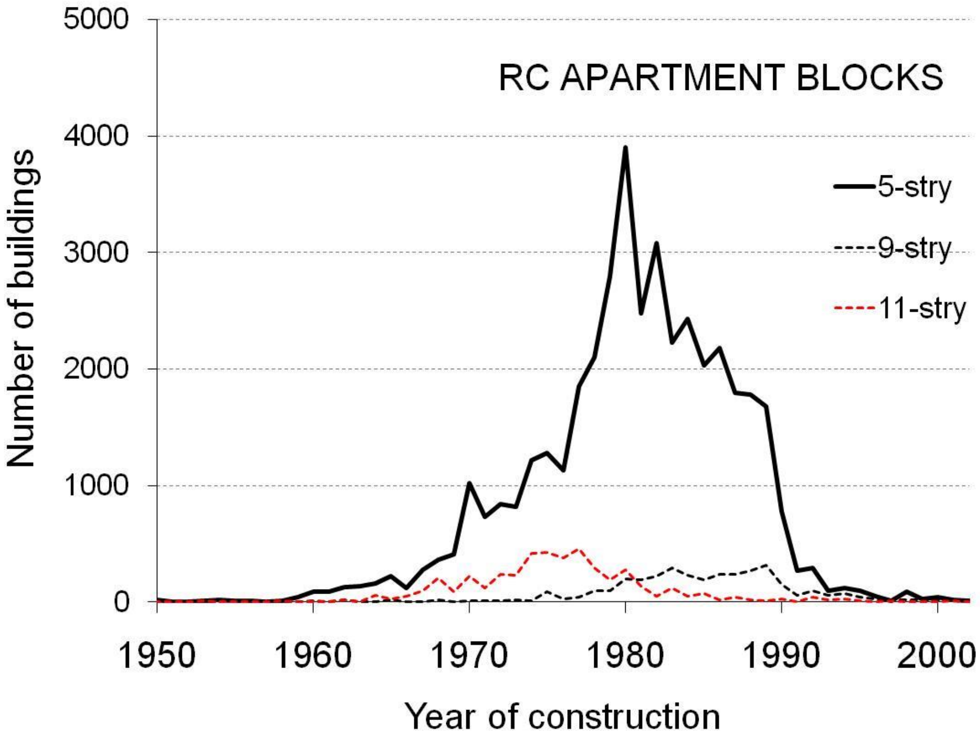
Urban habitat

PRECAST REINFORCED CONCRETE LARGE PANEL (PRCLP) BUILDINGS



-57 000+ buildings
-40 000+ are 5 story PRCLP
-3500+ are 9 story PRCLP
-4500+ are 11 story PRCLP

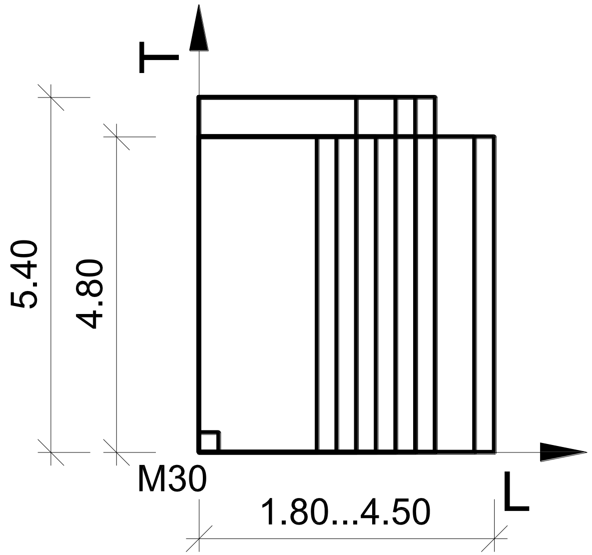
Data from National Institute of Statistics - Romania (NIS). 2002. http://www.insse.ro.

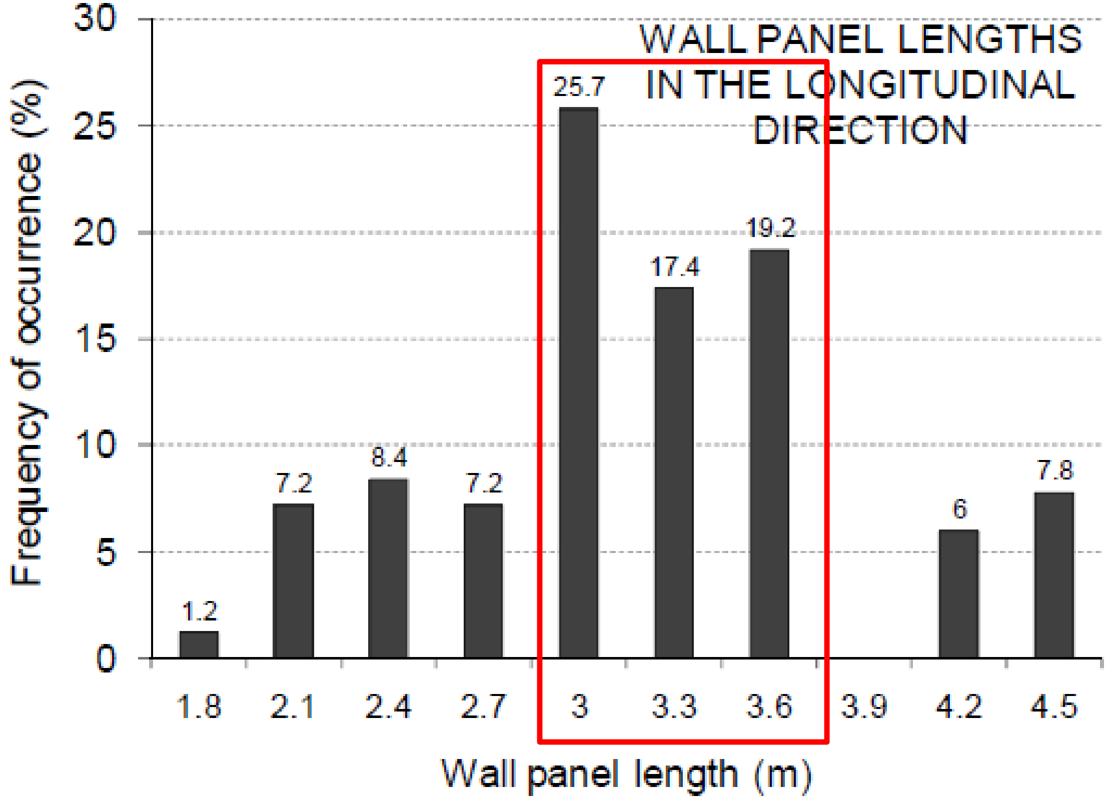


- Early period in the 1960s
- Large scale from 1970
- Era of P+4 PRCLP between 70'-90' (36 000+)
- Decline from 1990

Data from National Institute of Statistics - Romania (NIS). 2002. http://www.insse.ro.

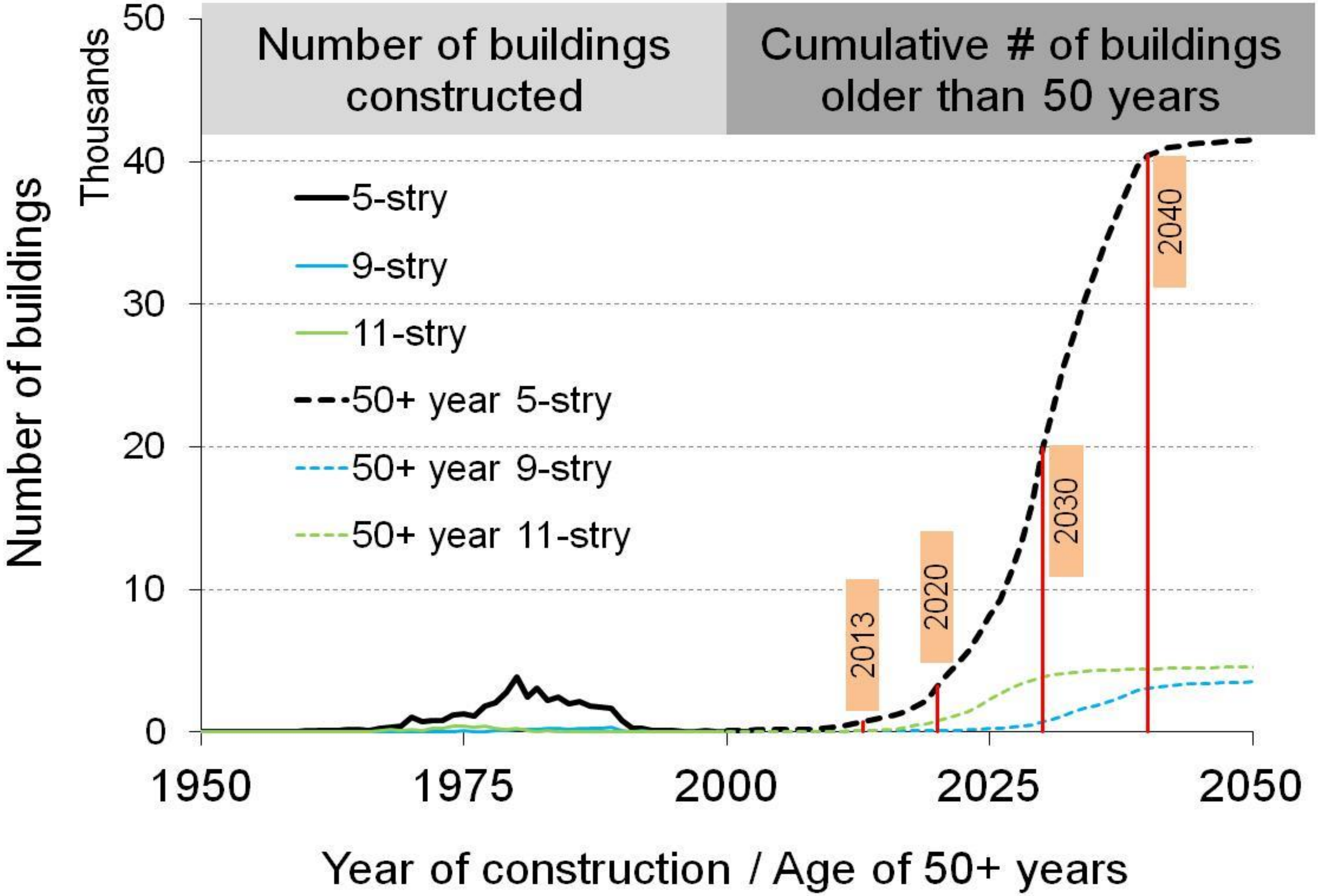
Nominal room dimensions in horizontal plane



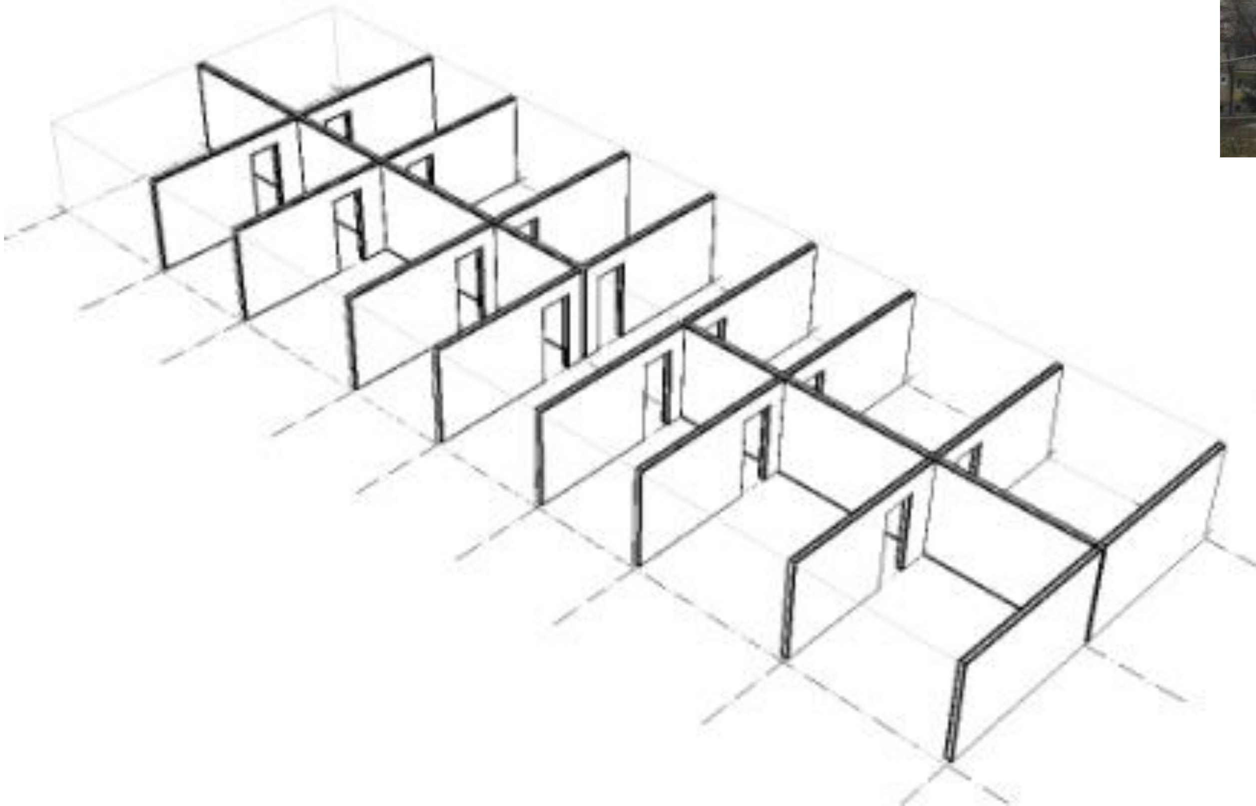


Structural indicators:

Wall area (I1): 6%
Mass / wall area (I2): 0.9 MPa

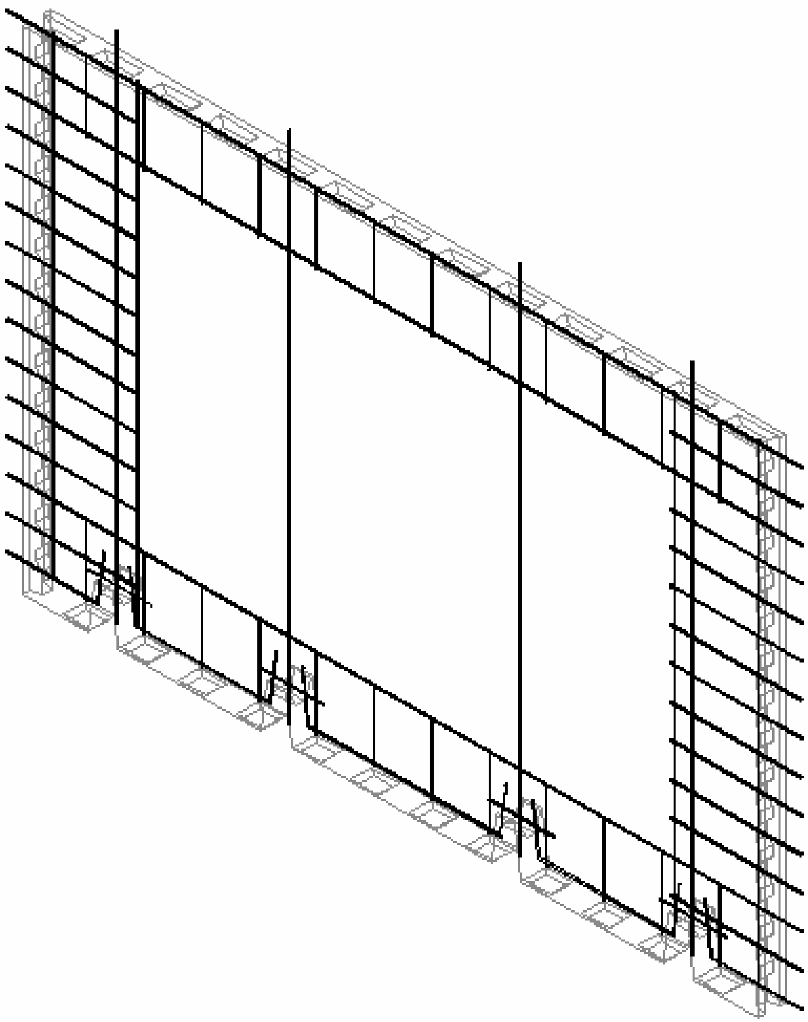

Number of buildings constructed
Cumulative # of buildings older than 50 years
Thousands
Number of buildings
50
40
30
20
10
0
5-stry
9-stry
11-stry
50+ year 5-stry
50+ year 9-stry
50+ year 11-stry
2013
2020
2030
2040
1950
1975
2000
2025
2050
Year of construction / Age of 50+ years

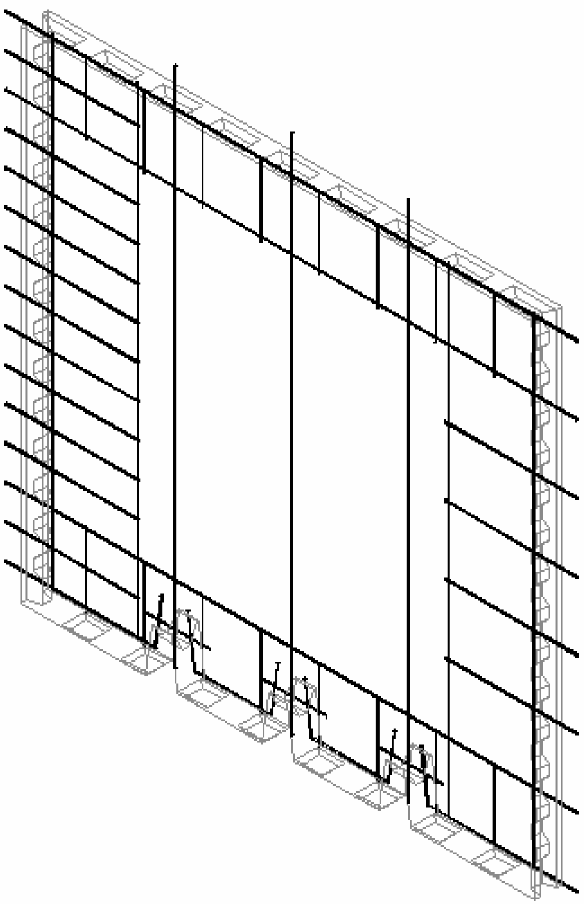
Typical plan 1615/X - 1973



RC Large Panel Buildings

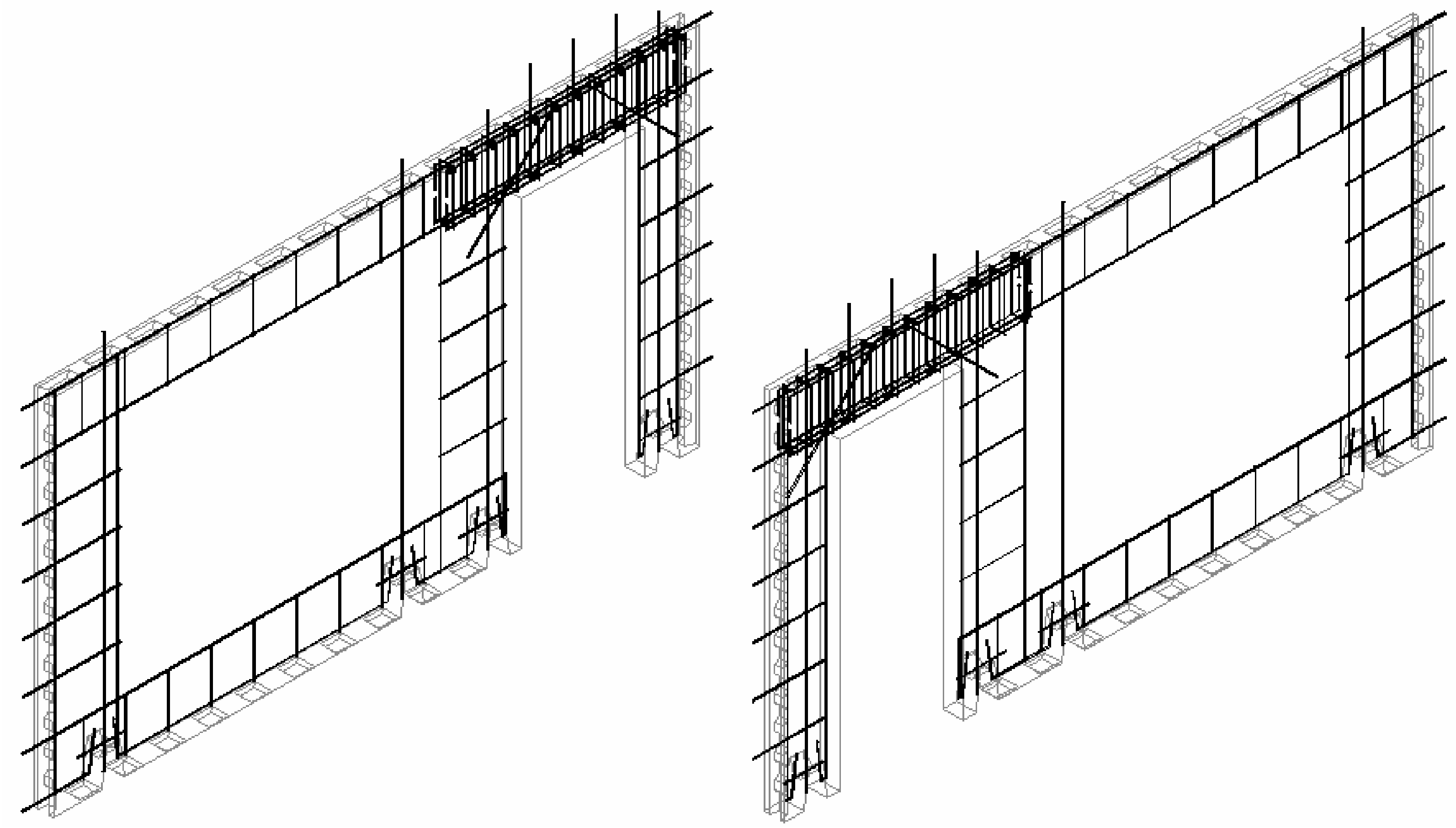
Reinforcement arrangement





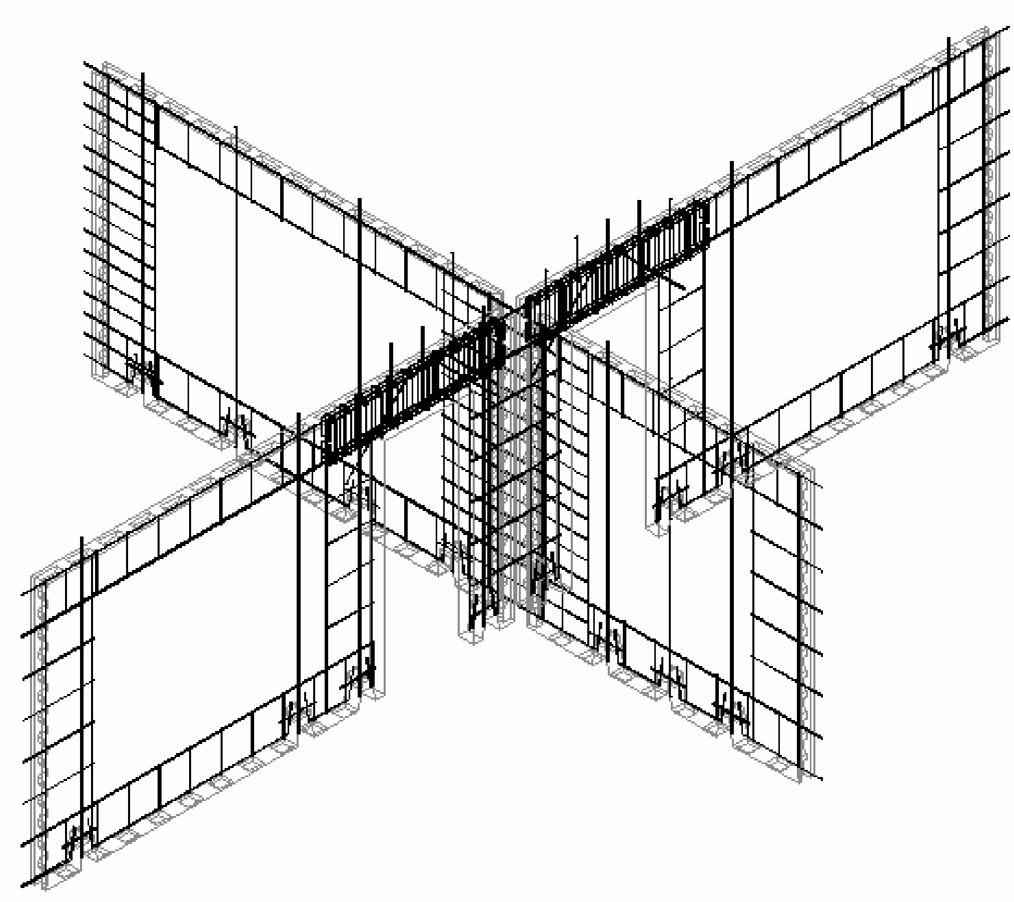
RC Large Panel Buildings

Reinforcement arrangement



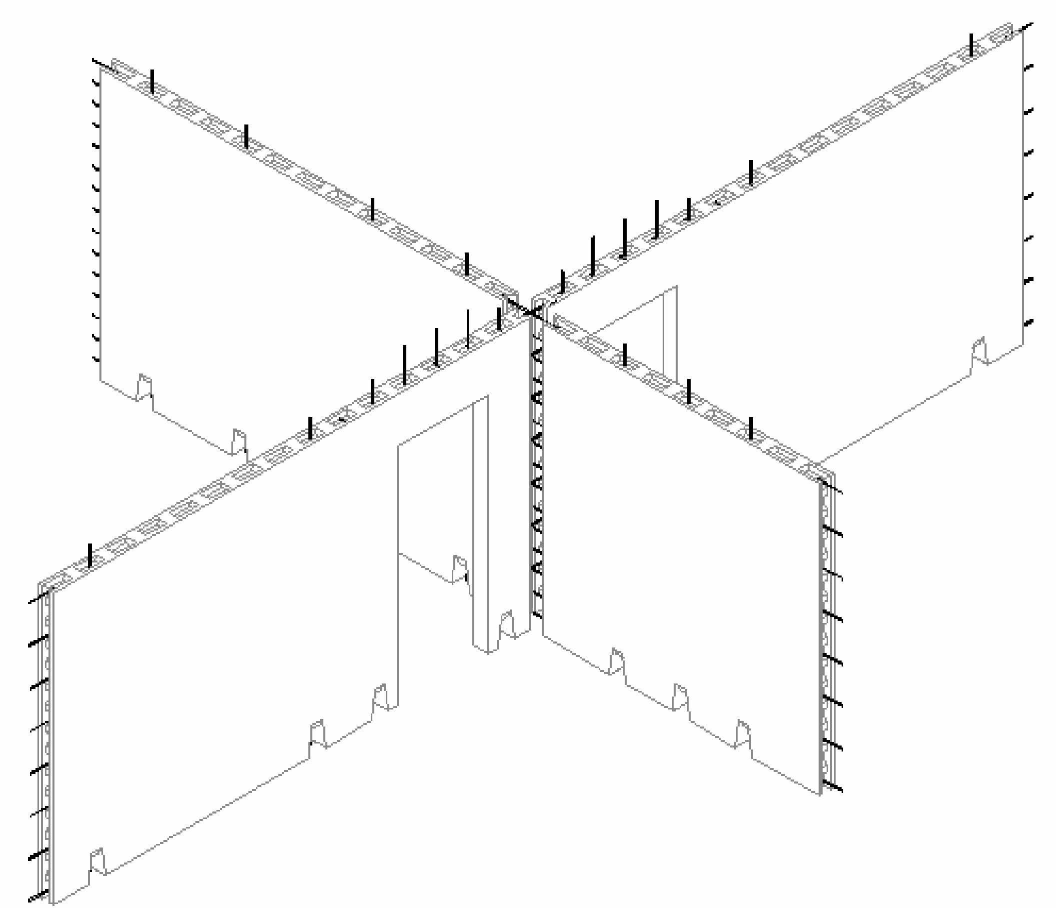
RC Large Panel Buildings

Vertical joint



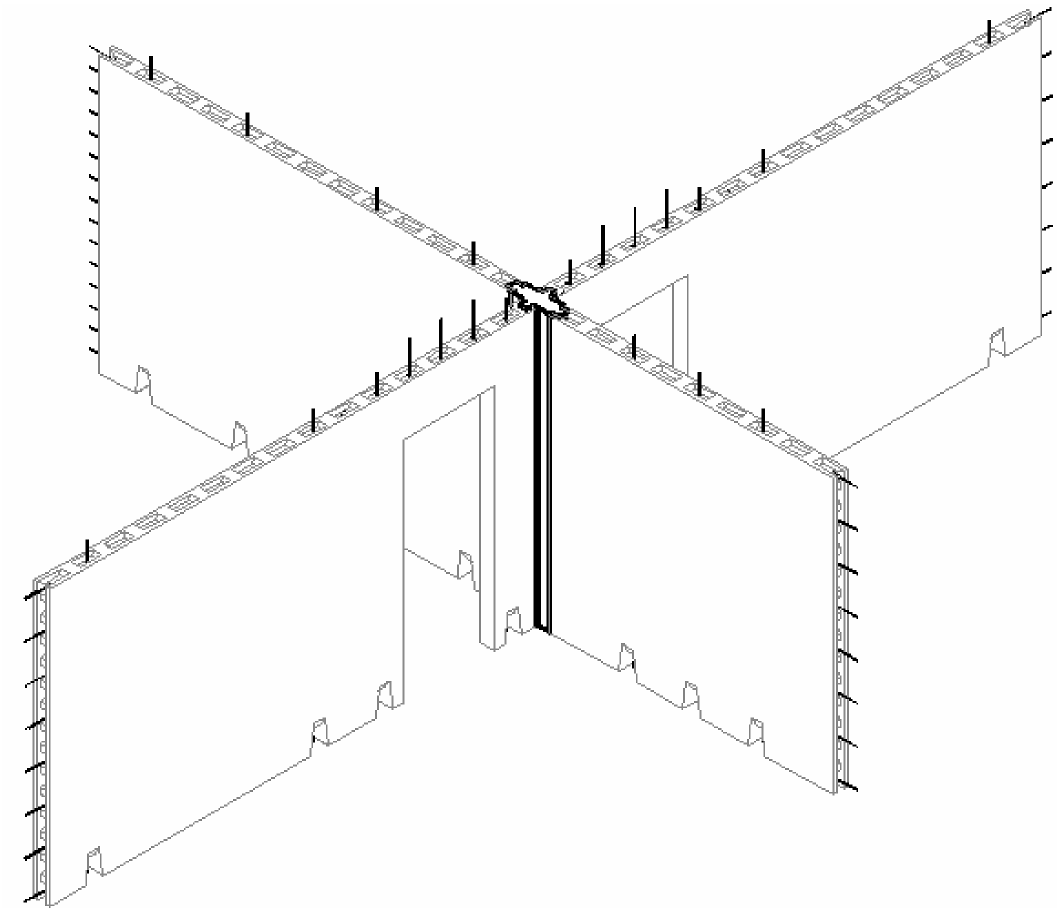
RC Large Panel Buildings

Vertical joint



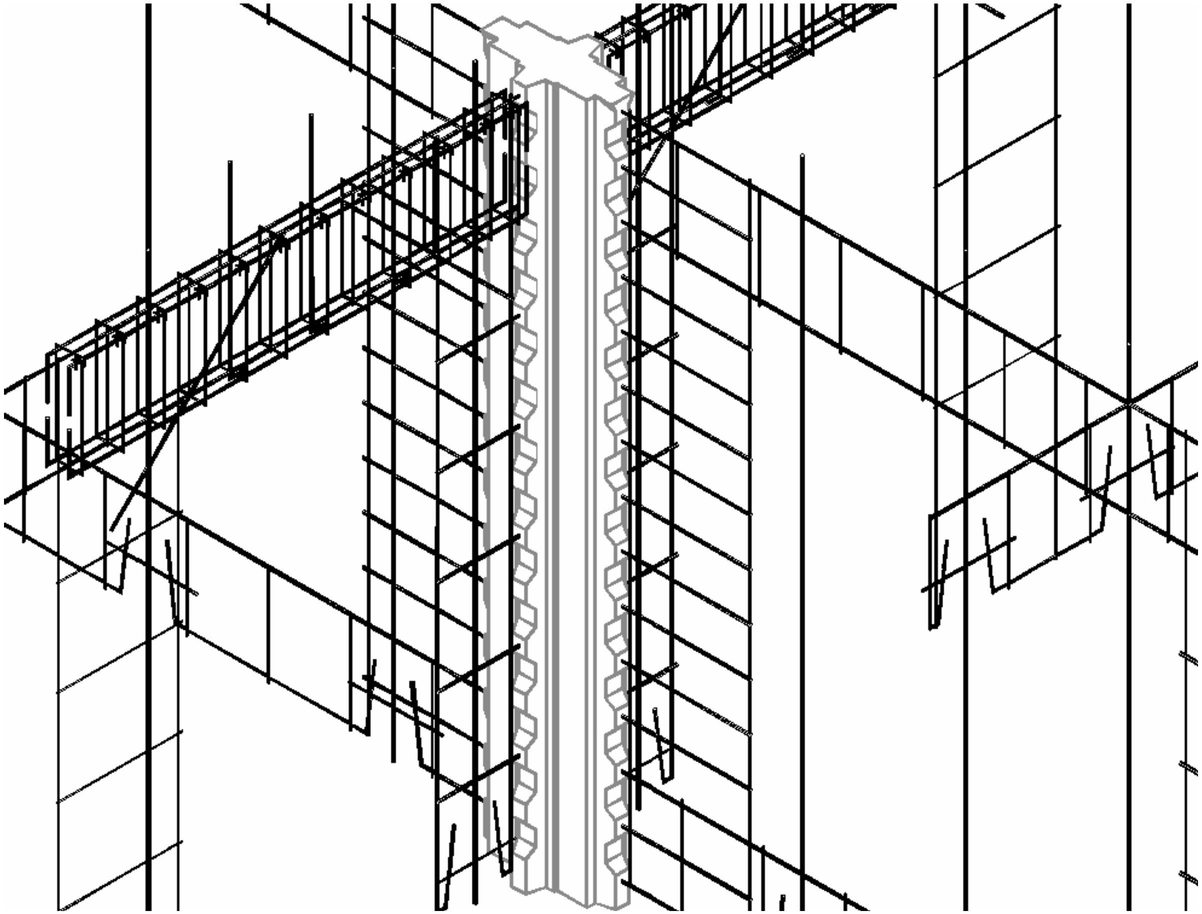
RC Large Panel Buildings

Vertical joint

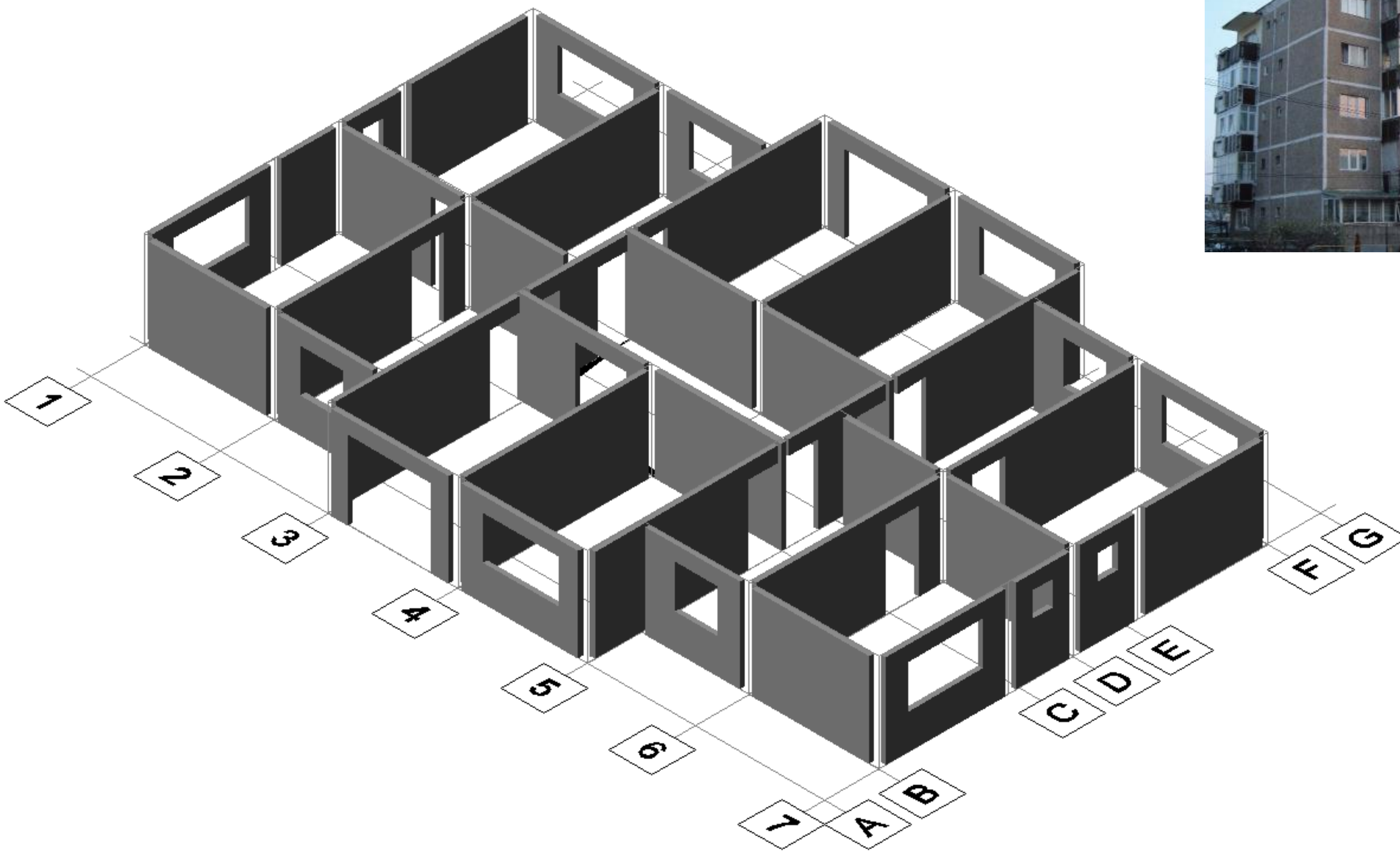


RC Large Panel Buildings

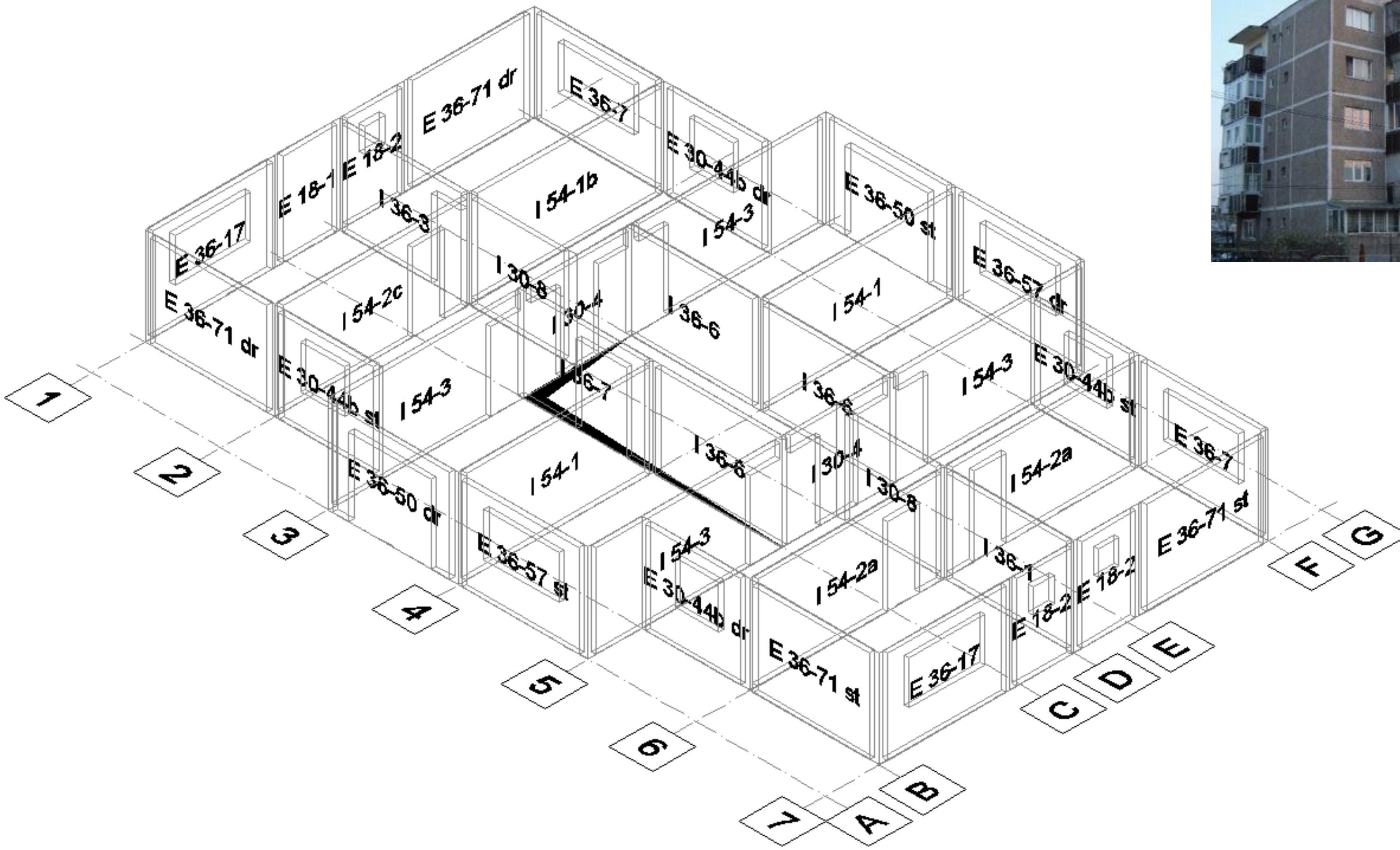
Vertical joint



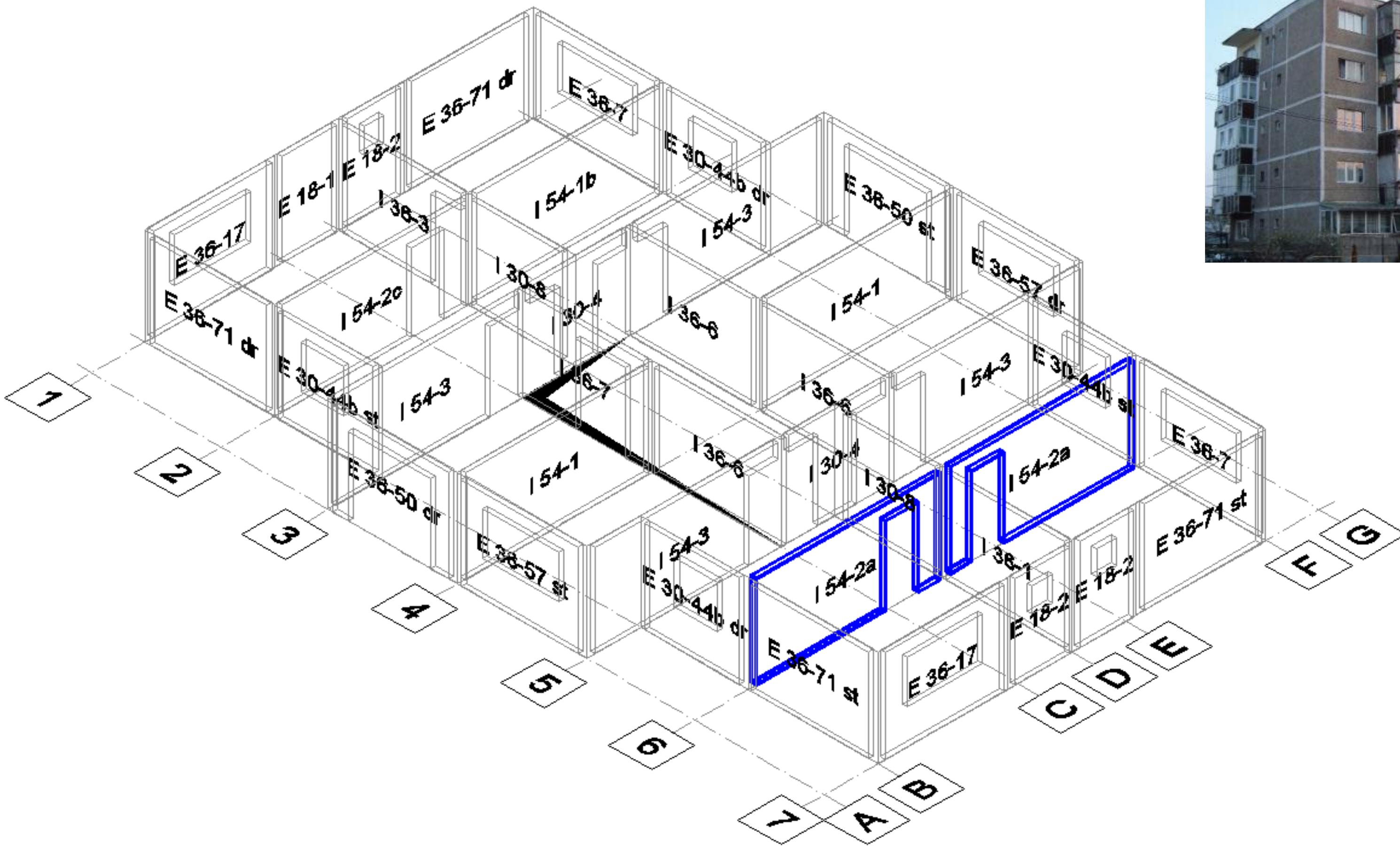
PRCLP building, typical plan 770-81, 1982

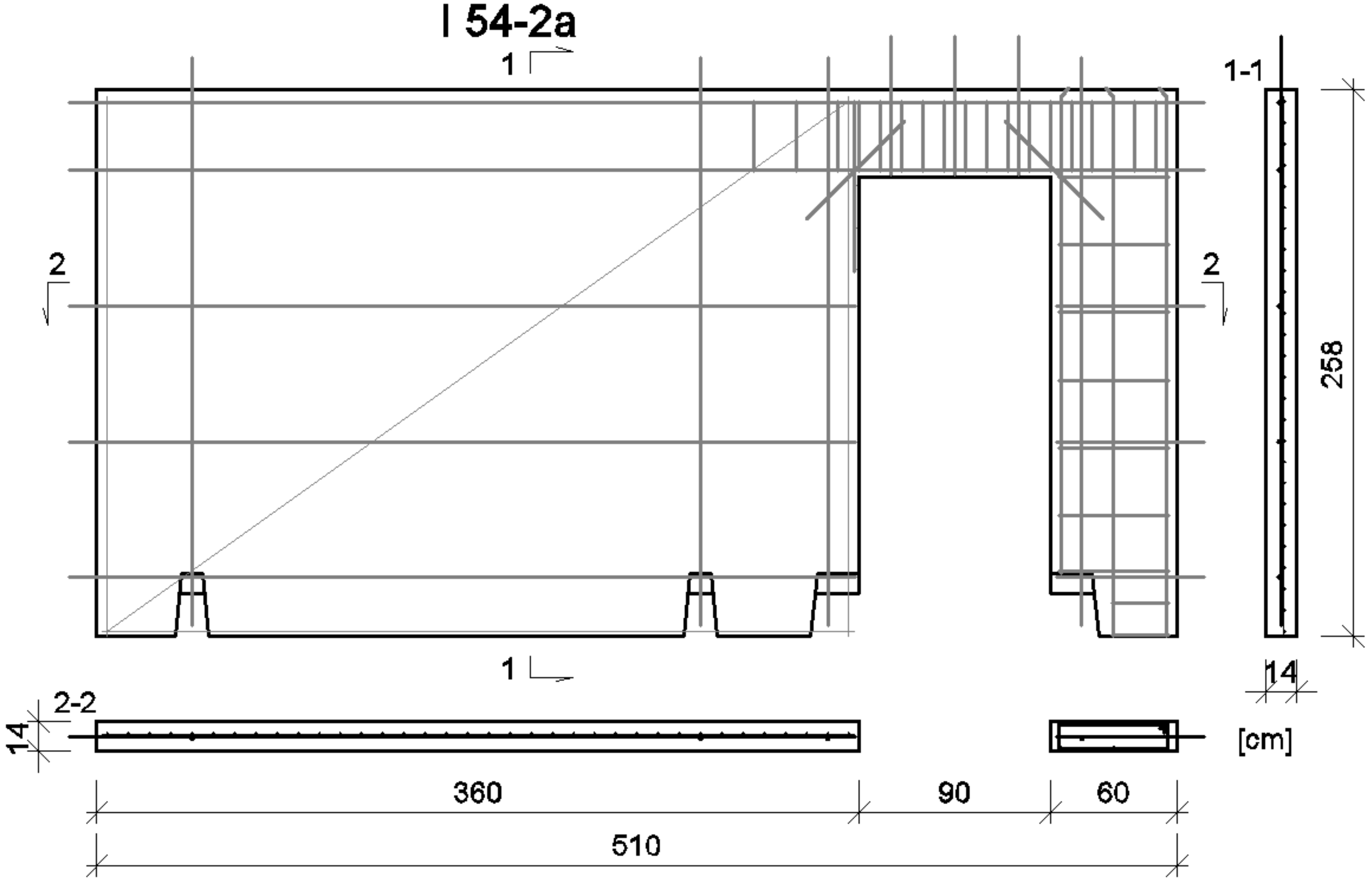


PRCLP building, typical plan 770-81, 1982

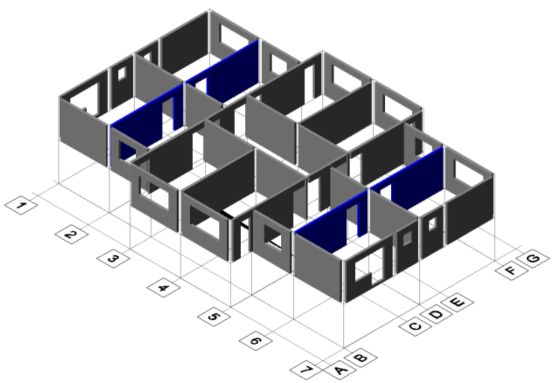


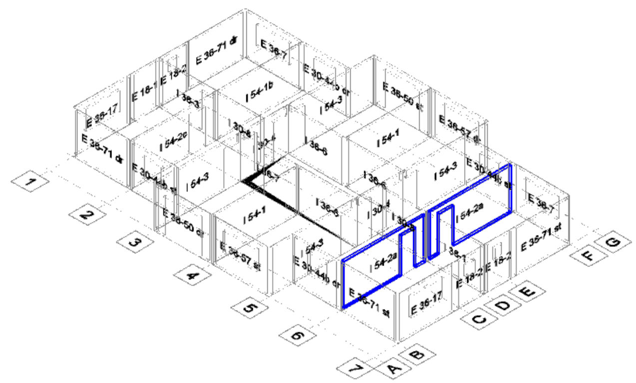
PRCLP building, typical plan 770-81, 1982

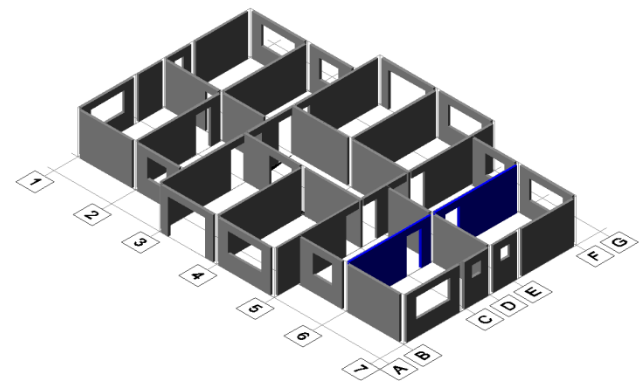


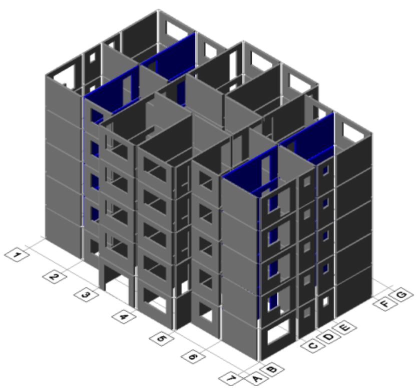

I 54-2a
1
1
2
2
1-1
258
14
2-2
14
[cm]
360
90
60
510

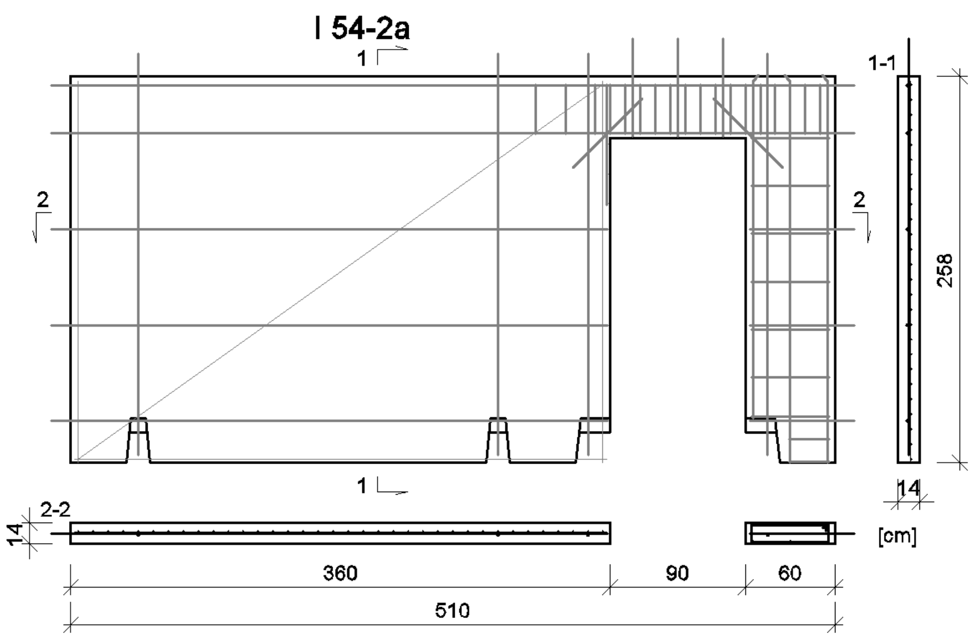
PRCLP building, typical plan 770-81, 1982

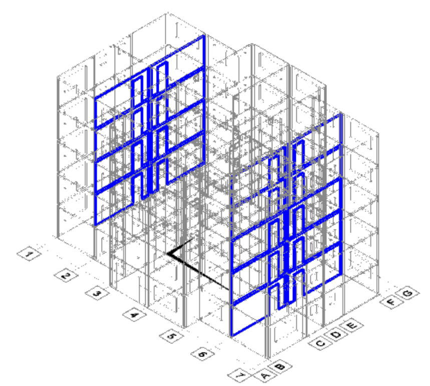




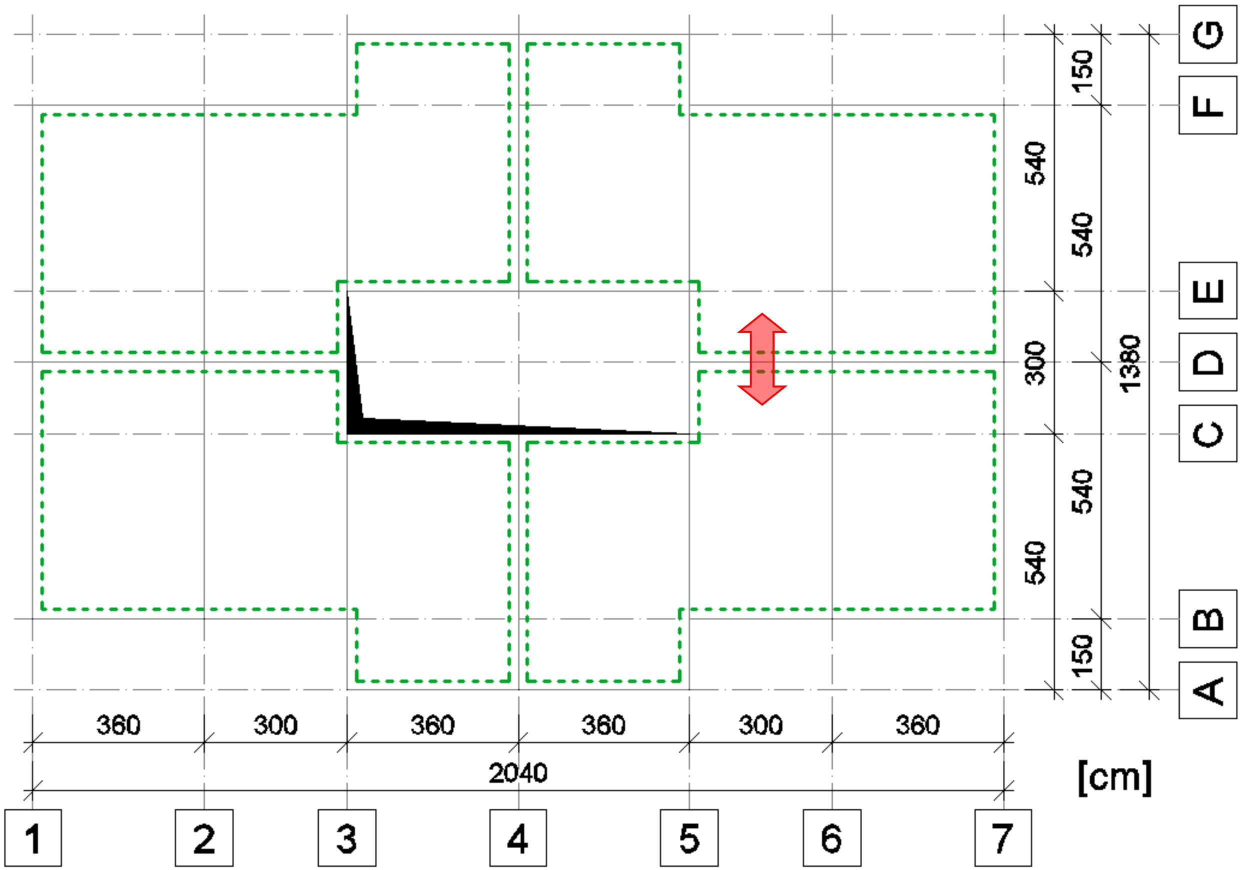


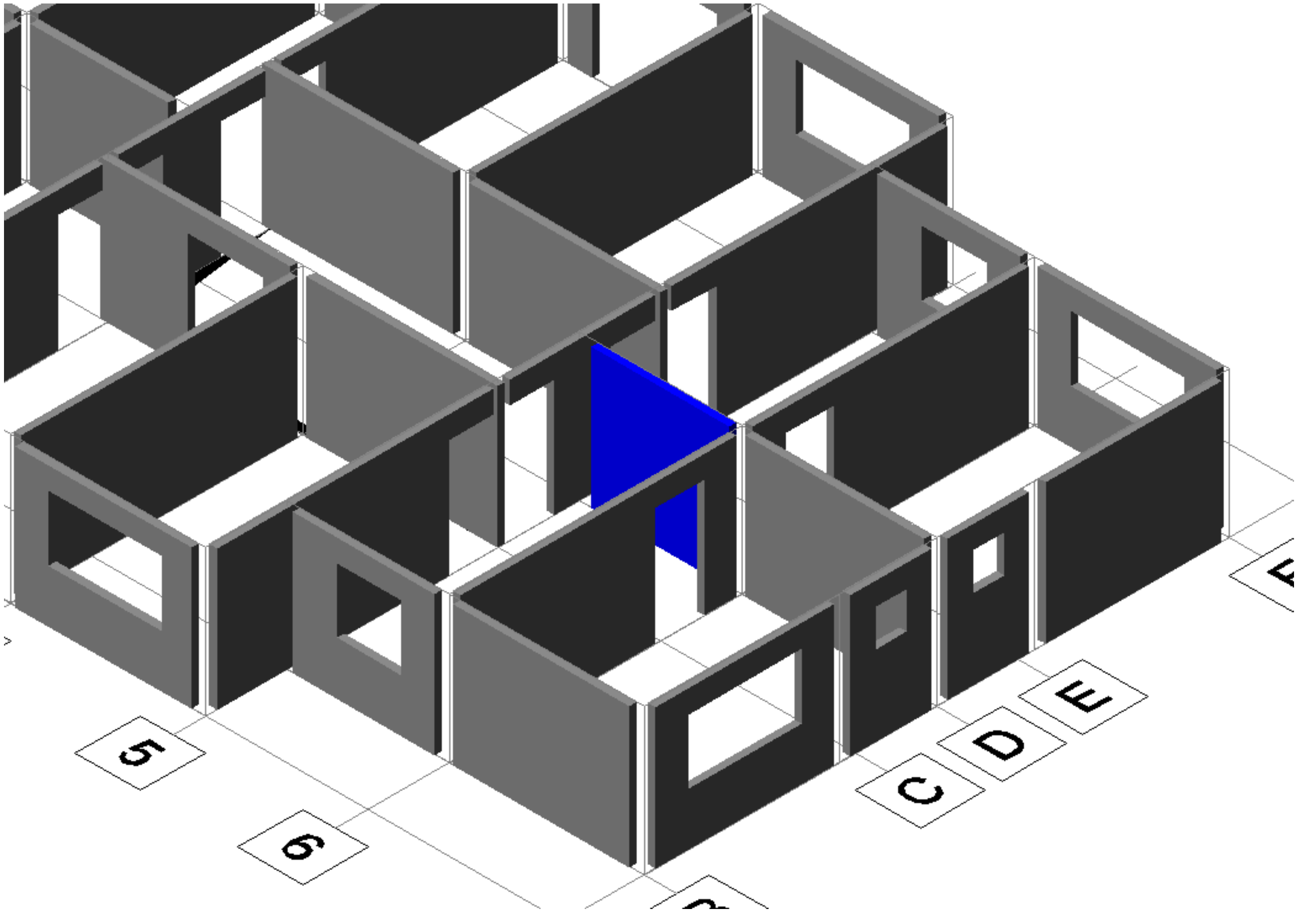


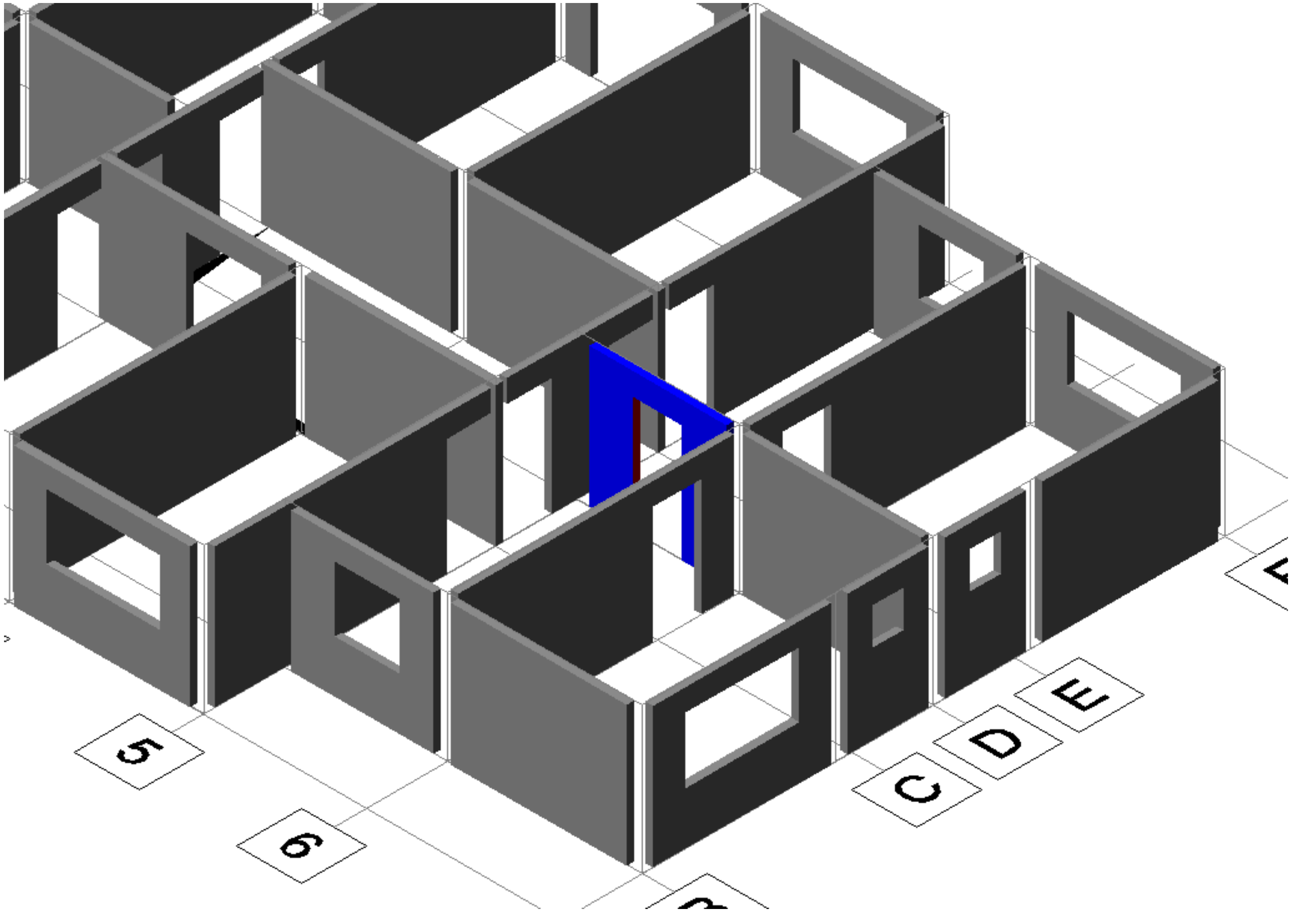


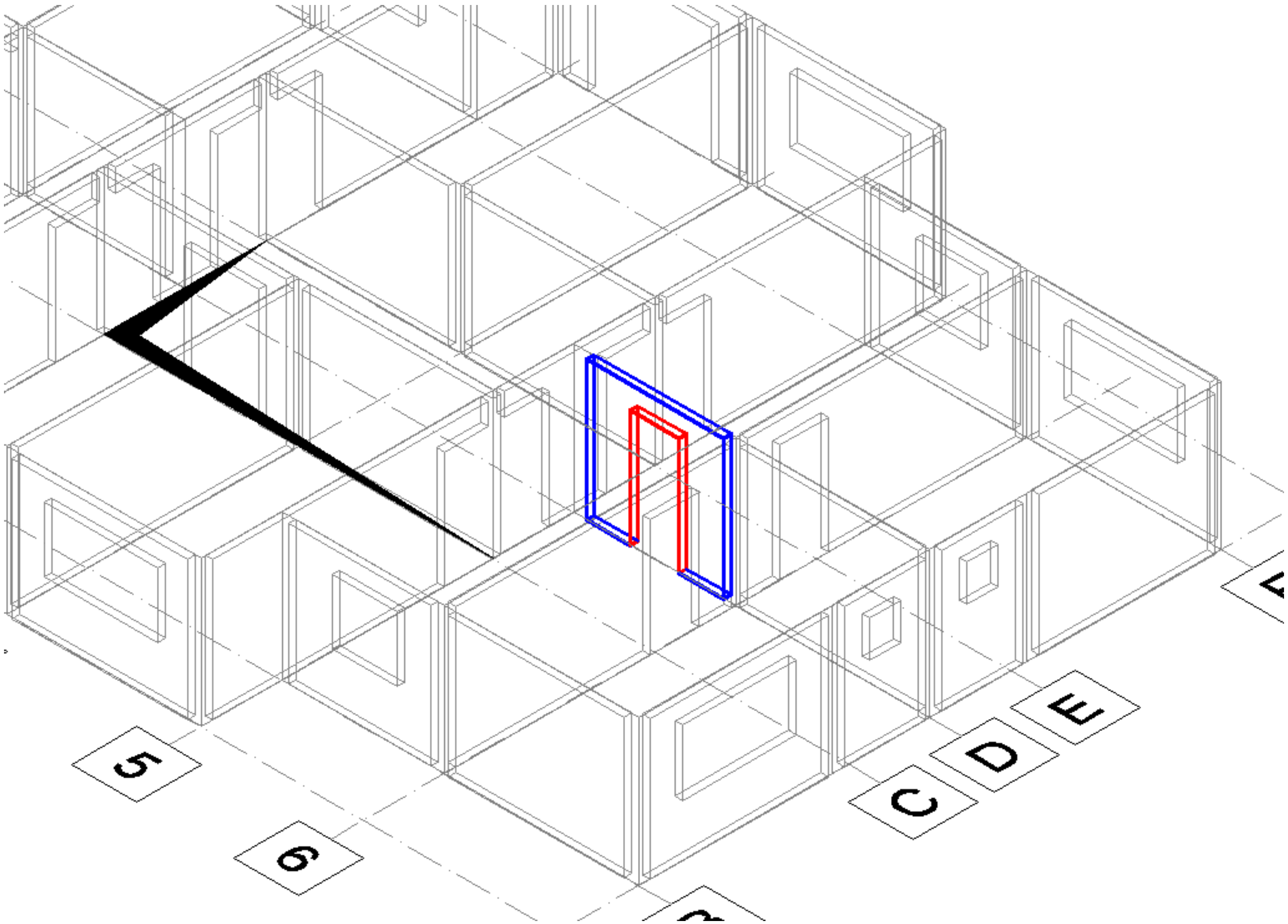


Cut-out openings




5
6
C
D
E


5
6
C
D
E


5
6
C
D
E

INVESTIGATE THE PROBLEM OF CUT-OUT OPENINGS IN PRECAST REINFORCED CONCRETE WALL PANELS SUBJECTED TO SEISMIC LOADING CONDITIONS

AND

PROPOSE STRENGTHENING SOLUTIONS USING FIBER REINFORCED POLYMER COMPOSITES.

→ **literature survey**

→ **available design guidelines**

→ **theoretical analysis**

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BASIC PRINCIPLE OF THE EXPERIMENTAL TESTING METHODS:

REPRODUCE THE *IN SITU* CONDITIONS IN THE *LABORATORY*.

BASIC PRINCIPLE OF THE EXPERIMENTAL TESTING METHODS:

REPRODUCE, as much as possible**,** THE ***IN SITU*** **CONDITIONS IN THE *LABORATORY*.**

CONSIDERING:

→ AVAILABLE INFRASTRUCTURE AND TESTING FACILITIES.

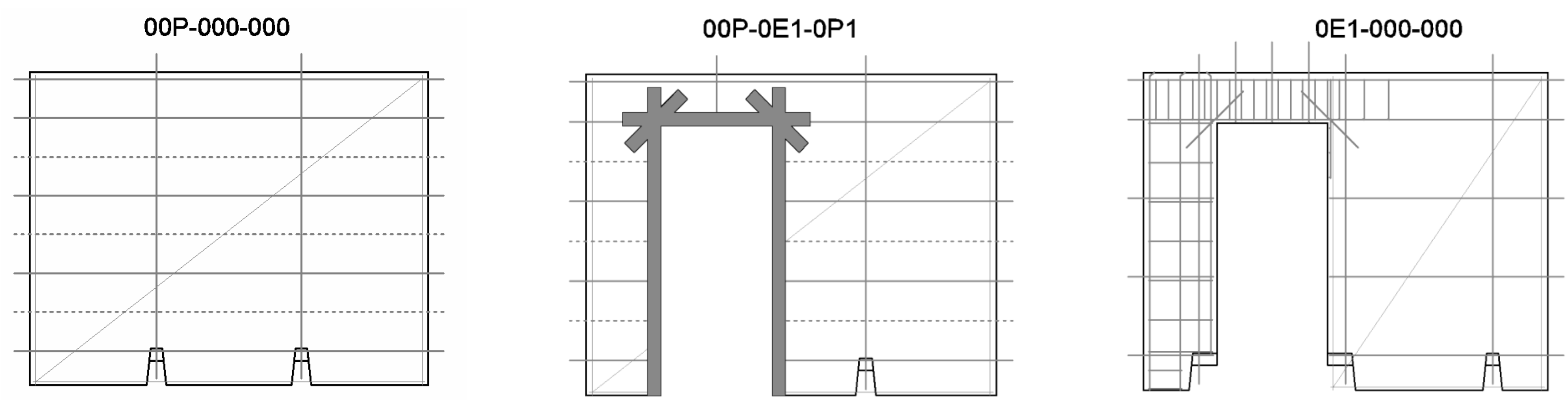
→ FINANCIAL AND HUMAN RESOURCES.

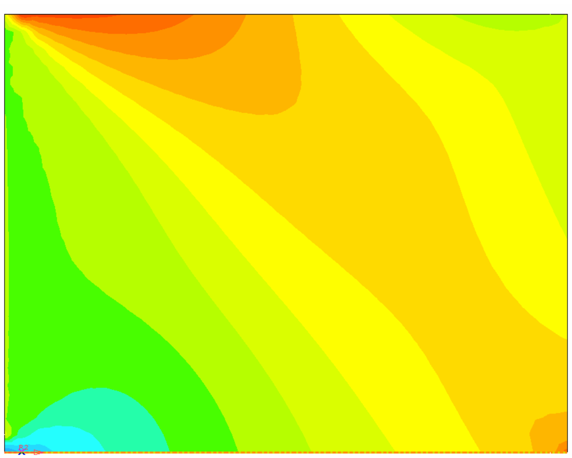
DECISION:

→ experimental specimens: INDIVIDUAL WALL PANELS.

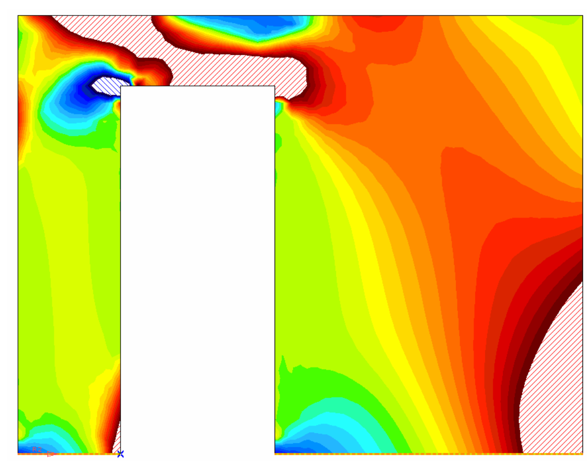
→ loading strategy: IN-PLANE, CYCLIC, QUASI-STATIC.

→ test set-up: CAPABLE TO REPRODUCE THE BOUNDARY AND LOADING CONDITIONS.





10 t
20 t
30 t
40 t
50 t



ADVANTAGES OF DATABASE

-INCLUDES A LARGE NUMBER OF DATA-LINES
-IDENTIFIES SIGNIFICANT PARAMETERS
-FACILITATE COMPARISON
-IT CAN BE SEARCHED AND/OR SORTED

Data sources: ACI Structural Journal, EERI Earthquake Spectra, IAEE Earthquake Engineering & Structural Dynamics, EAEE Bulletin of Earthquake Engineering, ASCE Journal of Structural Engineering, World Conference on Earthquake Engineering series 1 to 14, PCA Research and Development Bulletin, European Conference on Earthquake Engineering series, Engineering Structures

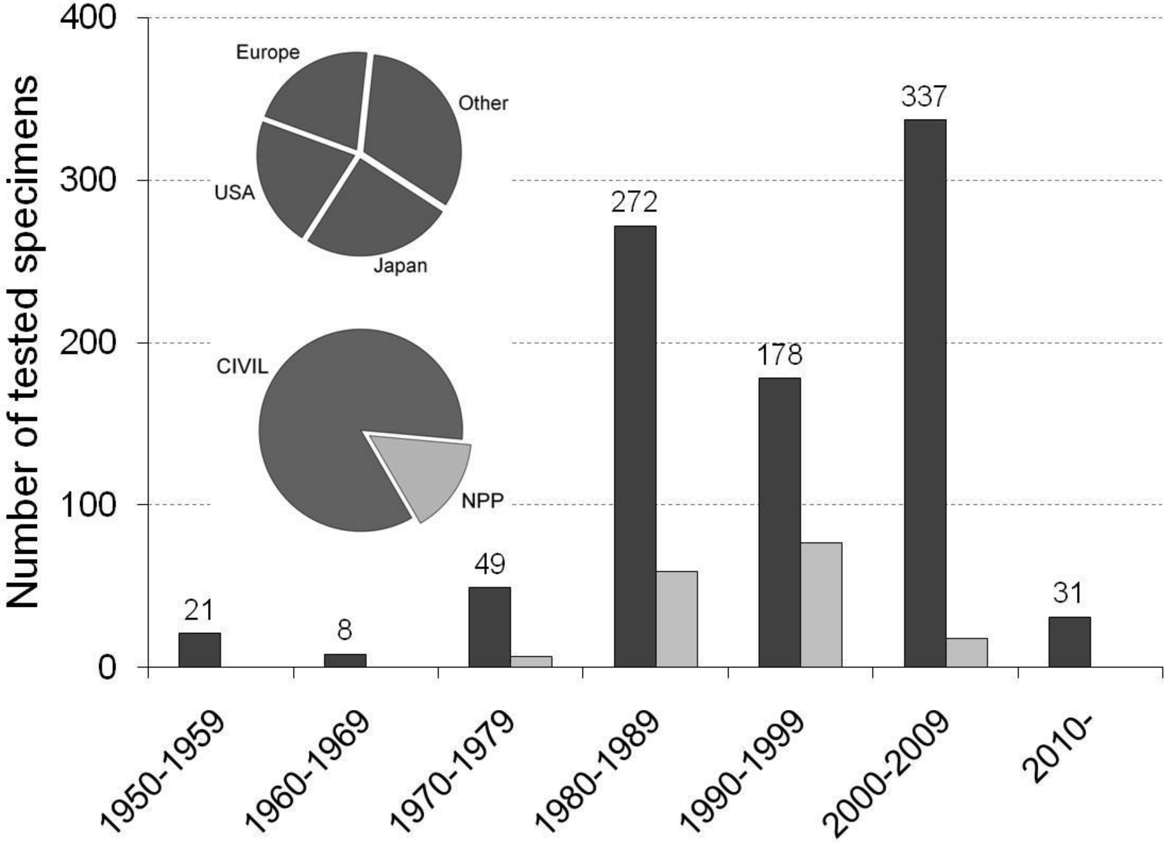
EXISTING RC WALL DATABASES

Hirosawa (1975)
Wood (1990)
Panagiotakos and Fardis (2001)
Biskinis et al. (2004)
Gulec and Whittaker (2009)

REFERENCE LISTS AND CATALOGUES

Abrams (1991)
Farrar et al. (1993)

YEAR, TYPE AND REGION



Early laboratory tests in USA, Japan, Canada, New-Zealand

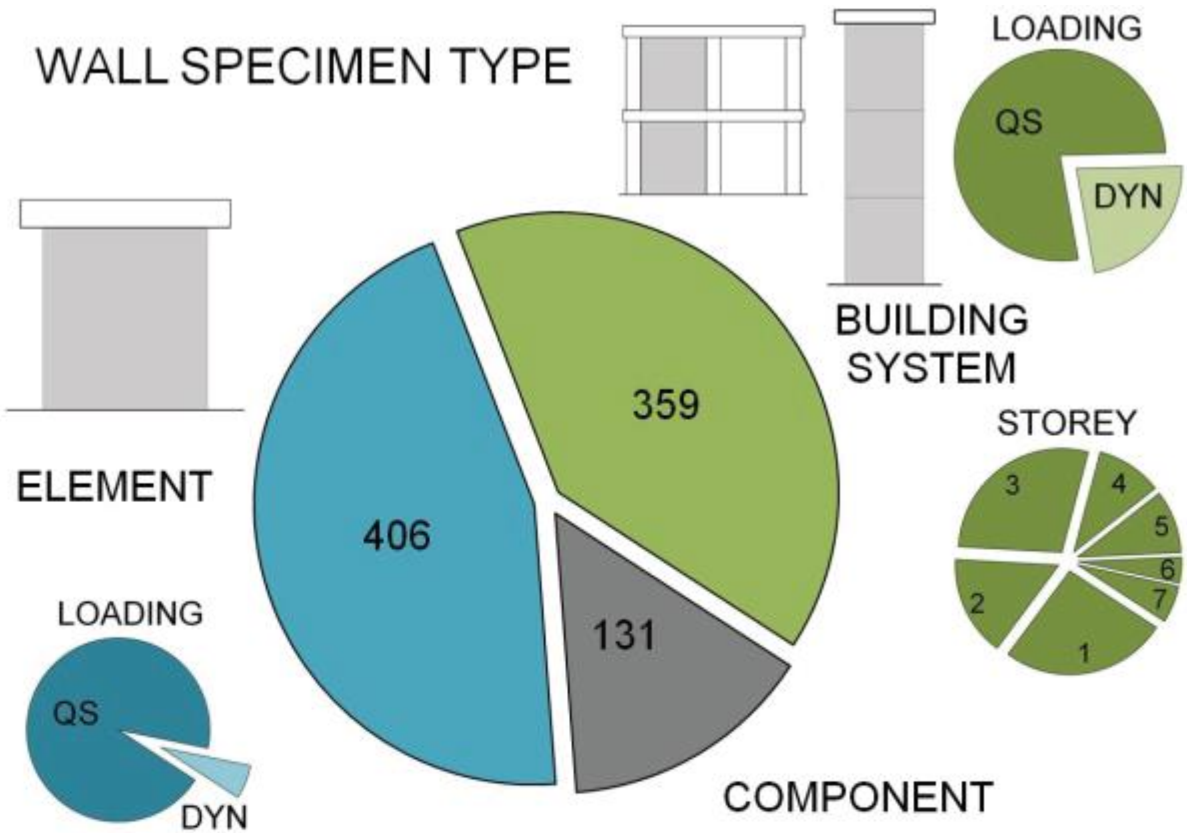
Europe: earliest ref. **1984**

Construction: Civil or Nuclear Power Plant

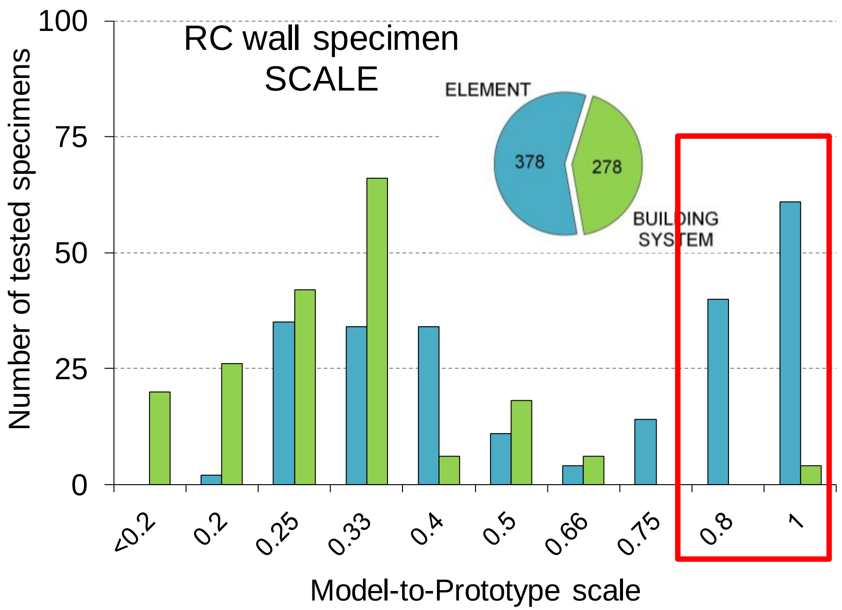
Romania: **7 programs**
- **4 UPT**
- 1 INCERC-TM
- 1 UTCB
- 1 INCERC-CL

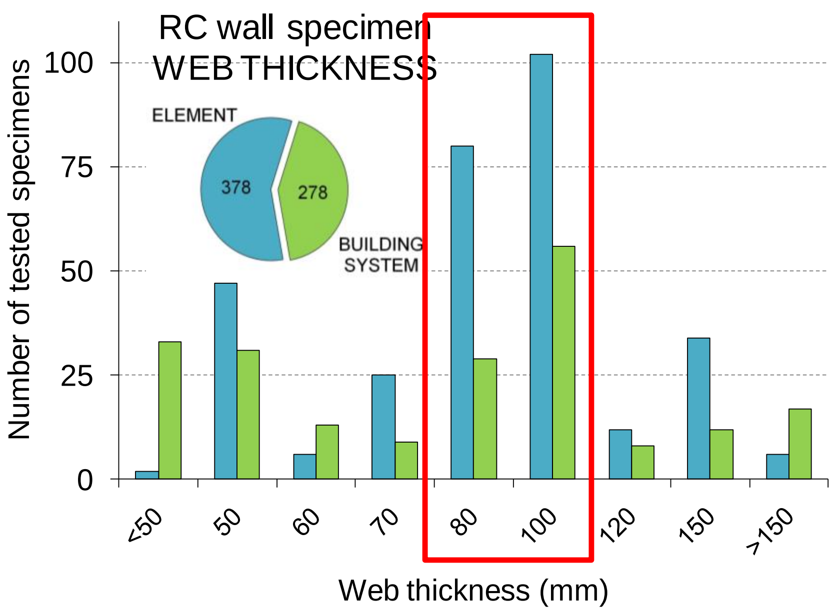
INCC-1992	1992	Romania	Unit	civil	wall-frame-slab s	precast	solid	non
UPT-1992	1992	Romania		civil	wall system	monolithic	door	non
INCT-1998	1998	Romania	M; F	civil	wall system	precast	solid	non
UPT-2005	2005	Romania	SW; RW	civil	wall system	monolithic	solid; door	non; FRP-EBR
UTCB-2007	2007	Romania	W	civil	wall system	monolithic	solid	non
UPT-2010	2010	Romania	PRCWP	civil	wall element	precast	solid; door cut-ou	non; FRP-EBR
UPT-2011	2011	Romania	CSRCW	civil	wall system	monolithic	solid	non; FRP-EBR

WALL TYPES

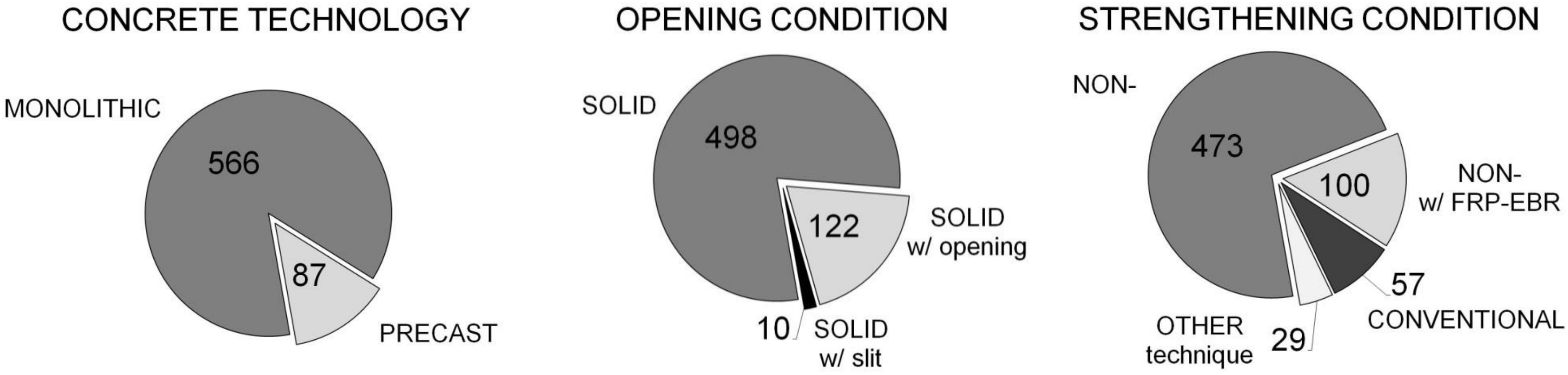

WALL SPECIMEN TYPE
ELEMENT
406
359
131
COMPONENT
BUILDING SYSTEM
LOADING
QS
DYN
LOADING
QS
DYN
STOREY
3
4
5
6
7
2
1

WALL SCALE AND THICKNESS





ELEMENT CHARACTERISTICS



Programs that included **precast** wall panels: 16 (87 specimens)

Programs that included wall with **openings**: 14 (122 specimens)

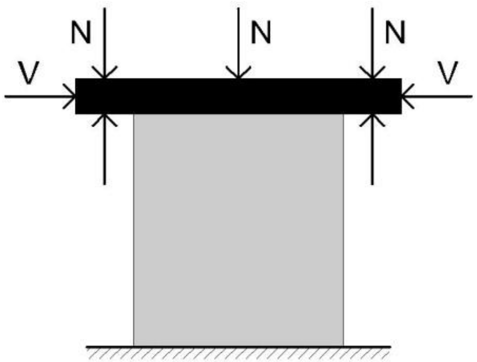
Programs that included walls strengthened by **CFRP**: 16 (100 specimens)

EXPERIMENTAL PROGRAMS ON FRP STRENGTHENED WALLS

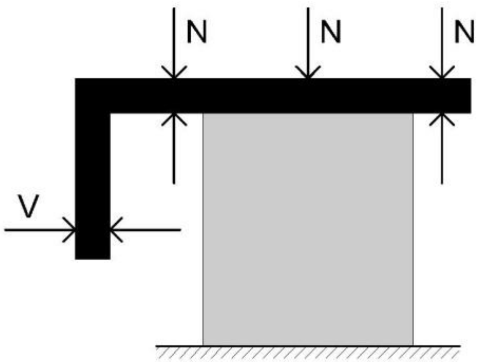
ID			SPECIMEN						
No.	Year	Country	Designation	Construction	Type	concrete technol	opening	strengthening	No. of spec.
						wall			
CARLT-2000	2000	Canada	wall	civil	wall element	monolithic	solid	non; FRP EBR	7
EMSI-2000	2000	France-EU	CAMUS 1 to 4	civil	wall system	monolithic	solid	non; FRP-EBR	4
TOKYU-2000	2000	Japan	T; U; RC; CF; CFR;	civil	column wing-wal	monolithic	n/a	non; FRP-EBR	15
TUSJ-2000	2000	Japan	Specimen	civil	wall-frame syster	monolithic	solid; door; wind	non; FRP-EBR	10
ELSA-2001	2001	France-EU	T	nuclear	wall element	monolithic	solid	non; FRP EBR	13
MGILL-2003	2003	Canada	W	civil	wall system	monolithic	solid	non; FRP-EBR; RC;	4
AUTH-2003	2003	Greece	MSW; LSW; FRPM	civil	wall element	monolithic	solid	non; FRP EBR	11
UUTAH-2003	2003	USA	Specimen; wall as	civil	wall system	precast	solid	FRP-EBR connecti	9
MMCAN-2004	2004	Canada	CW; RW	civil	wall element	monolithic	solid	non; FRP-EBR	3
HOKU-2004	2004	Japan	WA	civil	wall-frame syster	monolithic	door; window	non; FRP-EBR	3
NCREE-2004b	2004	Taiwan	PF; WF	civil	wall-frame syster	monolithic	solid; frame	non; FRP-EBR	6
UFUK-2005	2005	Japan	W; specimen	civil	wall-frame syster	monolithic	solid	non; FRP-EBR	6
UPT-2005	2005	Romania	SW; RW	civil	wall system	monolithic	solid; door	non; FRP-EBR	5
UCNZ-2007	2007	New Zealand	W	civil	wall element	monolithic	solid; slitted	non; selective we	4
UPT-2010	2010	Romania	PRCWP	civil	wall element	precast	solid; door cut-ou	non; FRP-EBR	5
NTUSG-2010	2010	Singapore		civil	wall element	monolithic		FRP-EBR	4
UPT-2011	2011	Romania	CSRCW	civil	wall system	monolithic	solid	non; FRP-EBR	6

EXPERIMENTAL STANDS - LOADING DEGREE

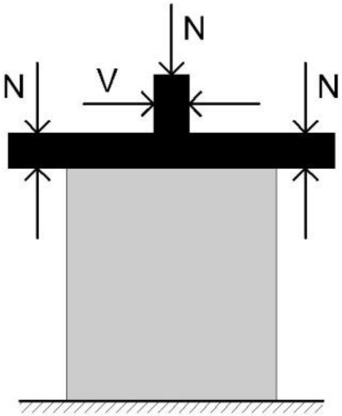
Number and location of the axial and lateral loads



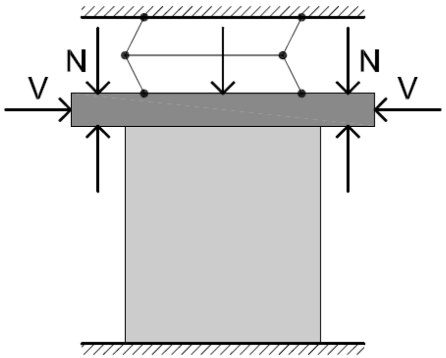
Type A test setup



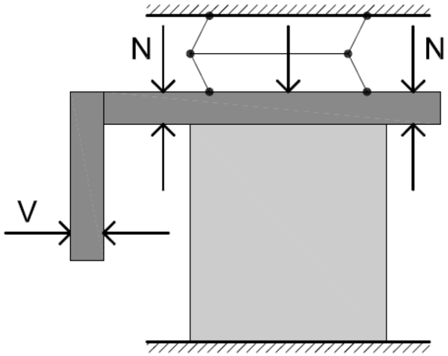
Type B test setup



Type C test setup

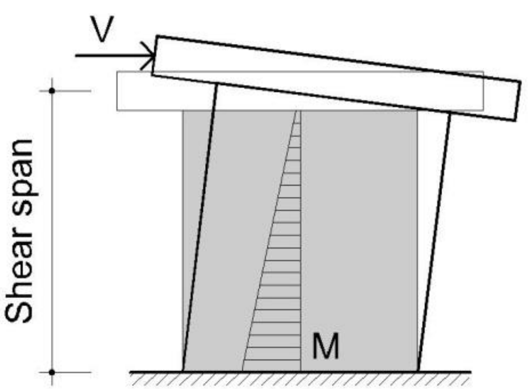


Type A setup with pantograph

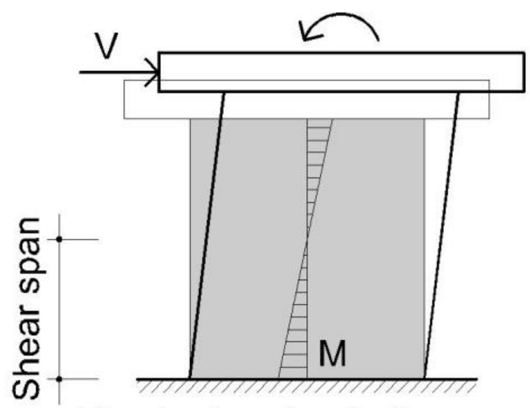


Type B setup with pantograph

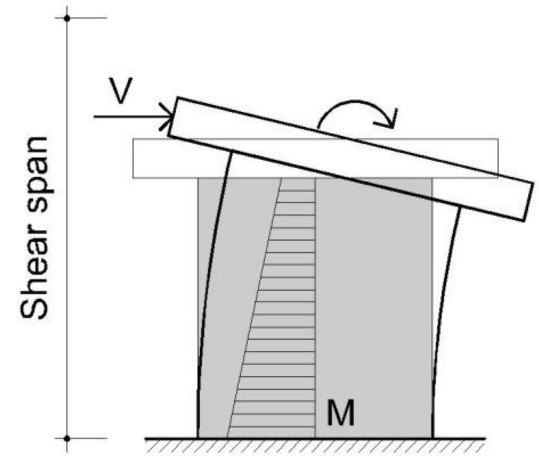
BOUNDARY CONDITIONS



Cantilever

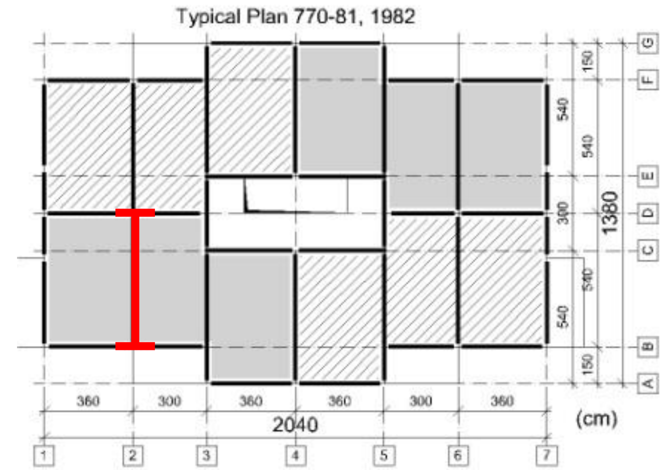


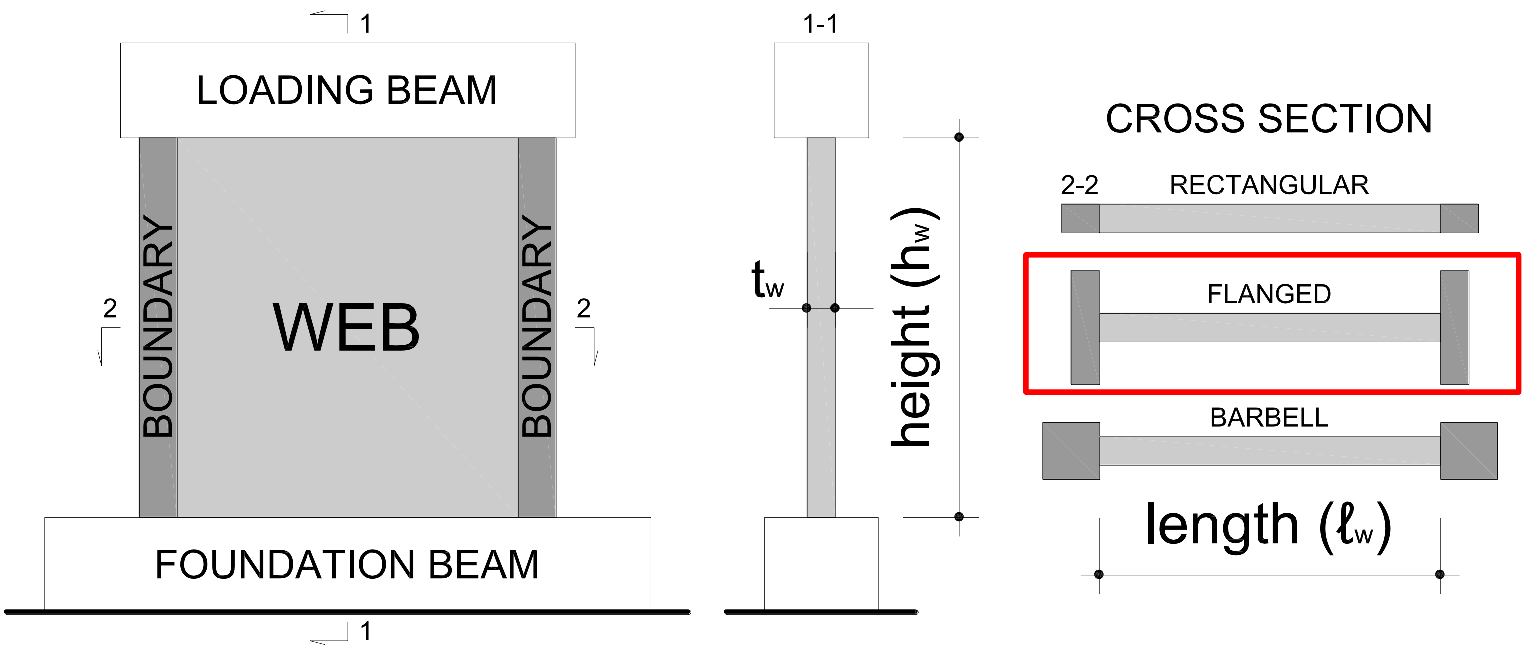
Restrained rotation



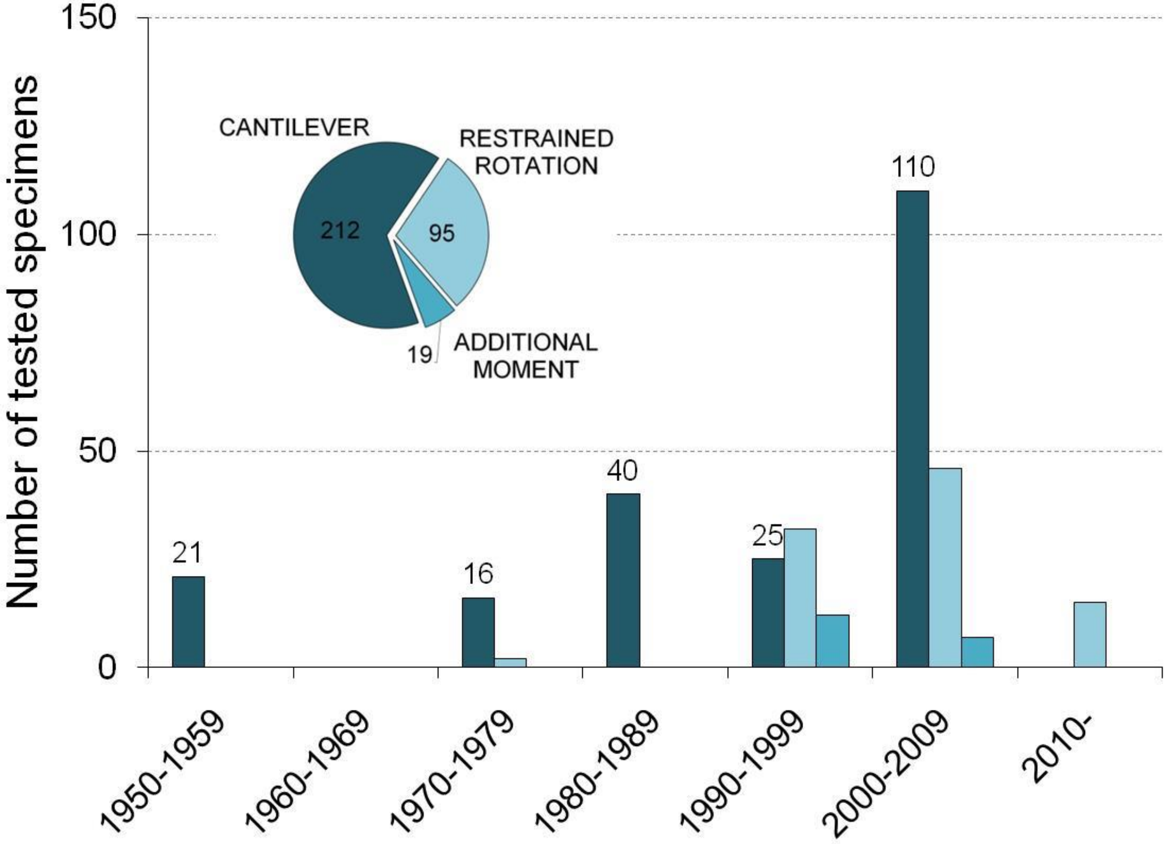
Additional moment

BOUNDARY CONDITIONS



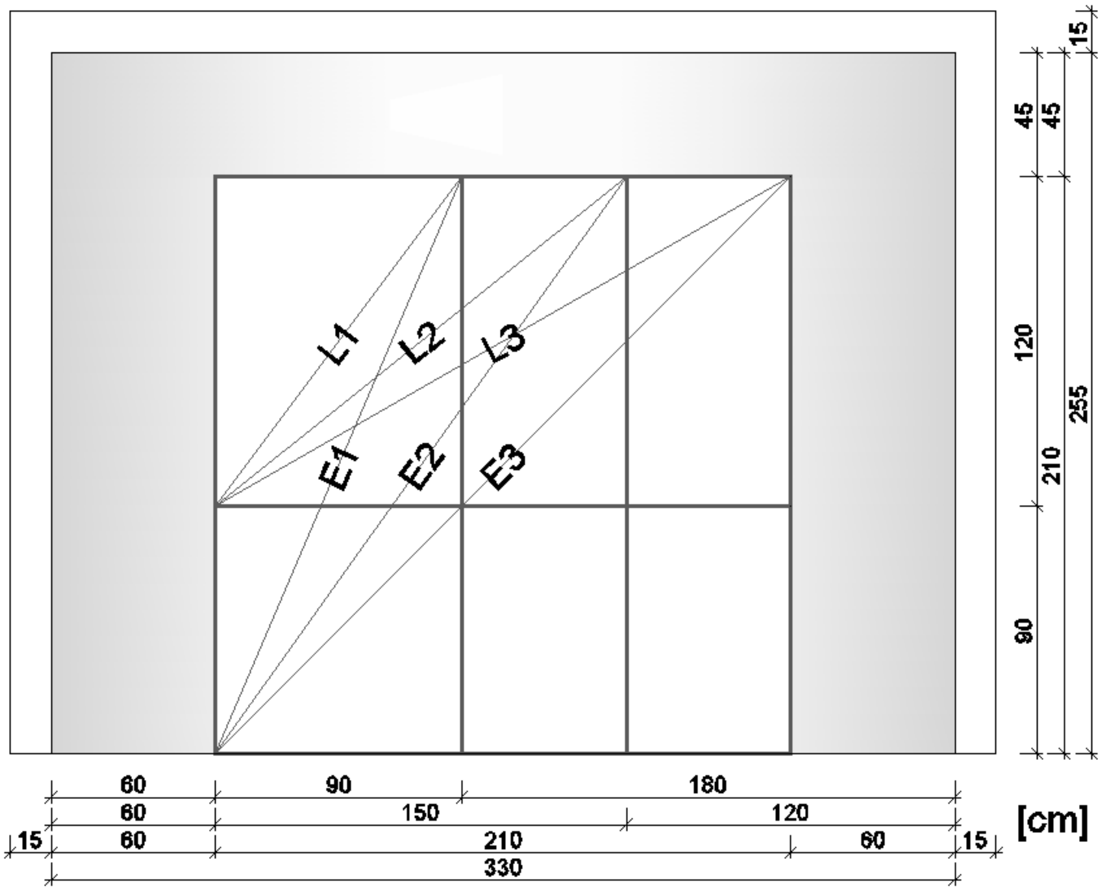


BOUNDARY CONDITIONS FOR WALL ELEMENTS



- Prevails the number of **cantilever tests**

- Increasing number of **restrained rotation** tests since 1990



OPENING TYPE:

DOOR (E), WINDOW (L) AND DOOR-WINDOW (EL).

OPENING SIZE:

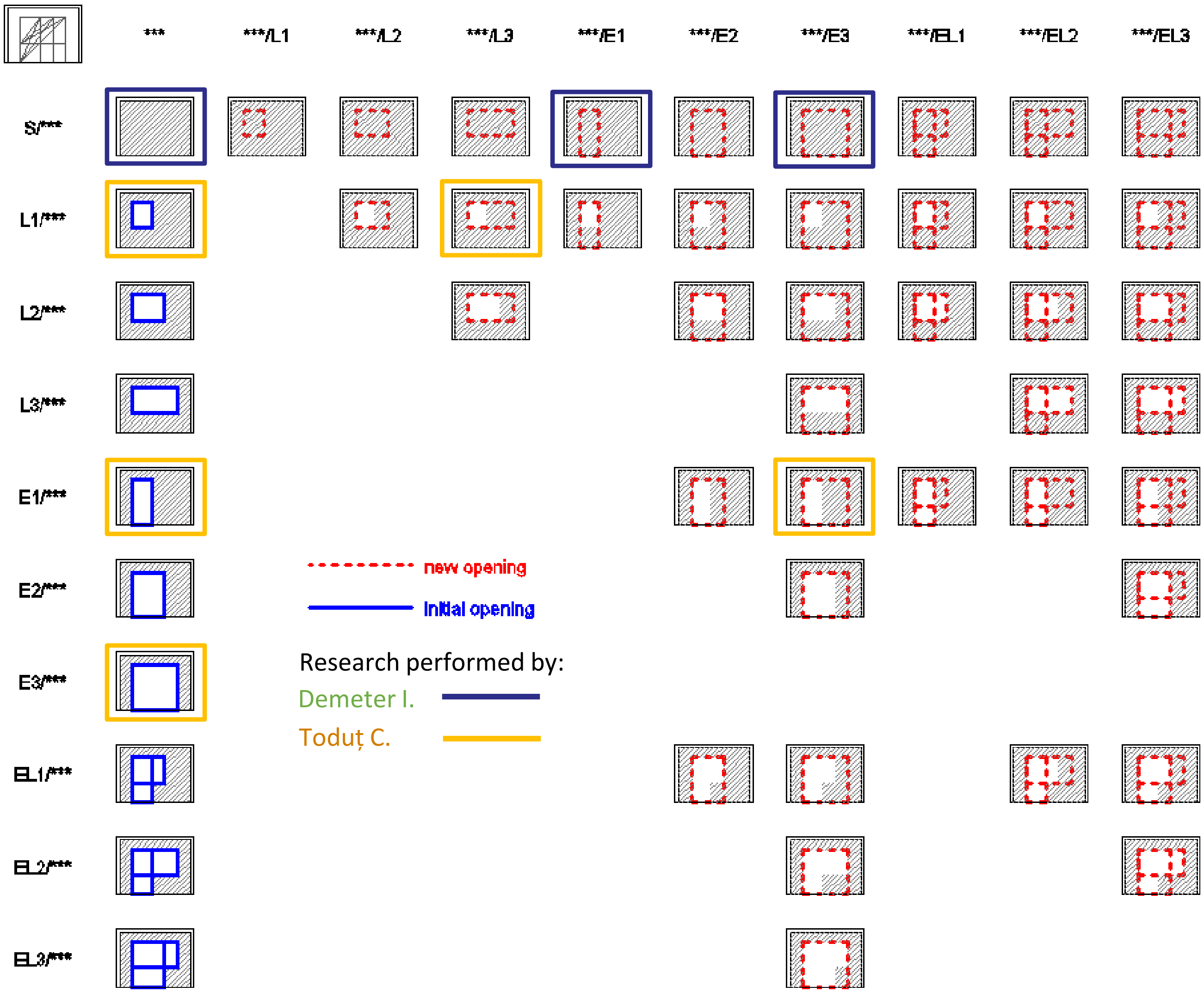
NARROW (1), MODERATE (2) AND WIDE (3).

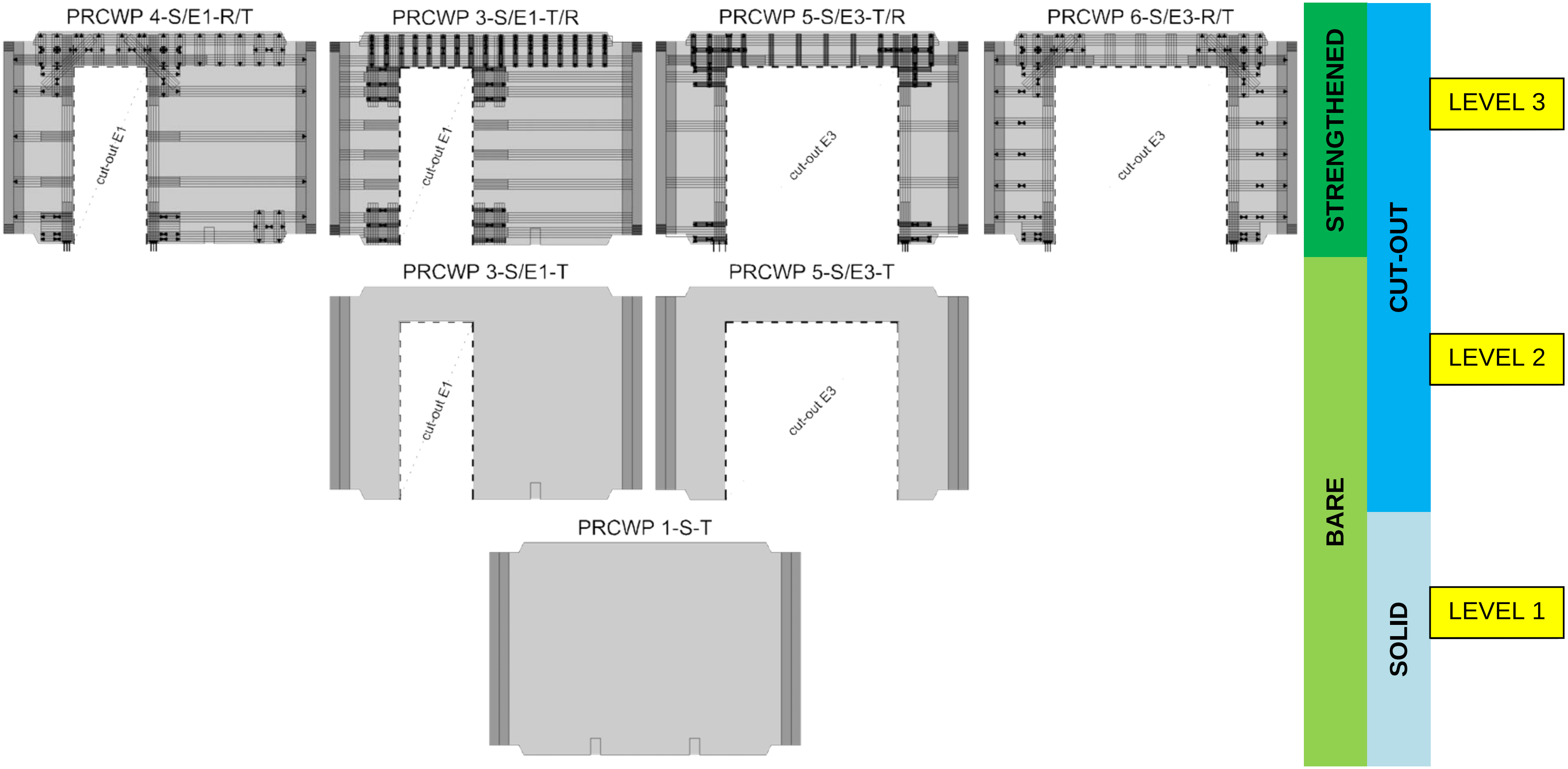
OPENING NATURE:

INITIAL, ENLARGED AND CUT-OUT.

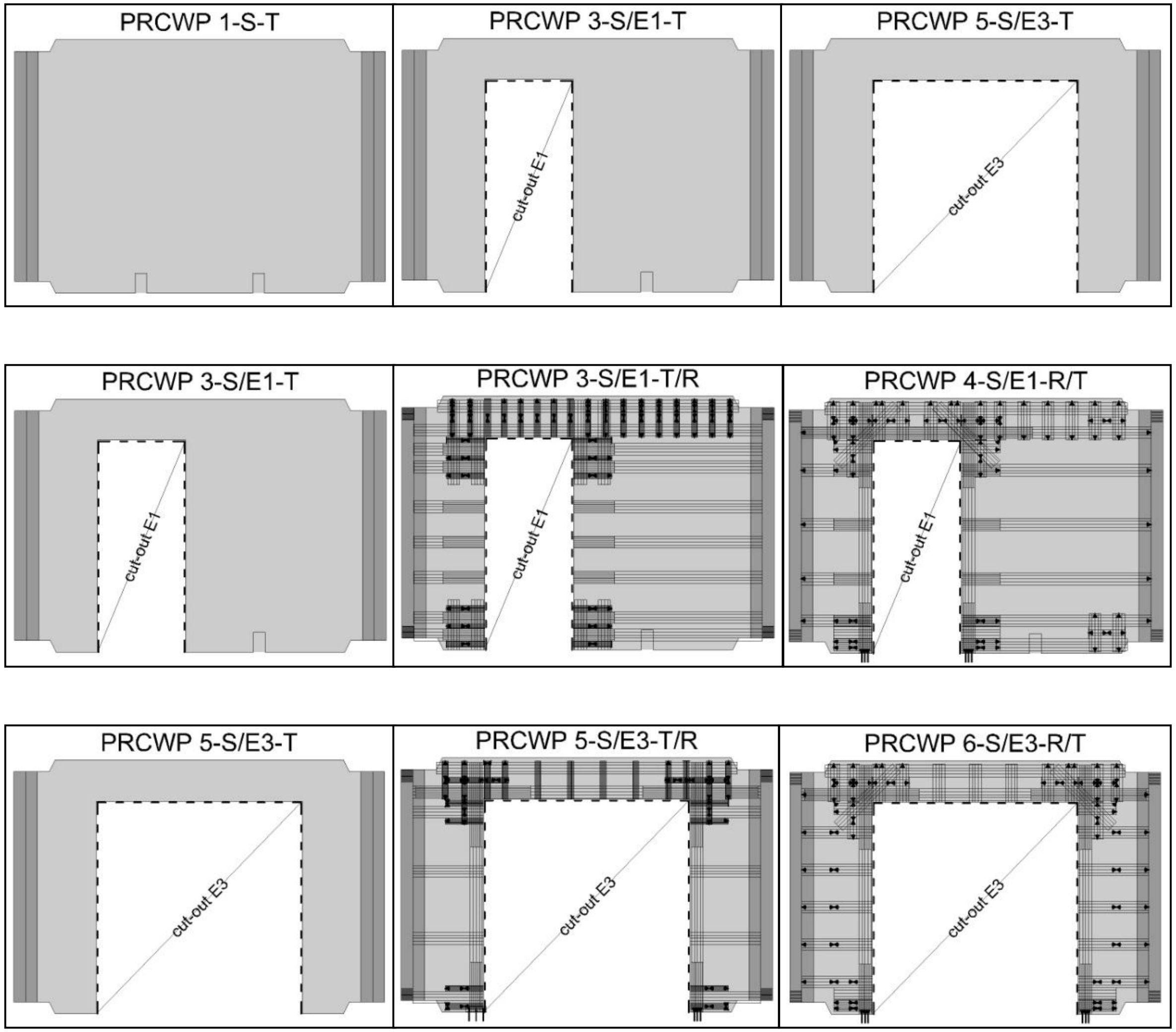
WITHOUT OPENING, i.e. SOLID WALL (S).

Opening configuration matrix




PRCWP 4-S/E1-R/T
PRCWP 3-S/E1-T/R
PRCWP 5-S/E3-T/R
PRCWP 6-S/E3-R/T
PRCWP 3-S/E1-T
PRCWP 5-S/E3-T
PRCWP 1-S-T
cut-out E1
cut-out E3
STRENGTHENED
BARE
CUT-OUT
SOLID
LEVEL 3
LEVEL 2
LEVEL 1

EXPERIMENTAL PROGRAMME *Lines of comparison*



Line 1

<u>Weakening effect of doorway cut-out</u>

REFERENCE: solid wall
VARIABLE: cut-out width

Lines 2 and 3

<u>Strengthening effect of CFRP-EBR</u>

REFERENCE: bare wall with cut-out door

VARIABLE: strengthening condition

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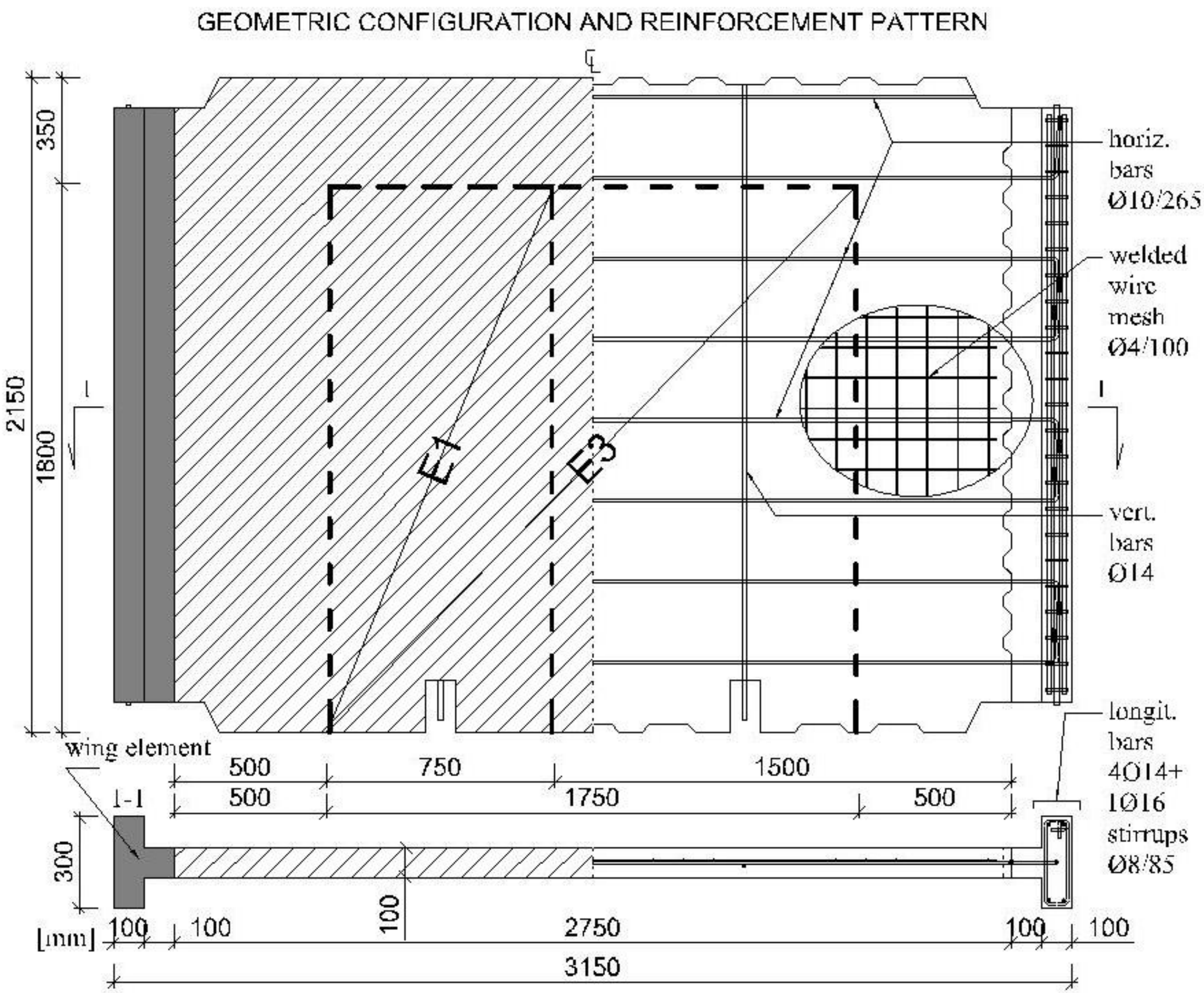


Concrete outlines

- Web thickness: 100 mm
- Shear keys and threshold to prevent sliding

Opening ratio

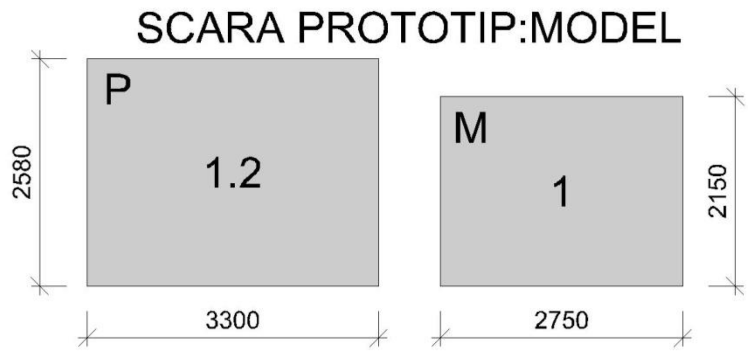
- E1 27% (P=0.48)
- E3 64% (P=0.73)

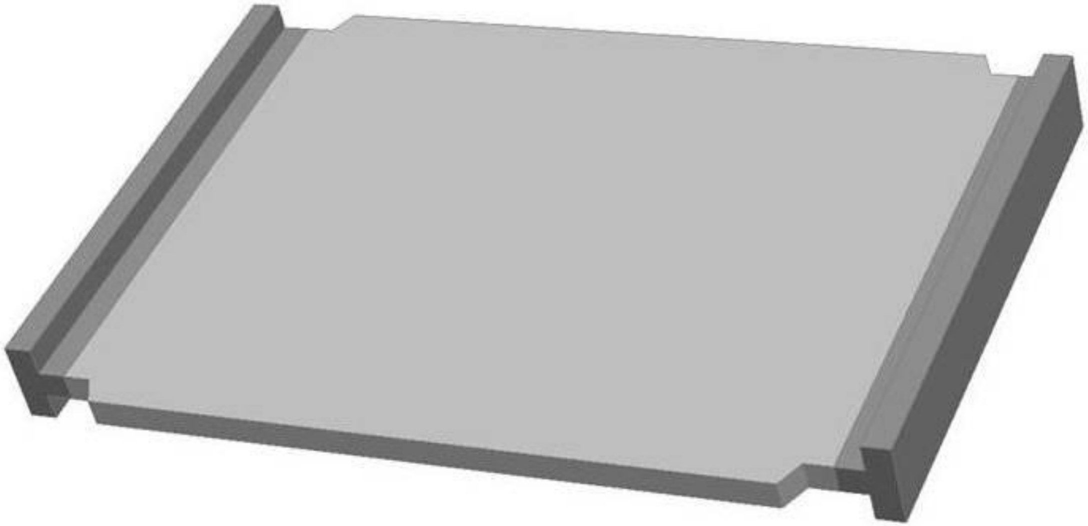
Opening position

-Eccentric
-Centric

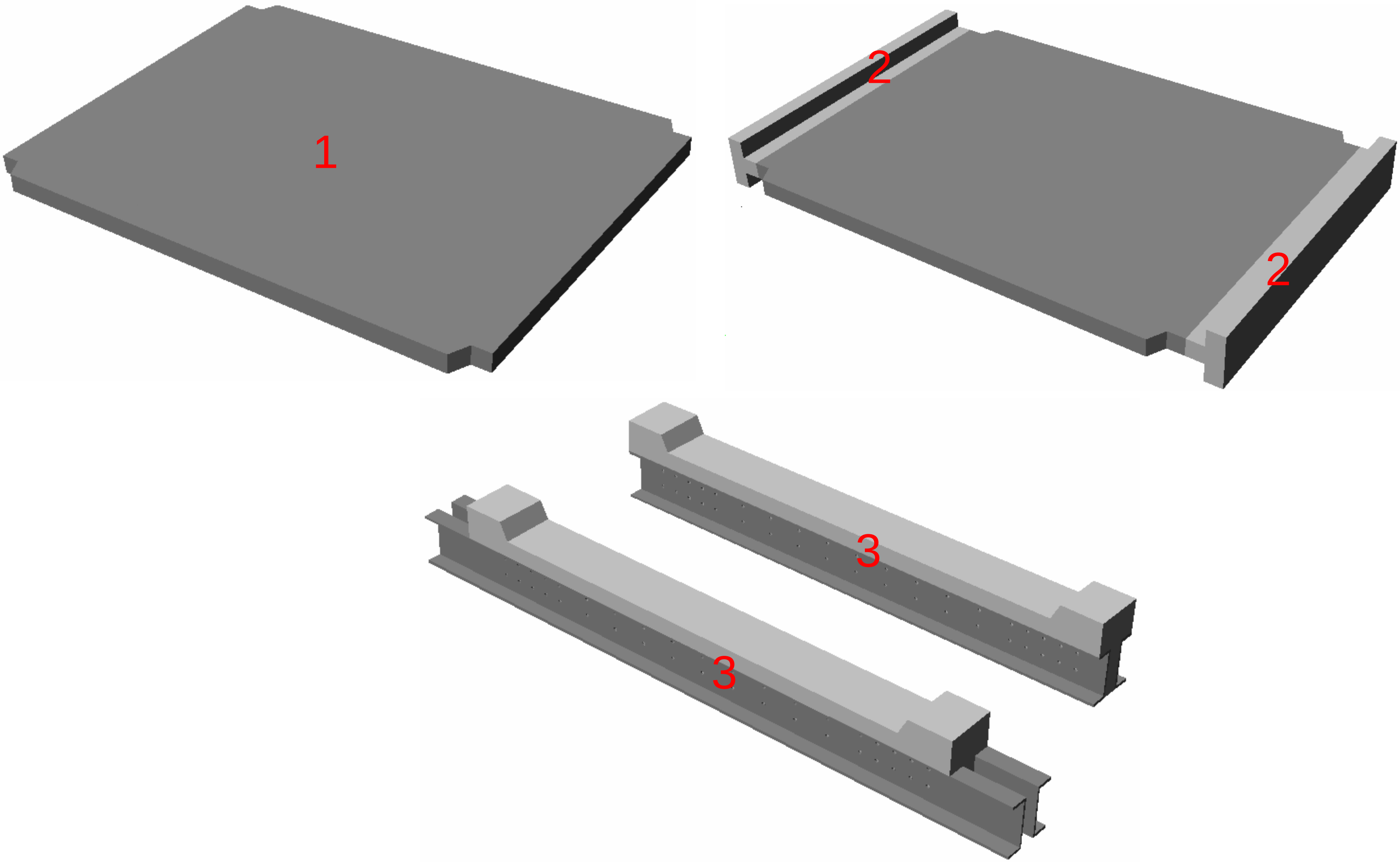
Reinforcement

-Single curtain
-Web steel ratio:
0.42% (h)
0.24%(v)





Prototype:	wall panel I 36-1; 770-81, 1982
Type:	wall element (1-stry)
Scale:	0.83 (1:1.2)
Aspect ratio:	0.8
Cross section type:	flanged
Components:	web-panel boundary wings
Concrete:	precast


1
2
2
3
3

EXPERIMENTAL ELEMENT

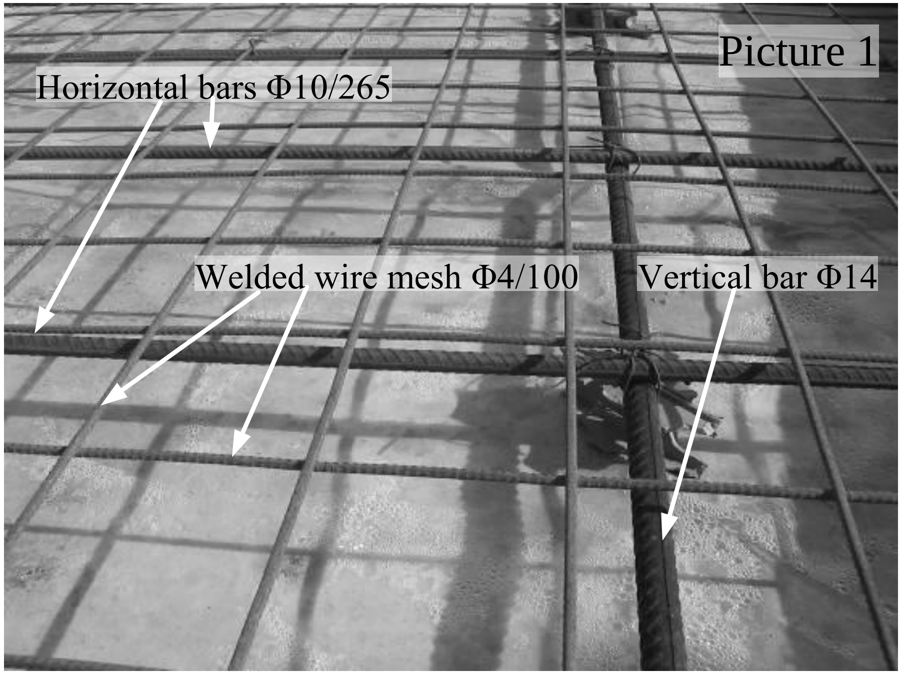
Construction phases

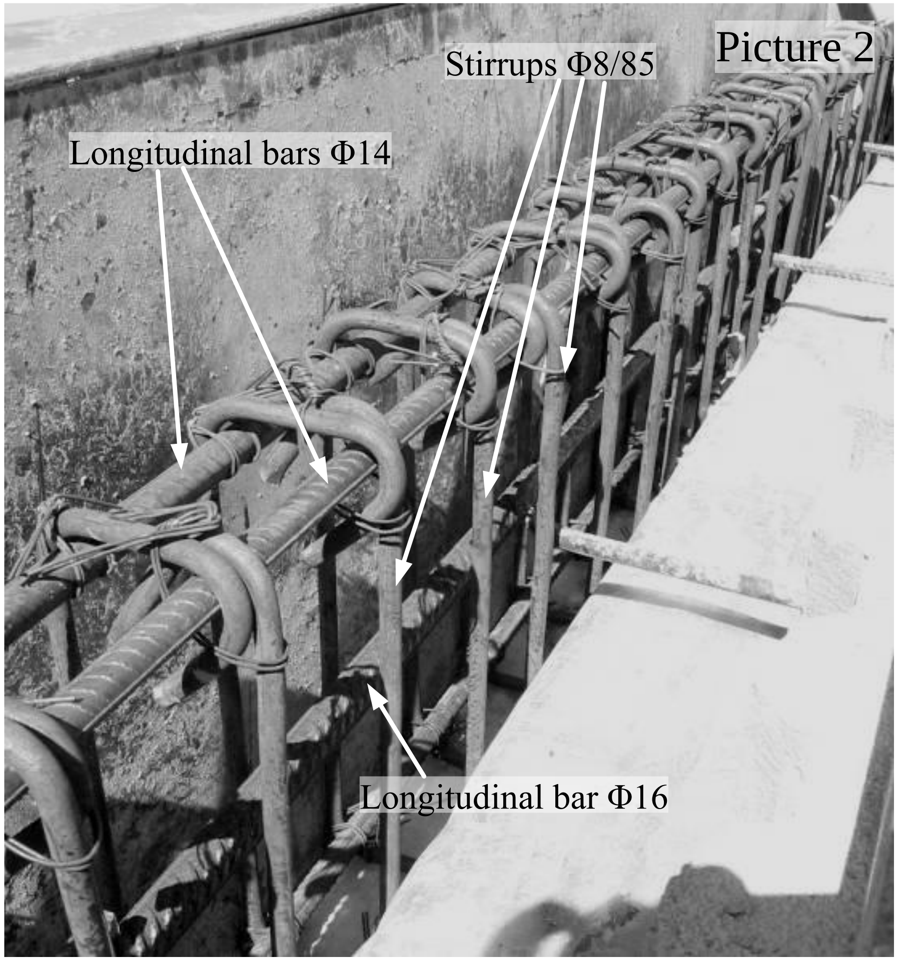






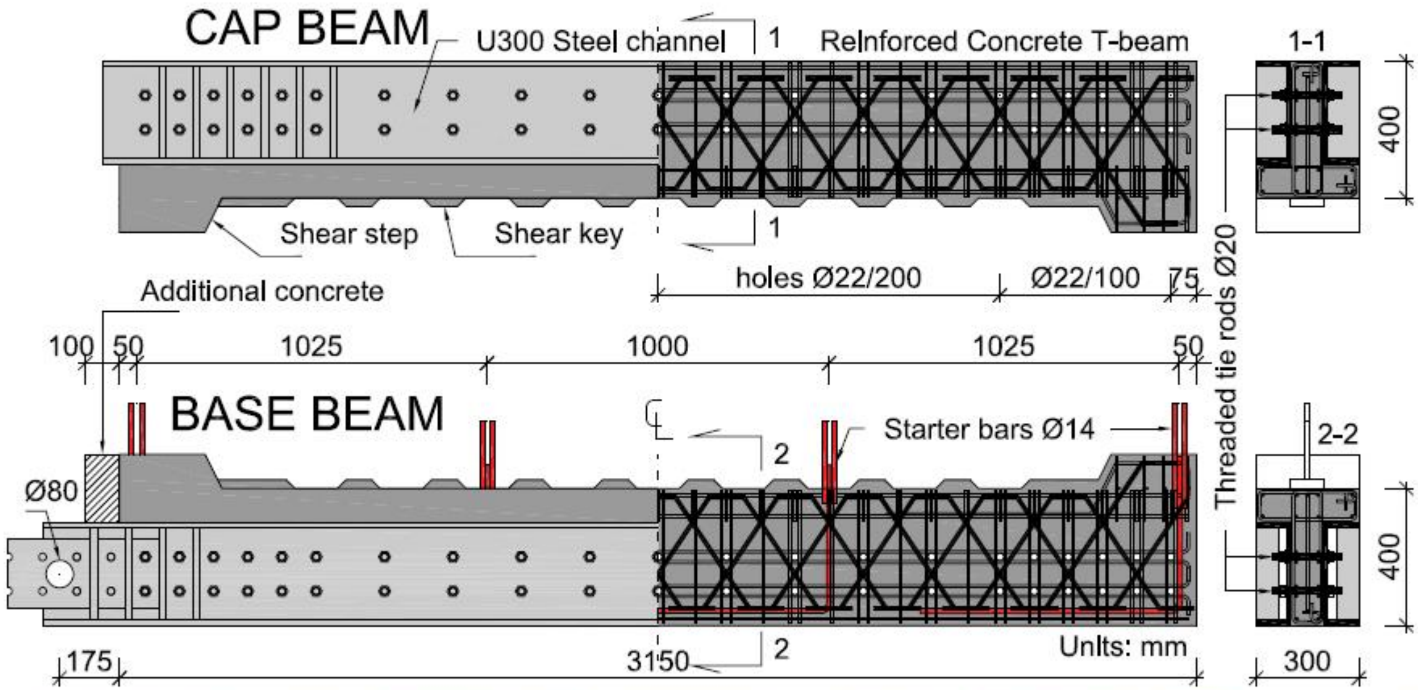


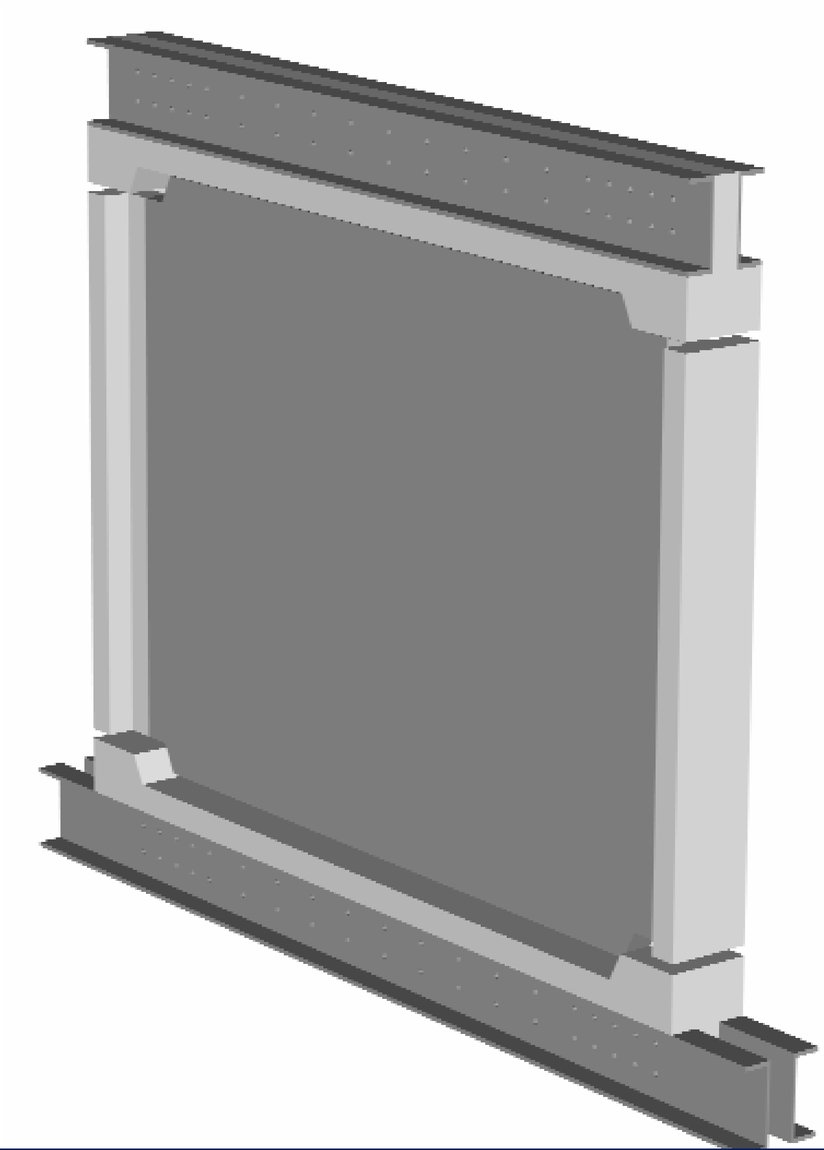

Picture 1
Horizontal bars Φ10/265
Welded wire mesh Φ4/100
Vertical bar Φ14


Picture 2
Stirrups Φ8/85
Longitudinal bars Φ14
Longitudinal bar Φ16

EXPERIMENTAL ELEMENT

Experimental specimens





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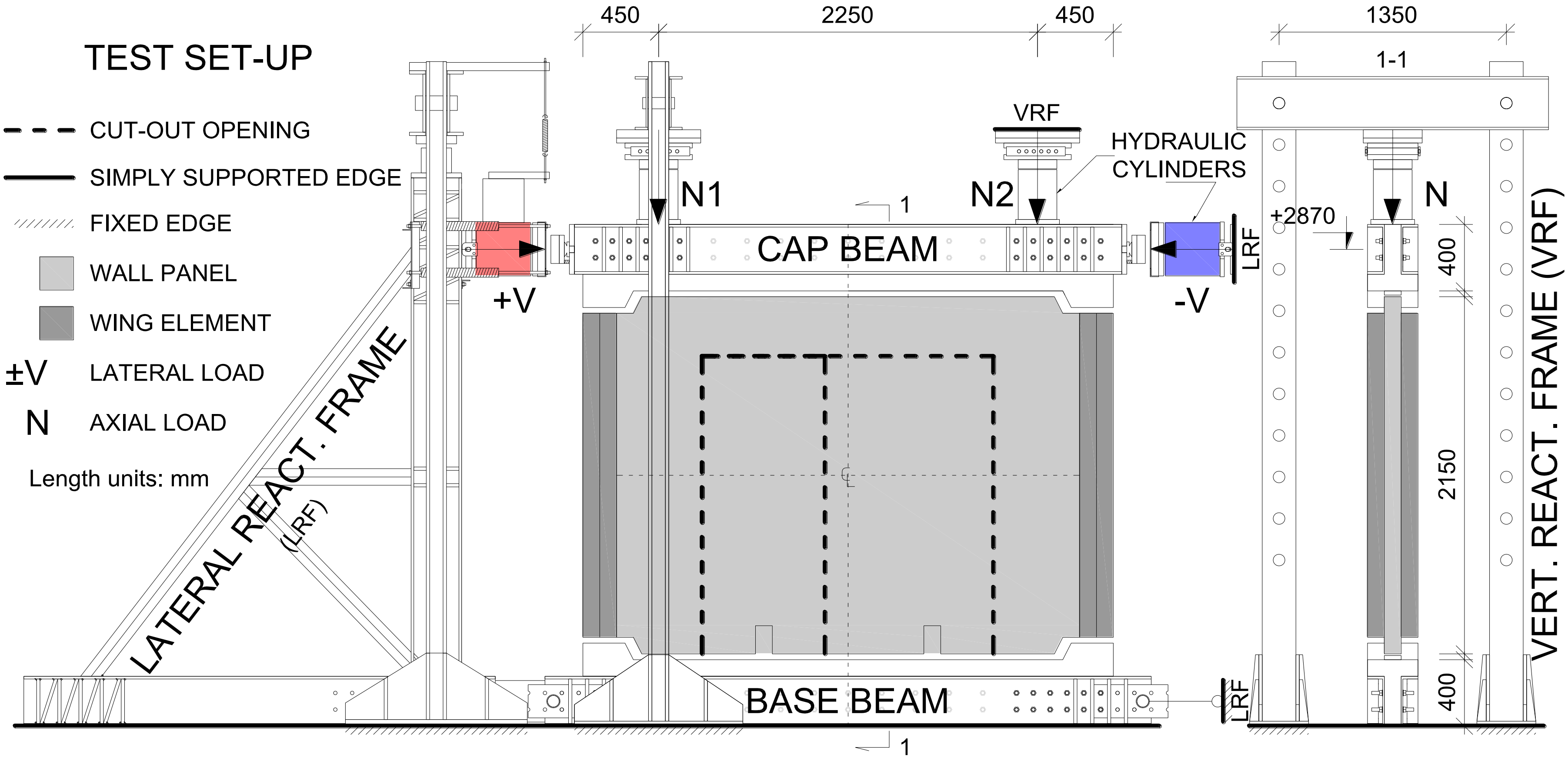
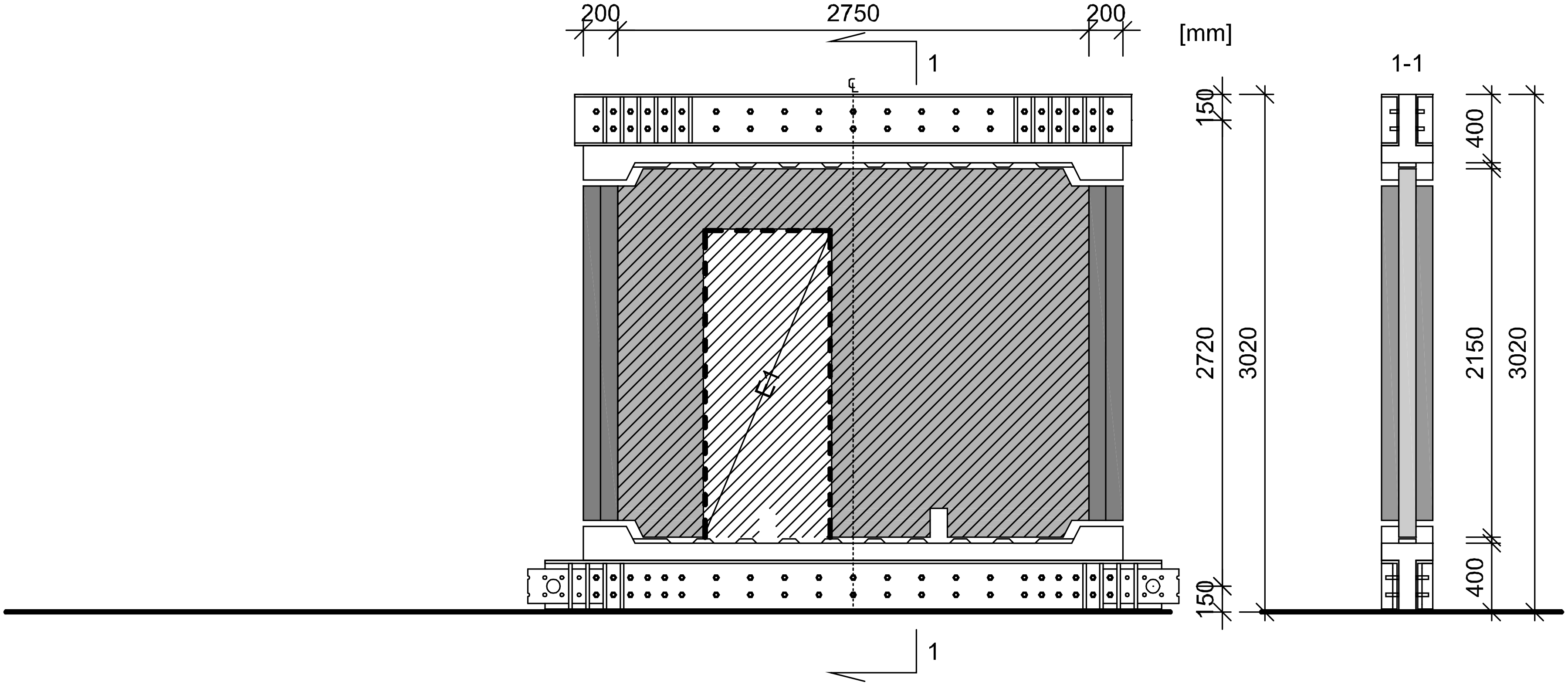
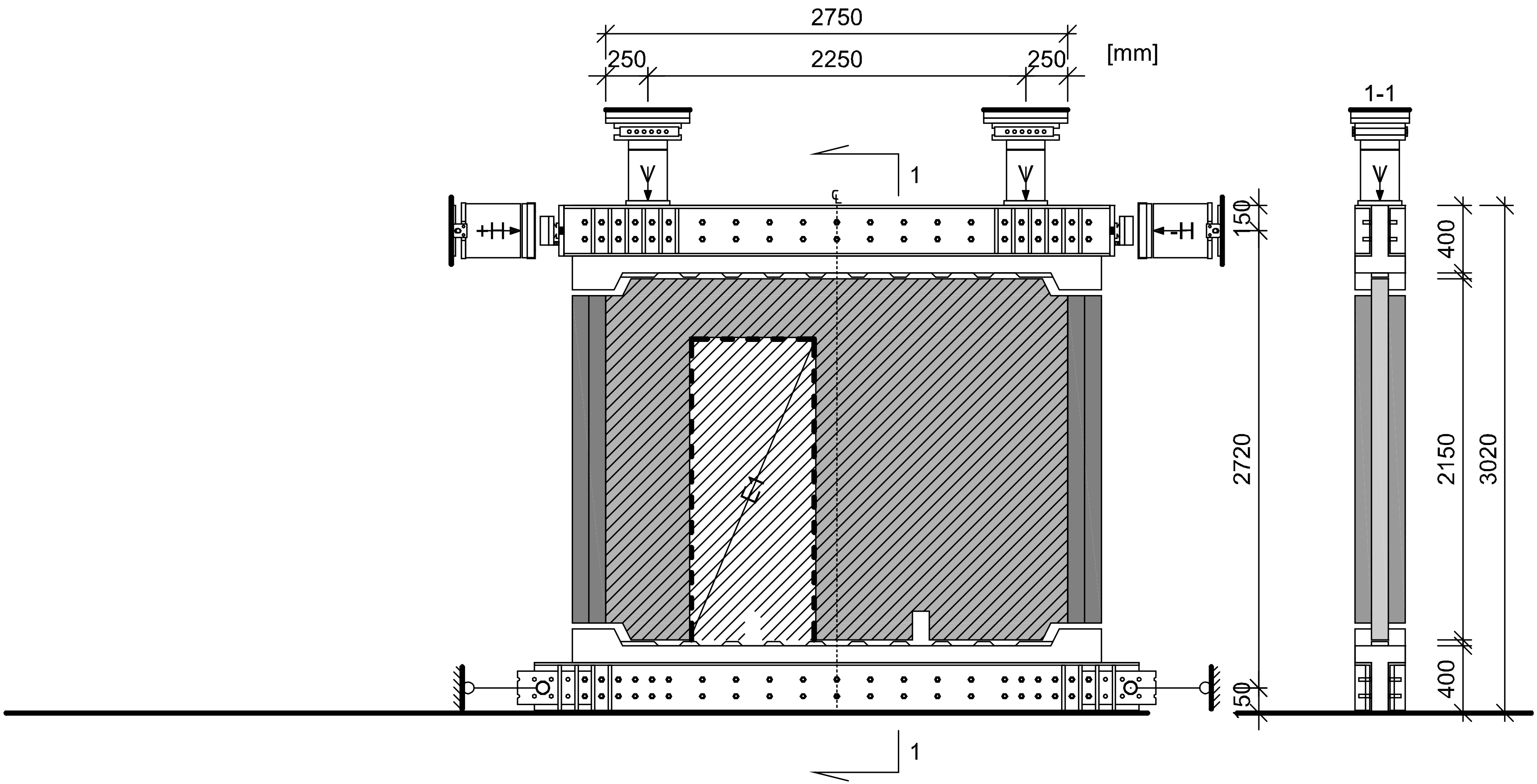

TEST SET-UP
CUT-OUT OPENING
SIMPLY SUPPORTED EDGE
FIXED EDGE
WALL PANEL
WING ELEMENT
±V LATERAL LOAD
N AXIAL LOAD
Length units: mm
450
2250
450
1350
1-1
VRF
HYDRAULIC CYLINDERS
N1
N2
N
1
CAP BEAM
+V
-V
LRF
+2870
400
2150
400
LATERAL REACT. FRAME (LRF)
VERT. REACT. FRAME (VRF)
BASE BEAM
1

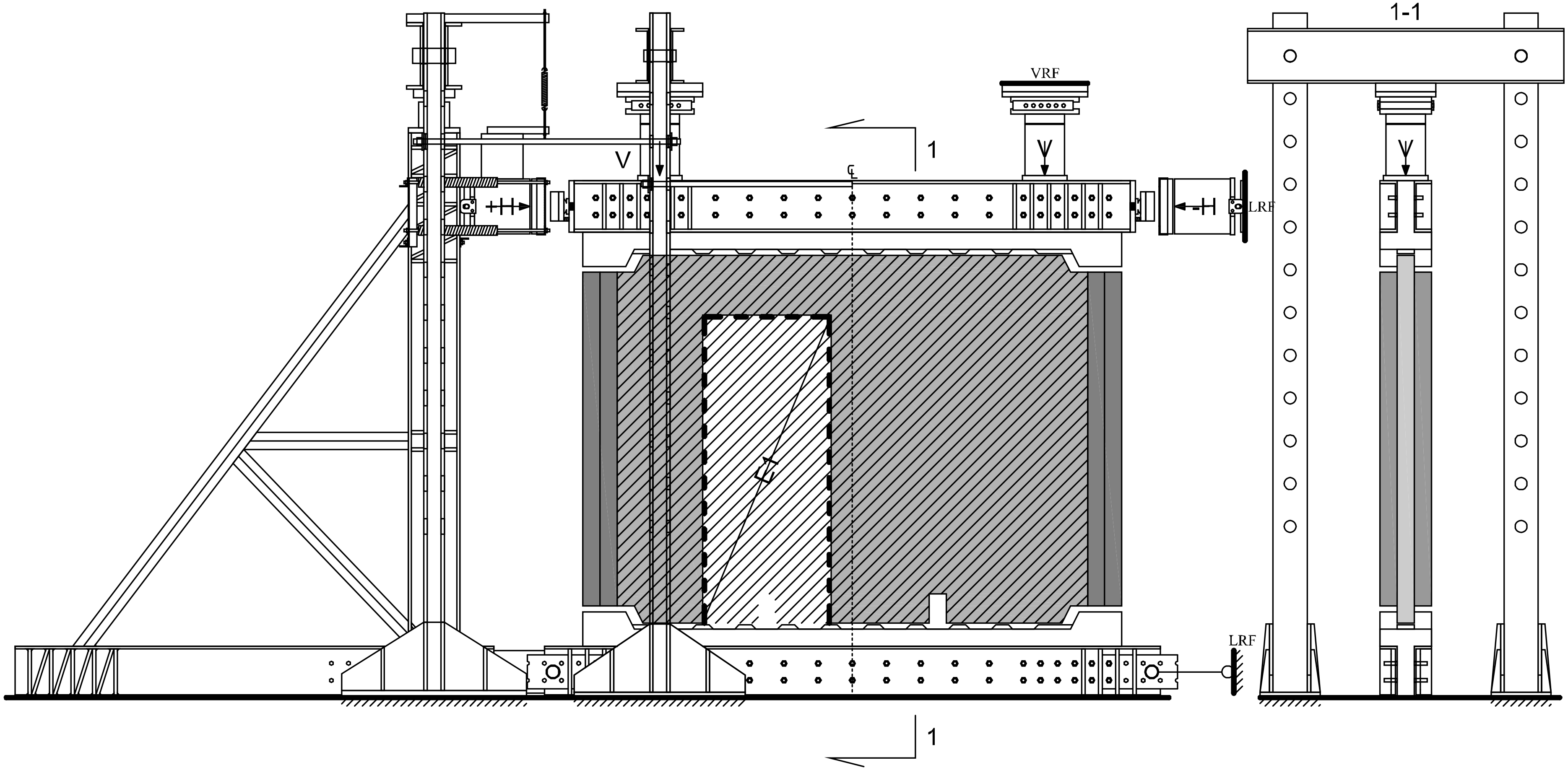
TEST SET-UP

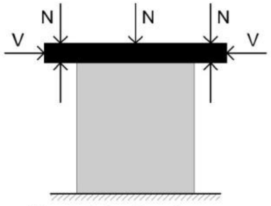


TEST SET-UP



TEST SET-UP





Type A test setup

Set-up type: A

Loading degree: 4 (2N+2V)

Base and cap beams: heavily reinforced steel-concrete composite

Base beam not fixed, only supported

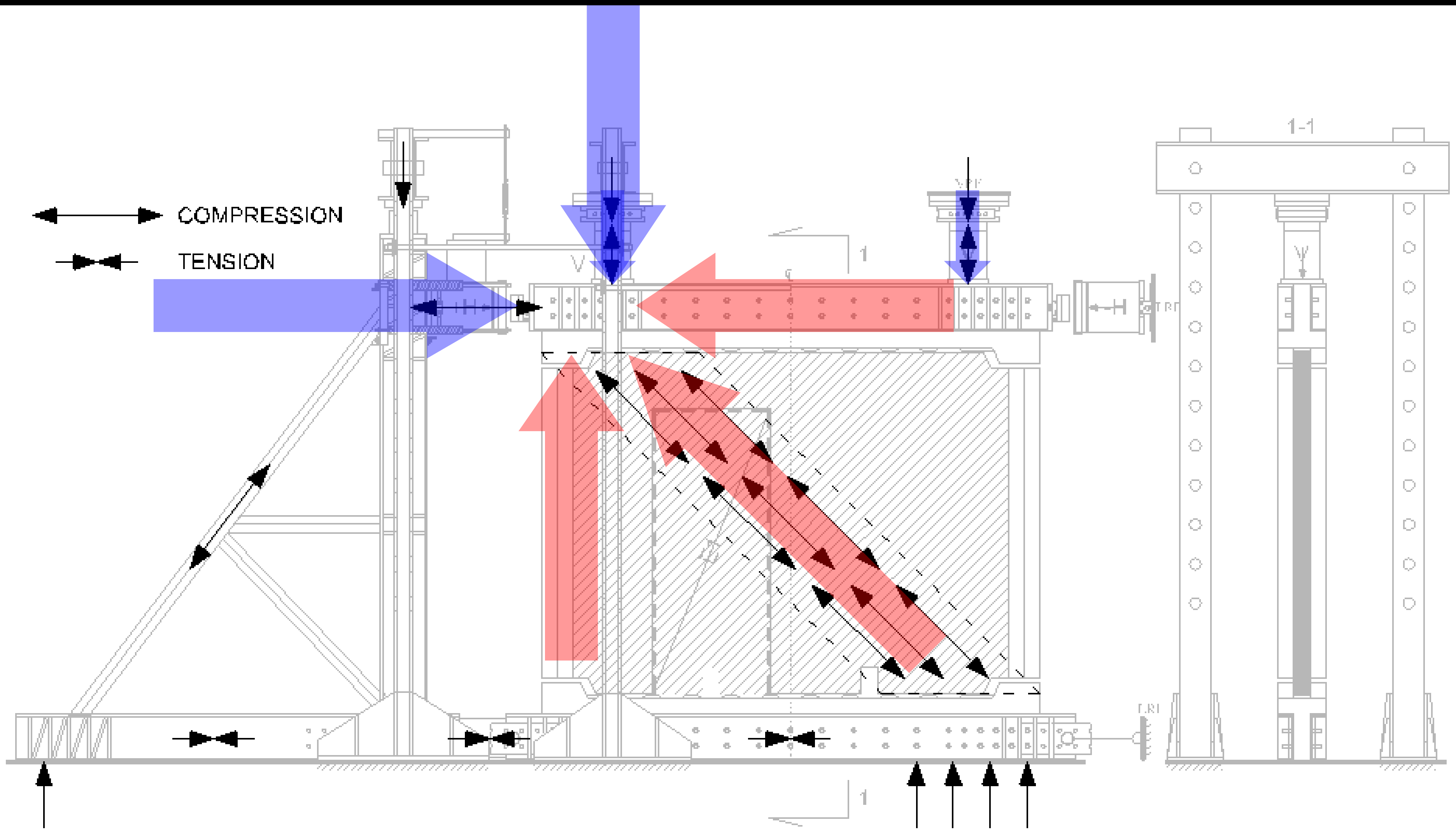
Specimen-to-base beam anchorage: lap-welding of 4 re-bars (ratio 0.17%)

TEST SET-UP

TEST SET-UP

TGL
kp/cm²
0
20
40
60
80
100
120
140
180
200
220
240
260
280
300
320
340
360
380
400

Static scheme



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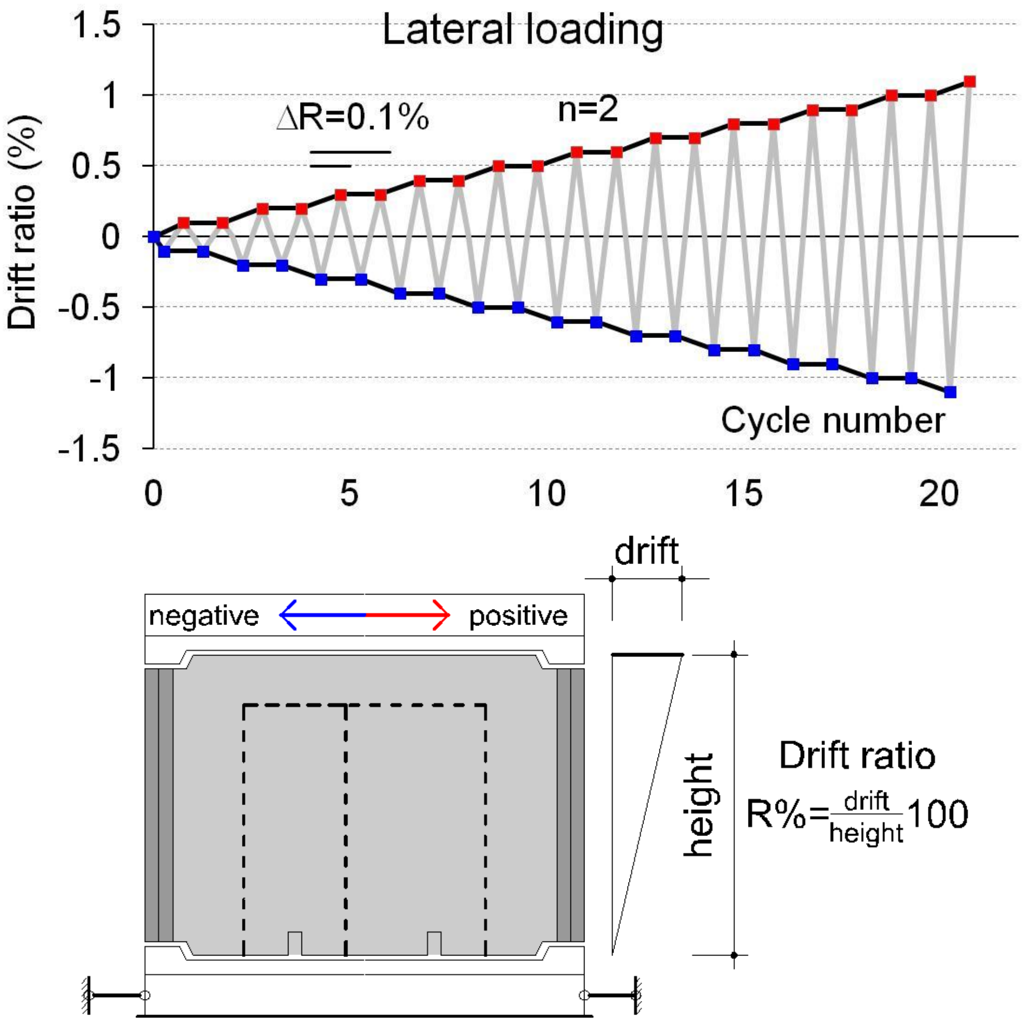
LOADING STRATEGY

QUASI-STATIC	PSEUDO-DYNAMIC	DYNAMIC

LOADING	AXIAL	LATERAL
DIRECTION	IN-PLANE VERTICAL	IN-PLANE HORIZONTAL
CHARACTERISTICS	PSEUDO-CONSTANT	REVERSED CYCLIC

The experimental elements will be subjected to in-plane reversed cyclic lateral (horizontal) and pseudo-constant axial (vertical) forces, simulating the seismic loading conditions at a quasi-static rate.



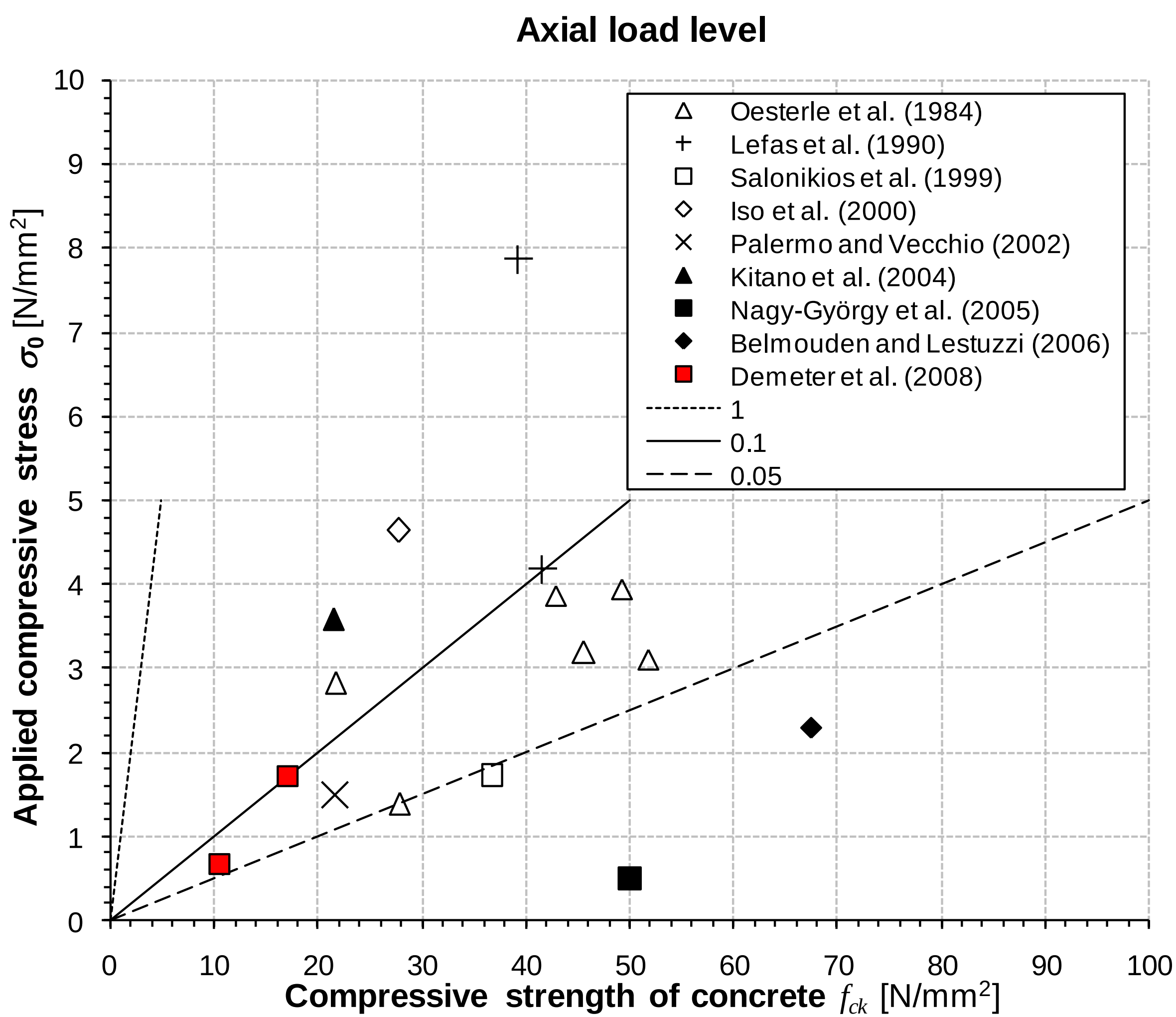
Principal characteristics:
- quasi-static
- in-plane
- reversed cyclic

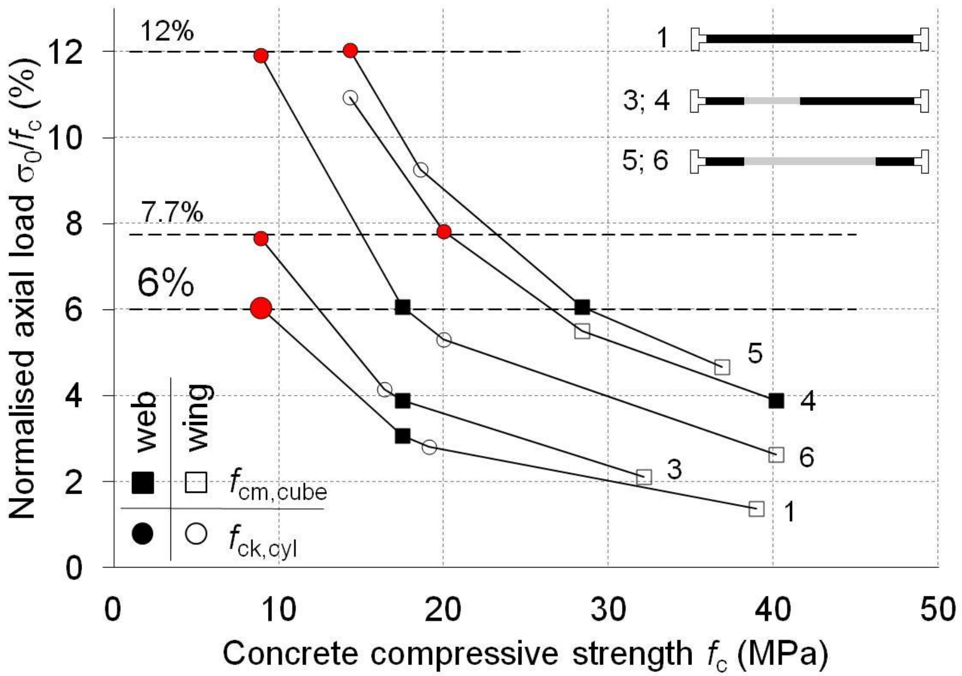
Control: drift ratio

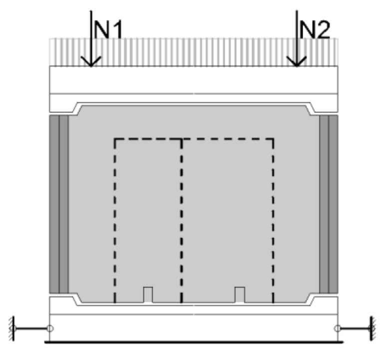
Drift ratio increment:
constant, 0.1%

Number of cycles on a level: 2

Failure criterion:
20% load carrying capacity loss


Axial load level
Applied compressive stress σ_0 [N/mm^2]
Compressive strength of concrete f_{ck} [N/mm^2]
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
80
90
100
Oesterle et al. (1984)
Lefas et al. (1990)
Salonikios et al. (1999)
Iso et al. (2000)
Palermo and Vecchio (2002)
Kitano et al. (2004)
Nagy-György et al. (2005)
Belmouden and Lestuzzi (2006)
Demeter et al. (2008)
1
0.1
0.05



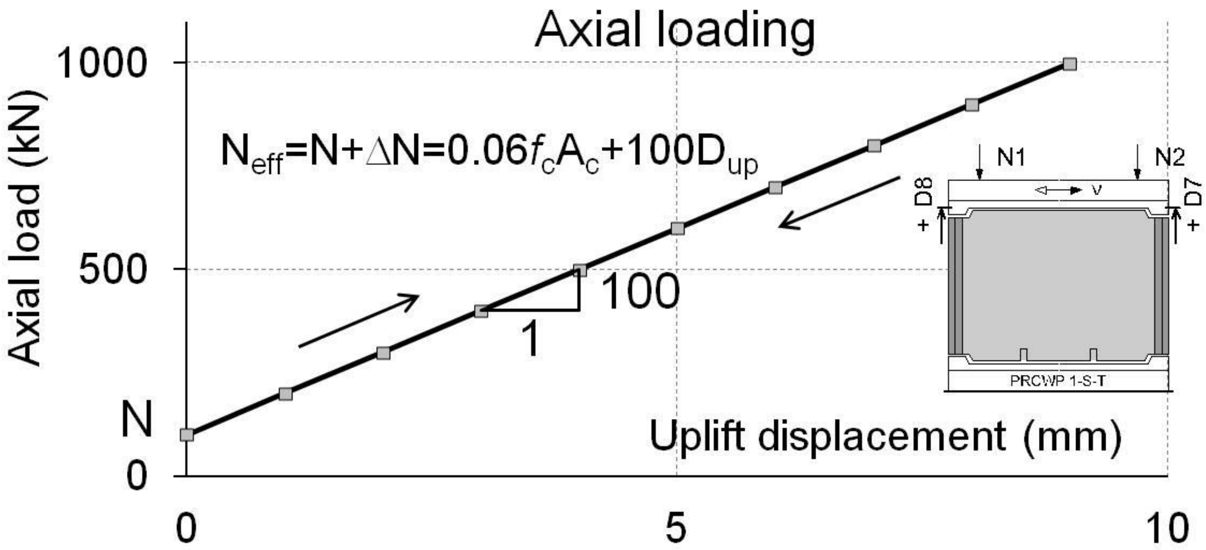


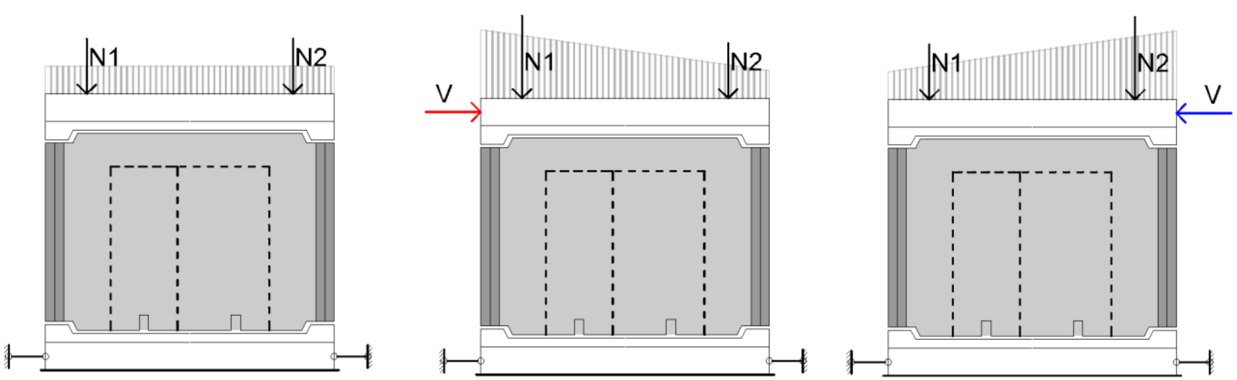
Principal characteristics: two-component featuring a constant level and an alternating part

Constant axial load level
Normalised axial load: 6%

Reference strength: $f_{ck,cyl}$ of the web

Reference cross section: solid wall





Axial loading

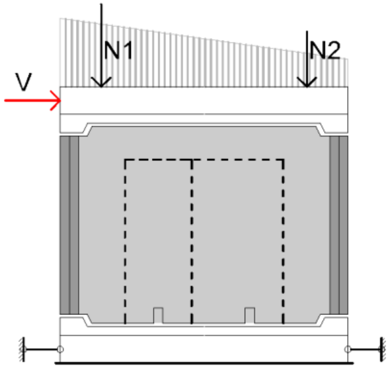
<u>Alternating component</u>
Control: displacement (uplift) of the cap beam's loaded end

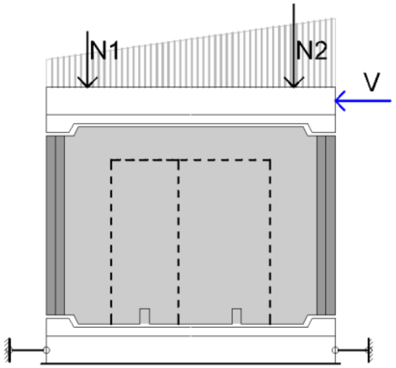
Rate: 100 kN/mm (based primarily on test-setup limitations)

Note that the base beam is not fixed to the laboratory floor

Outrigger canoe

source http://www.ballinaoutriggers.com.au





Outrigger effect

Restrained rotation by additional eccentric axial loading

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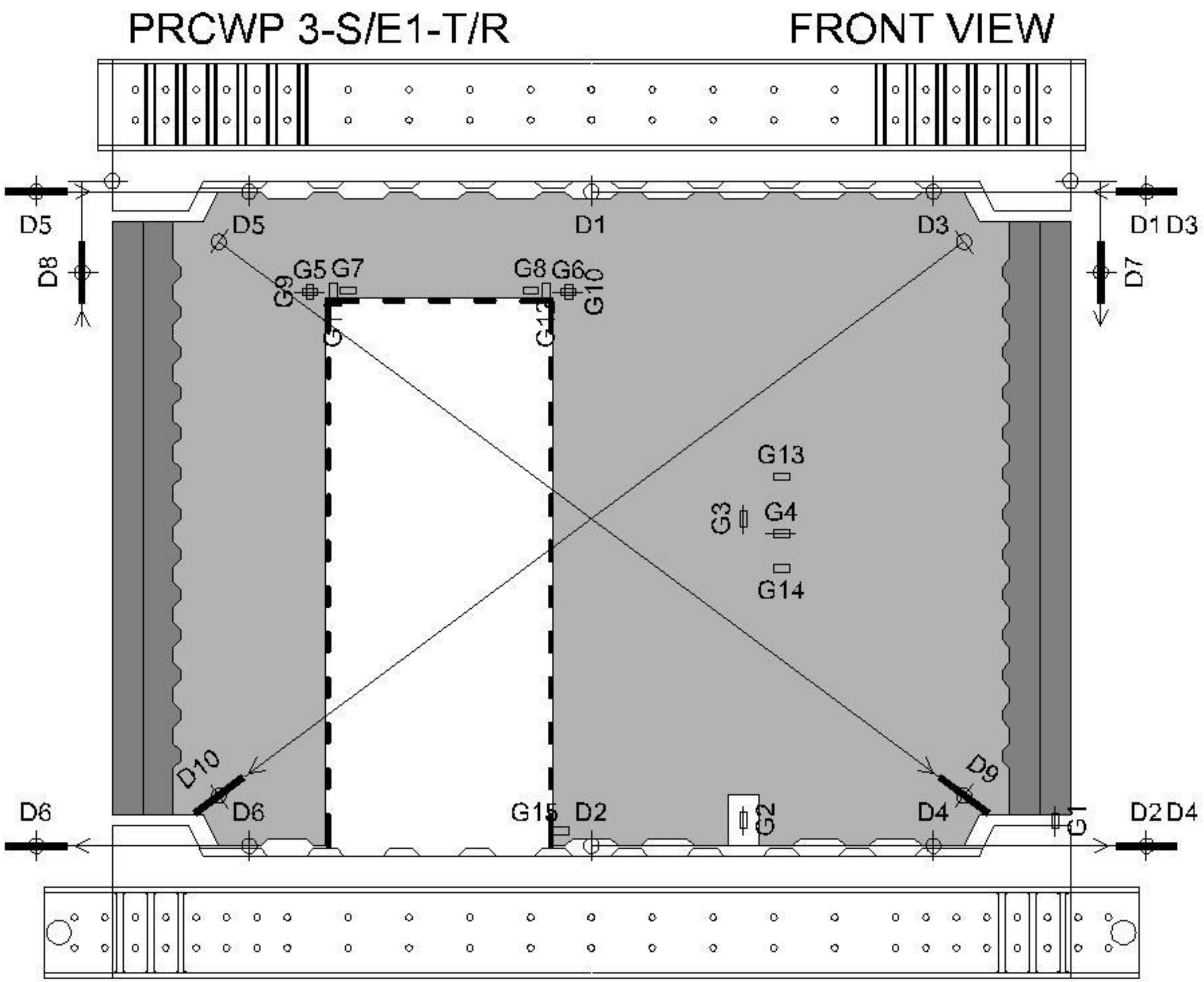
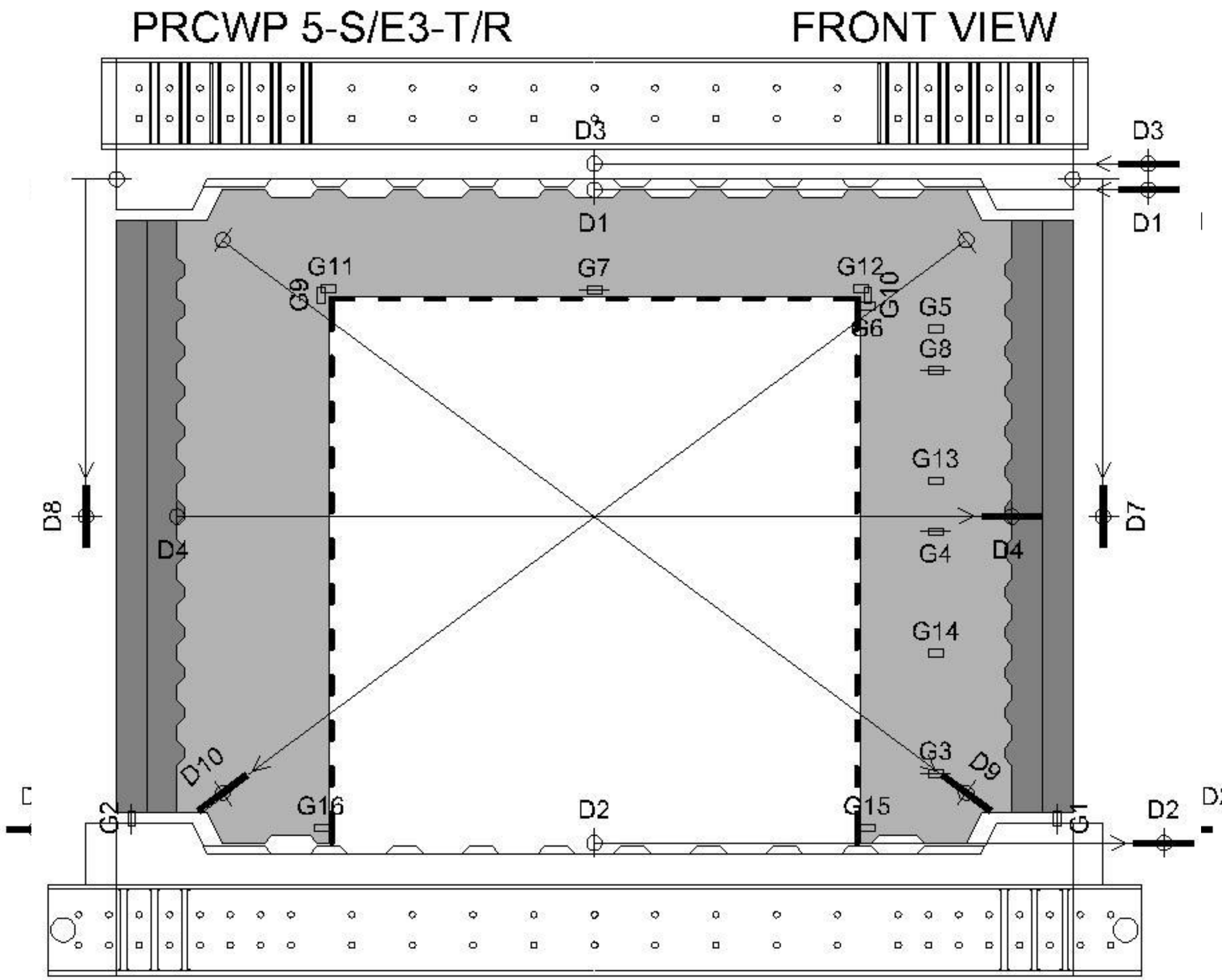
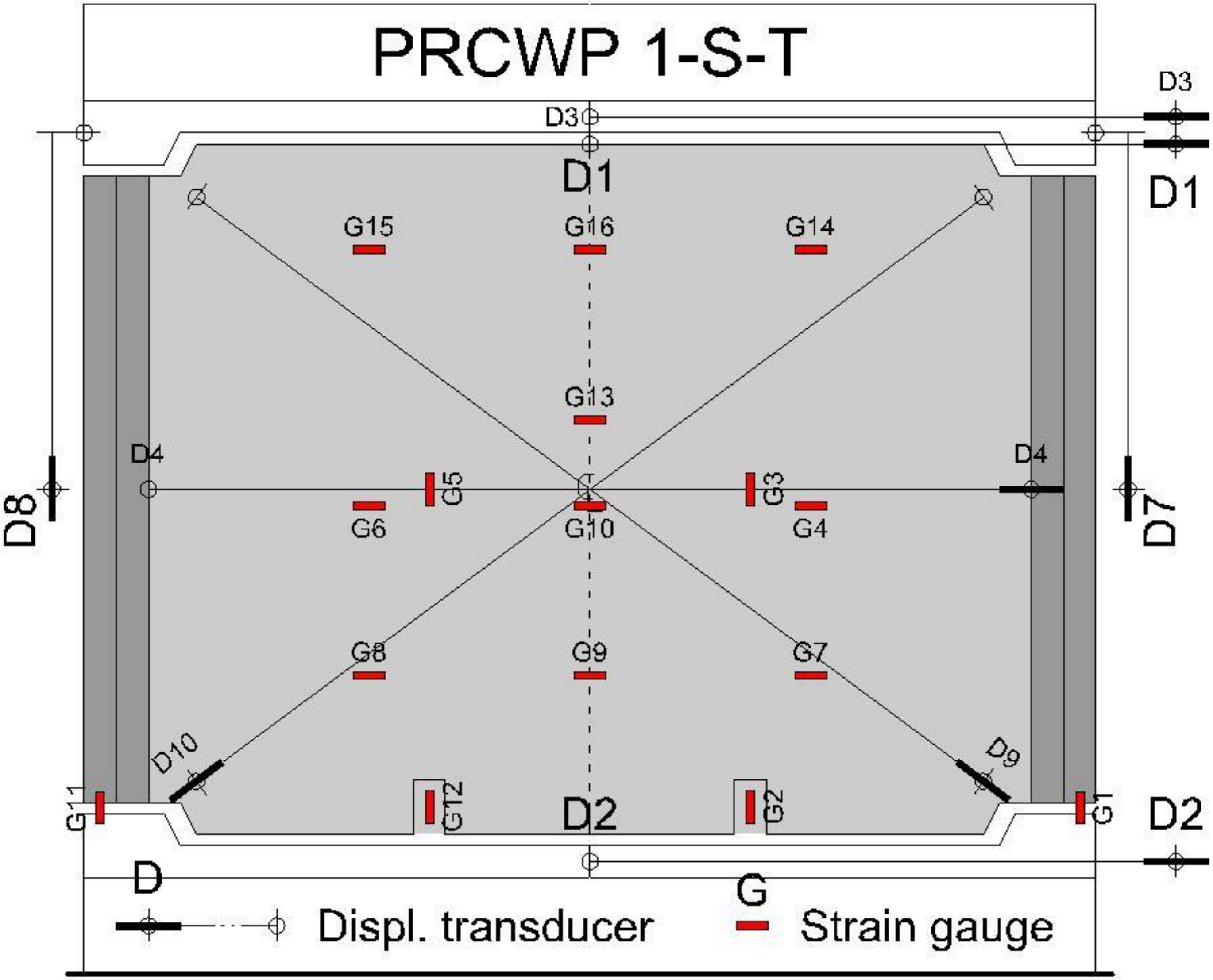
INSTRUMENTATION



INSTRUMENTATION



INSTRUMENTATION



<u>Displacement</u>
10+ transducers
Arrangement: horizontal, vertical, diagonal
Support: external, internal

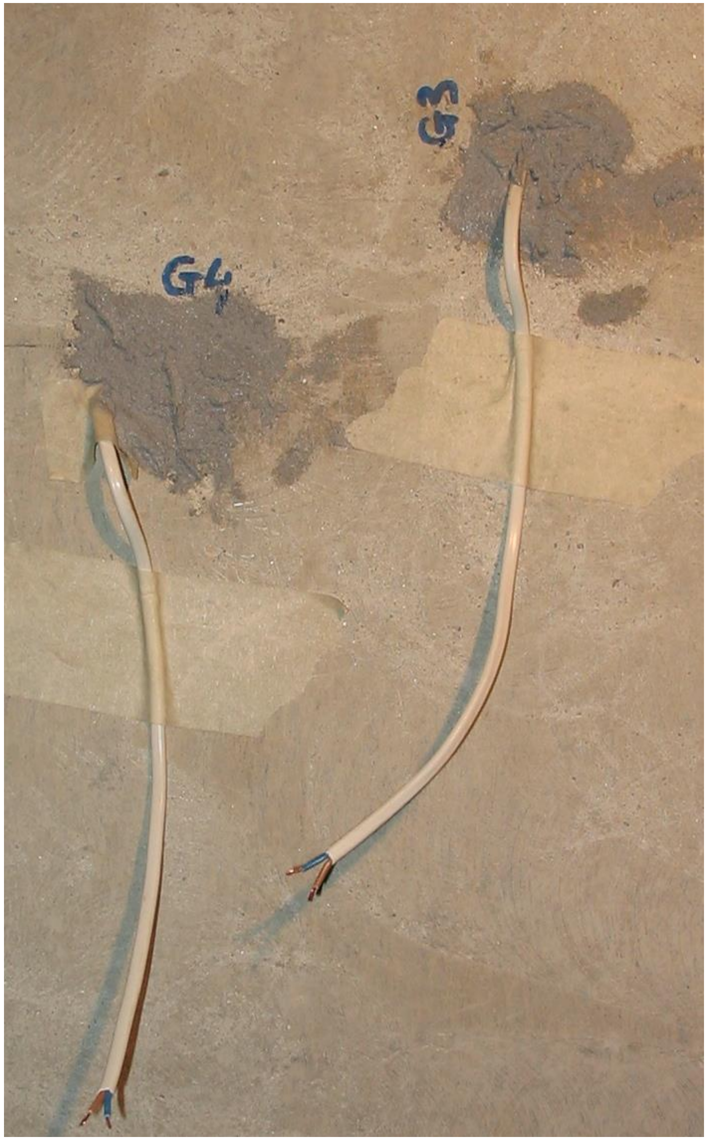
<u>Strain gauges</u>
16 gauges
Steel bars and CFRP

<u>Load</u>
3 pressure transducers on the hydraulic lines

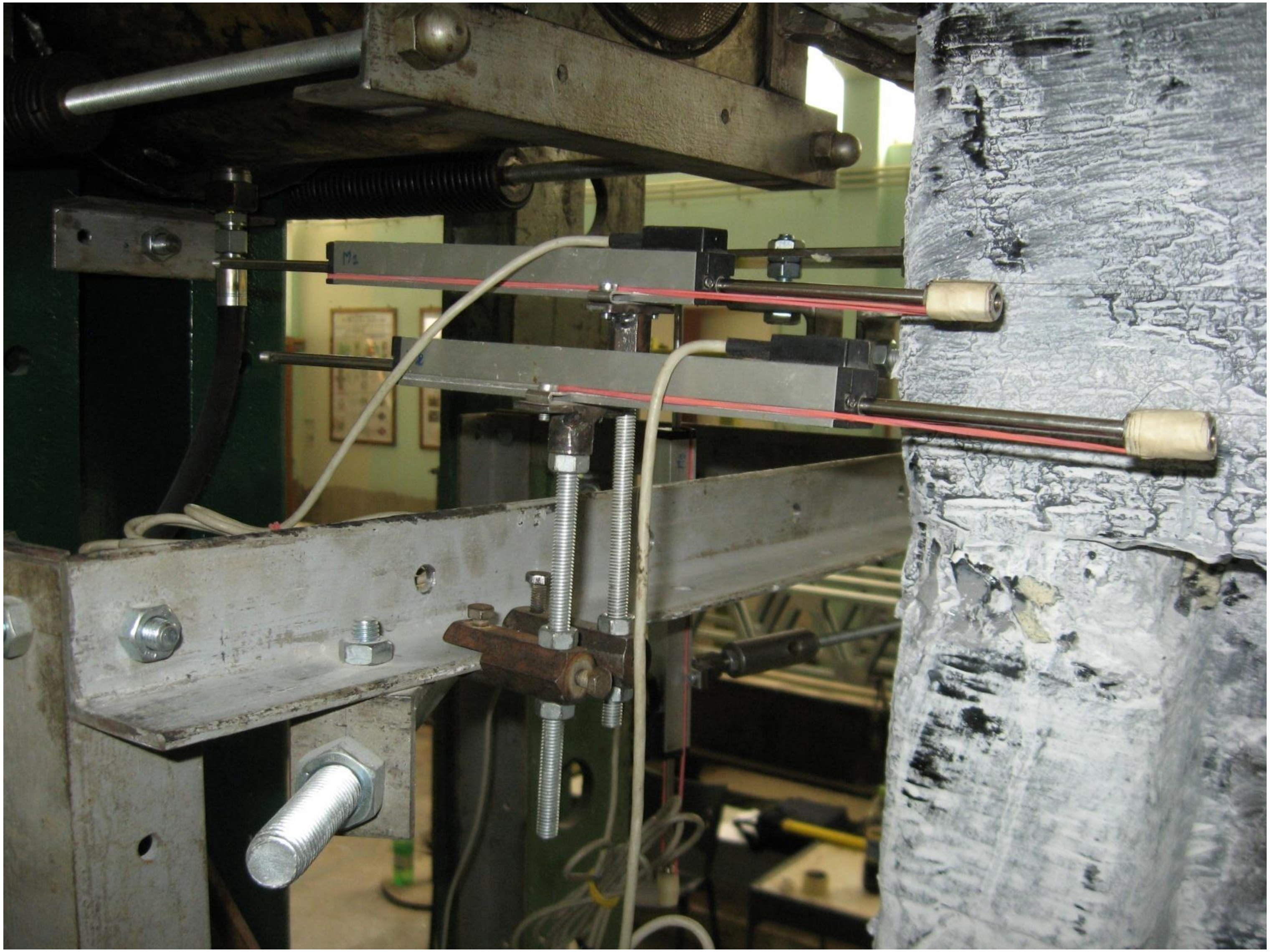
INSTRUMENTATION


G3
G4

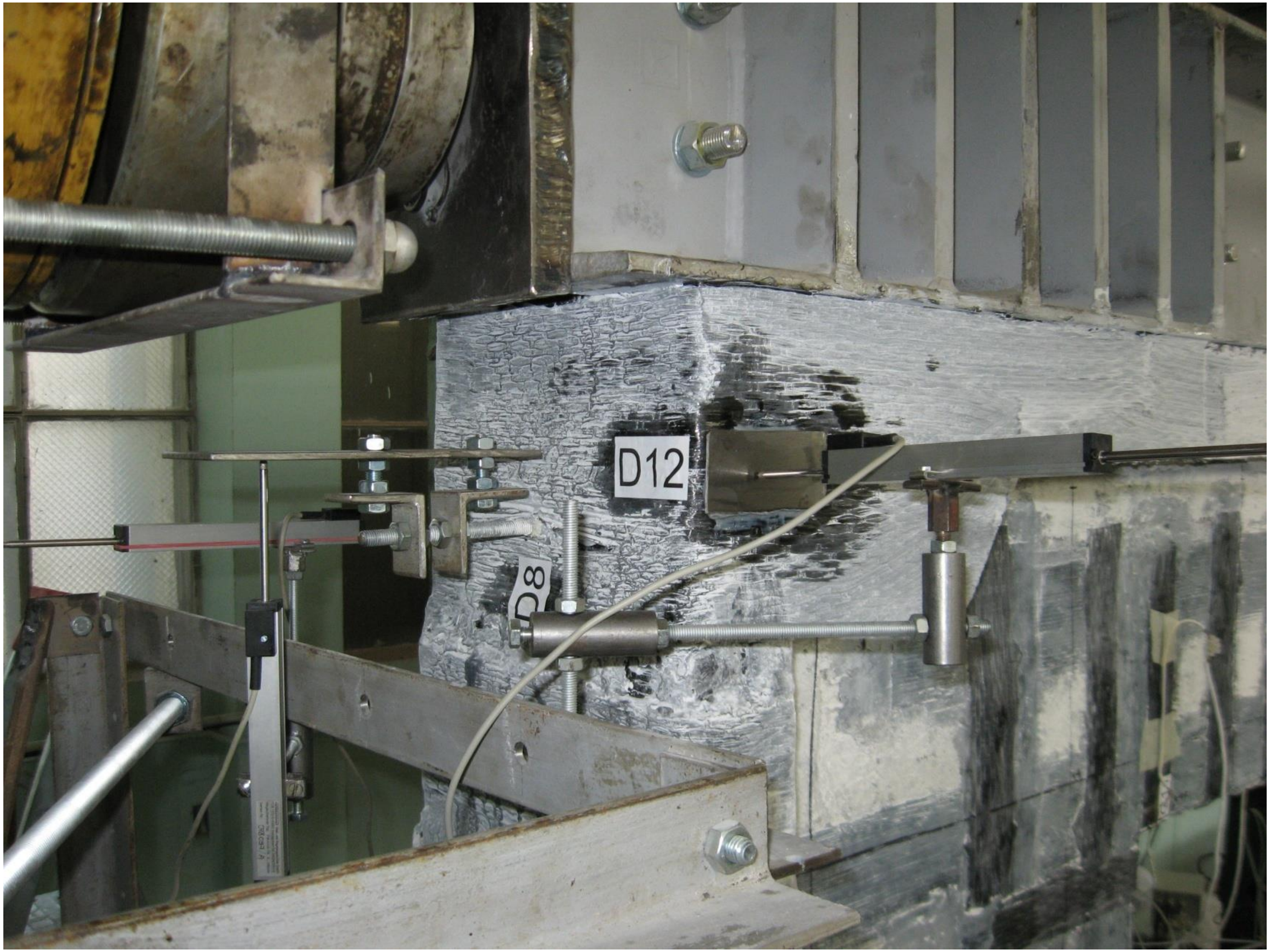
INSTRUMENTATION



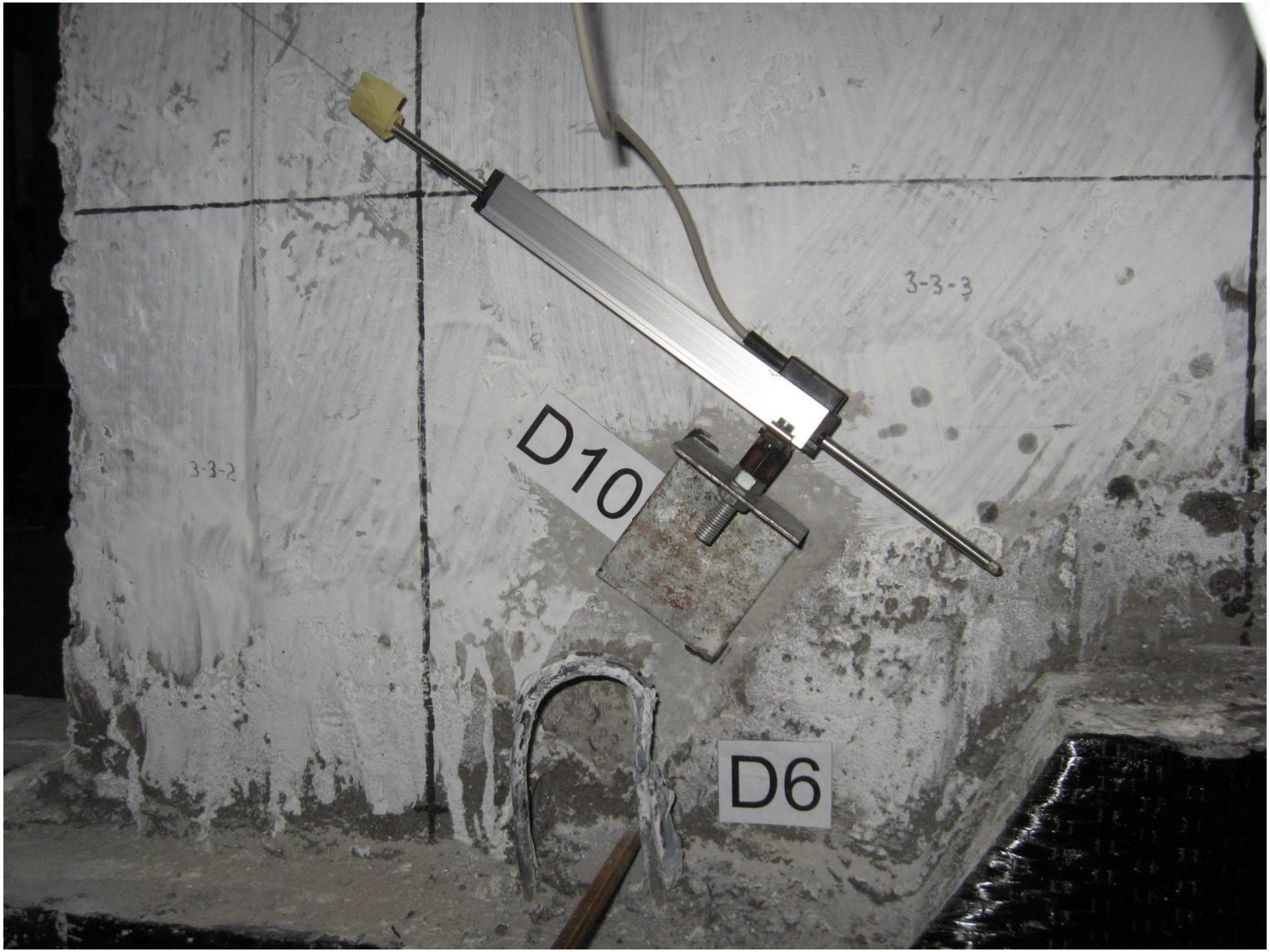
INSTRUMENTATION



INSTRUMENTATION


D12
D8

INSTRUMENTATION



INSTRUMENTATION

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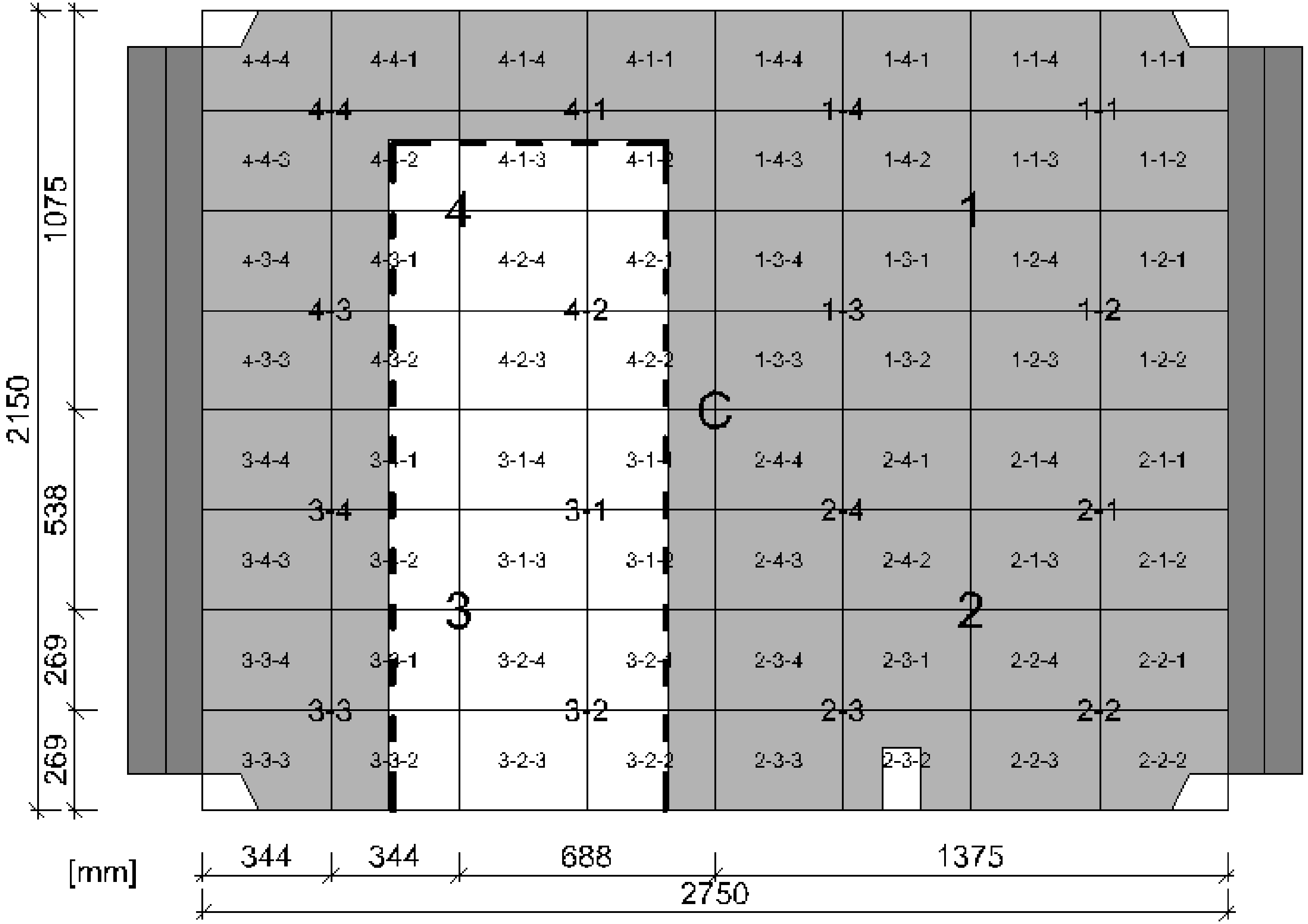
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538
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269
[mm]
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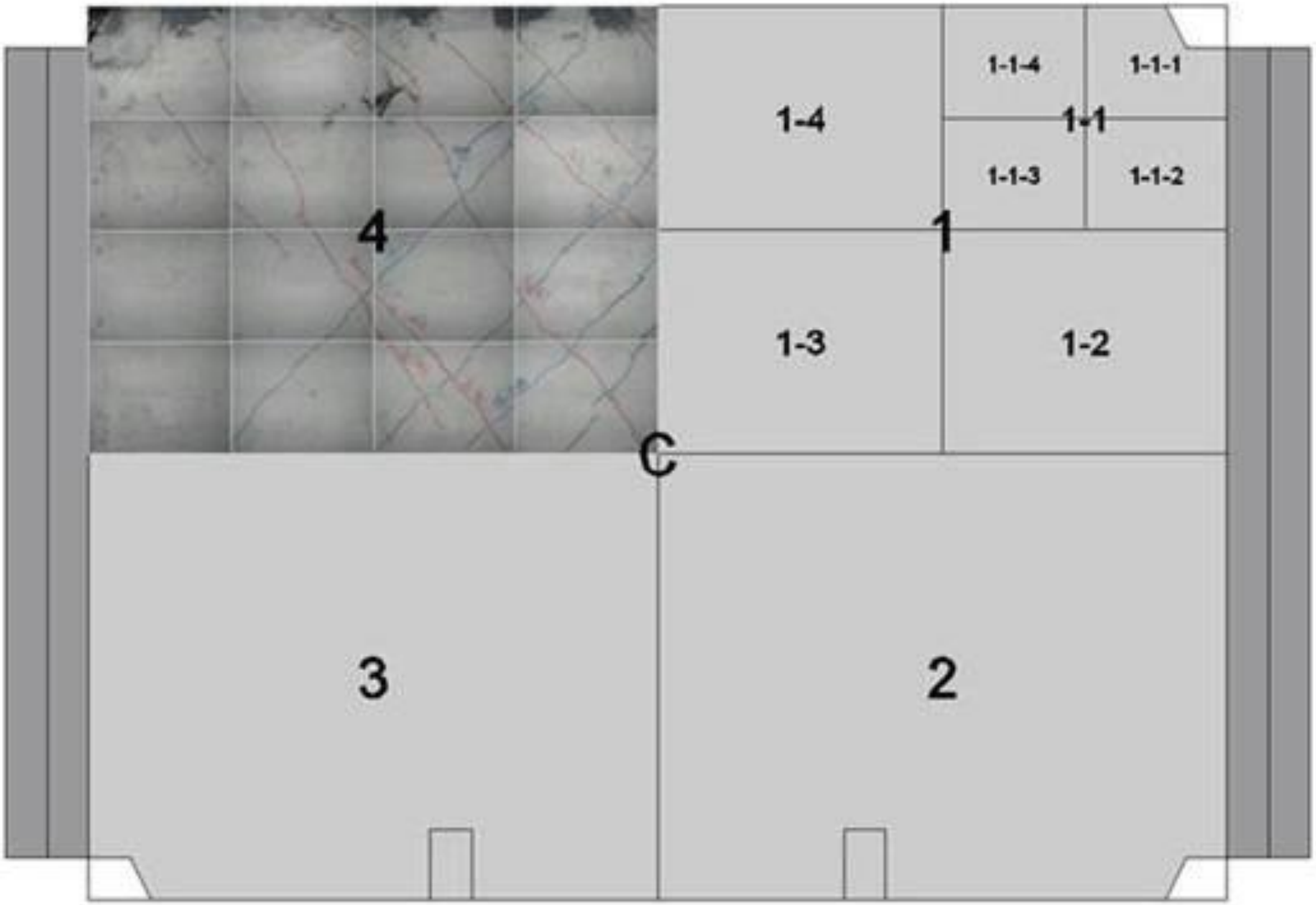
344
688
1375
2750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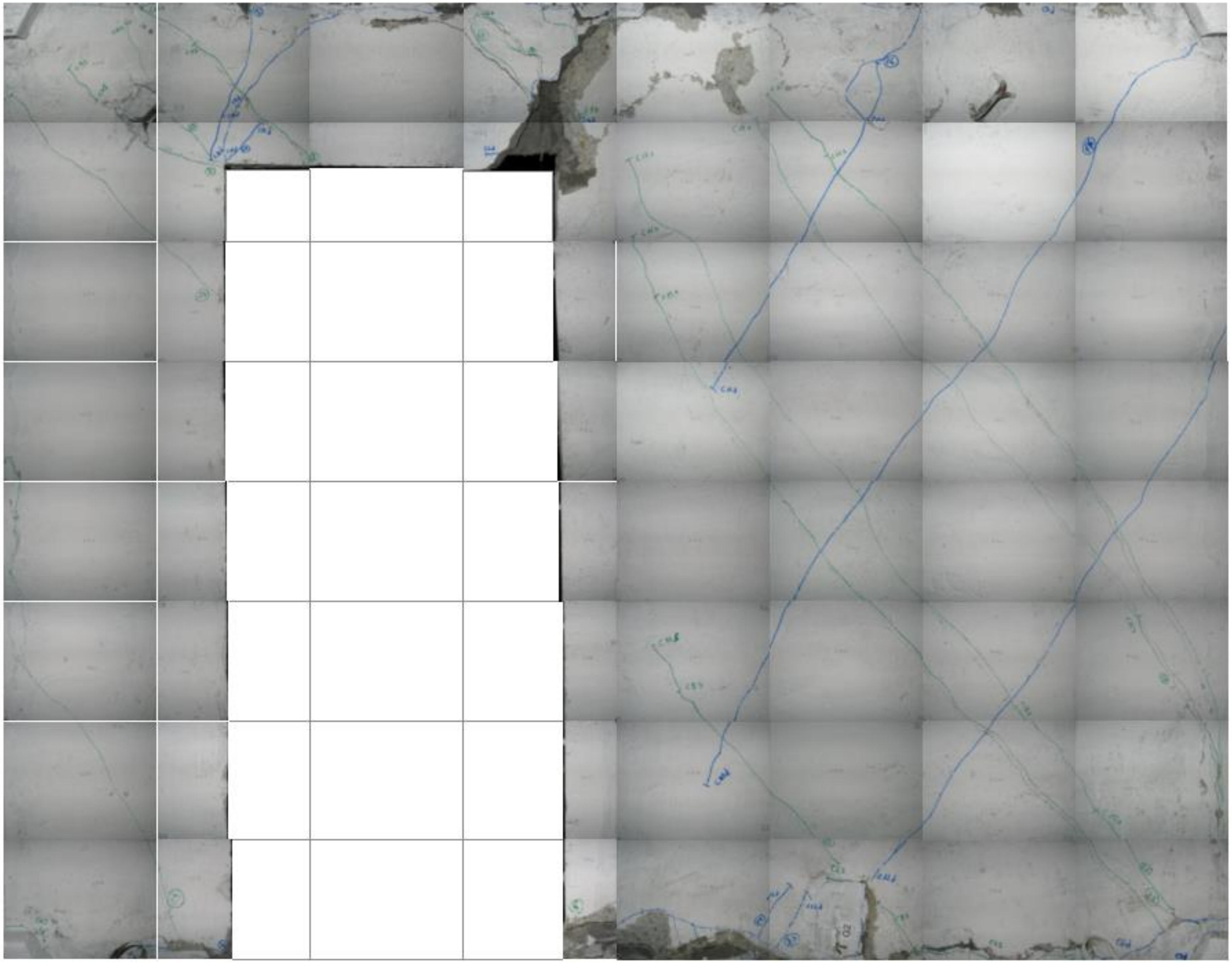

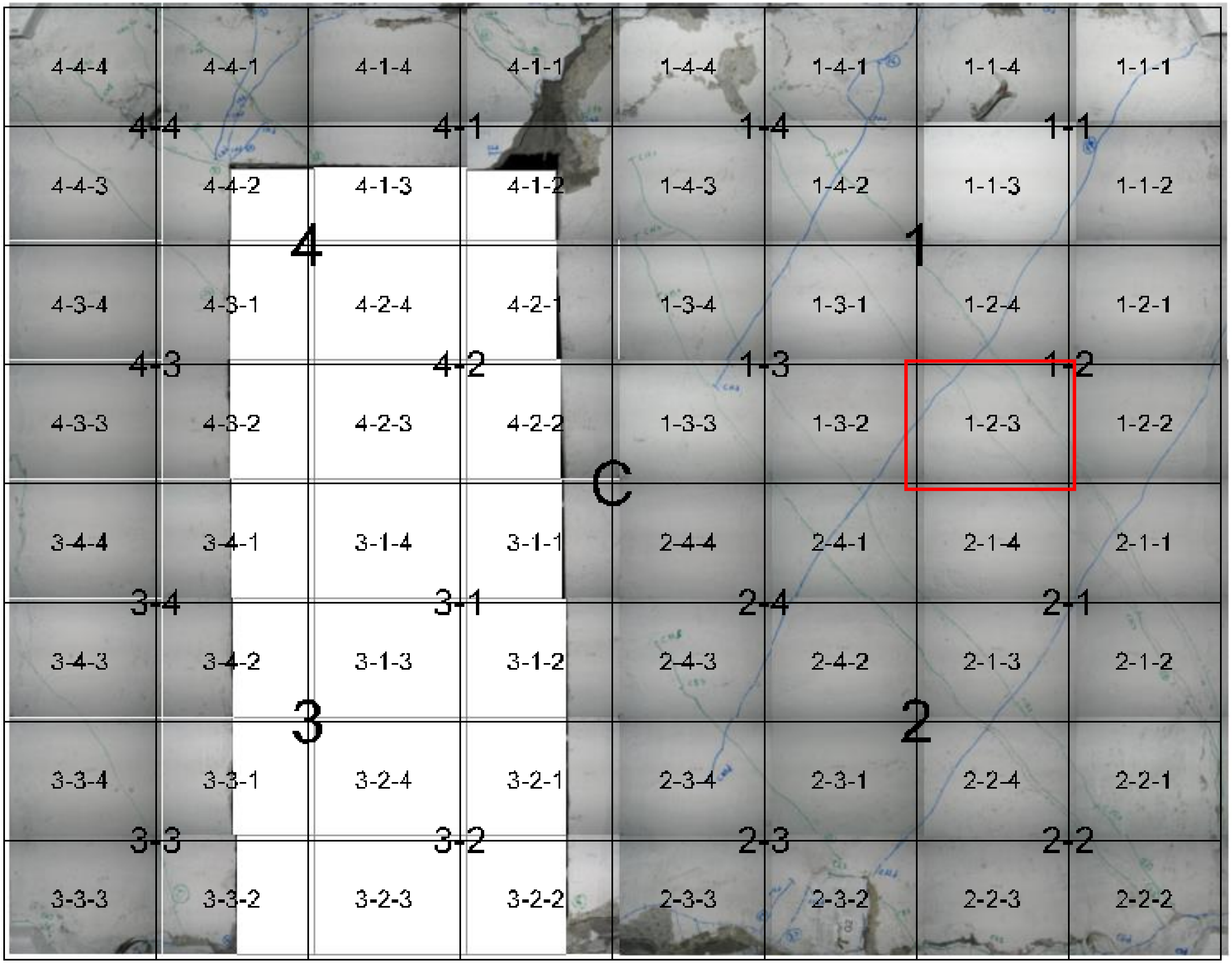
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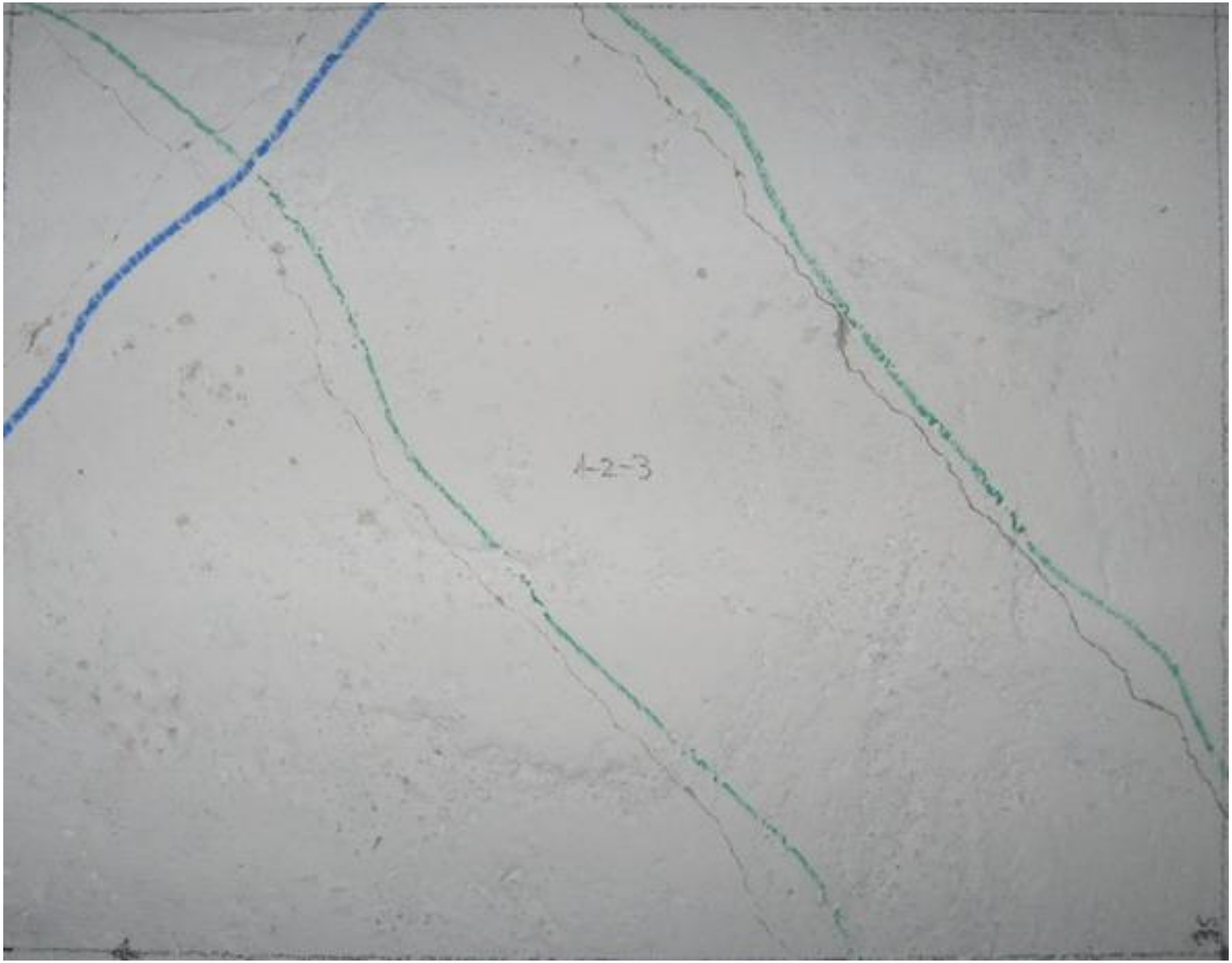
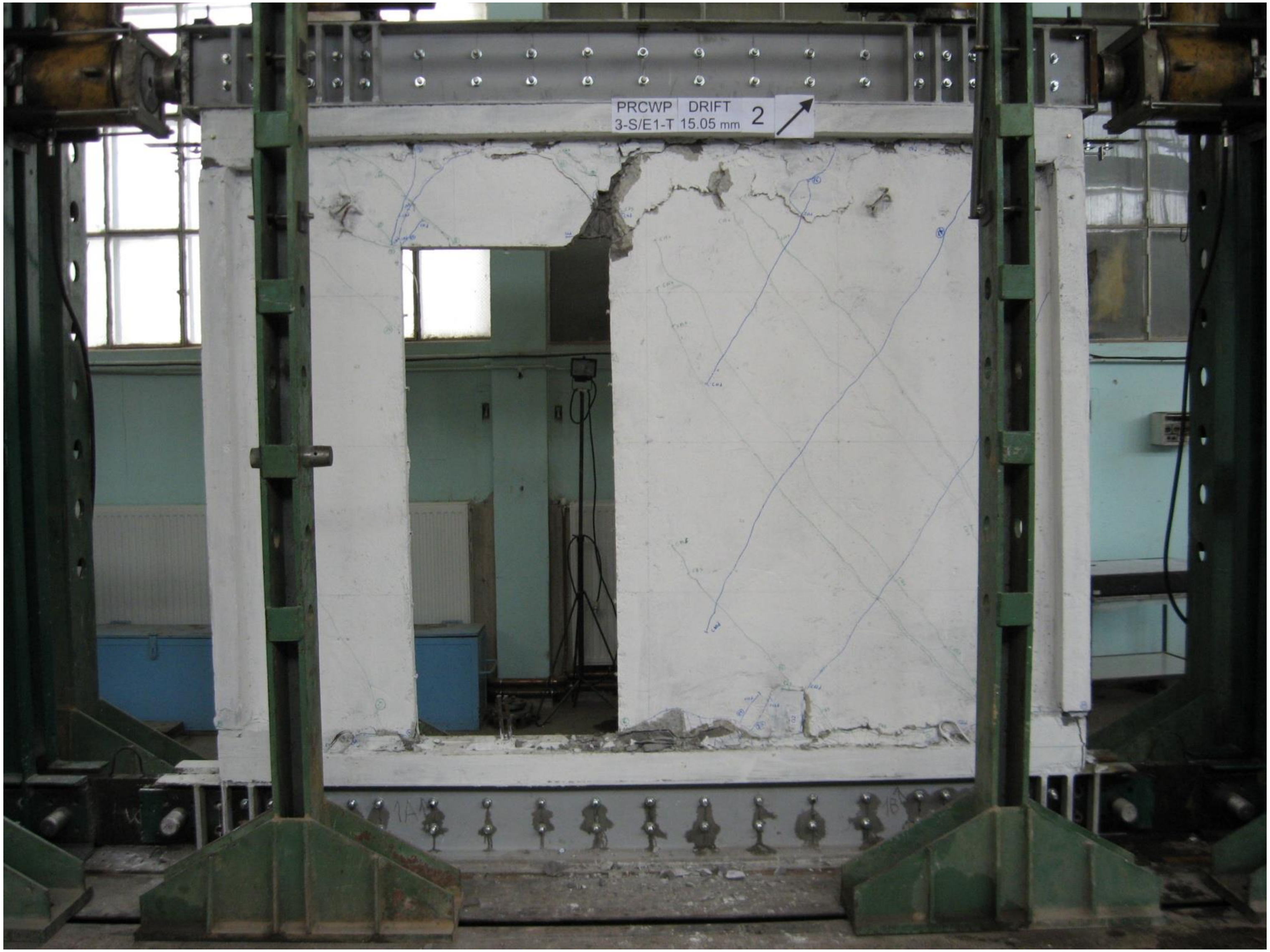
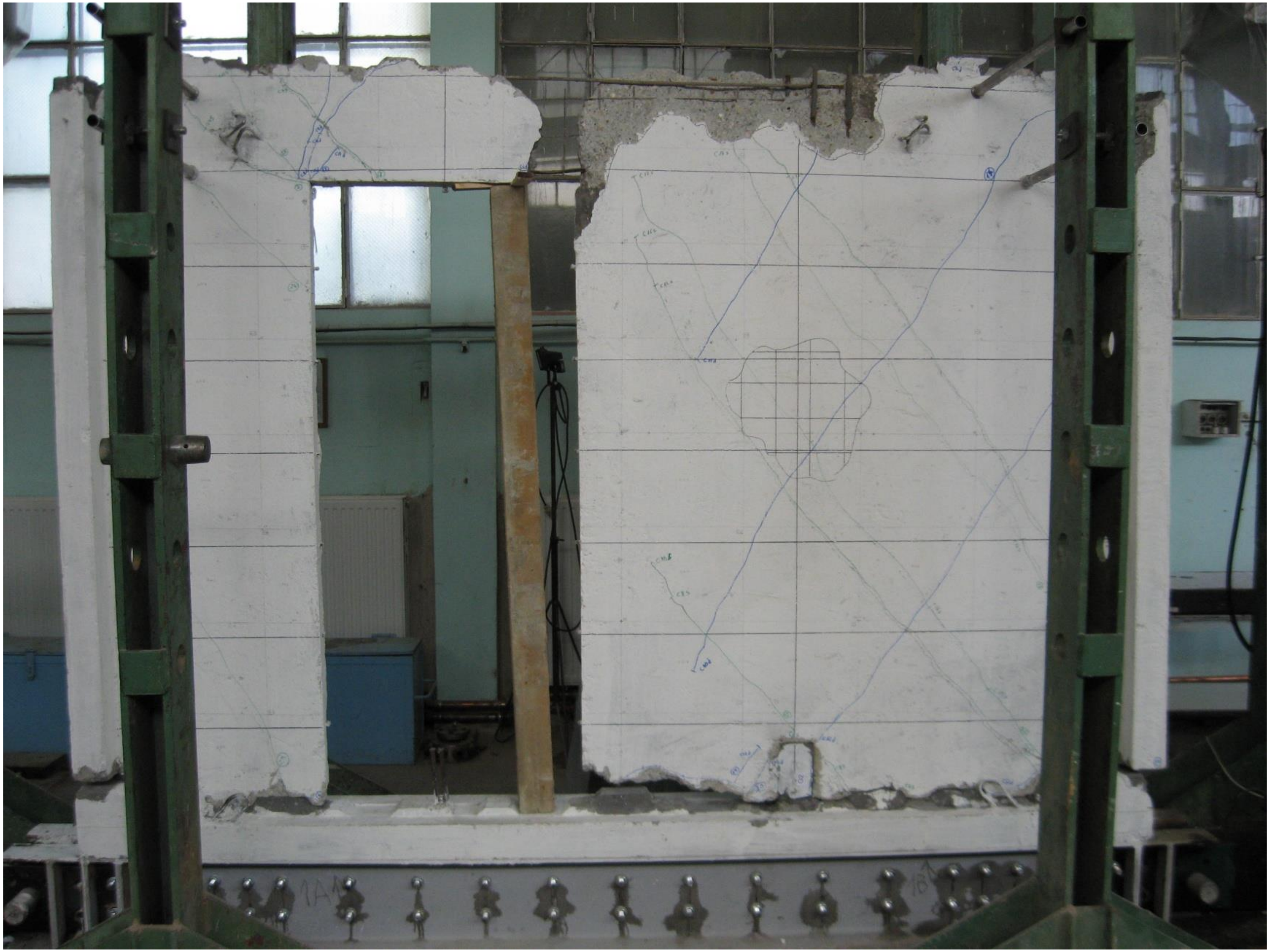

A-2-3


PRCWP 3-S/E1-T
DRIFT 15.05 mm
2

DAMAGE ASSESSMENT

DAMAGE ASSESSMENT



DAMAGE ASSESSMENT

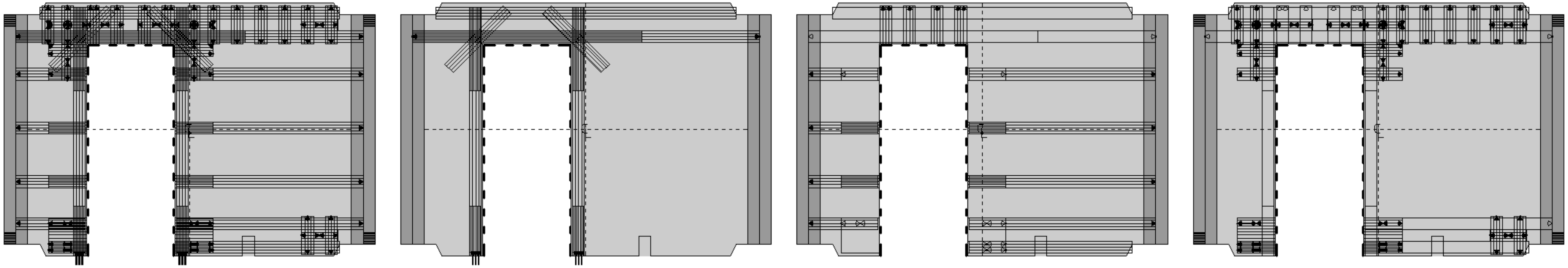
REPAIR

REPAIR

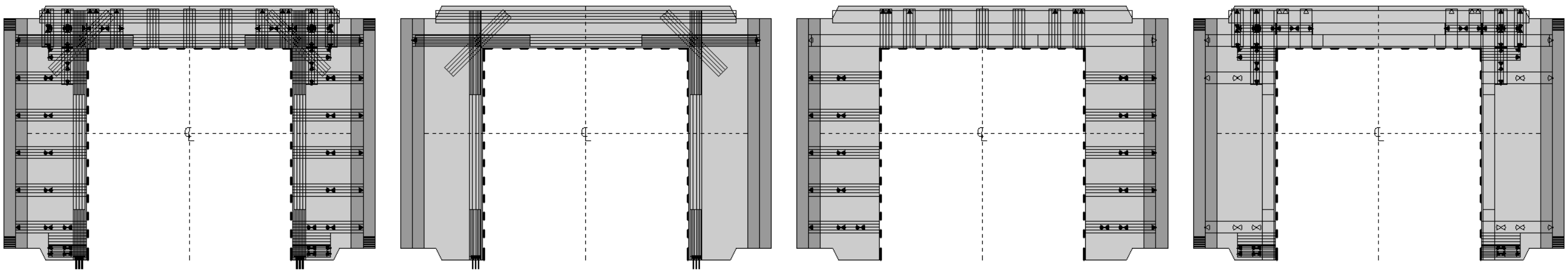
STRENGTHENING

FLEXURAL | SHEAR | CONFINEMENT

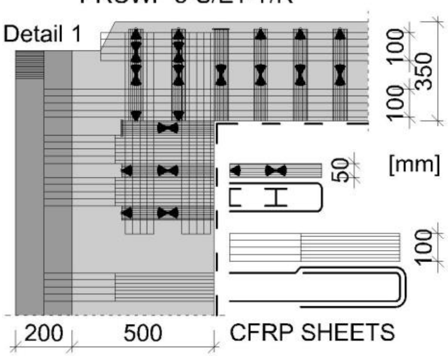
PRCWP 4-S/E1-R/T



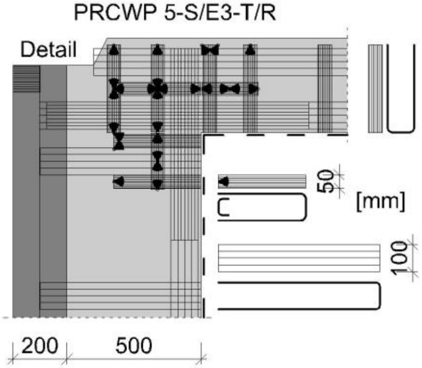
PRCWP 6-S/E3-R/T



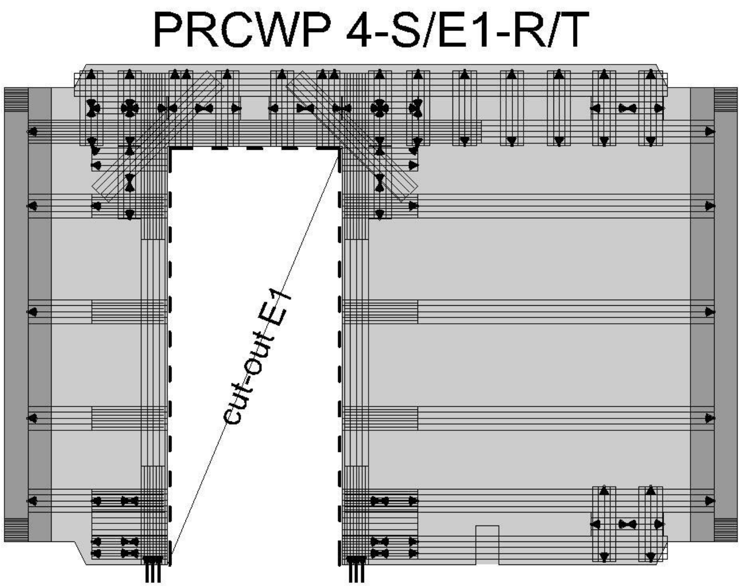
PRCWP 3-S/E1-T/R

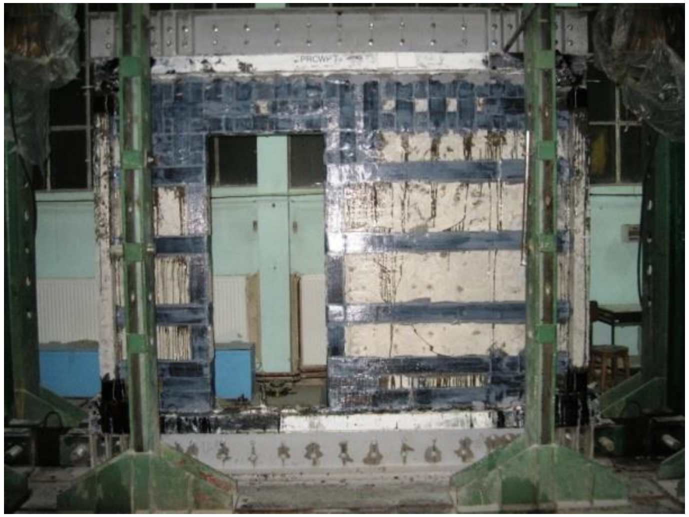


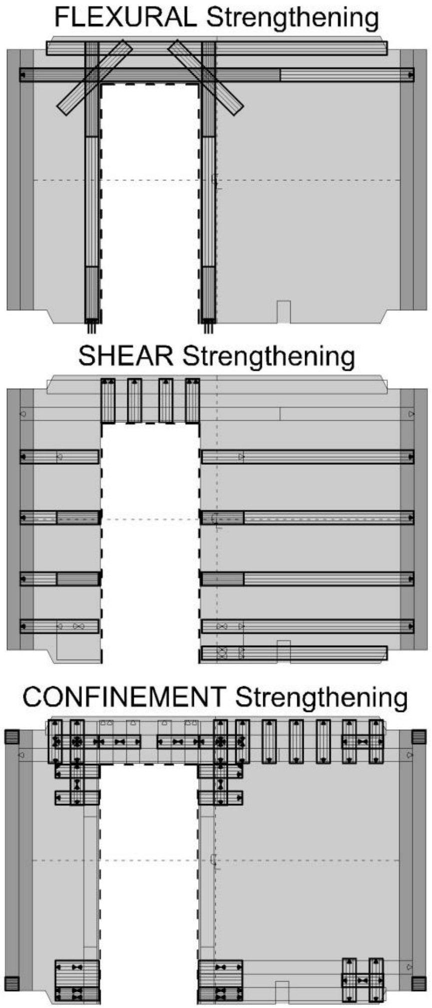
PRCWP 5-S/E3-T/R



STRENGTHENING







CFRP-EBR

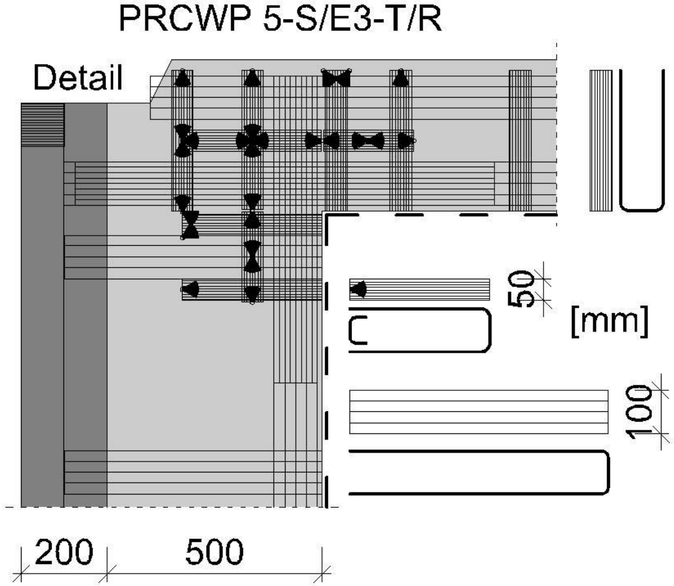
CF-strips of 50/100 mm width

Average CFRP usage (4RT):
CF 0.85
Resin 1.2 kg/sqm

Arrangement: FL, SH, CNF

Note inclined diagonal strips at the upper corners

Improvements: end anchorage of SH-strips



Pier-beam connection

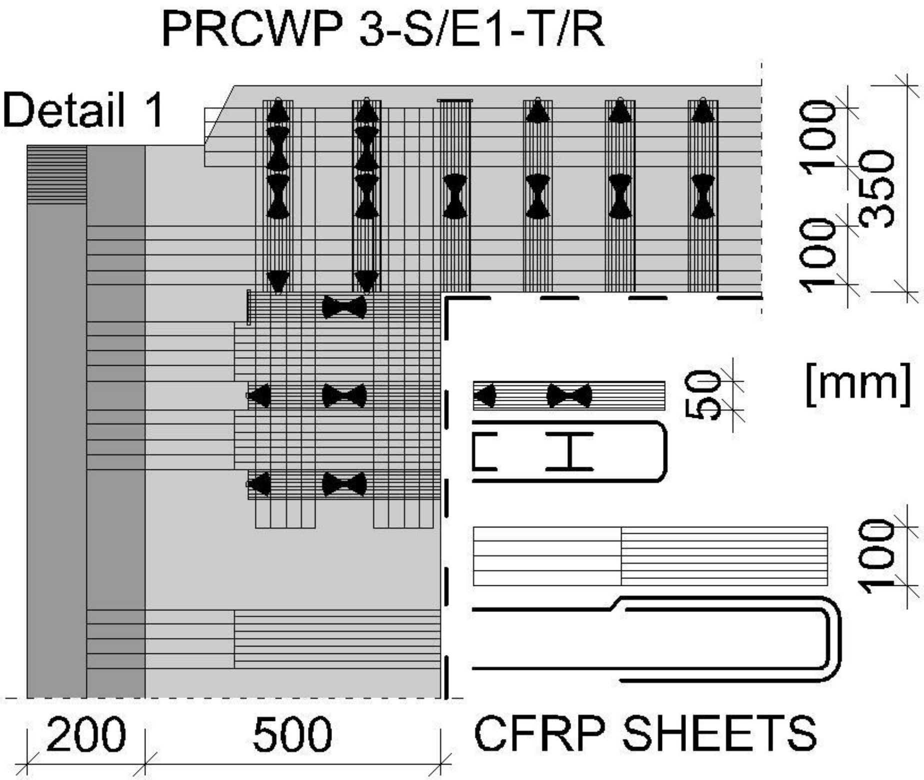
Substrate preparation

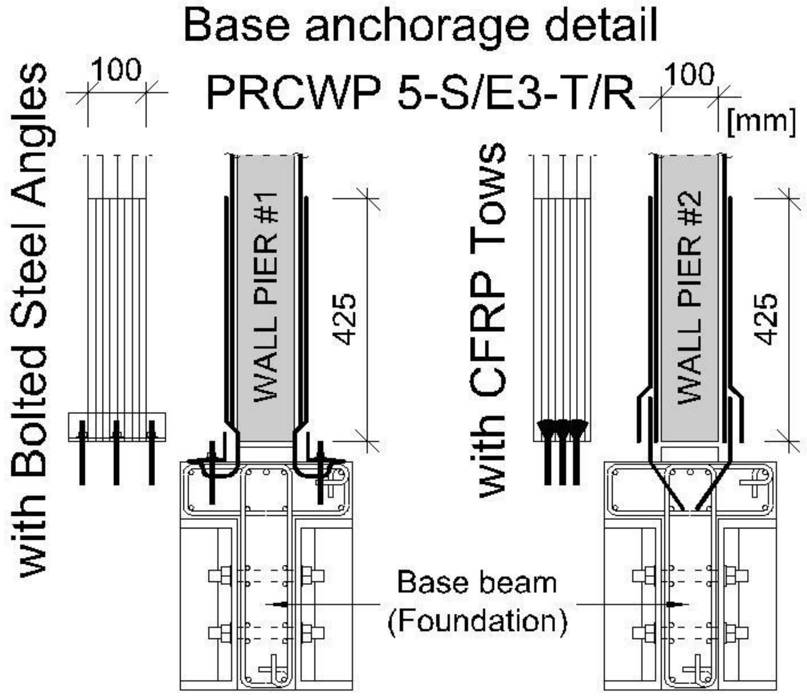
Flexural strips

Through-wall anchorages (CFRP tows)

Shear strips

Confinement strips


PRCWP 3-S/E1-T/R
Detail 1
100
100
350
50
[mm]
100
200
500
CFRP SHEETS

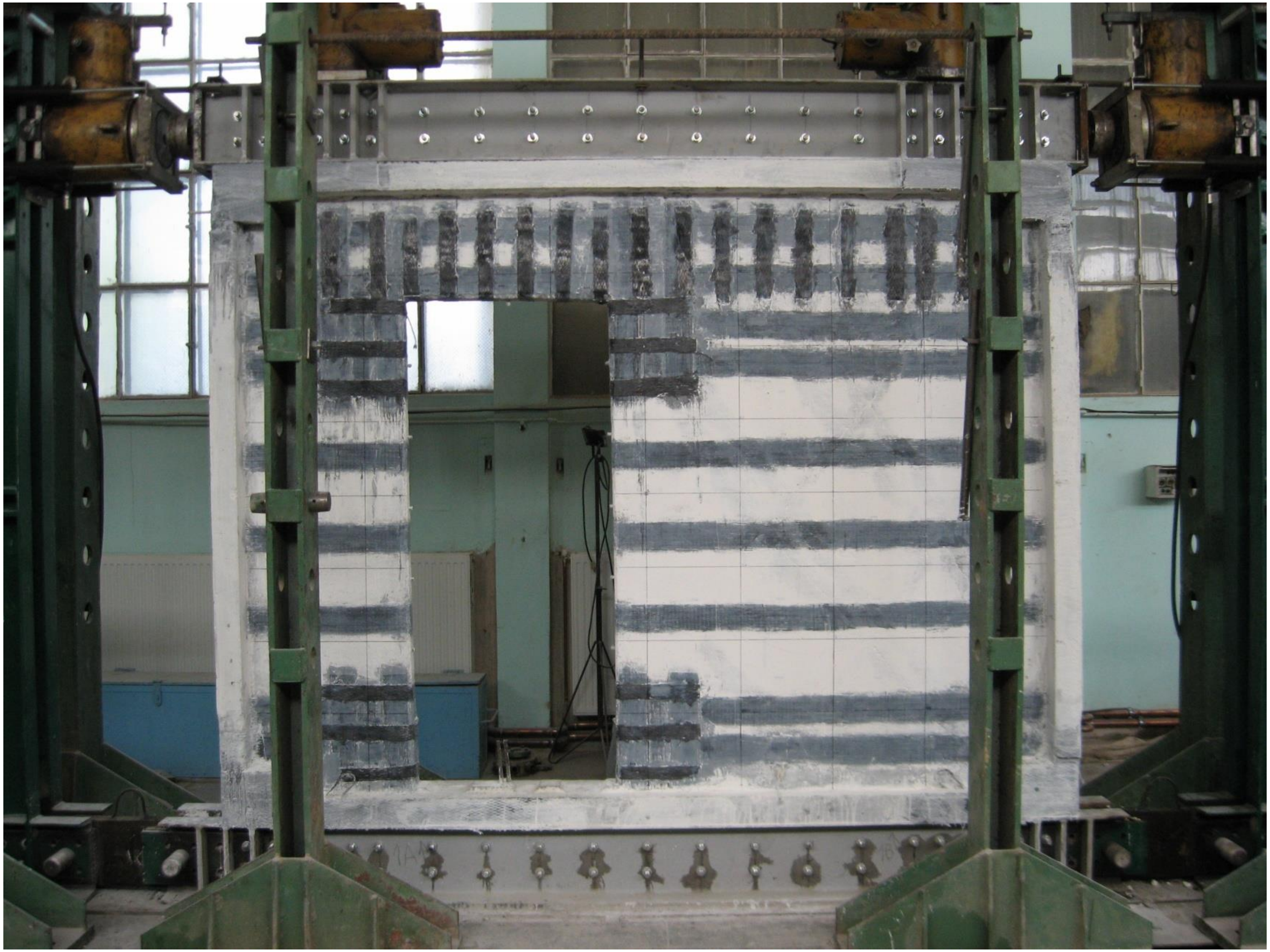


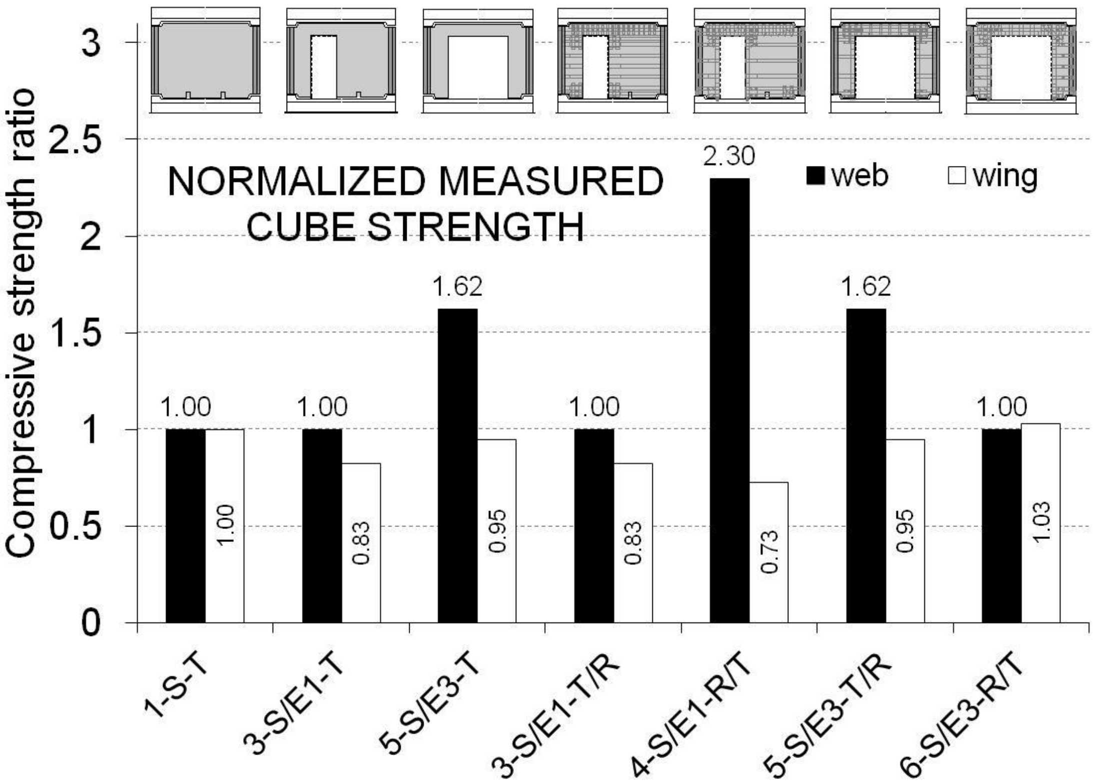
Base anchorage

<u>Solution 1</u>
Bolted steel angles

<u>Solution 2</u>
CFRP tows

Corner detail

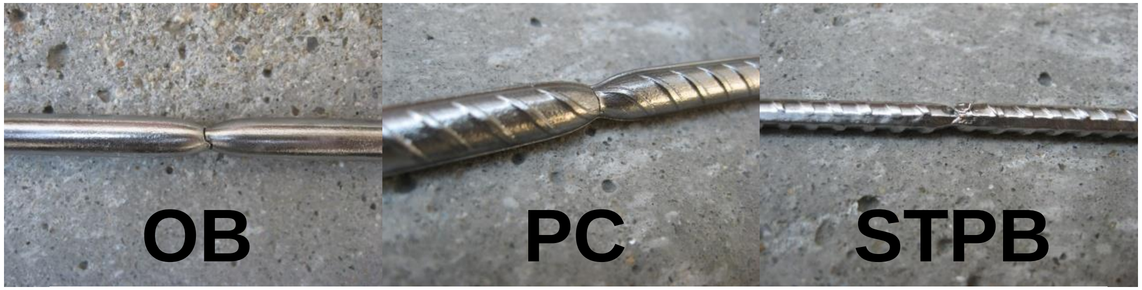


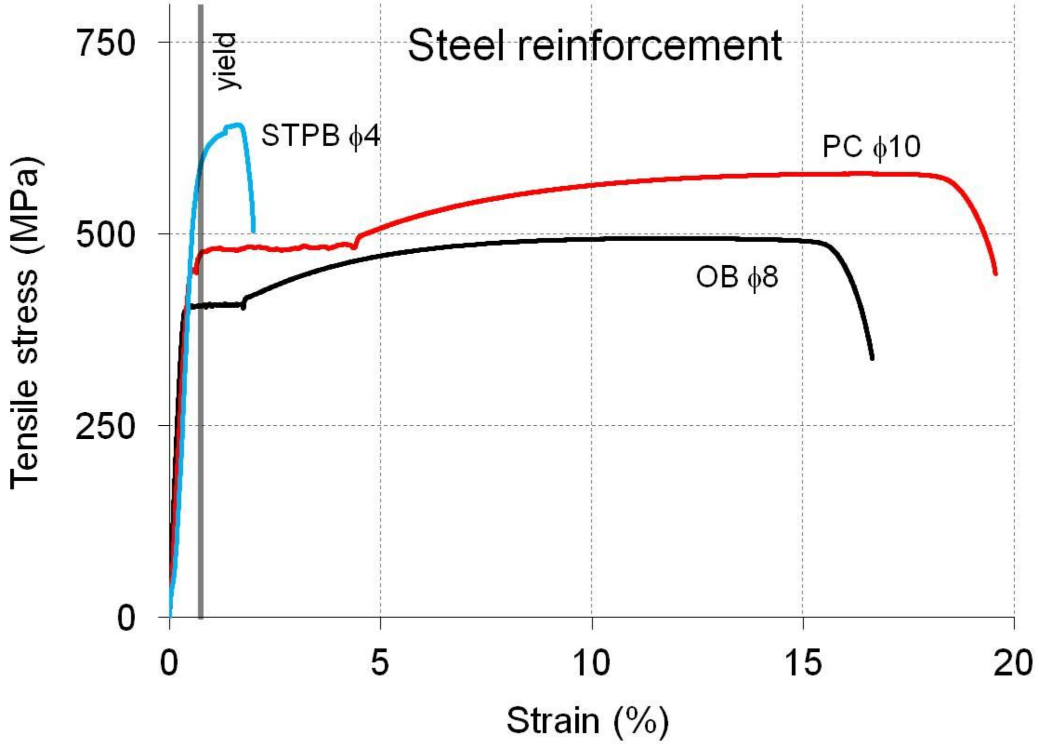


Concrete samples

Three 150 mm cubes from each concrete batch (cylinder and prism samples only from one batch)

Reference strength
Web: 17.5 MPa
Wing: 39 MPa



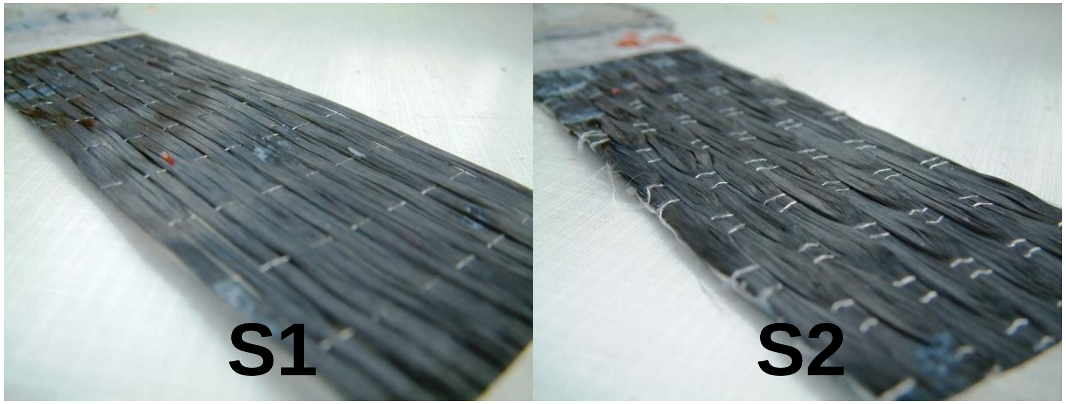


Steel reinforcement

<u>OB-type reinforcement</u>
Measured yield strength:
410 MPa

<u>PC-type reinforcement</u>
Measured yield strength:
450 MPa

<u>STPB-type wires</u>
Measured yield strength:
600 MPa



Carbon Fibre (CF)	S1 CF-sheet	S2 CF-sheet
Tensile strength (MPa)	4100	3900
Tensile elongation at break (%)	1.5	1.5

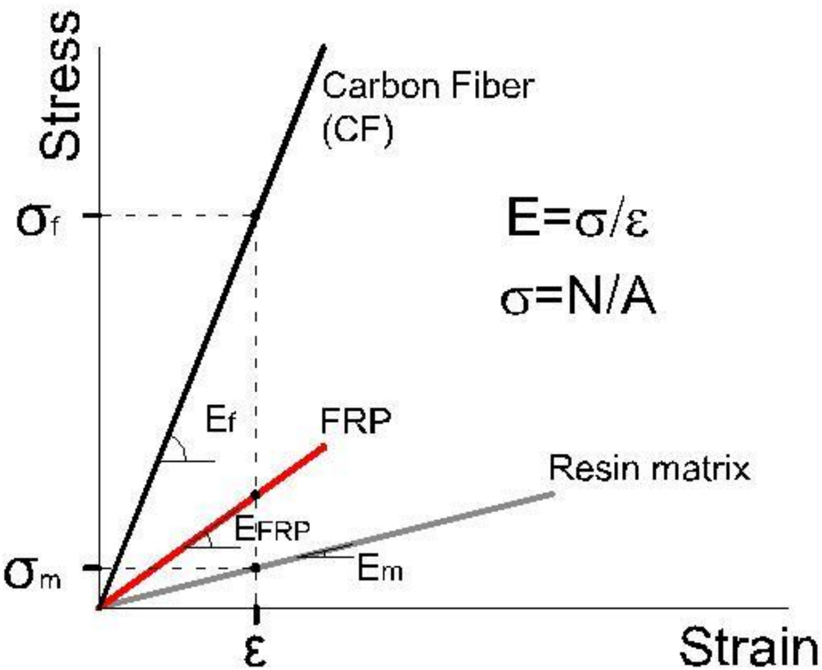
CFRP-EBR reinforcement

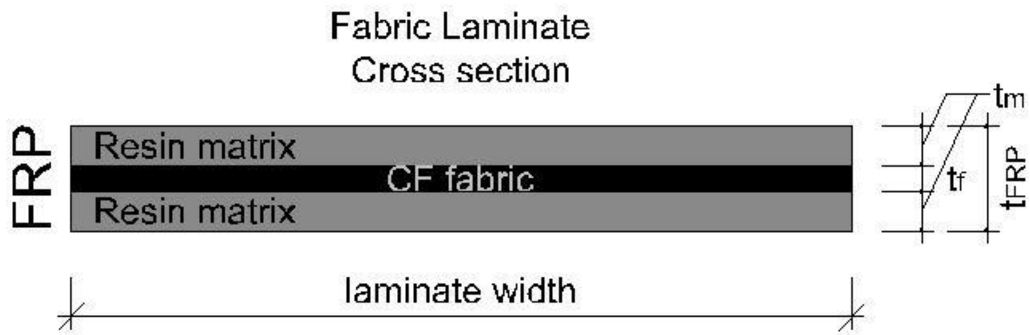
<u>S1-type CF sheet</u>
Unidirectional
Thickness: 0.122 mm

<u>S2-type CF sheet</u>
Unidirectional
Thickness: 0.337 mm

<u>Impregnation resin</u>
Tensile strength:
30÷45 MPa

CFRP-EBR reinforcement

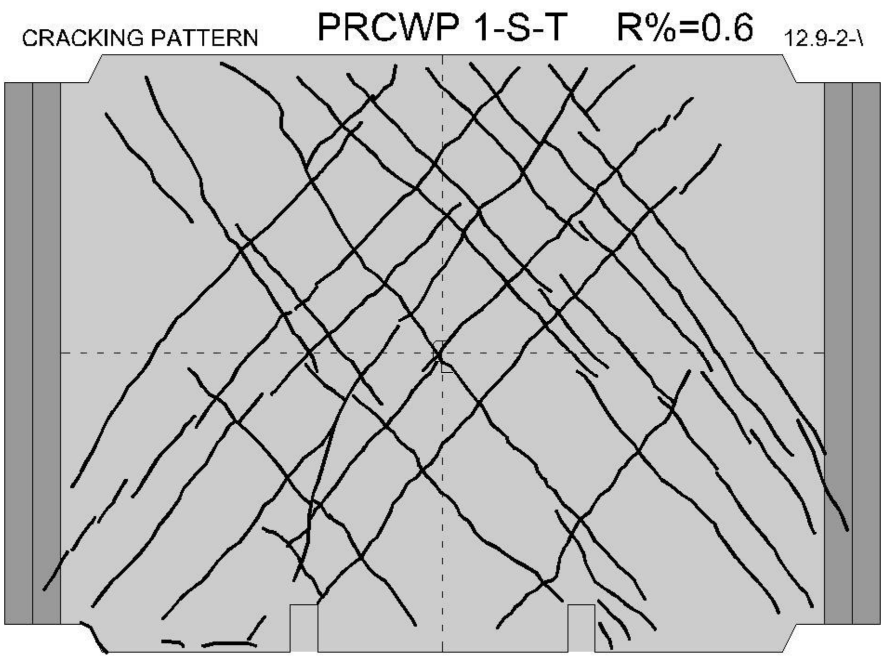


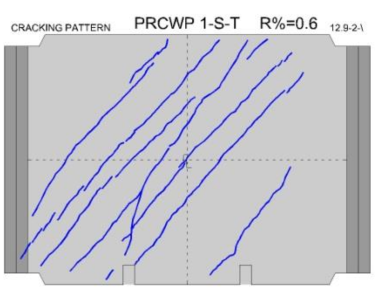


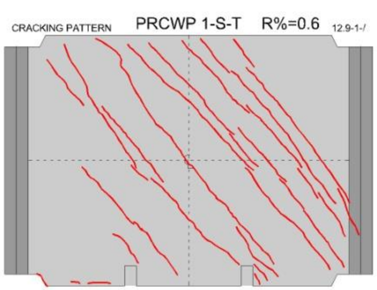
Rule of mixtures

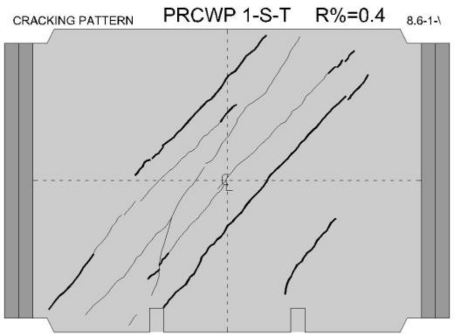
$$E_{FRP} = \frac{E_f \varepsilon A_f + E_m \varepsilon A_m}{A_{FRP}\varepsilon} = E_f \frac{A_f}{A_{FRP}} + E_m \frac{A_m}{A_{FRP}}$$

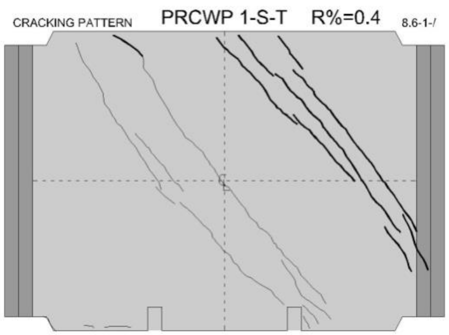
Qualitative analysis

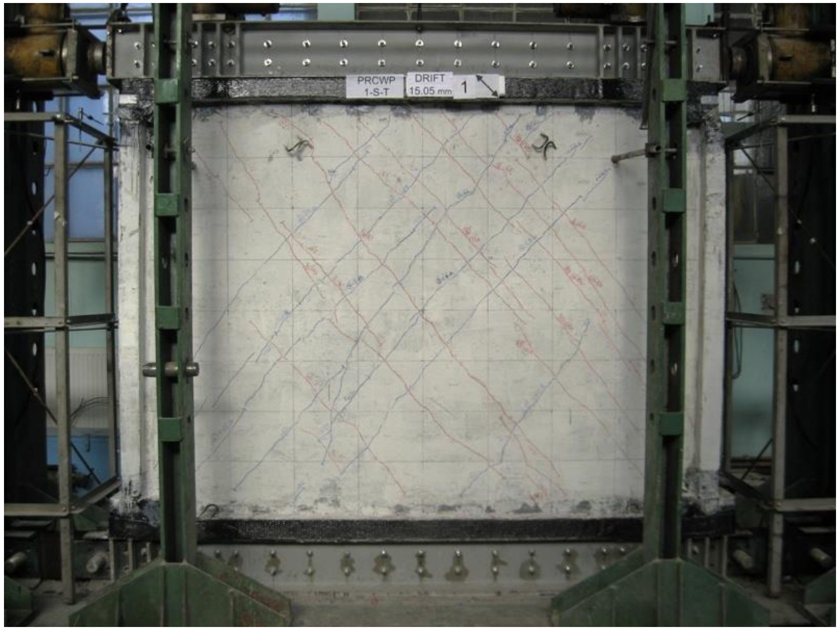




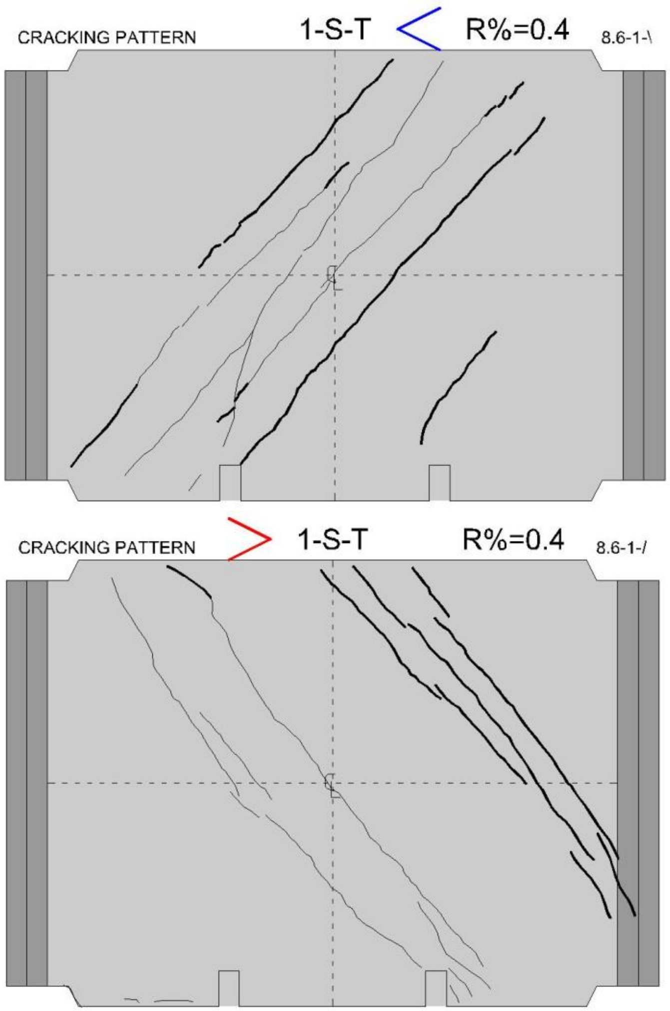


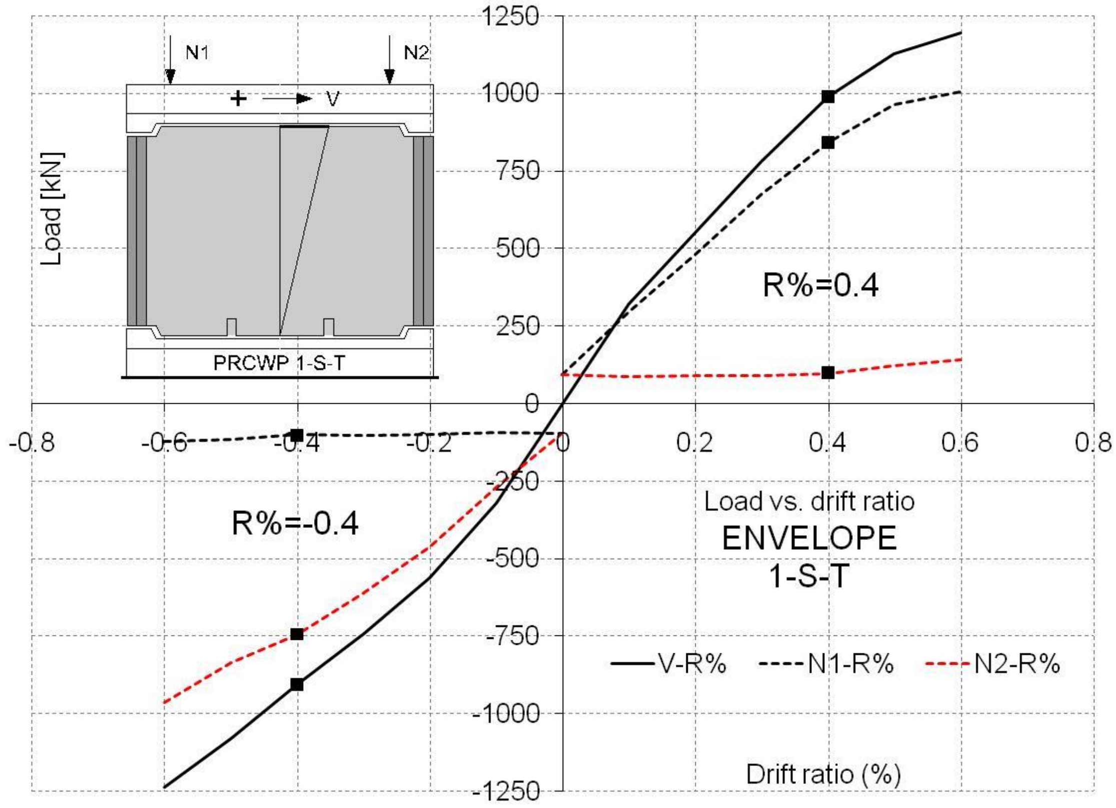






Quantitative analysis

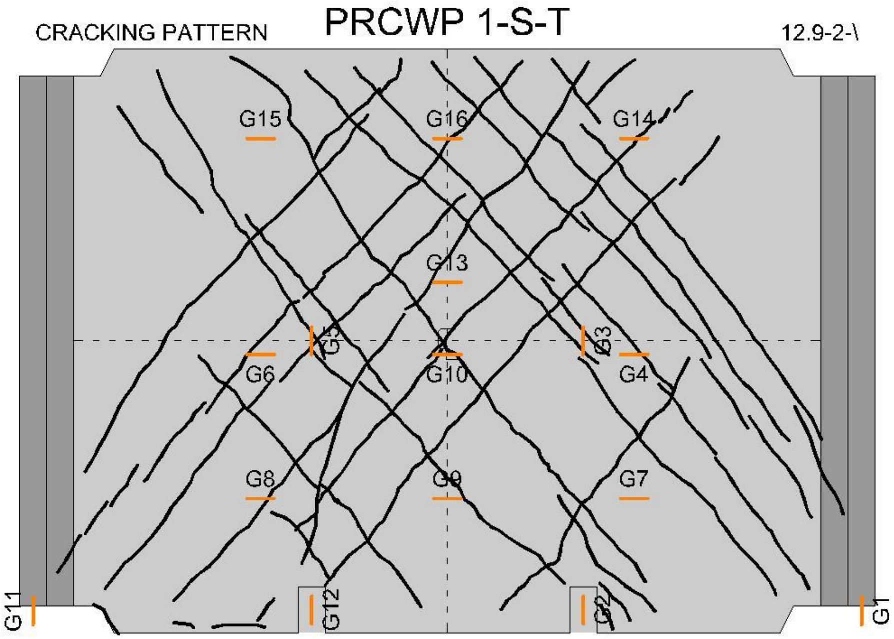


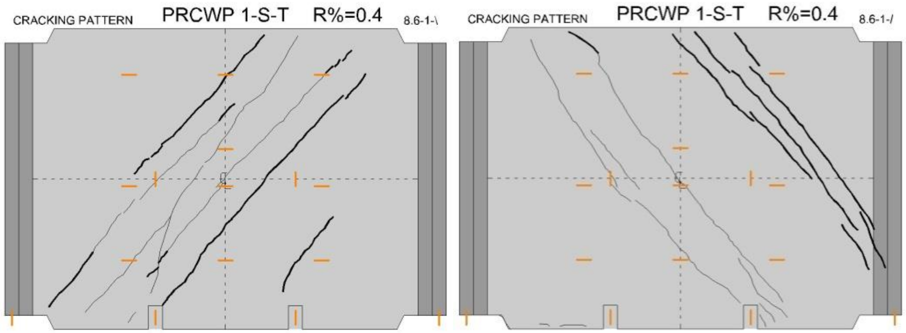


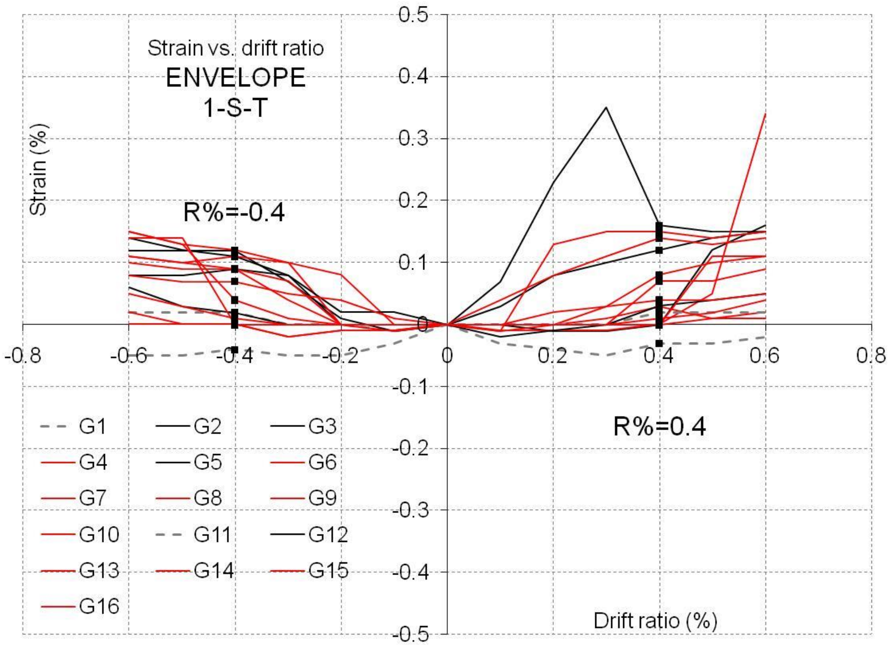
Crack correlation with the loads

Quantitative analysis

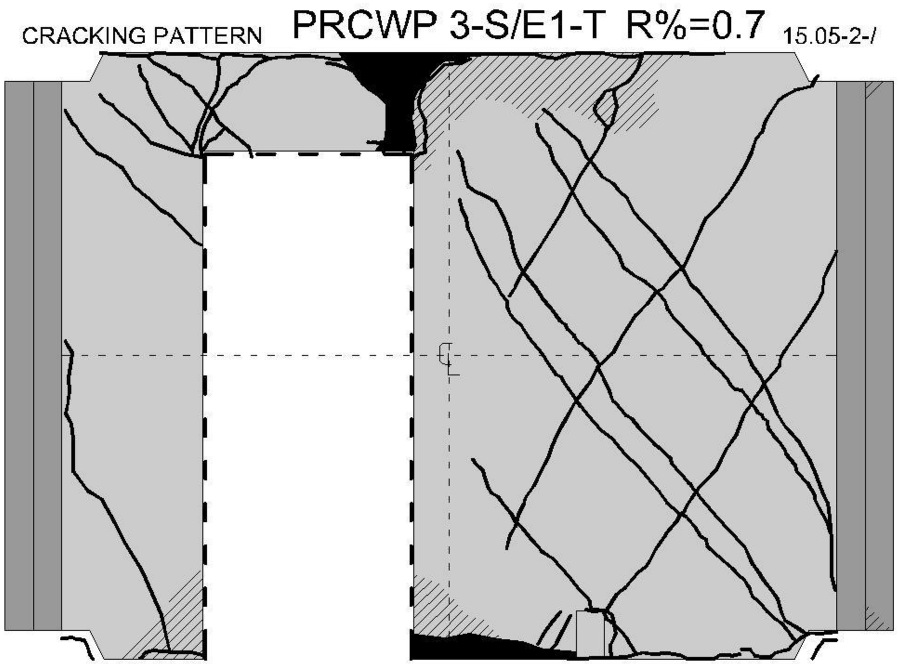
Crack correlation with the strains in reinforcements

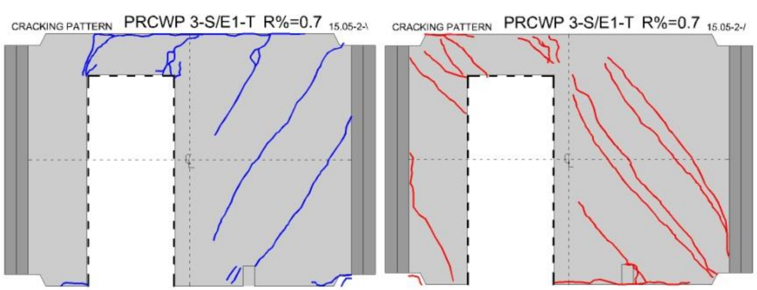






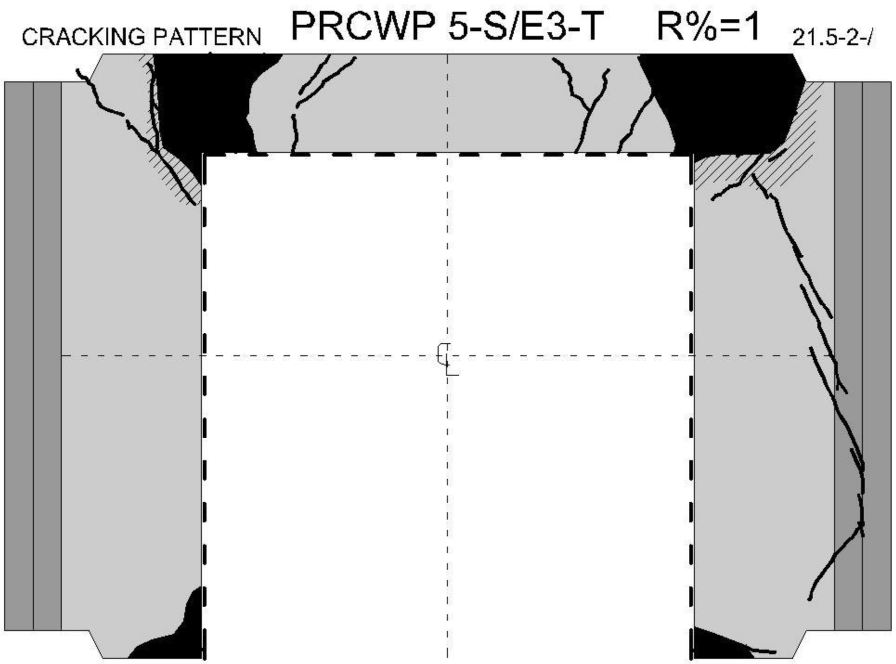
Qualitative analysis

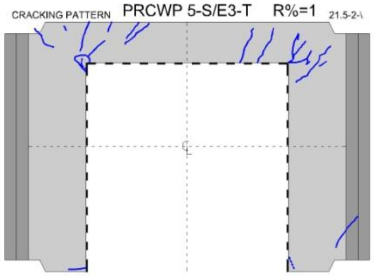


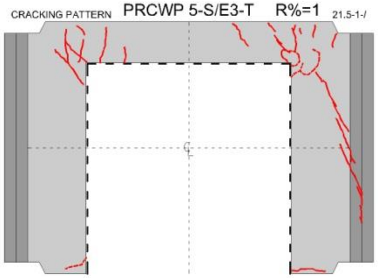


Qualitative analysis

Qualitative analysis







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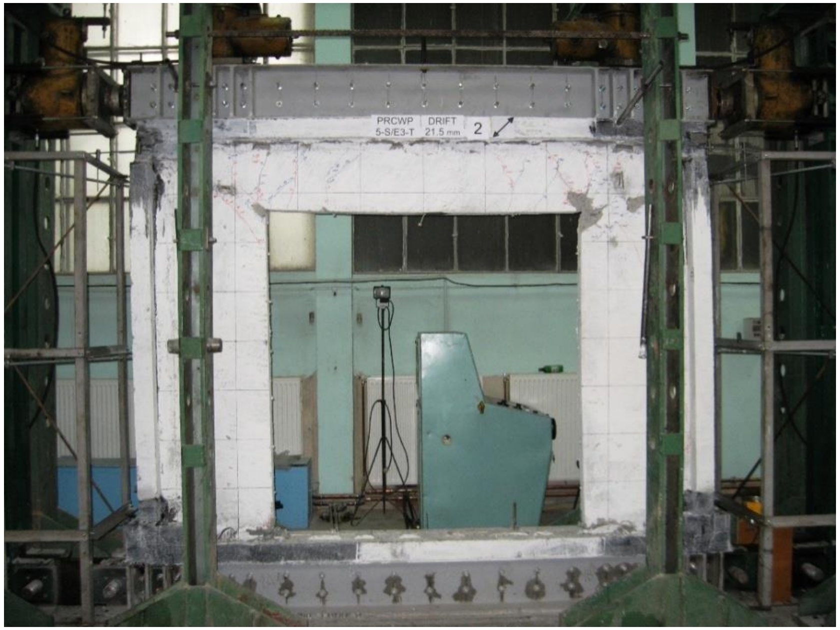

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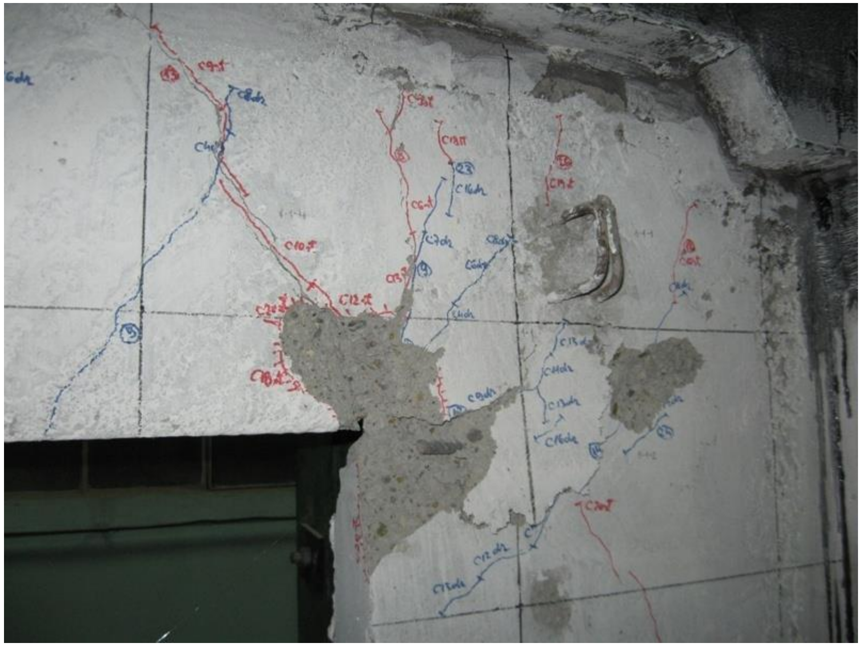
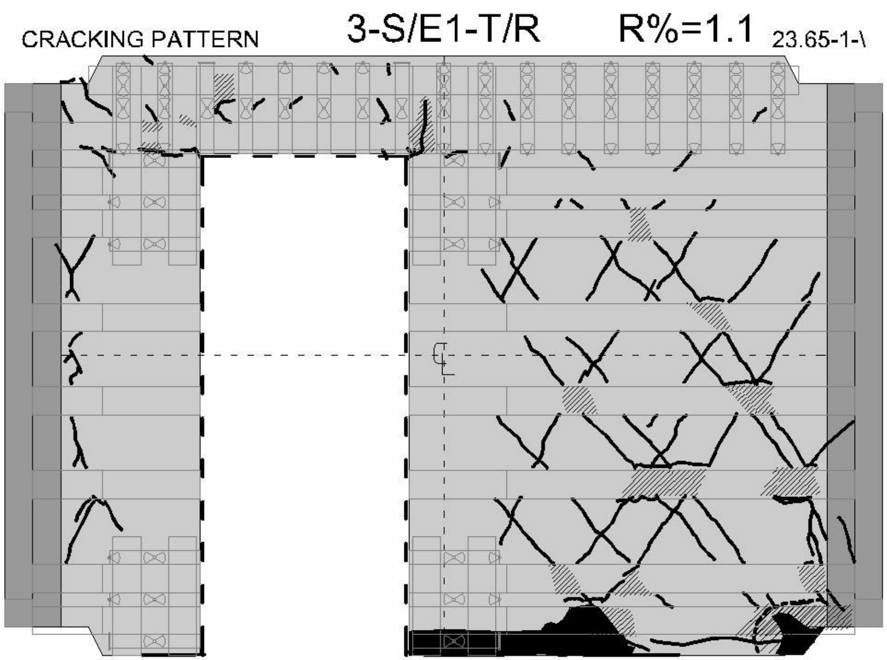
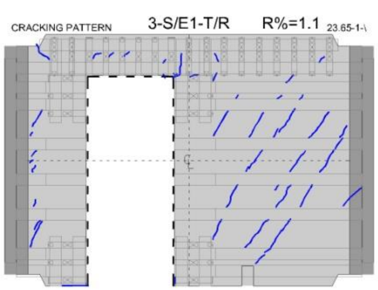


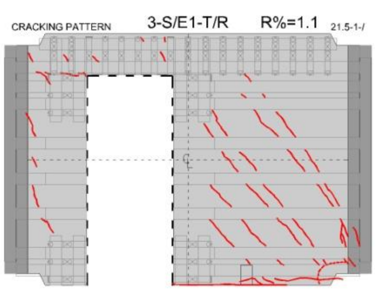
Qualitative analysis

Qualitative analysis

Qualitative analysis







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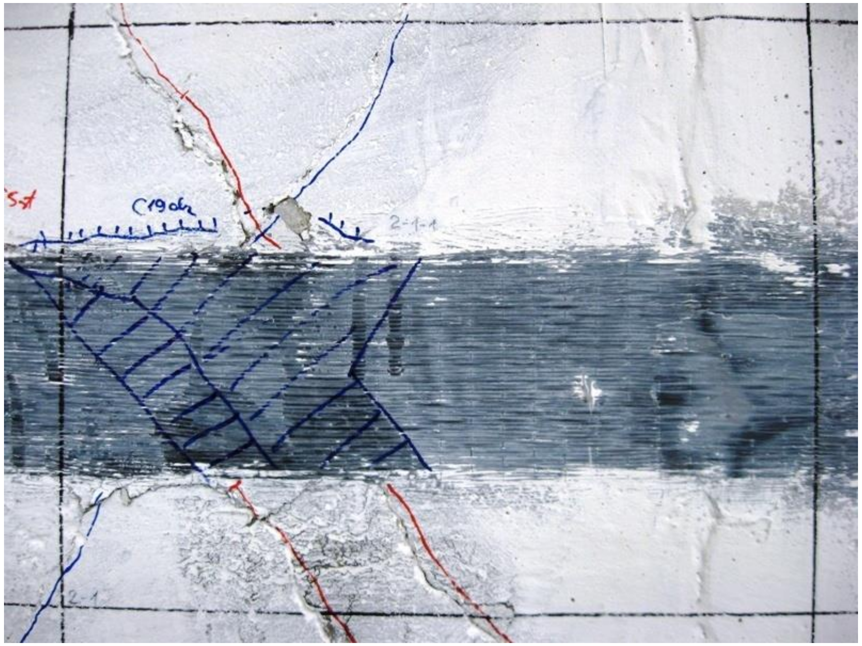

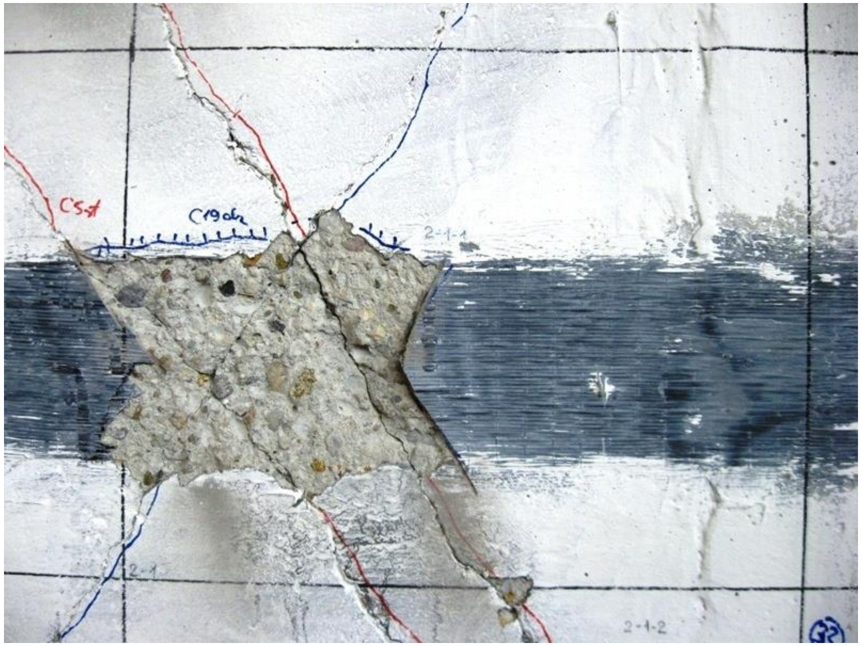

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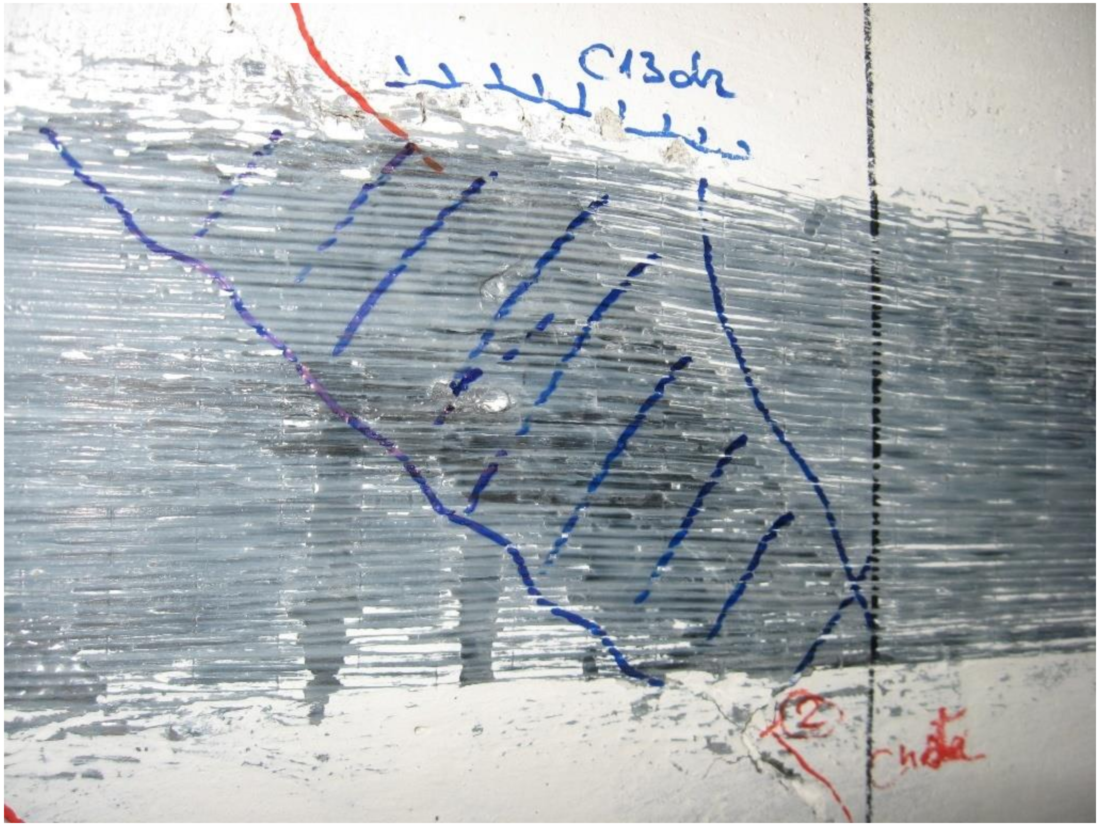

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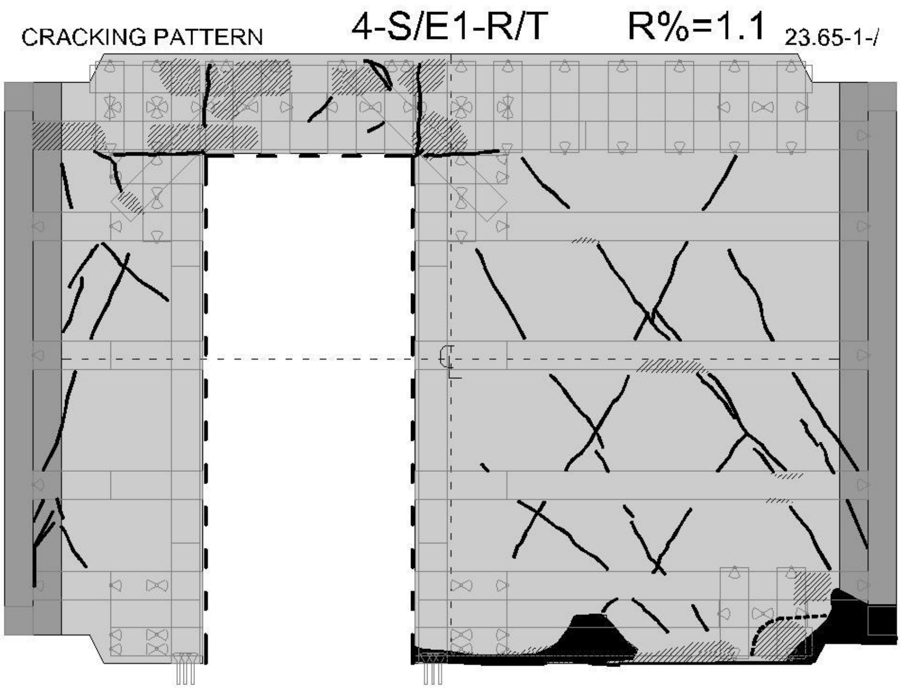
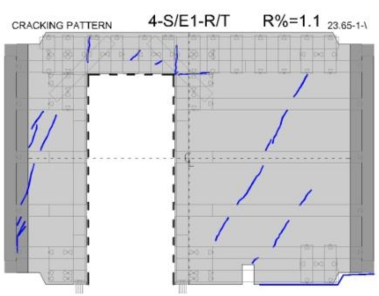
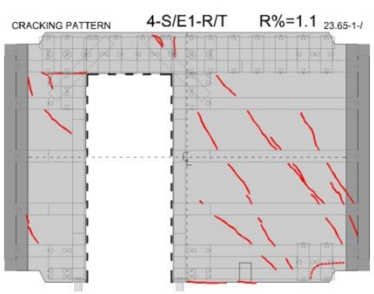
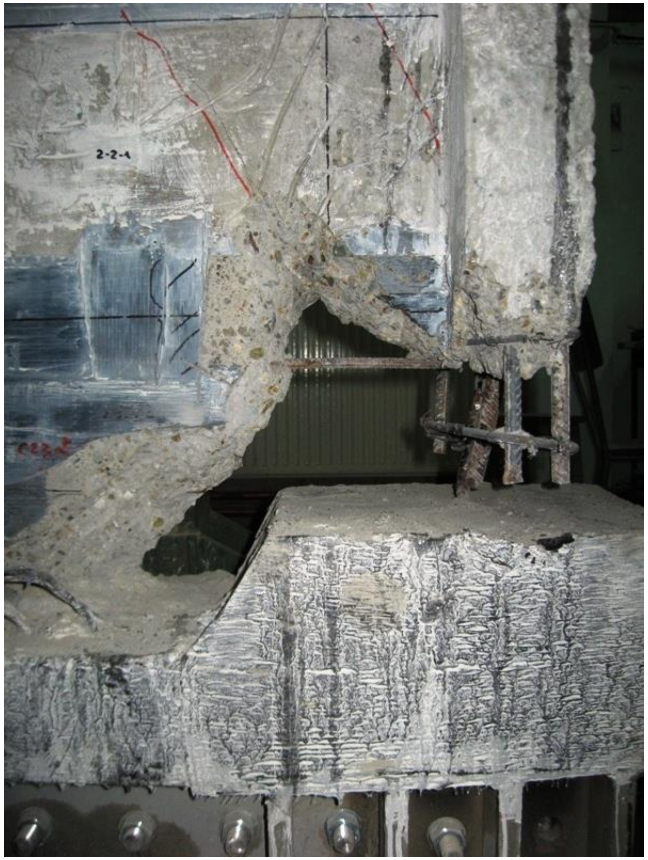
Qualitative analysis



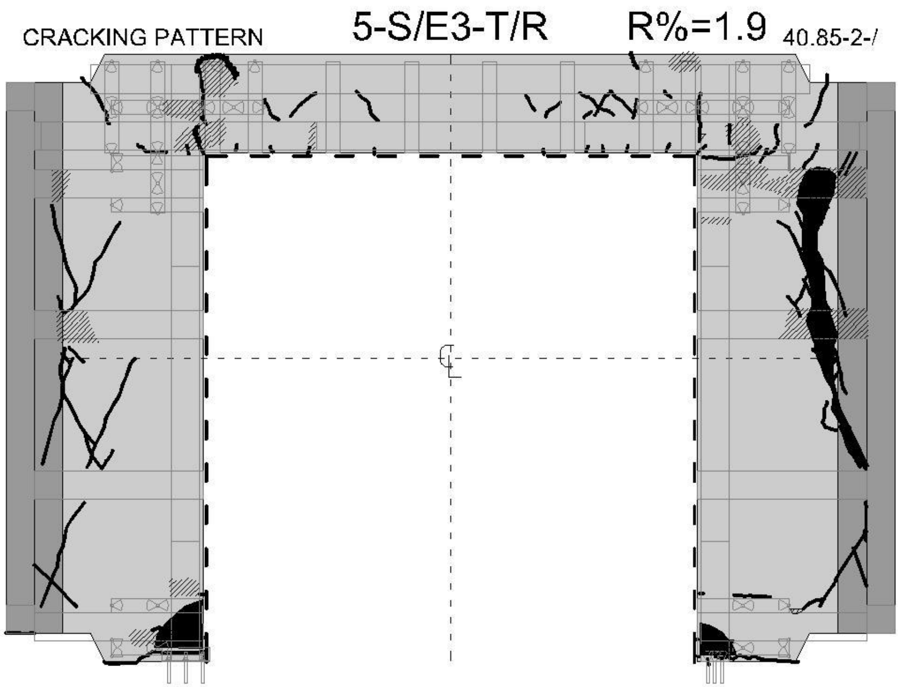


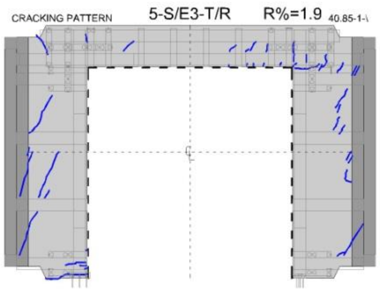


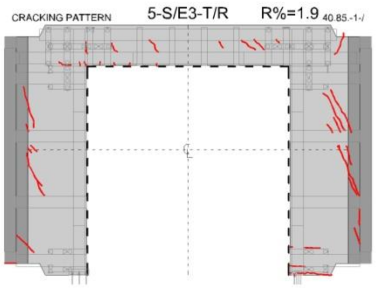


Qualitative analysis

Qualitative analysis



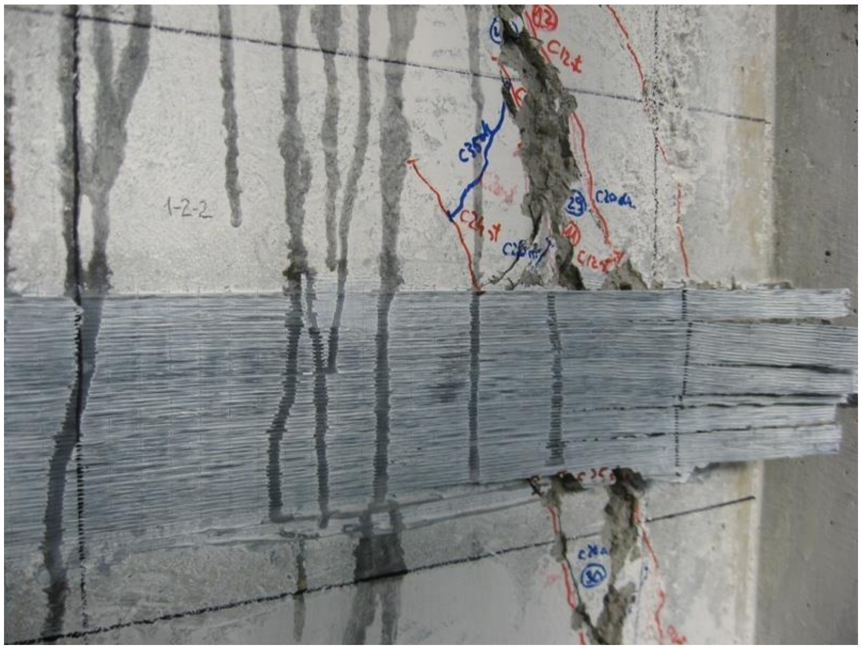




Qualitative analysis

Qualitative analysis

Qualitative analysis



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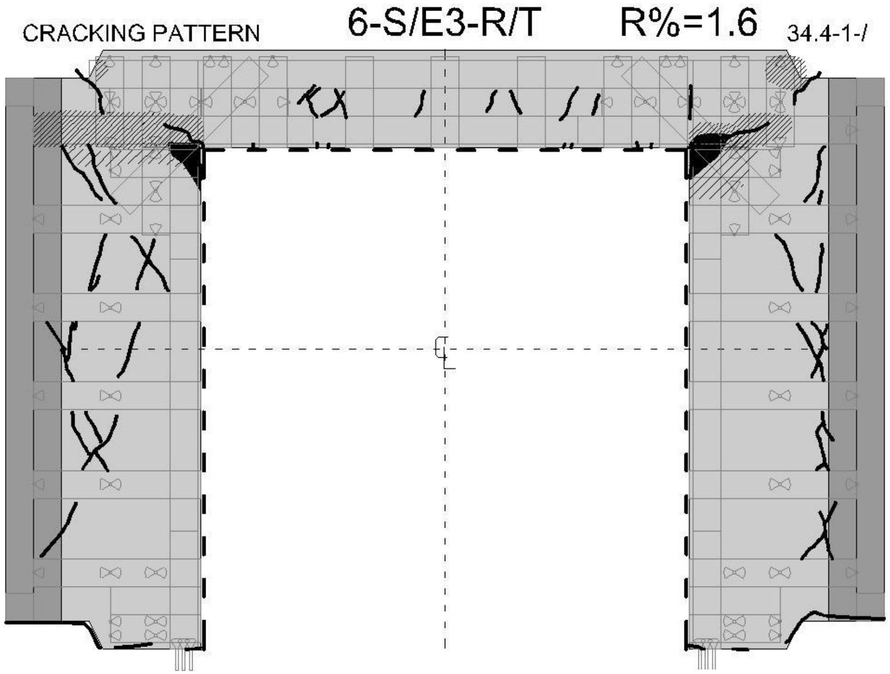
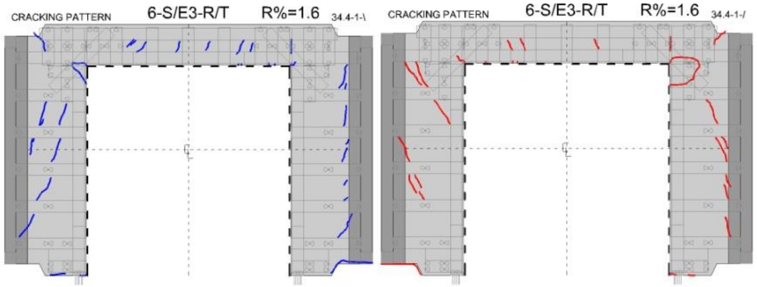


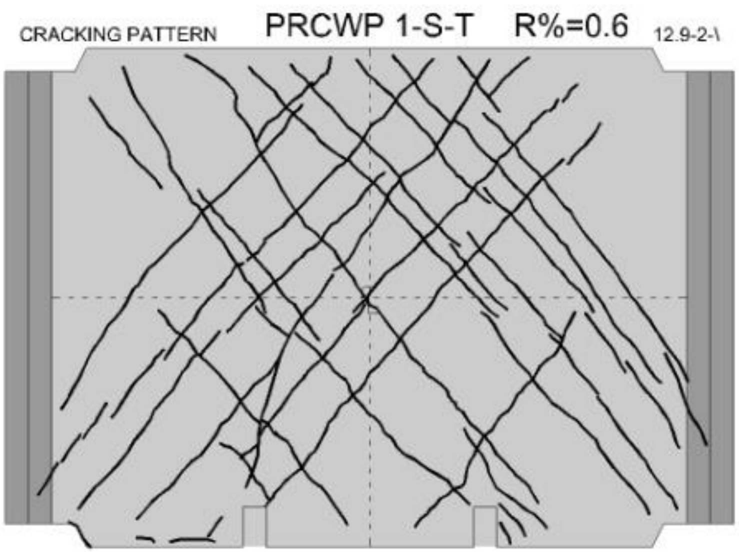


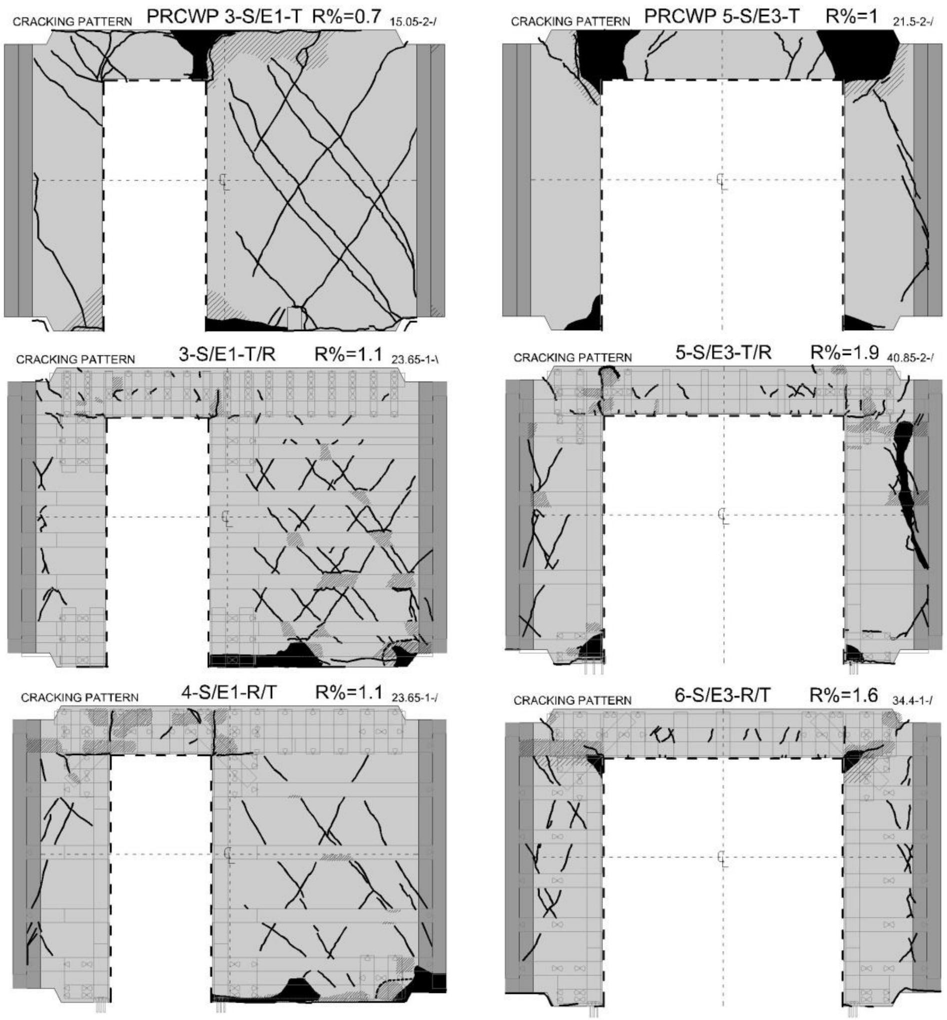
Qualitative analysis

Qualitative analysis

Qualitative analysis

Qualitative analysis





CONTENT

1. INTRODUCTION
2. EXPERIMENTAL PROGRAMME
3. EXPERIMENTAL ELEMENT
4. **TEST SET-UP**
5. **LOADING STRATEGY**
6. **INSTRUMENTATION**
7. **DAMAGE ASSESSMENT AND STRENGTHENING**
8. **EXPERIMENTAL RESULTS**
9. CONCLUSIONS

- DATA FILES
- ERROR/MISTAKE ANALYSIS
- PRIMARY DIAGRAMS
- ENVELOPE CURVES
- INTEGRATED/DERIVED DIAGRAMS

- INPUT CHANALS: 18÷29 (D = 10, V/N = 3, ε =16)
- CALCULATION CHANALS : (18÷29)+
- DATA LINES: 6000÷30000 (0.2÷1 LINES/SEC, ~8 HOURS/TEST)

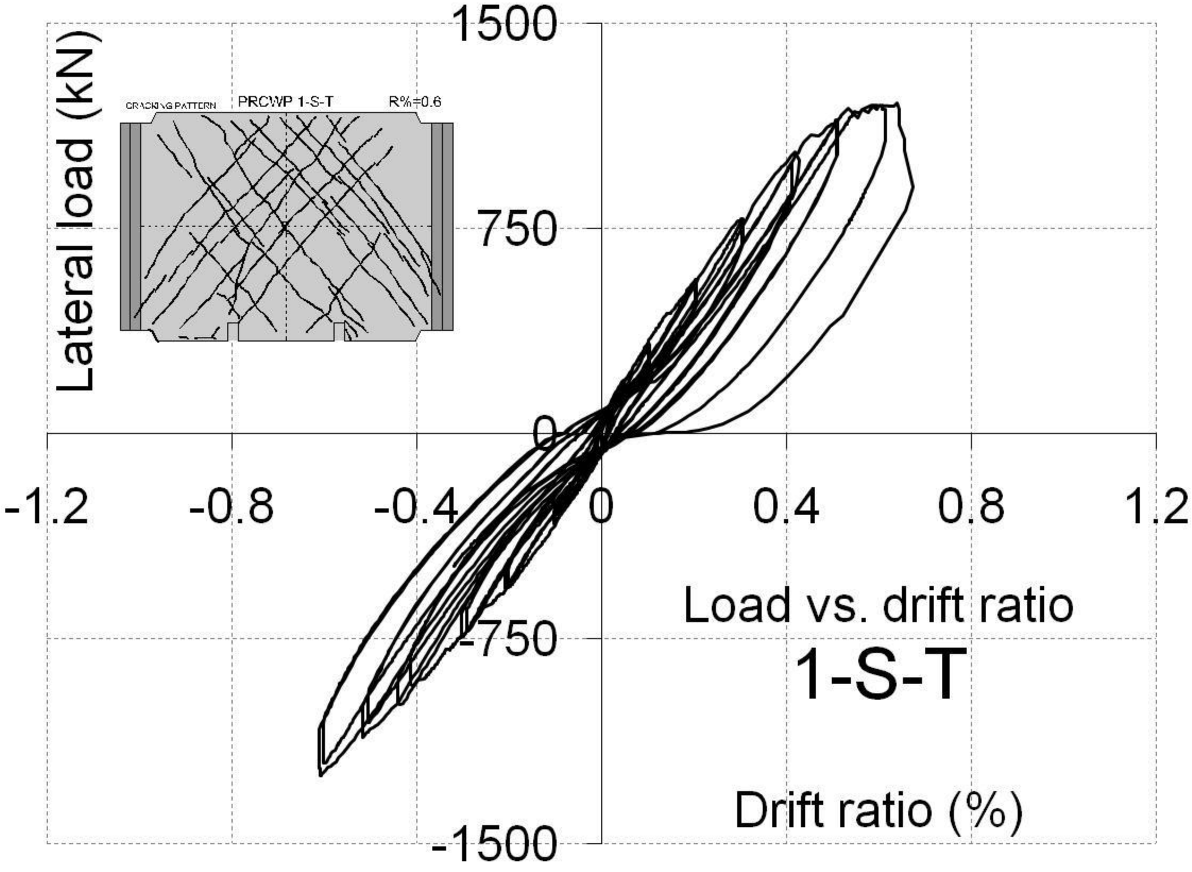
TOTAL DATA/TEST: 18000 (LINES) X 47 (COLUMS) = 846’000

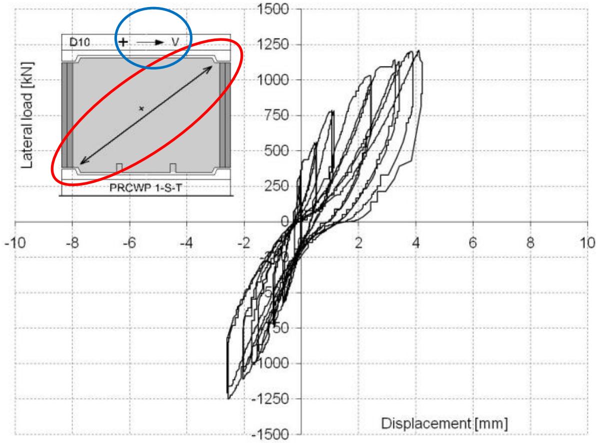
TOTAL DATA: 7 (TESTS) X 846000 ≅ **6’000’000**

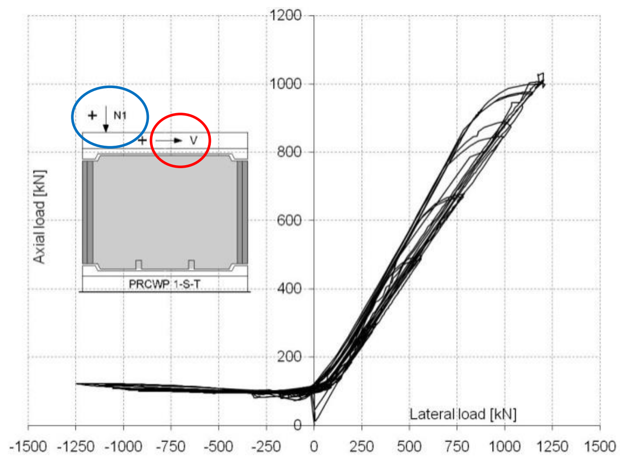
- LOAD - DISPLACEMENT
  - HORIZONTAL LOAD V (KN) VS HORIZONTAL DRIFT (MM OR %)
  - VERTICAL LOAD N1/2 (KN) VS VERTICAL DISPLACEMENT D8/7 (MM)
  - HORIZONTAL LOAD VS DISPLACEMENT (V-D)
  - VERTICAL LOAD VS DRIFT (N-DRIFT)

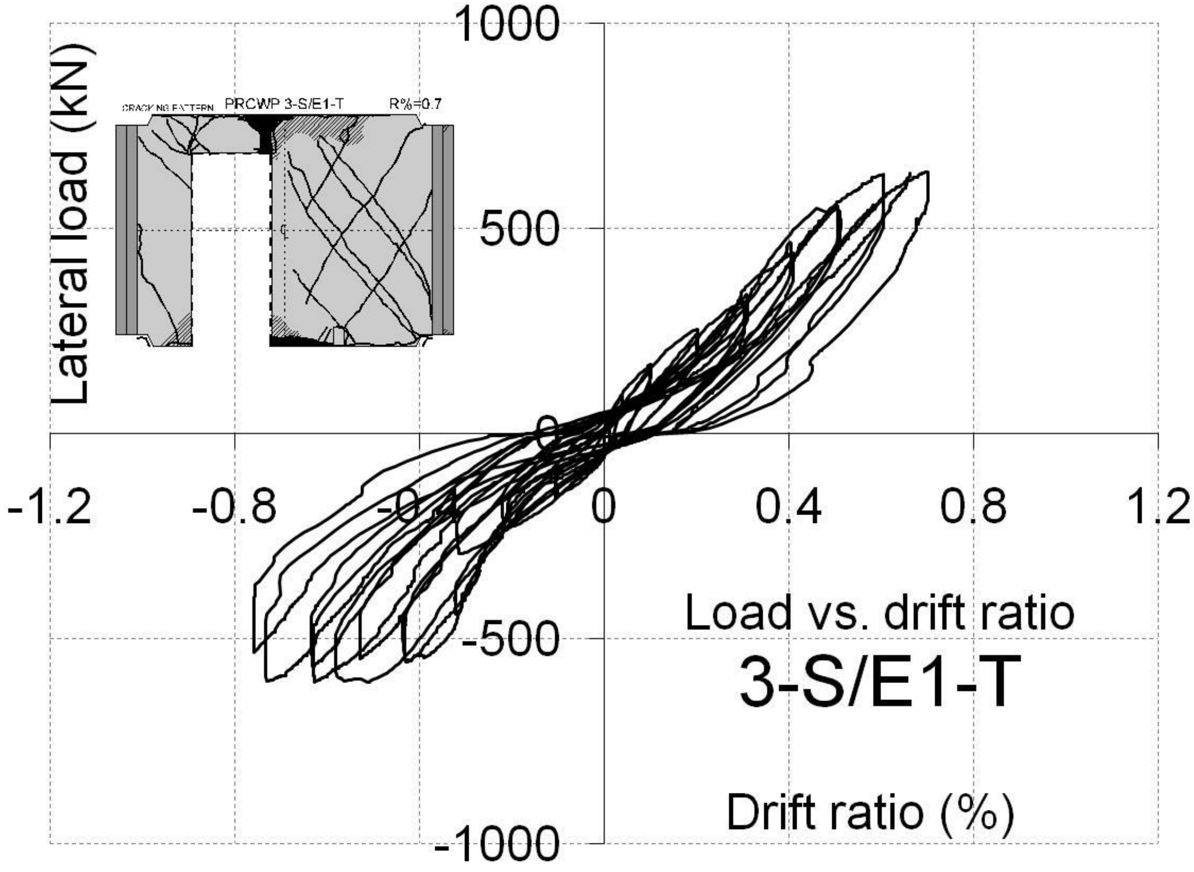
- LOAD - STRAIN (V-G%)
- LOAD - LOAD (N-V)
- STRAIN - DISPLACEMENT(G-DRIFT)

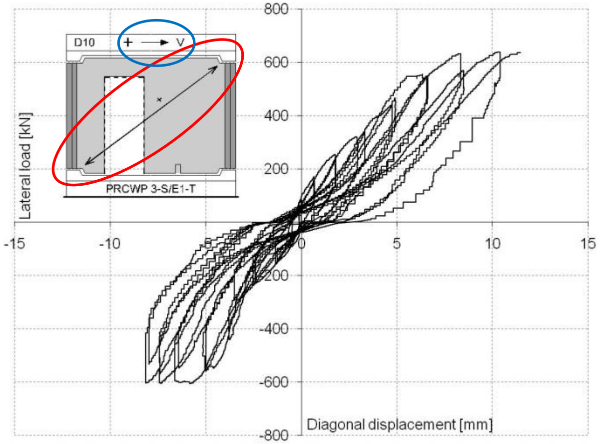
DIAGRAMS: 30/TEST, TOTAL: 7X30 = **210**

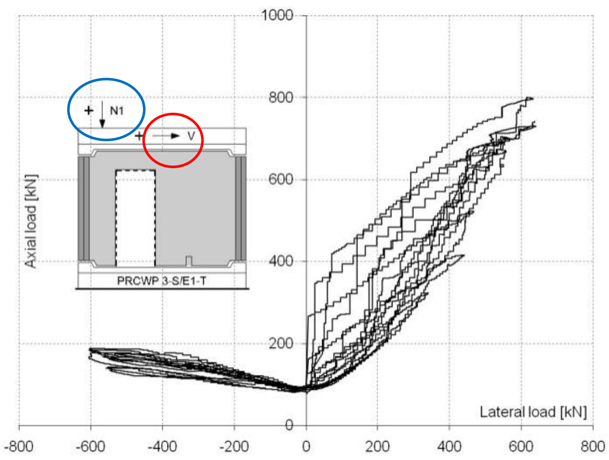

1500
750
0
-750
-1500
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
Lateral load (kN)
CRACKING PATTERN
PRCWP 1-S-T
R%=0.6
Load vs. drift ratio
1-S-T
Drift ratio (%)

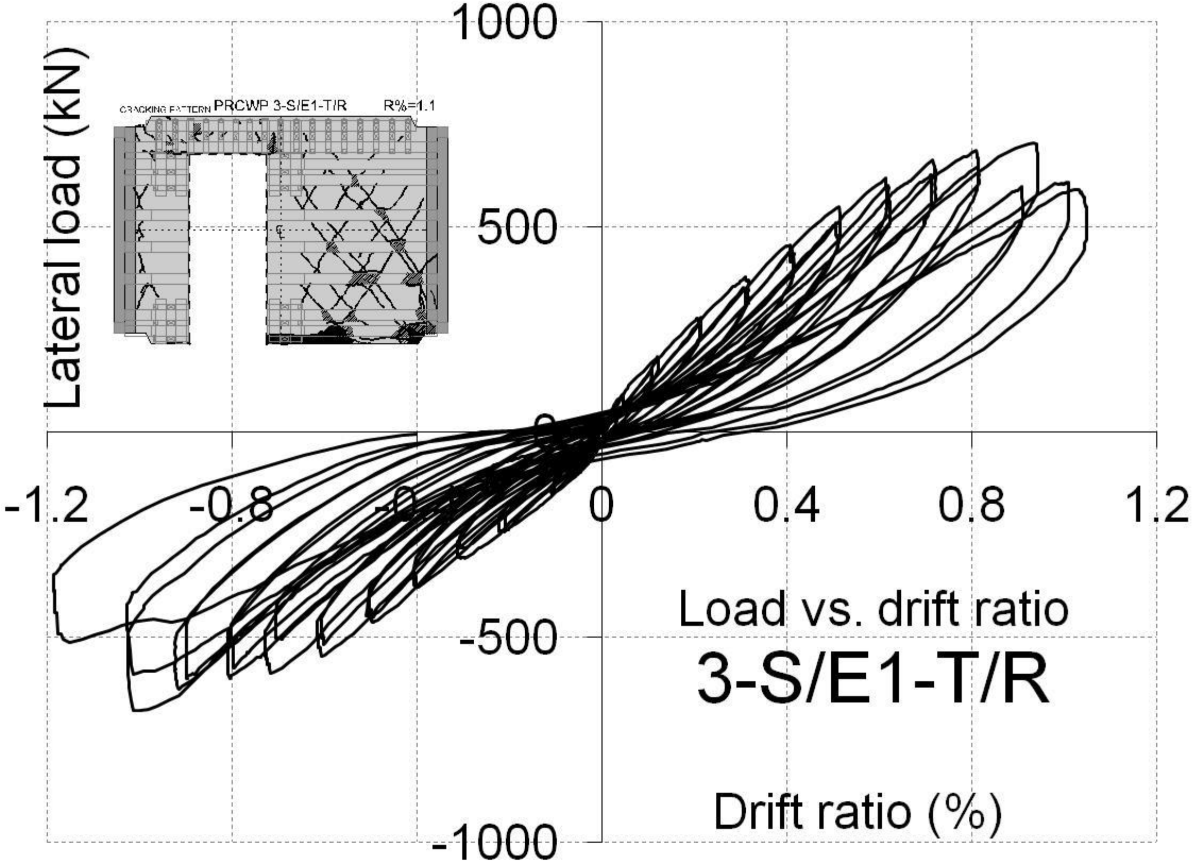

D10
V
PRCWP 1-S-T
Lateral load [kN]
Displacement [mm]

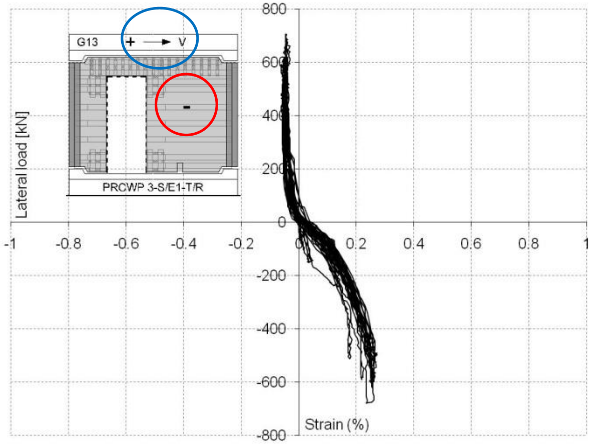

N1
V
PRCWP 1-S-T
Axial load [kN]
Lateral load [kN]

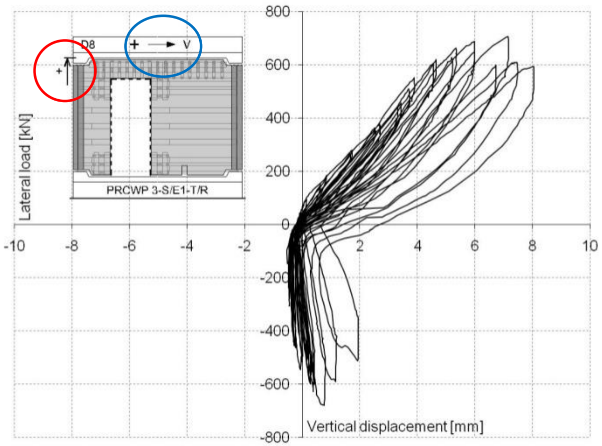

1000
500
-500
-1000
Lateral load (kN)
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
Drift ratio (%)
Load vs. drift ratio
3-S/E1-T
CRACKING PATTERN
PRCWP 3-S/E1-T
R%=0.7

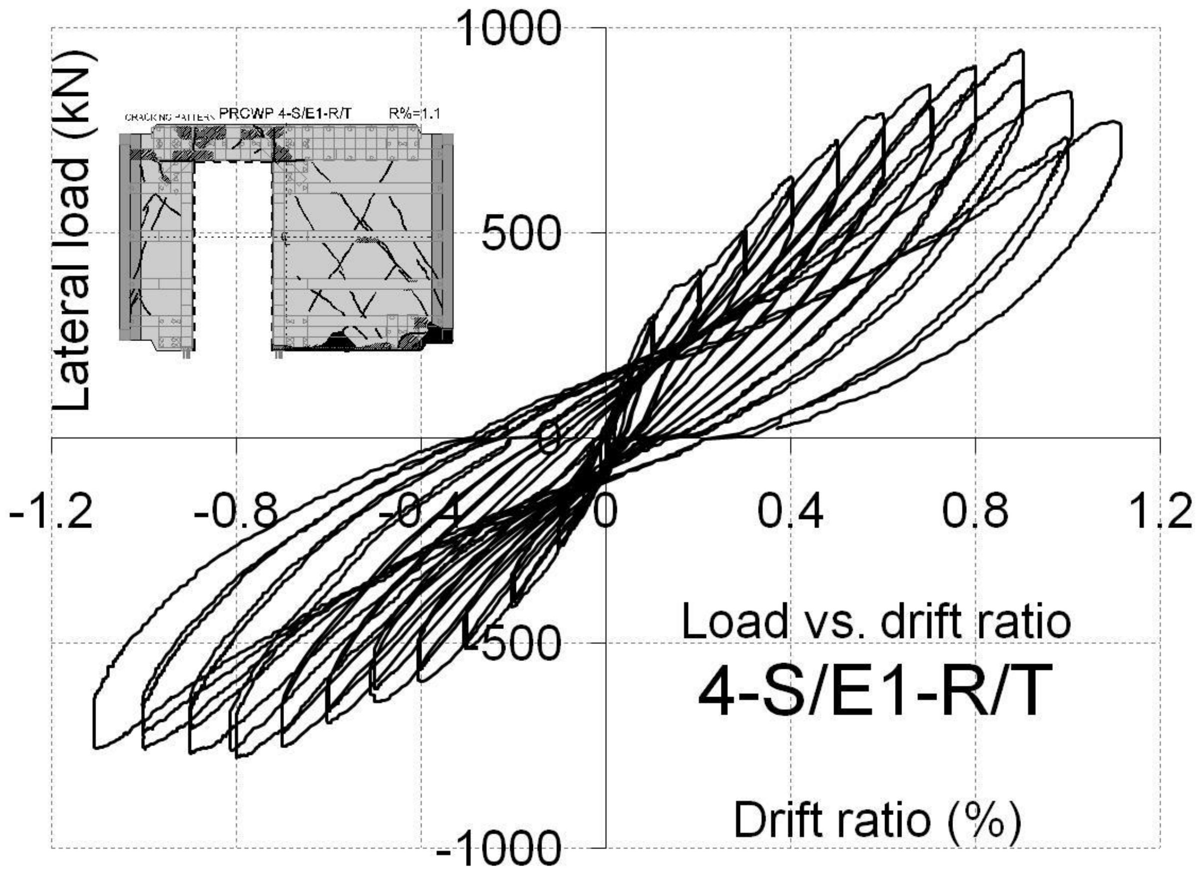

D10
V
PRCWP 3-S/E1-T
Lateral load [kN]
Diagonal displacement [mm]
800
600
400
200
-200
-400
-600
-800
-15
-10
0
5
10
15

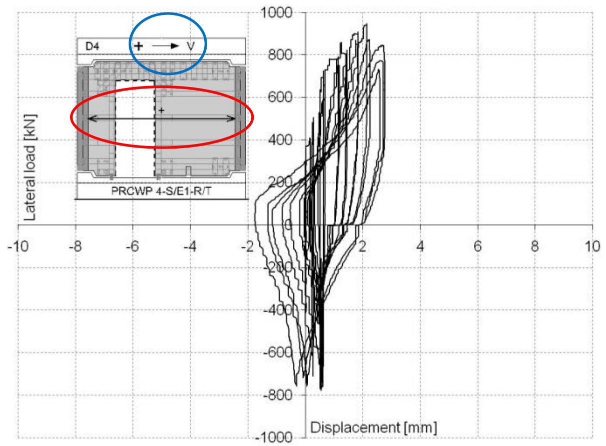

N1
V
PRCWP 3-S/E1-T
Axial load [kN]
Lateral load [kN]
1000
800
600
400
200
0
-800
-600
-400
-200
0
200
400
600
800

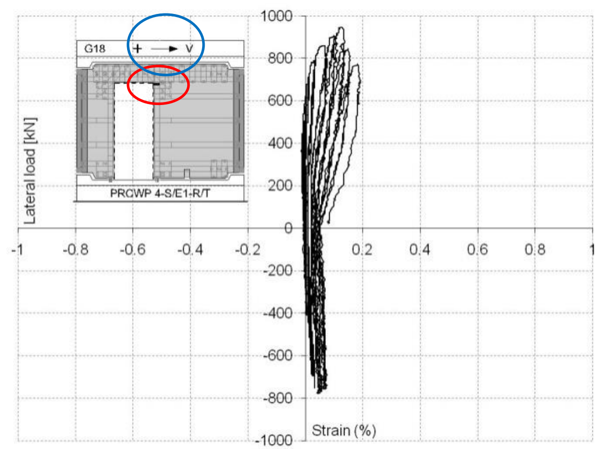

Lateral load (kN)
CRACKING PATTERN PRCWP 3-S/E1-T/R R%=1.1
1000
500
-500
-1000
-1.2
-0.8
0
0.4
0.8
1.2
Load vs. drift ratio
3-S/E1-T/R
Drift ratio (%)

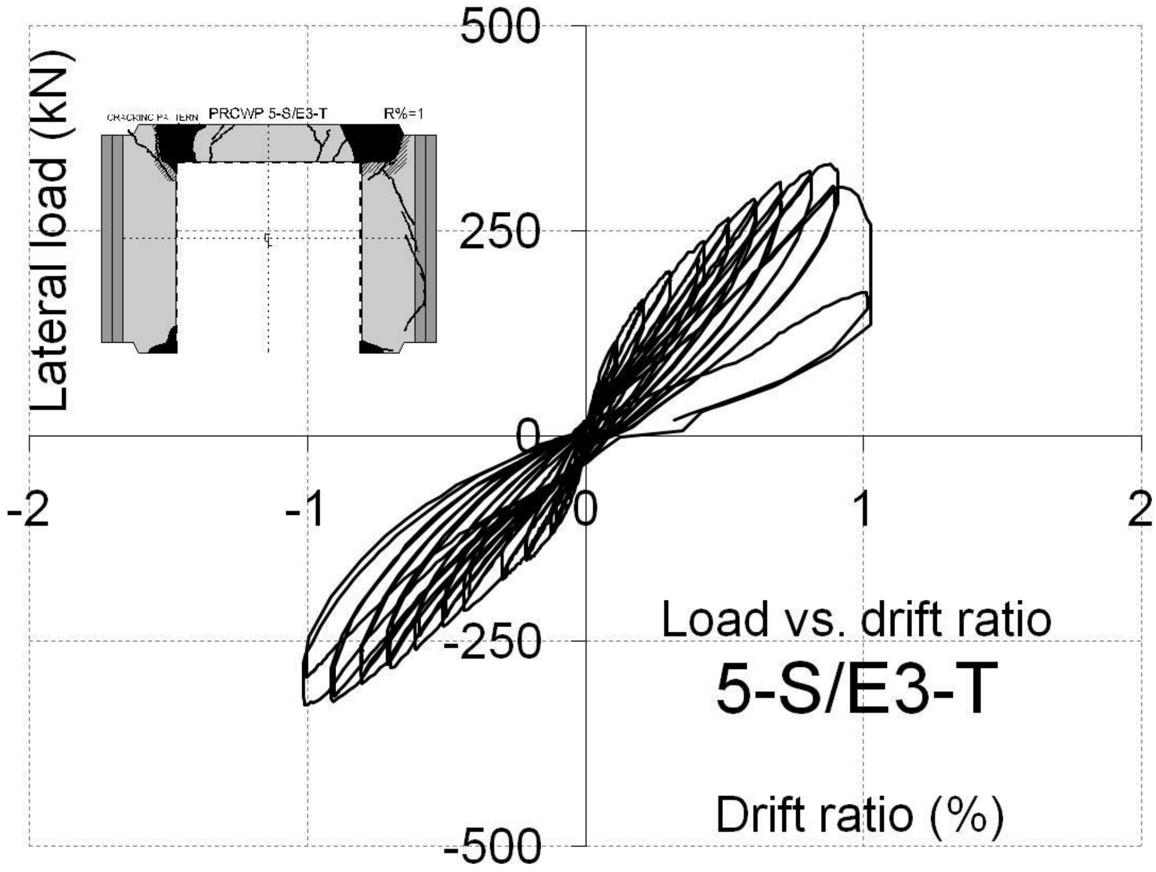

G13
+ → V
-
PRCWP 3-S/E1-T/R
Lateral load [kN]
Strain (%)

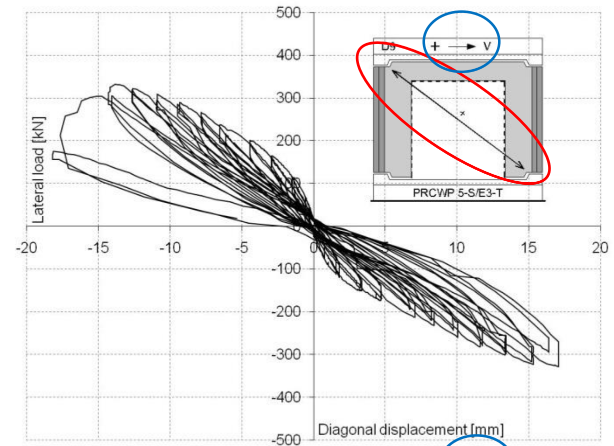

D8
+ → V
PRCWP 3-S/E1-T/R
Lateral load [kN]
Vertical displacement [mm]

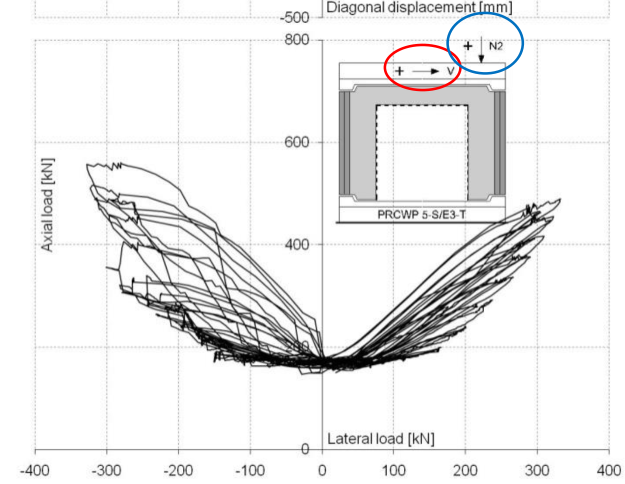

1000
500
-500
-1000
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
Lateral load (kN)
PRCWP 4-S/E1-R/T
R%=1.1
Load vs. drift ratio
4-S/E1-R/T
Drift ratio (%)

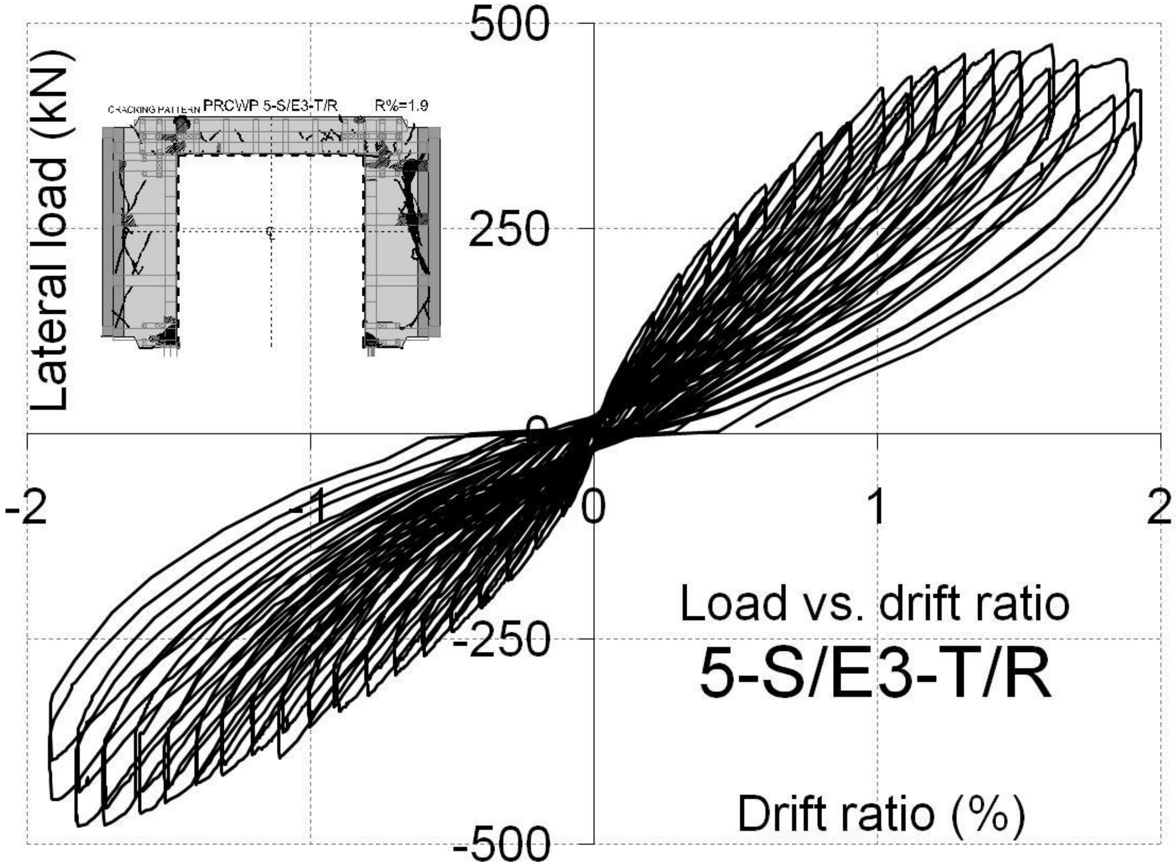

D4
+ V
PRCWP 4-S/E1-R/T
Lateral load [kN]
Displacement [mm]


G18
+ V
PRCWP 4-S/E1-R/T
Lateral load [kN]
Strain (%)

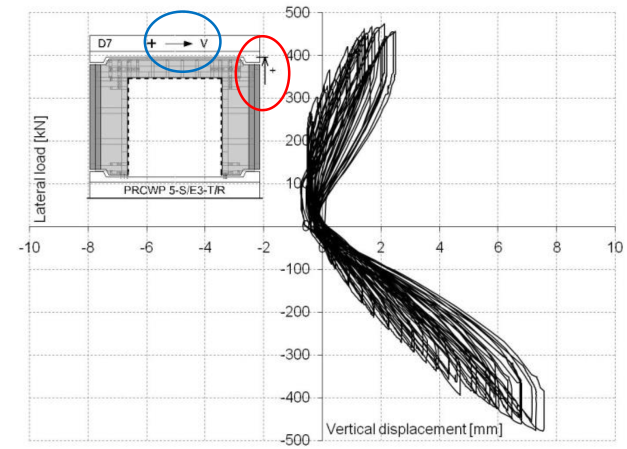

500
250
0
-250
-500
-2
-1
0
1
2
Lateral load (kN)
CRACKING PATTERN
PRCWP 5-S/E3-T
R%=1
Load vs. drift ratio
5-S/E3-T
Drift ratio (%)


500
400
300
200
-100
-200
-300
-400
-500
-20
-15
-10
-5
0
10
15
20
Lateral load [kN]
Diagonal displacement [mm]
+ V
PRCWP 5-S/E3-T

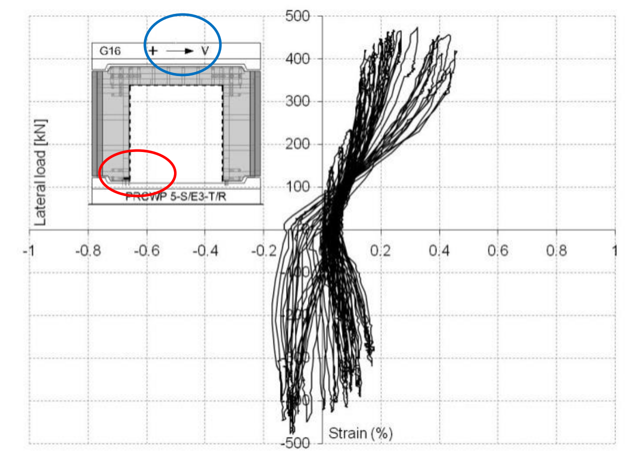

800
600
400
0
-400
-300
-200
-100
0
100
200
300
400
Axial load [kN]
Lateral load [kN]
+ V
+ N2
PRCWP 5-S/E3-T



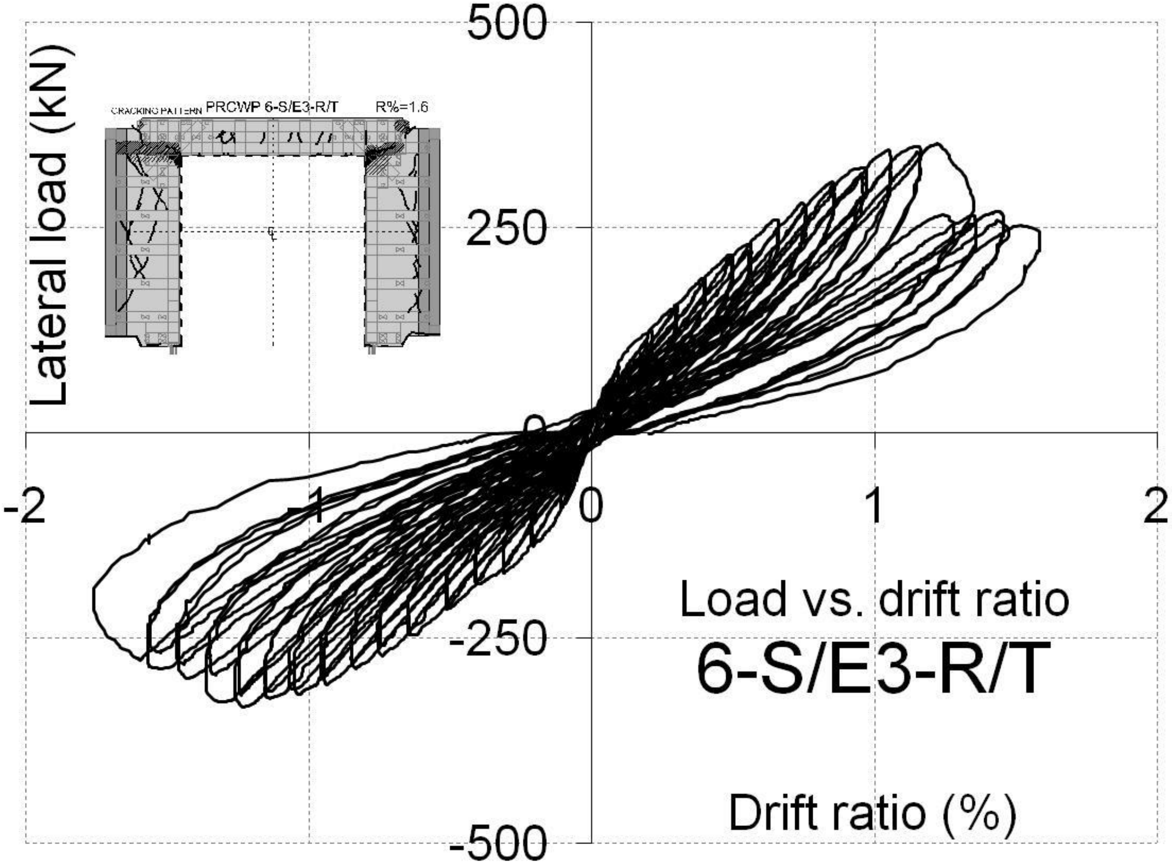
500
250
0
-250
-500
-2
-1
0
1
2
Lateral load (kN)
CRACKING PATTERN PRCWP 5-S/E3-T/R R%=1.9
Load vs. drift ratio
5-S/E3-T/R
Drift ratio (%)

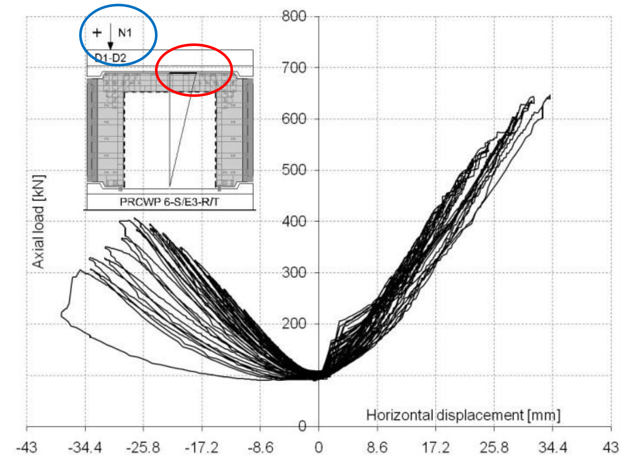


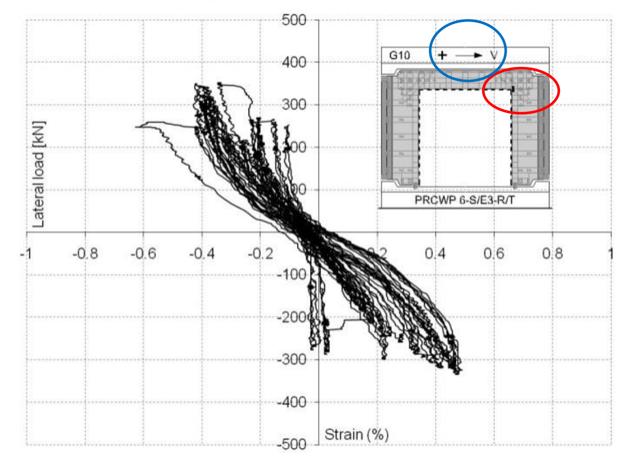
D7
+ V
PRCWP 5-S/E3-T/R
Lateral load [kN]
Vertical displacement [mm]



G16
+ V
PRCWP 5-S/E3-T/R
Lateral load [kN]
Strain (%)

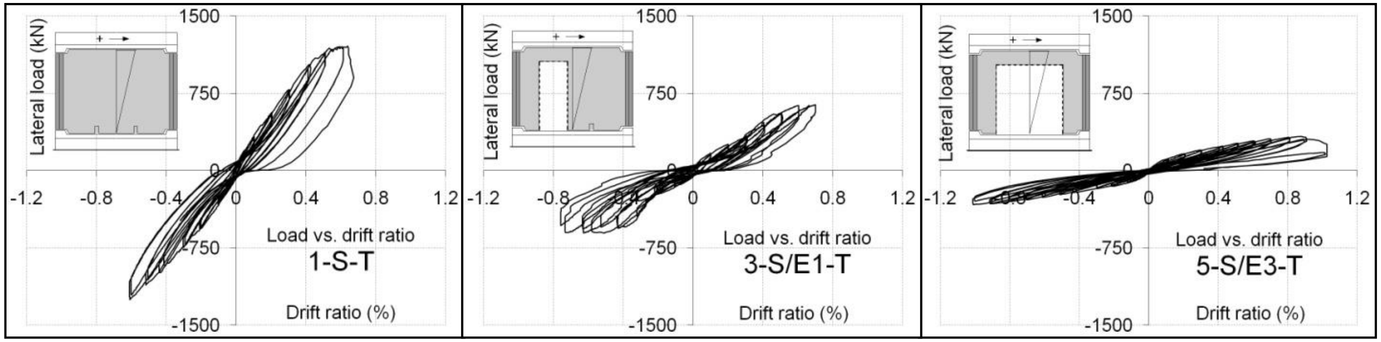

Lateral load (kN)
500
250
0
-250
-500
-2
-1
0
1
2
CRACKING PATTERN PRCWP 6-S/E3-R/T
R%=1.6
Load vs. drift ratio
6-S/E3-R/T
Drift ratio (%)


+ N1
D1-D2
PRCWP 6-S/E3-R/T
Axial load [kN]
800
700
600
500
400
300
200
0
Horizontal displacement [mm]
-43
-34.4
-25.8
-17.2
-8.6
0
8.6
17.2
25.8
34.4
43


G10
+ V
PRCWP 6-S/E3-R/T
Lateral load [kN]
500
400
300
-100
-200
-300
-400
-500
-1
-0.8
-0.6
-0.4
-0.2
0.4
0.6
0.8
1
Strain (%)

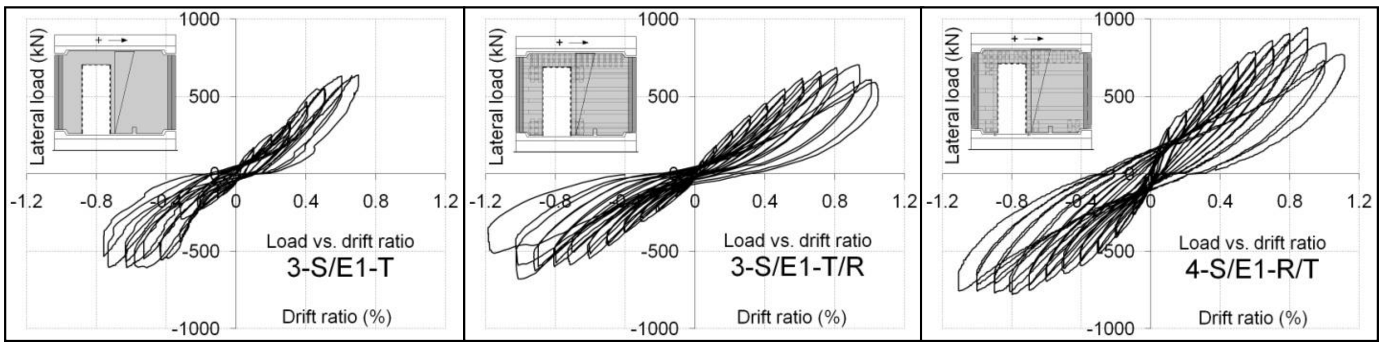
EXPERIMENTAL RESULTS

Comparison of the diagrams

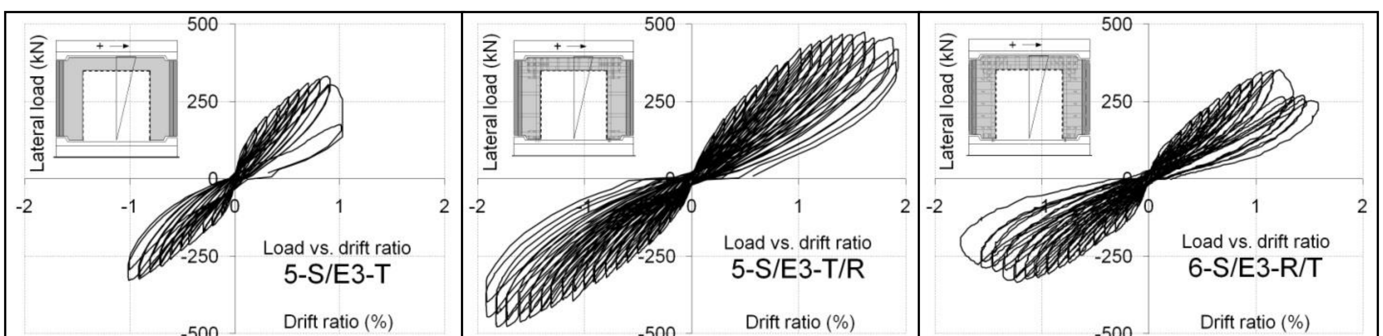


Comparison line

Weakening effect of doorway cut-out

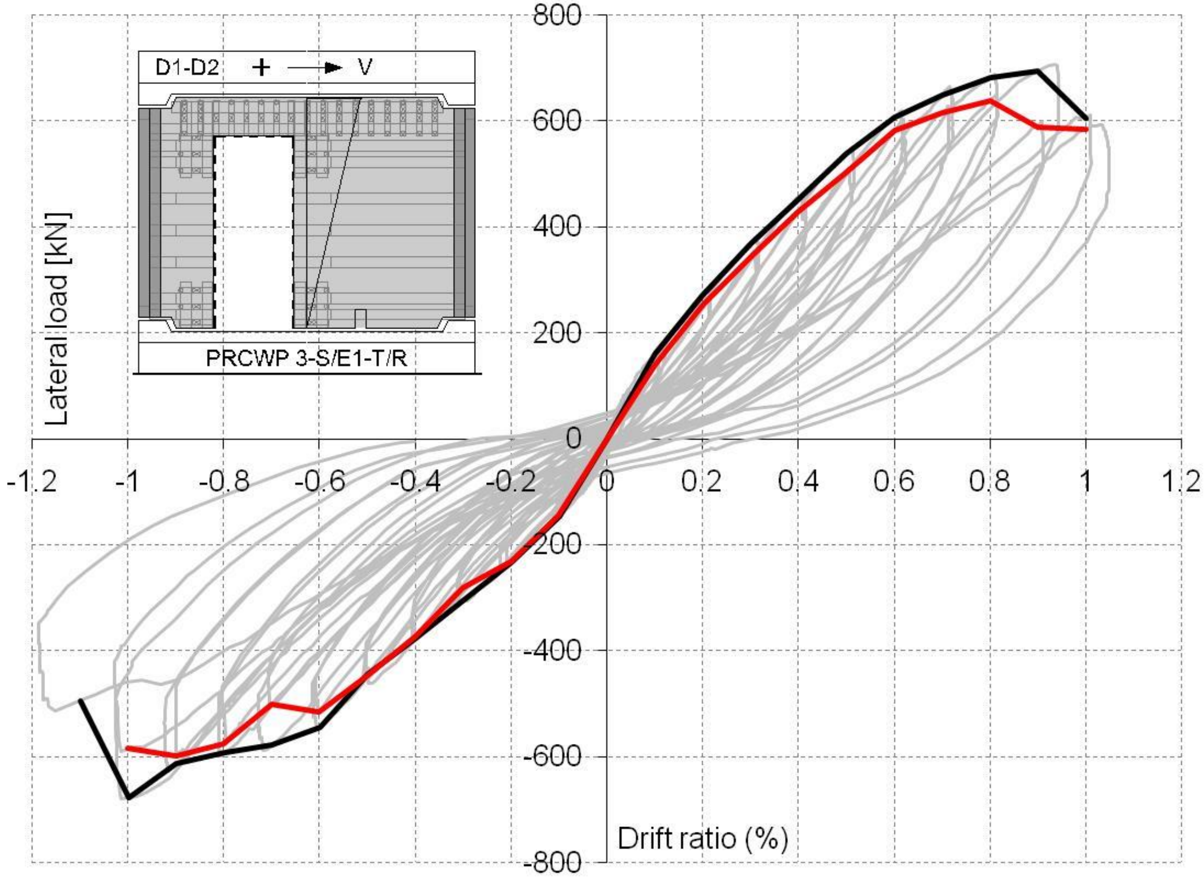


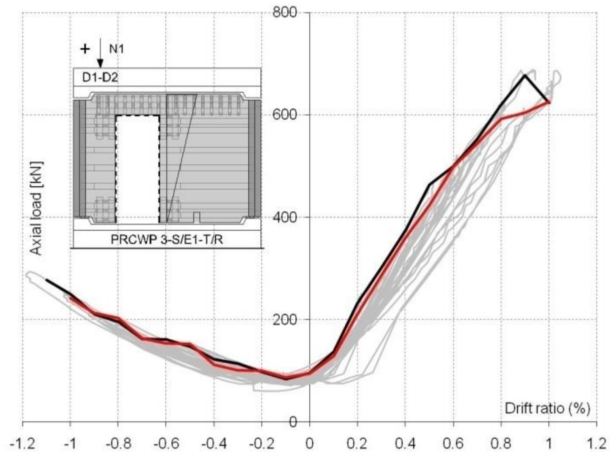
Strengthening effect of CFRP-EBR (a)

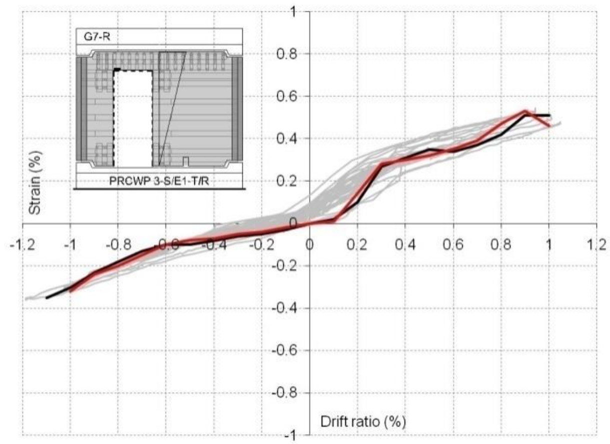


Strengthening effect of CFRP-EBR (b)

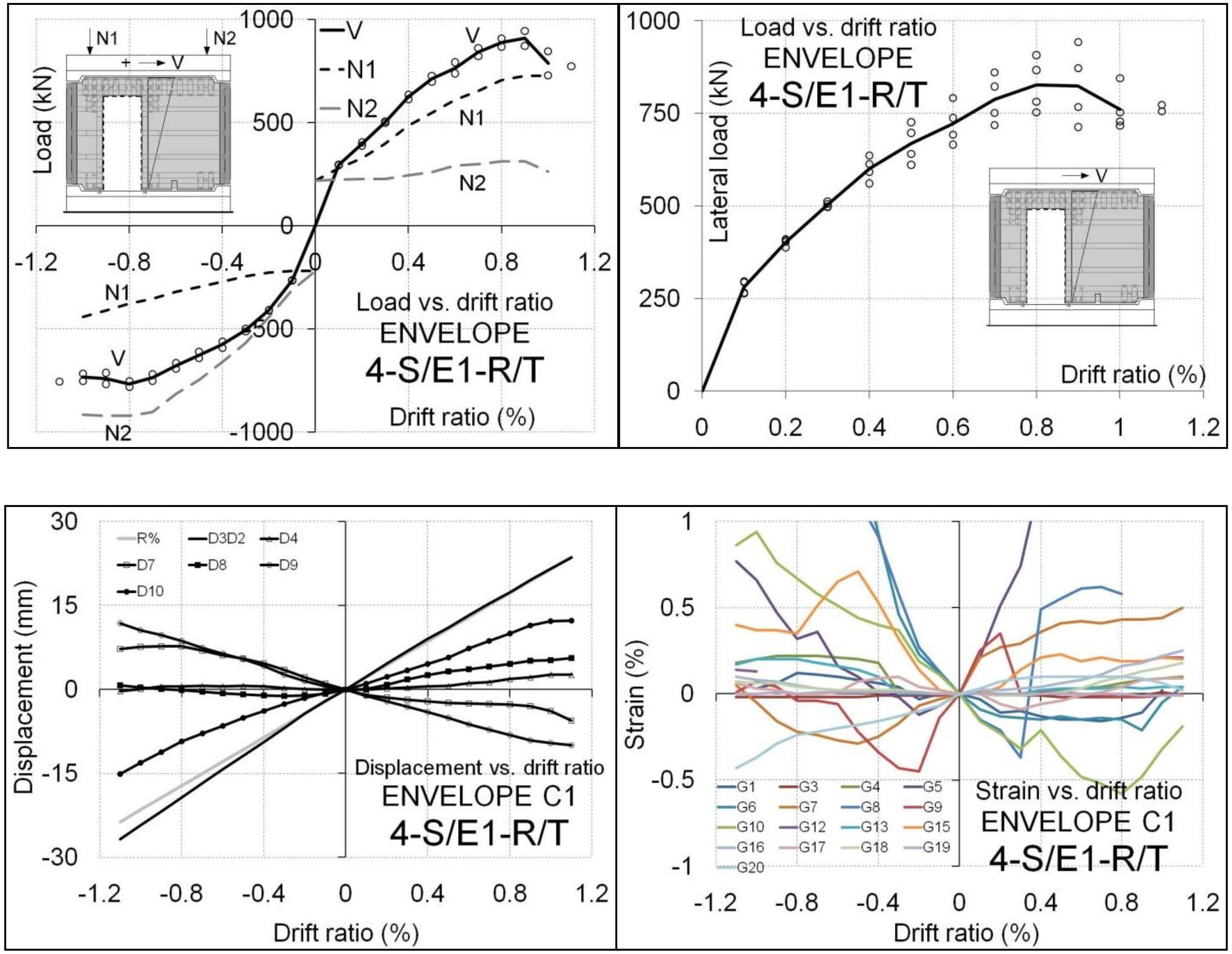
- DRAWING PROCESS
  - FILTERING TARGET DRIFT LINES (CICLE 1 AND CICLE 2)
  - CALCULATION (INTERPRETATION) OF N / D / ε AT THE TARGET DRIFT
  - CALCULATION AVERAGES OF C1/2 AND M FOR V/N - DRIFT
- DATA
  - ENVELOPE: 7(TAB) x 40(LINE) x 30(COL) = **8 400**
  - ENVELOPE AVERAGE (C12/M): 7(TAB) X 22/11(LINE) x 5(COL) = **770/385**


D1-D2
+ V
PRCWP 3-S/E1-T/R
Lateral load [kN]
Drift ratio (%)


+ N1
D1-D2
PRCWP 3-S/E1-T/R
Axial load [kN]
Drift ratio (%)


G7-R
PRCWP 3-S/E1-T/R
Strain (%)
Drift ratio (%)

EXPERIMENTAL RESULTS *Envelope curves*



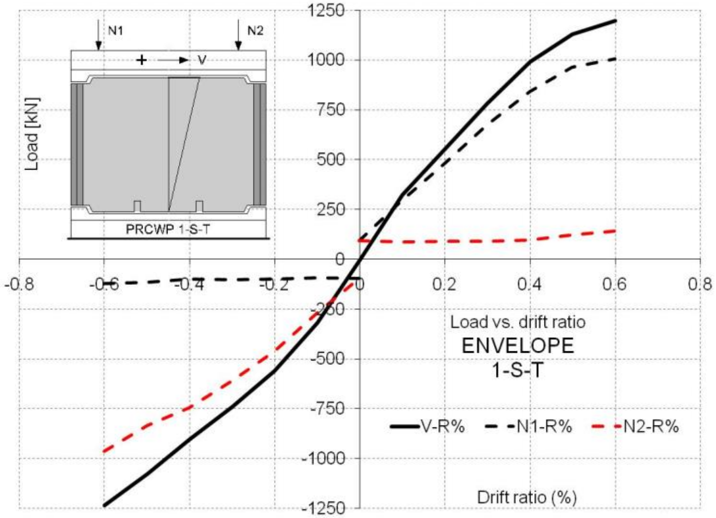
<u>Load envelopes</u>

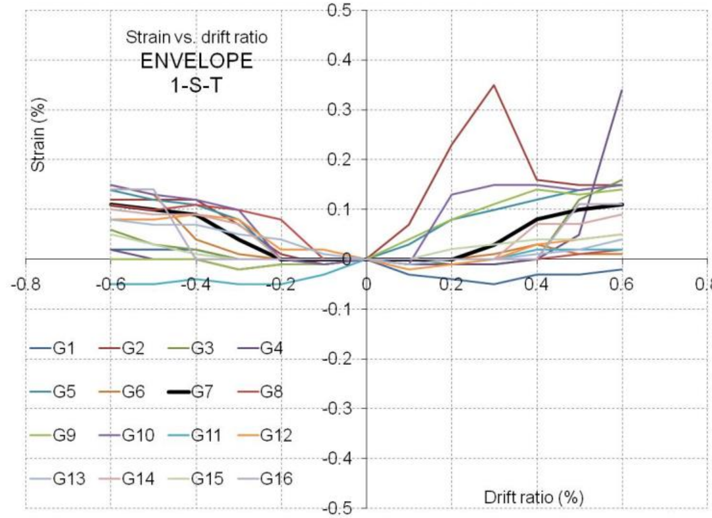
Cyclic: C1, C2, C (mean)
Monotonic: M, calculated only for lateral load

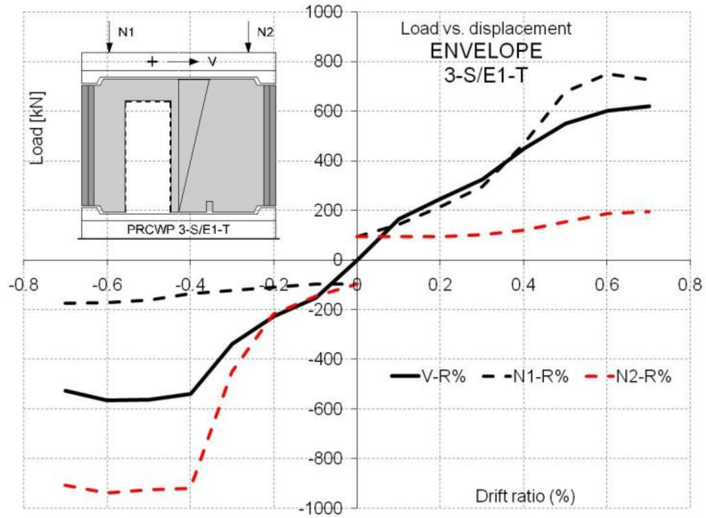
<u>Displacement envelopes</u>
Cyclic: C1, C2

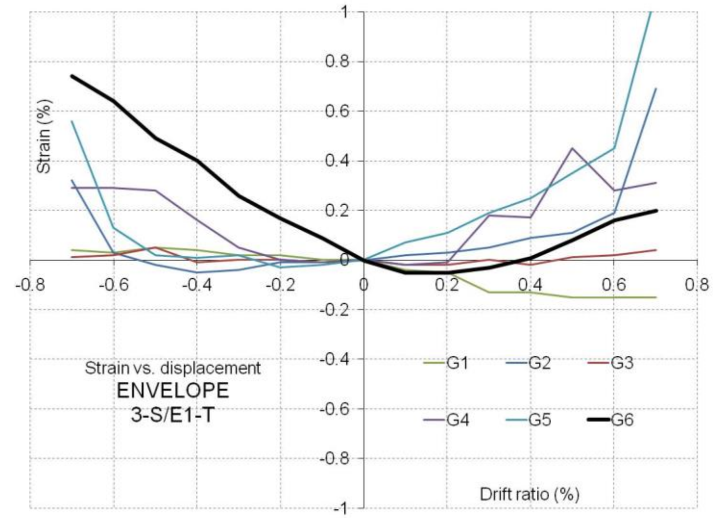
<u>Strain envelopes</u>
Cyclic: C1, C2

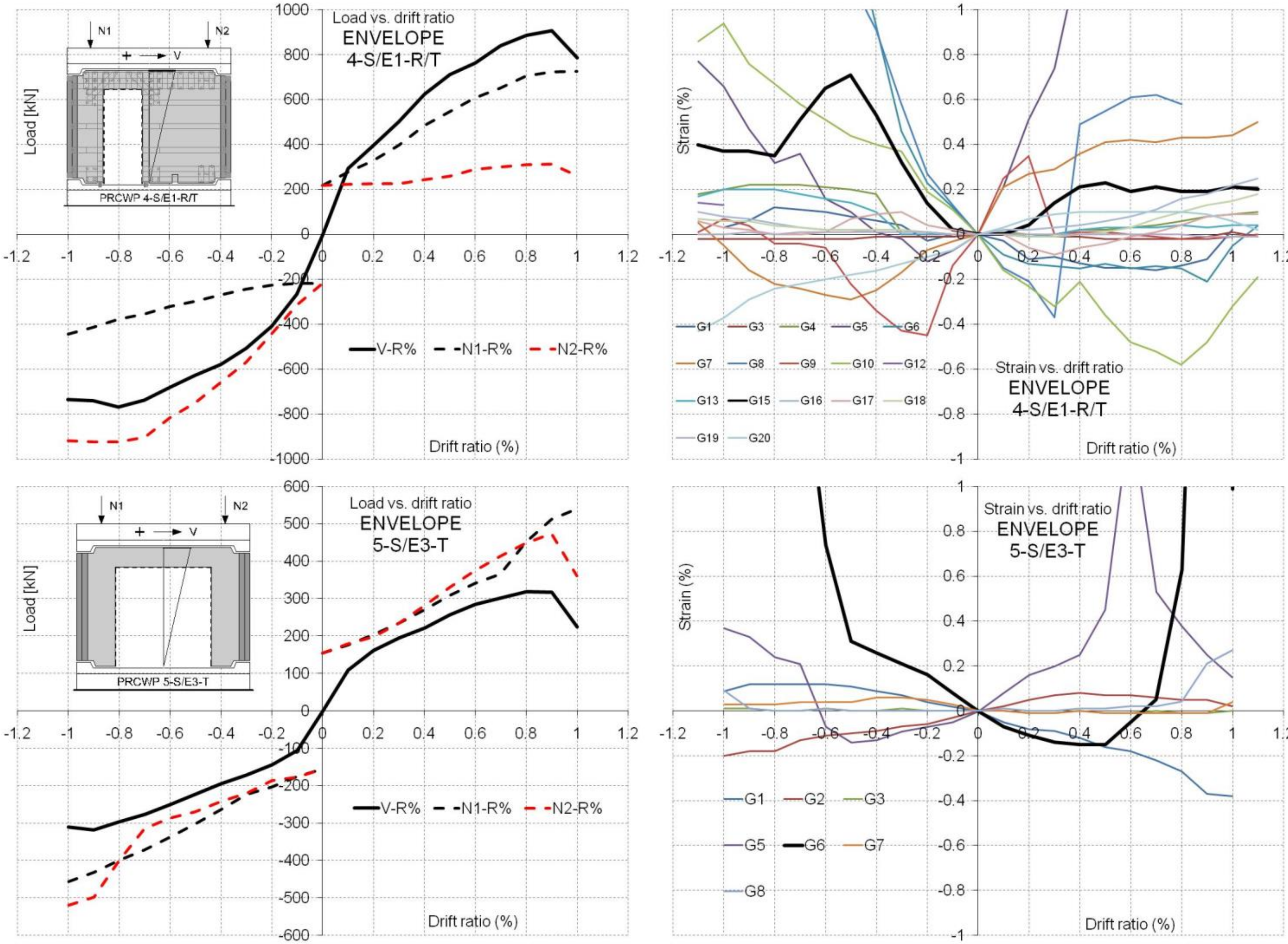
Envelope curves



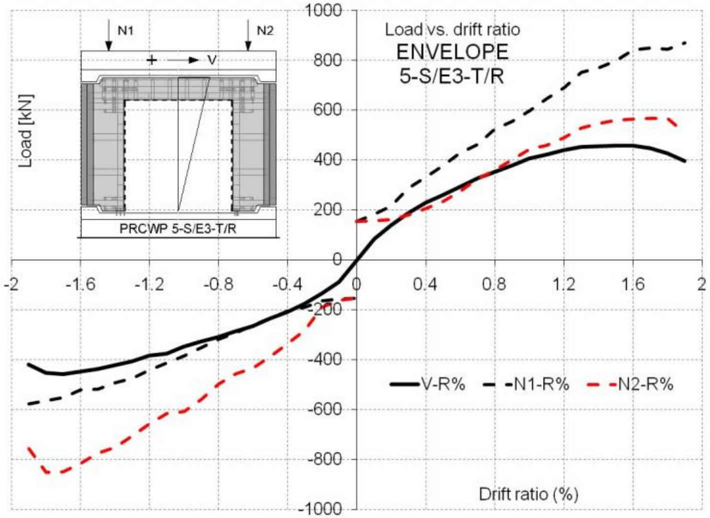


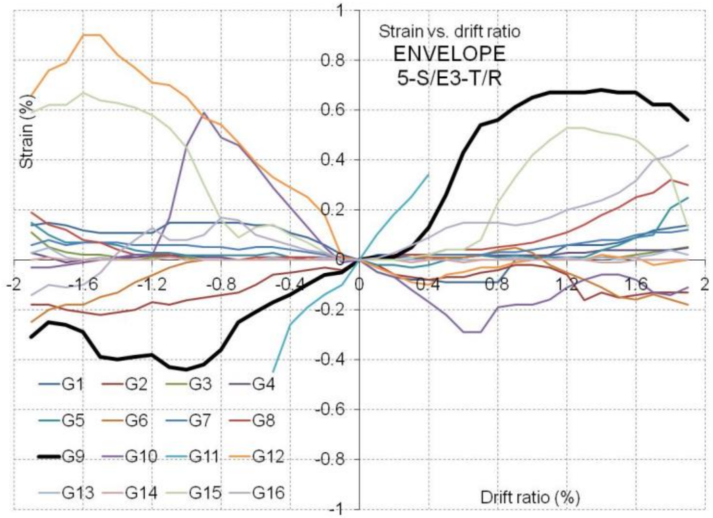


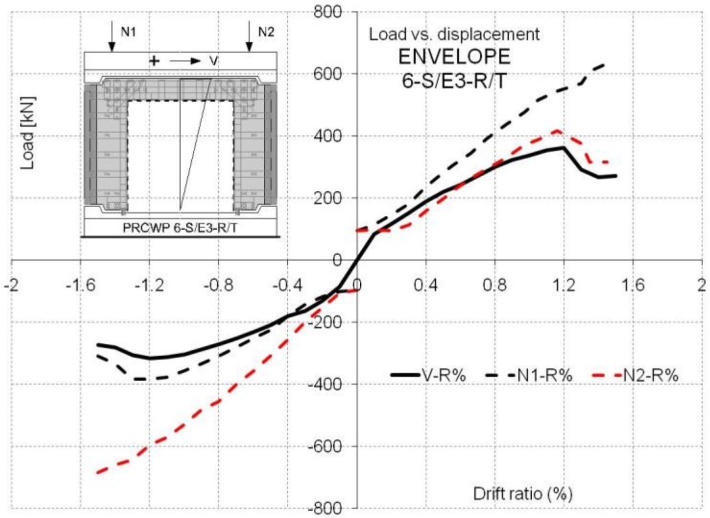


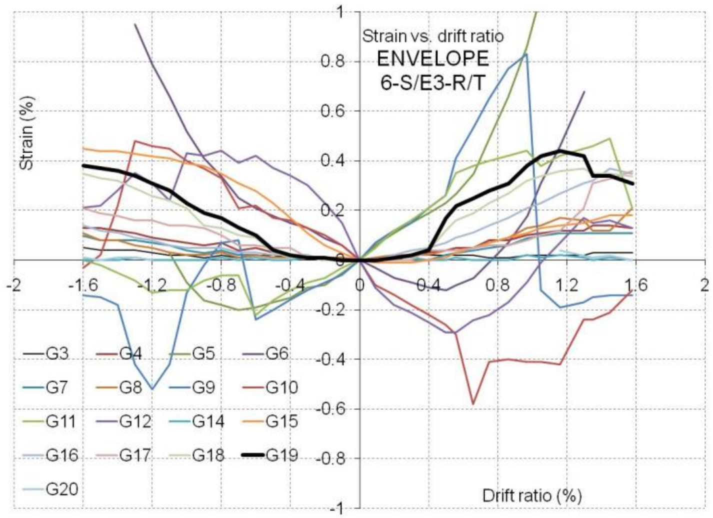


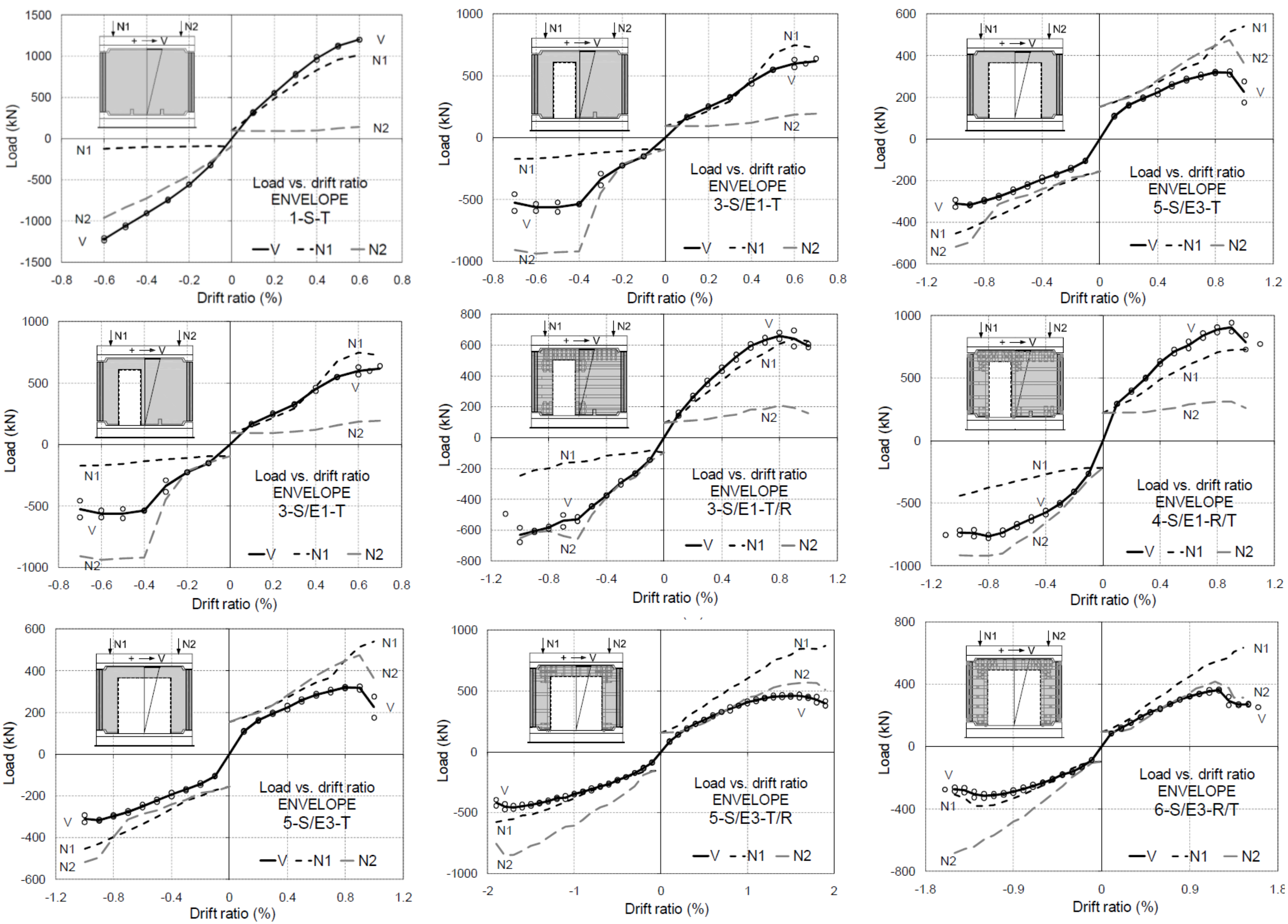
Load vs. drift ratio
ENVELOPE
4-S/E1-R/T
PRCWP 4-S/E1-R/T
N1
N2
V
Load [kN]
Drift ratio (%)
V-R%
N1-R%
N2-R%
Strain (%)
Strain vs. drift ratio
ENVELOPE
4-S/E1-R/T
G1
G3
G4
G5
G6
G7
G8
G9
G10
G12
G13
G15
G16
G17
G18
G19
G20
Load vs. drift ratio
ENVELOPE
5-S/E3-T
PRCWP 5-S/E3-T
Strain vs. drift ratio
ENVELOPE
5-S/E3-T
G2

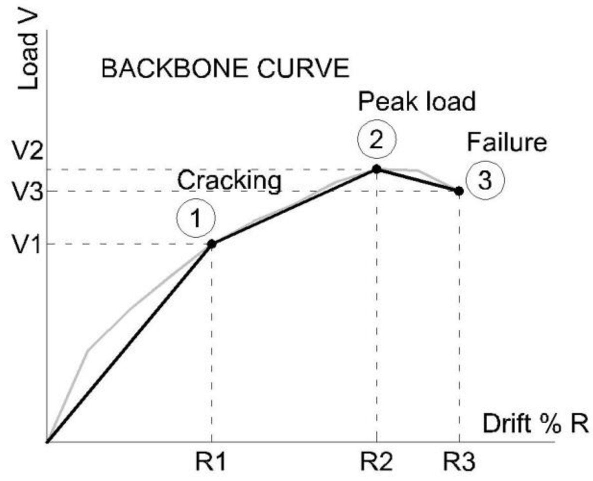

Load vs. drift ratio
ENVELOPE
5-S/E3-T/R
Load [kN]
Drift ratio (%)
V-R%
N1-R%
N2-R%
N1
N2
V
PRCWP 5-S/E3-T/R

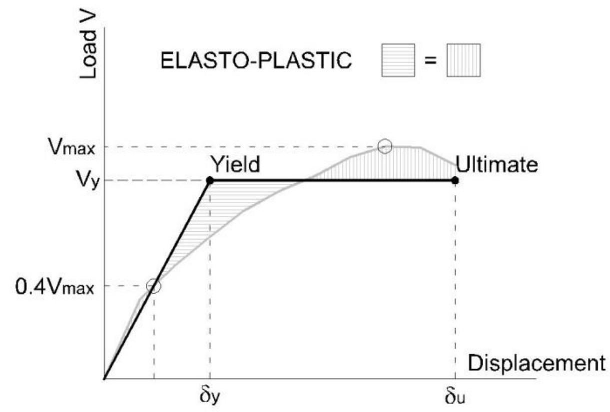

Strain vs. drift ratio
ENVELOPE
5-S/E3-T/R
Strain (%)
Drift ratio (%)
G1 G2 G3 G4
G5 G6 G7 G8
G9 G10 G11 G12
G13 G14 G15 G16


Load vs. displacement
ENVELOPE
6-S/E3-R/T
Load [kN]
Drift ratio (%)
V-R%
N1-R%
N2-R%
N1
N2
V
PRCWP 6-S/E3-R/T


Strain vs. drift ratio
ENVELOPE
6-S/E3-R/T
Strain (%)
Drift ratio (%)
G3 G4 G5 G6
G7 G8 G9 G10
G11 G12 G14 G15
G16 G17 G18 G19
G20

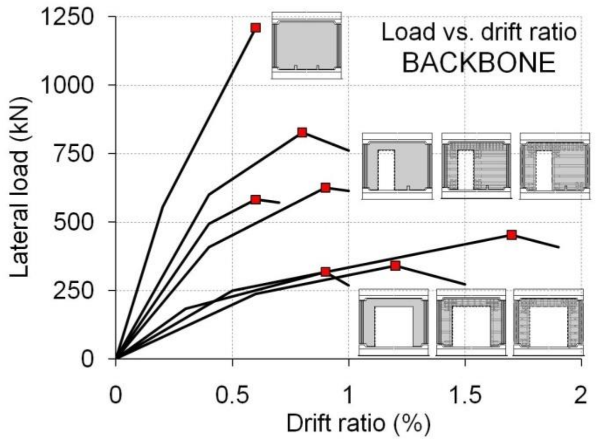

Load vs. drift ratio
ENVELOPE
1-S-T
Load vs. drift ratio
ENVELOPE
3-S/E1-T
Load vs. drift ratio
ENVELOPE
5-S/E3-T
Load vs. drift ratio
ENVELOPE
3-S/E1-T
Load vs. drift ratio
ENVELOPE
3-S/E1-T/R
Load vs. drift ratio
ENVELOPE
4-S/E1-R/T
Load vs. drift ratio
ENVELOPE
5-S/E3-T
Load vs. drift ratio
ENVELOPE
5-S/E3-T/R
Load vs. drift ratio
ENVELOPE
6-S/E3-R/T
Load (kN)
Drift ratio (%)
V
N1
N2

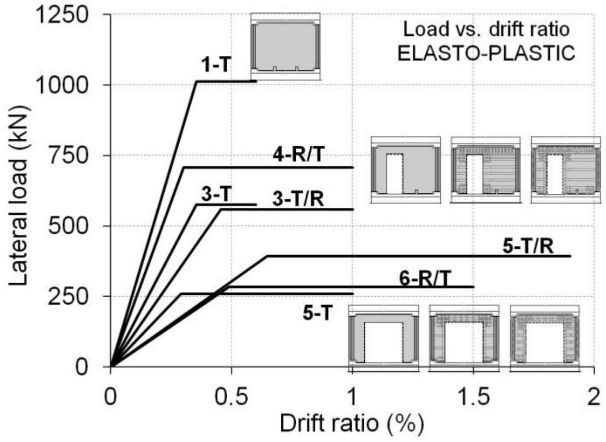




Backbone

Tri-linear
Point 1 (V1, R1): cracking
Point 2 (V2, R2): peak load
Point 3 (V3, R3): failure

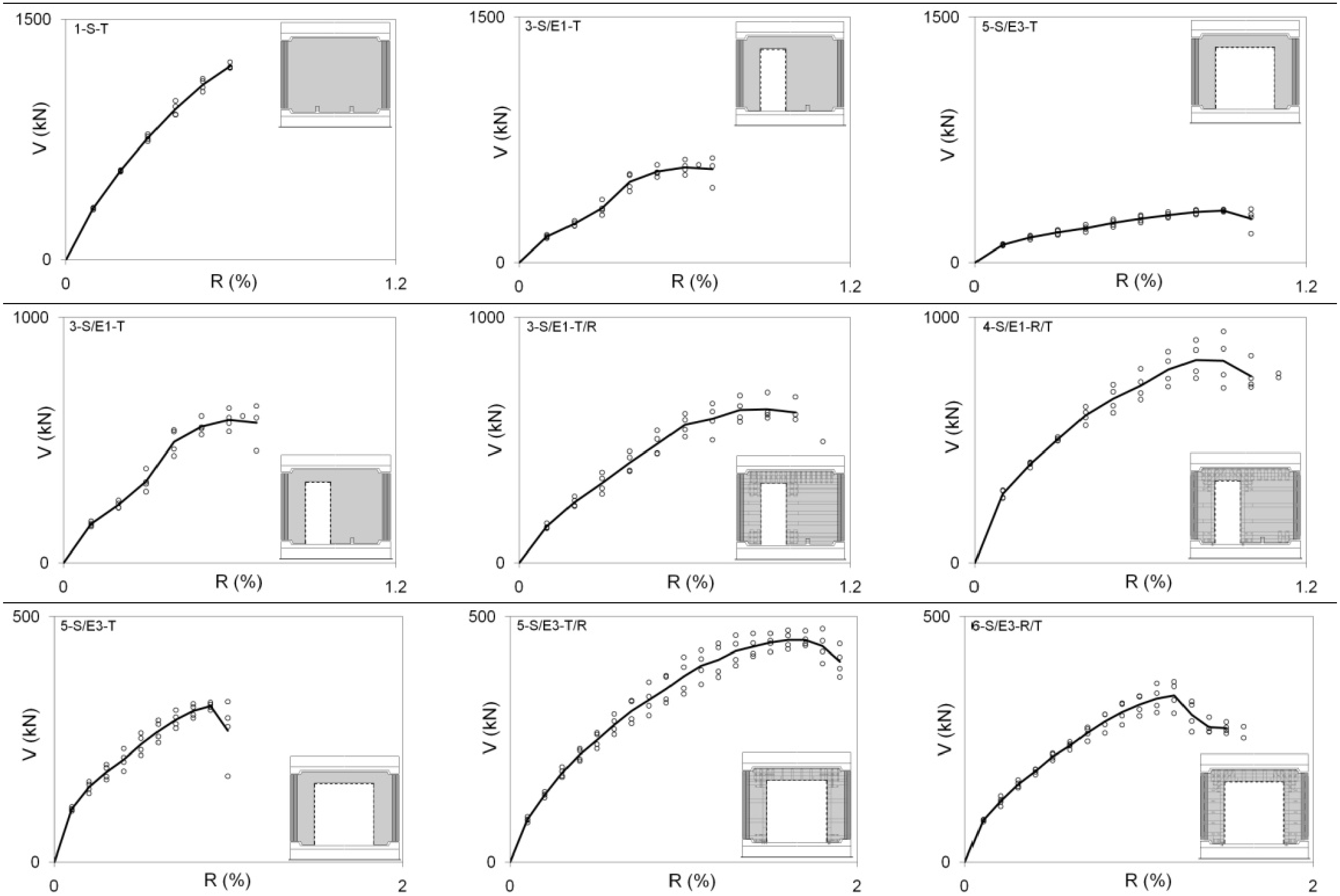


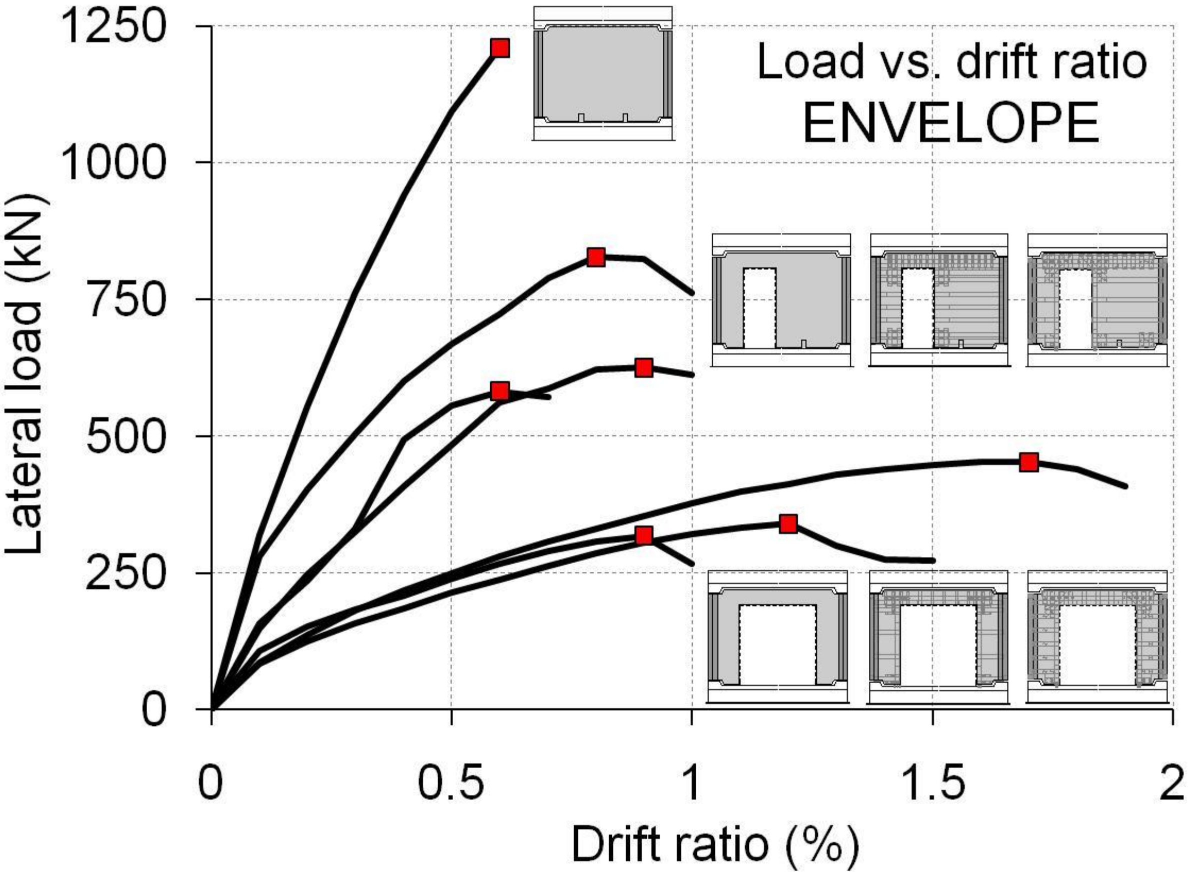


Elasto-plastic

Bi-linear
Point 1: yield
Point 2: ultimate

Equivalent envelope curves - Monotone





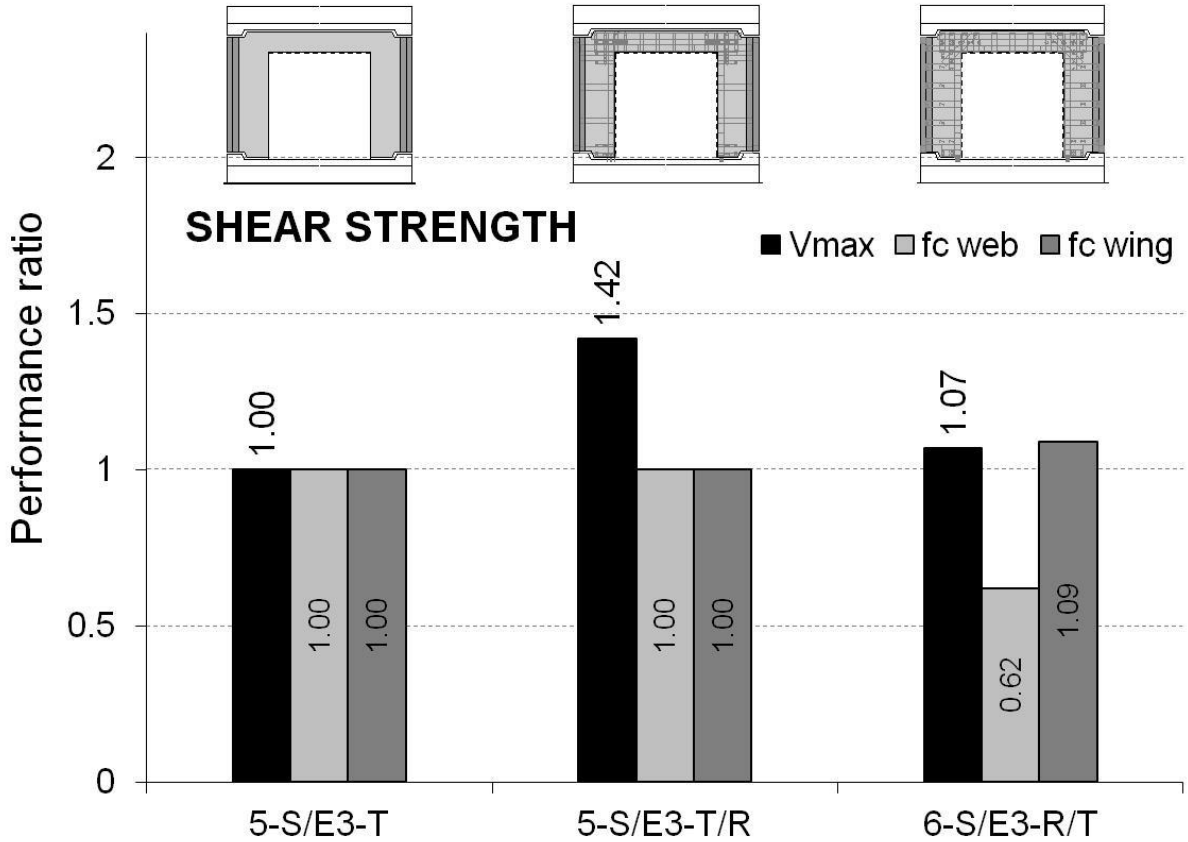
Three curve-clusters according to the cut-out condition

Strength

Stiffness

Drift at peak and failure

SHEAR STRENGTH COMPARISON

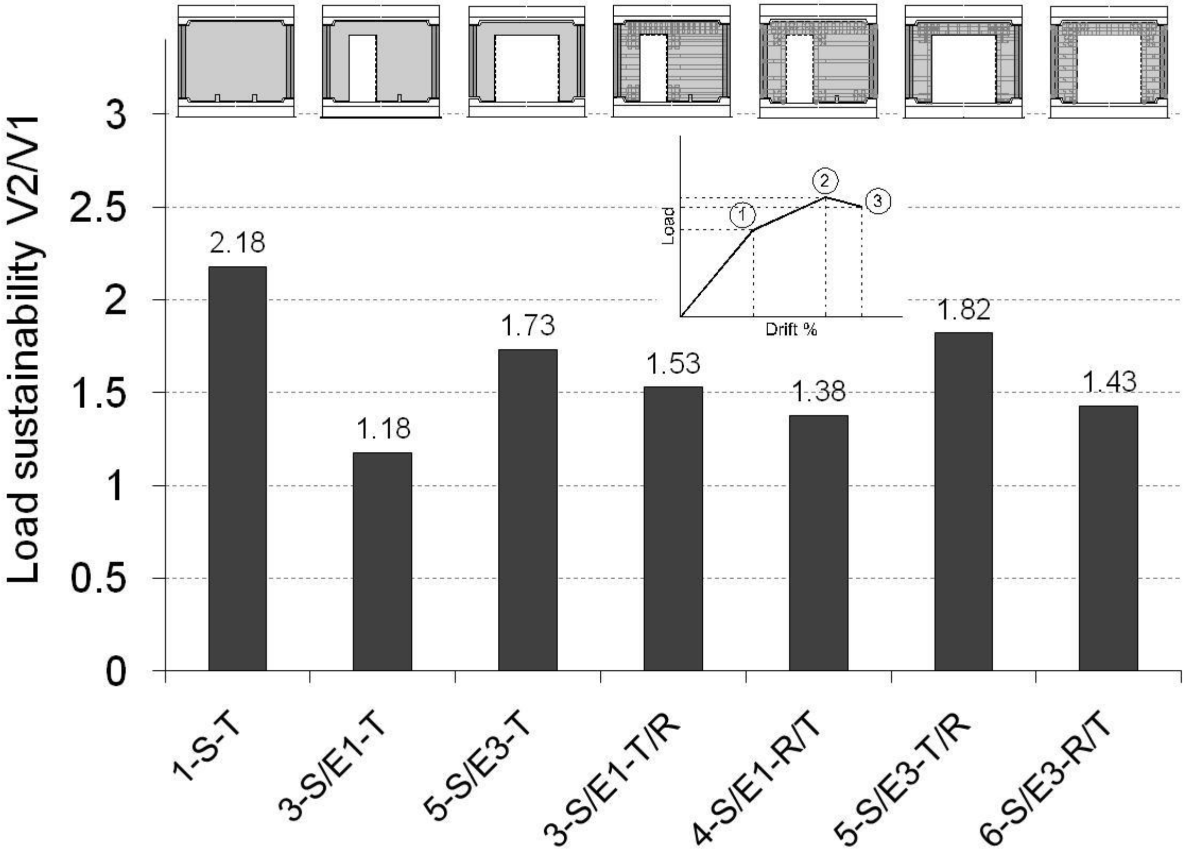


Effect of cut-out condition

Effect of strengthening condition

Effect of concrete strength

LOAD SUSTAINABILITY (OVERSTRENGTH) COMPARISON

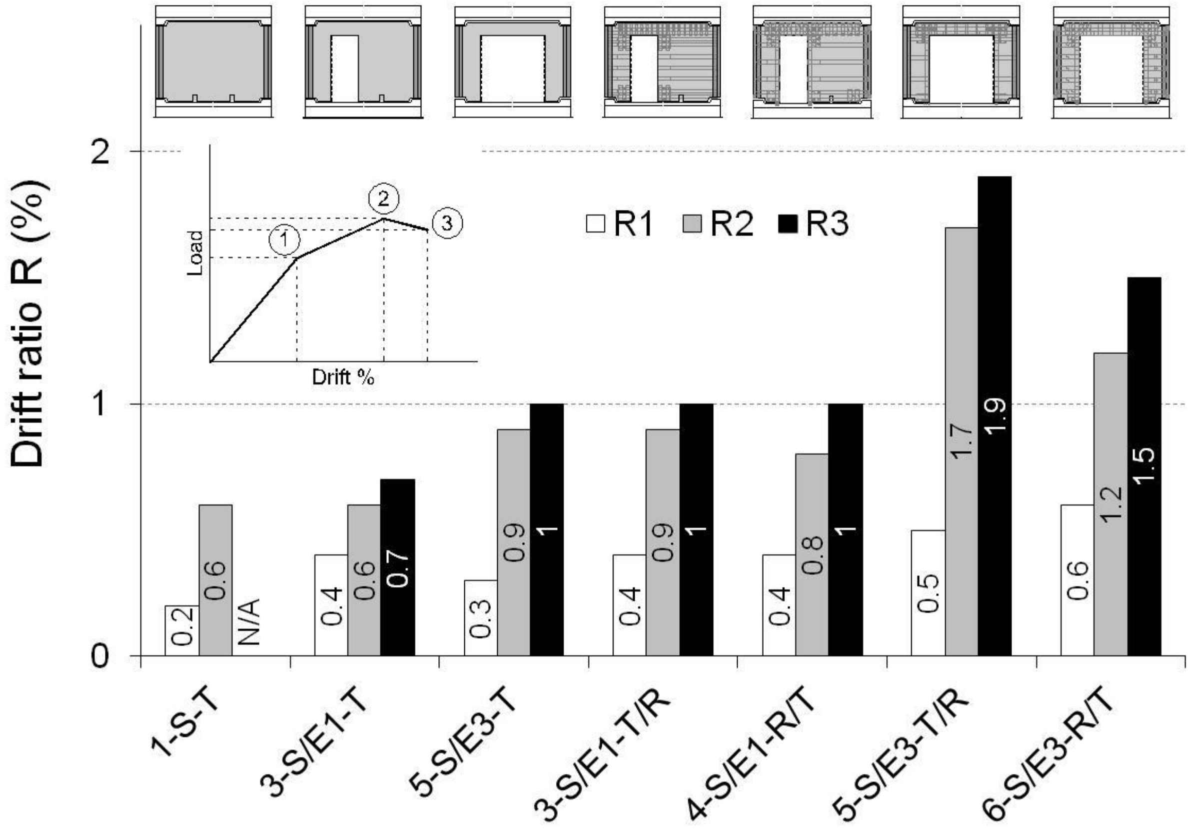


Effect of cut-out condition

Effect of strengthening condition

Effect of concrete strength

DRIFT RATIO COMPARISON

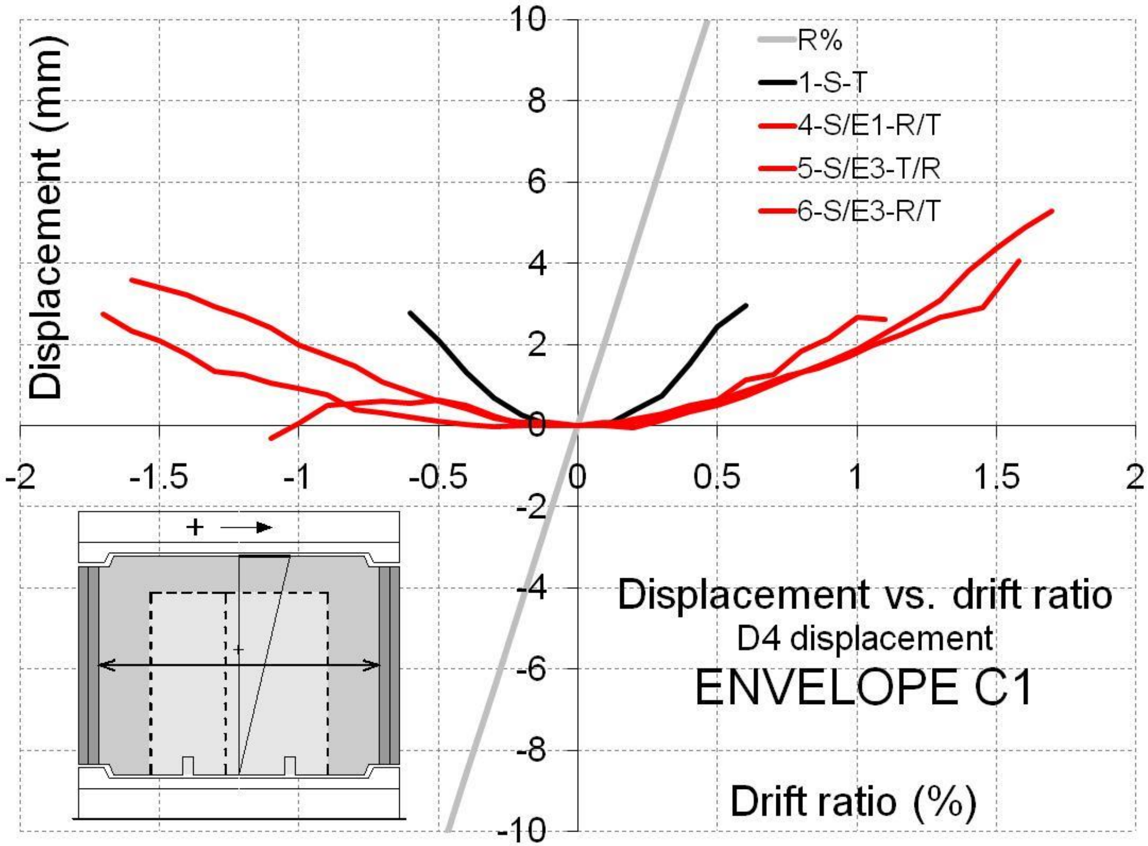


Effect of cut-out condition

Effect of strengthening condition

Effect of concrete strength

DISPLACEMENT ENVELOPE COMPARISON

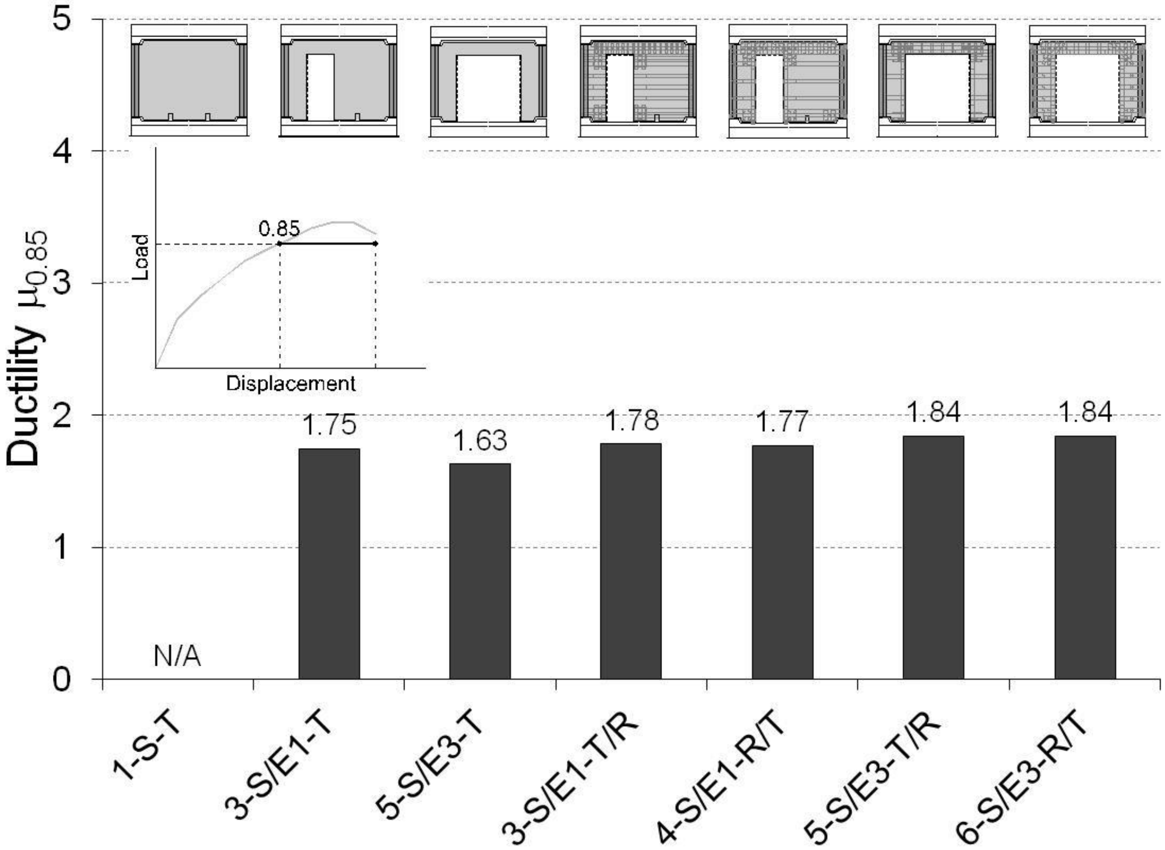


Shear characteristic horizontal lengthening at the mid-height of the walls.

This type of behaviour is exhibited intensively by the solid wall.

Cut-out condition reduces this effect.

DISPLACEMENT DUCTILITY COMPARISON



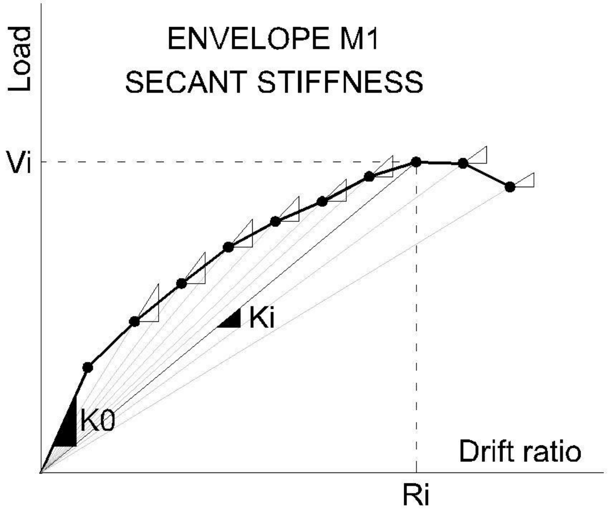
Effect of cut-out condition

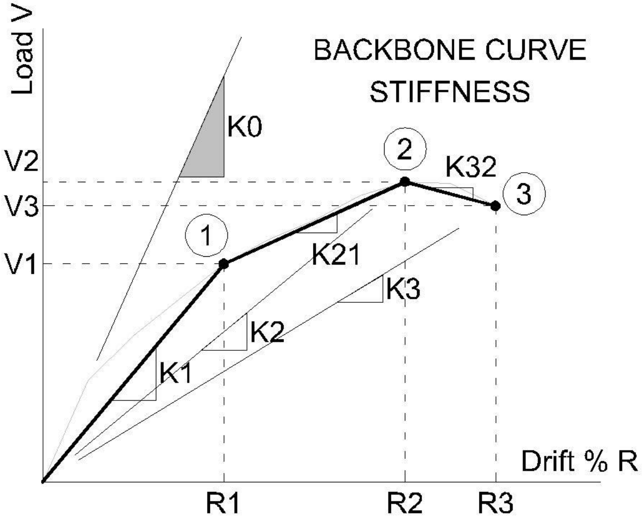
Effect of strengthening condition

Effect of concrete strength

$\approx$ 1.63 … 1.84

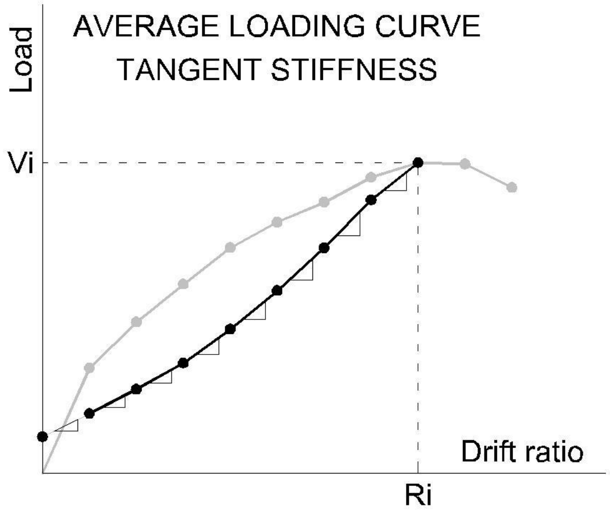
STIFFNESS DEFINITIONS





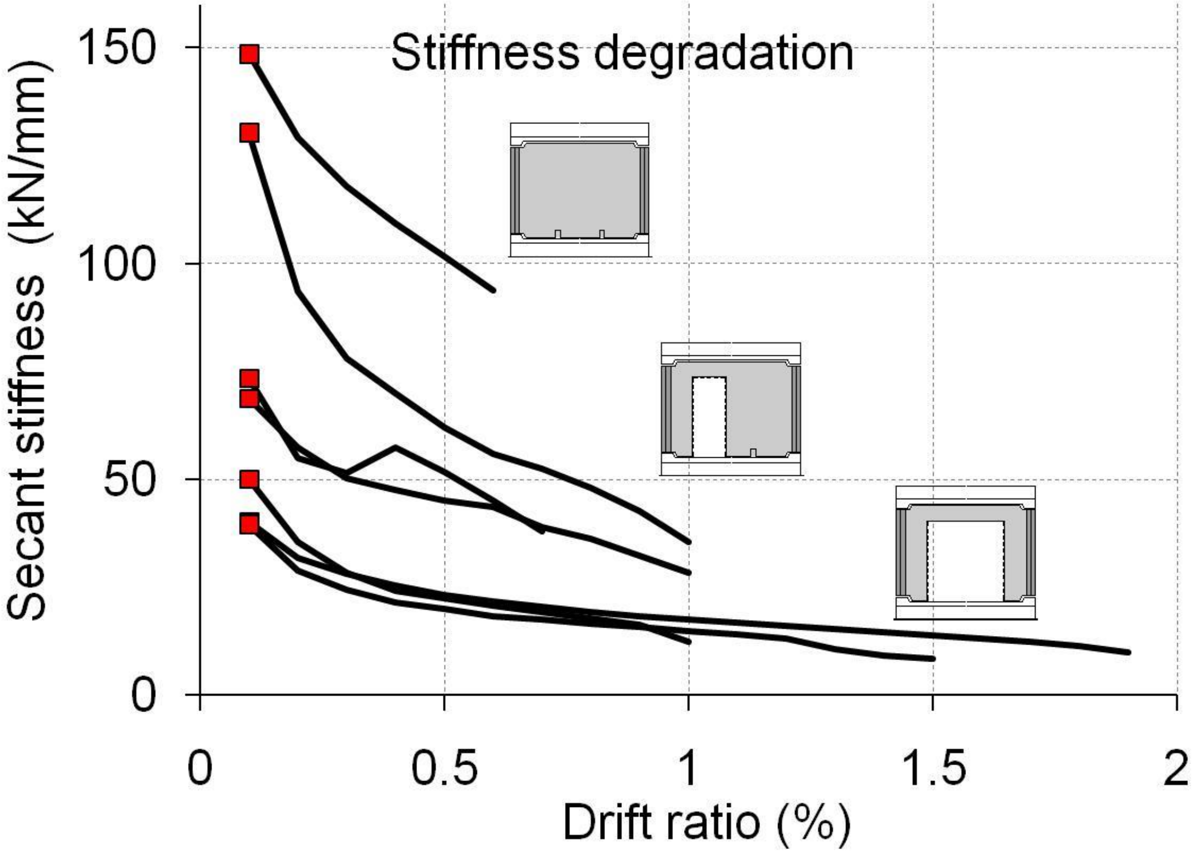
<u>Monotonic envelope stiffness</u>
secant; tangent

<u>Backbone stiffness</u>
secant; tangent



<u>Average loading curve stiffness</u>
secant; **tangent**

STIFFNESS DEGRADATION

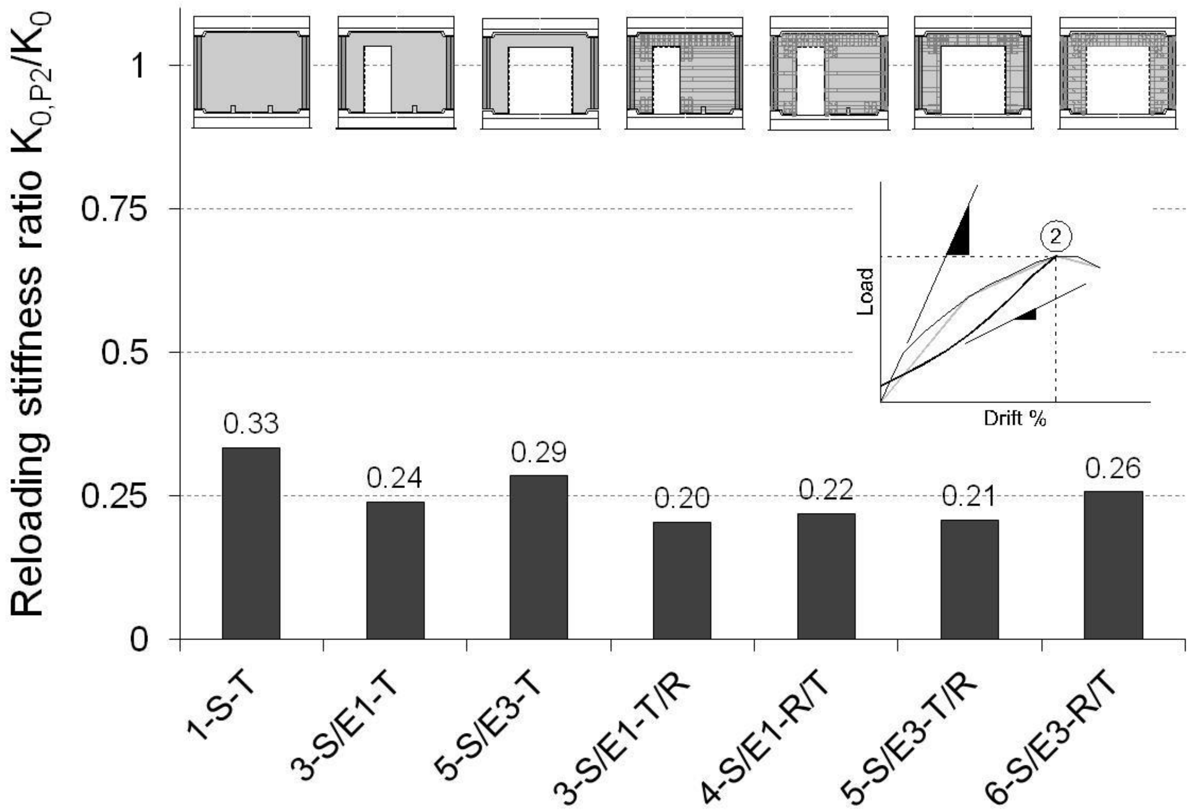


Comparison of the initial stiffness

Three groups of initial stiffness in accordance to the cut-out condition

Influence of concrete strength (spec No. 4)

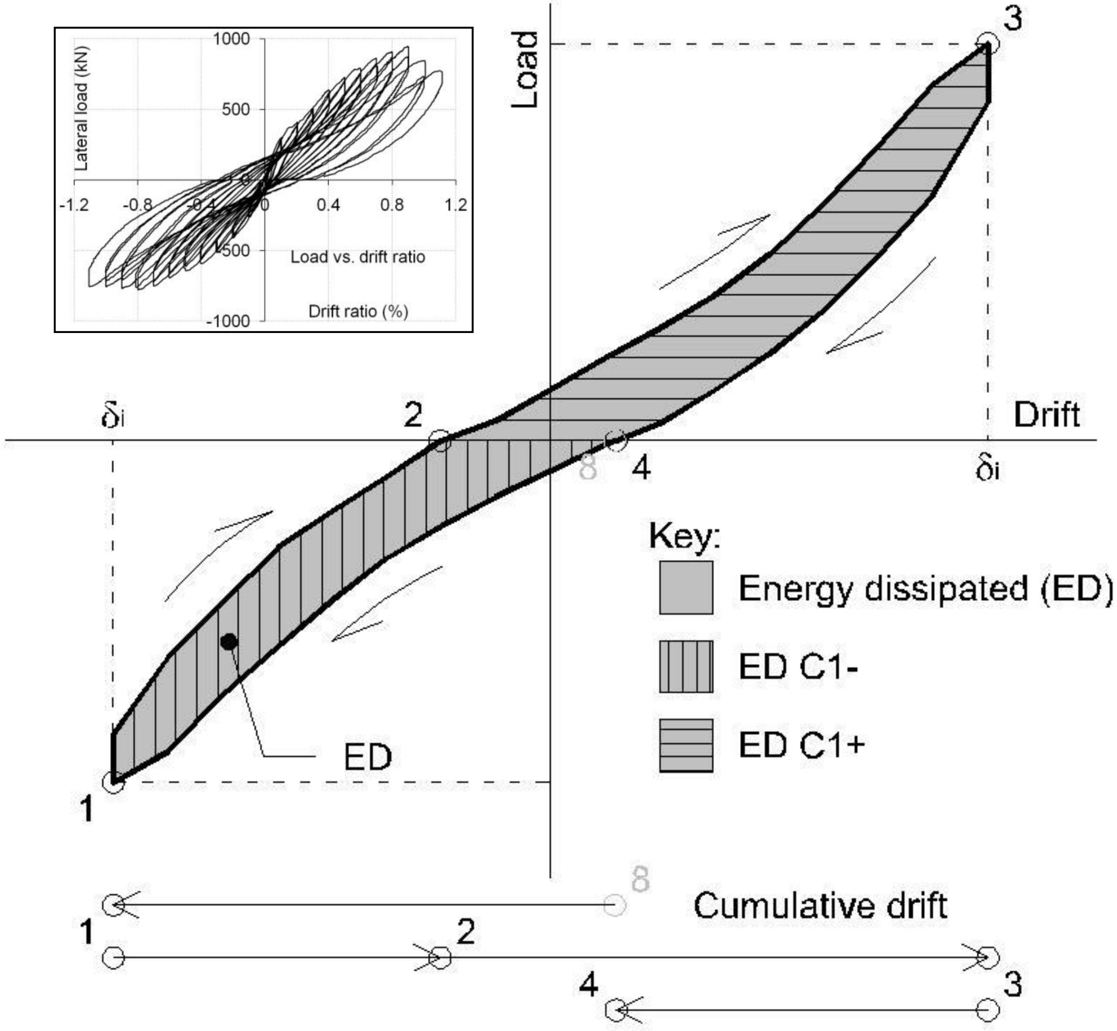
STIFFNESS COMPARISON



Effect of cut-out condition

Effect of strengthening condition

DEFINITION OF ENERGY ABSORPTION



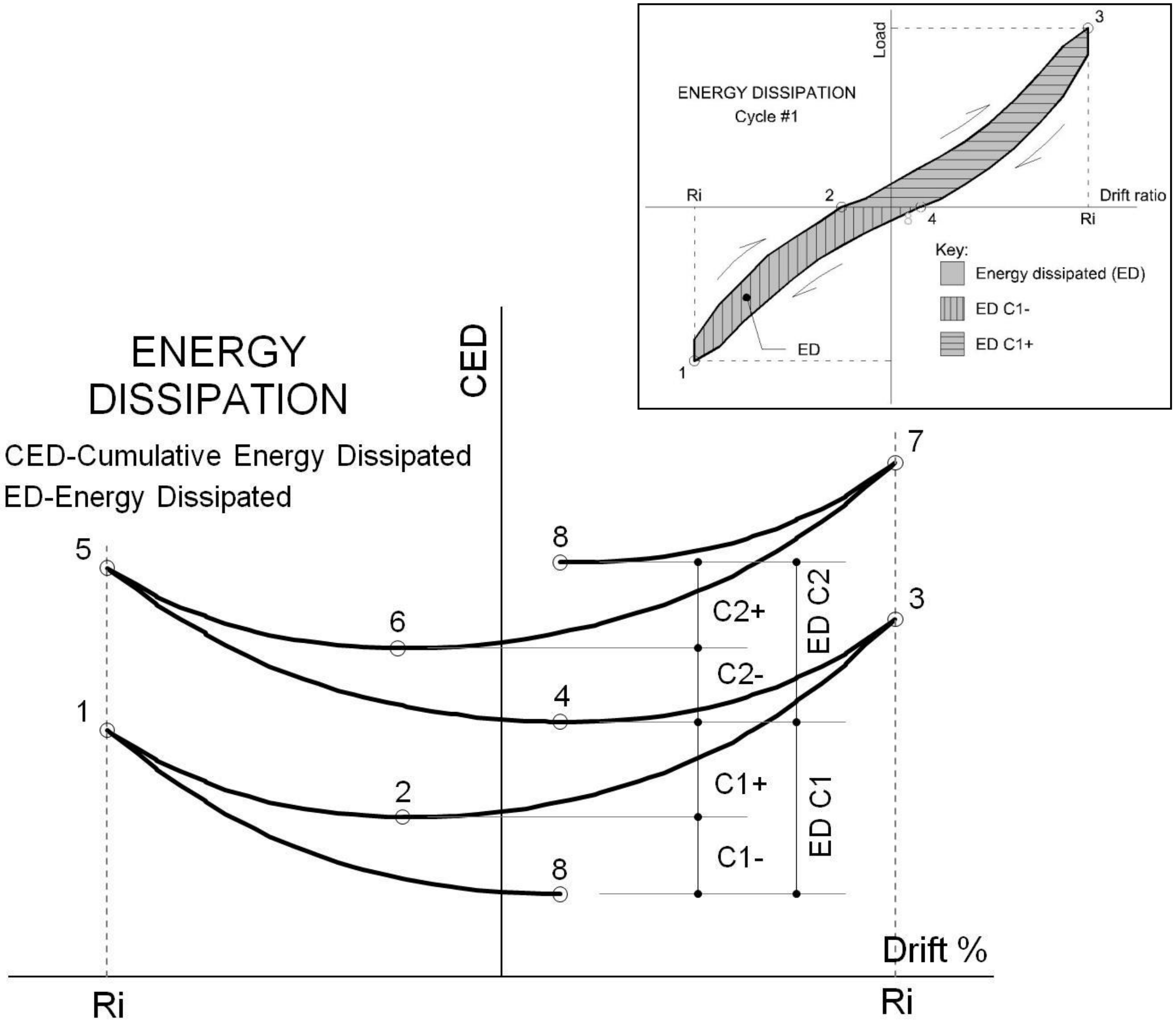
The area of the hysteresis loops (symbol: A or W, unit: kNm)

Characteristic loading points

Positive and negative half-cycle dissipation

Cumulative drift

CUMULATIVE DISSIPATION CURVE 1



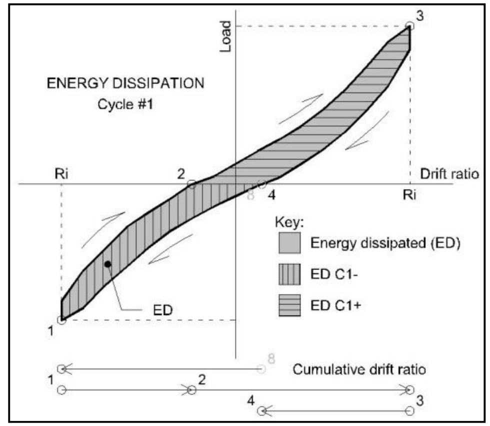
Continuous cumulative sum of the areas (with sign) below the load-drift curve

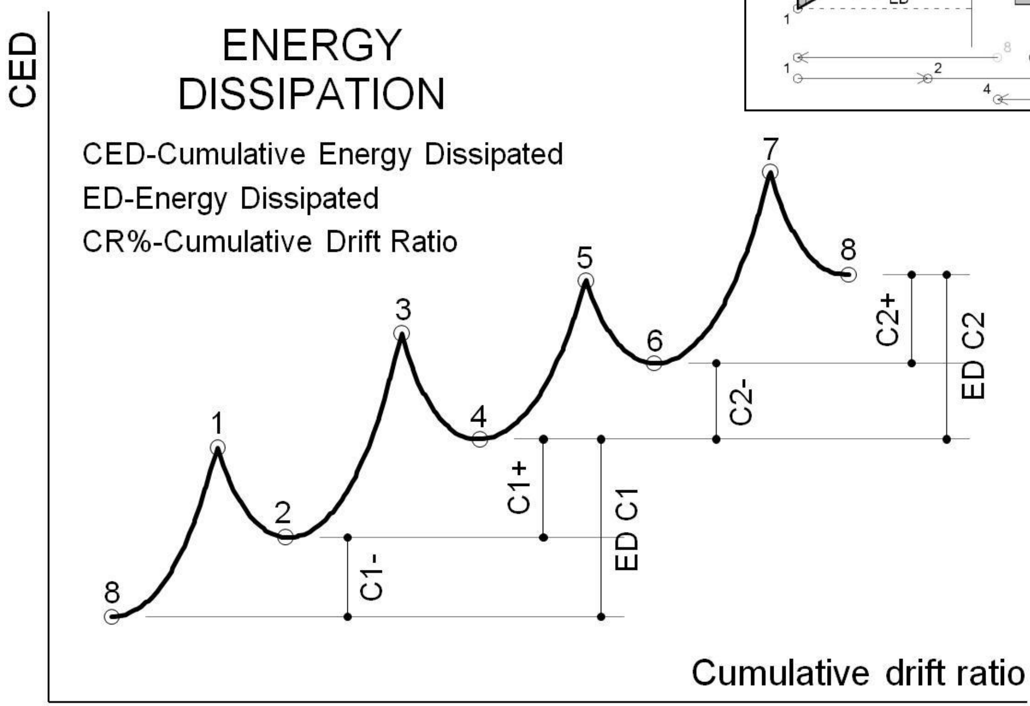
Characteristic points

Cyclic energy dissipation

Half-cycle energy dissipation

CUMULATIVE DISSIPATION CURVE 1





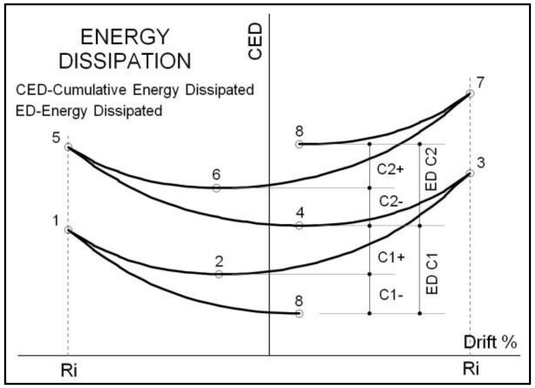
Continuous cumulative sum of the areas (with sign) below the load-drift curve vs cumulative drift ratio

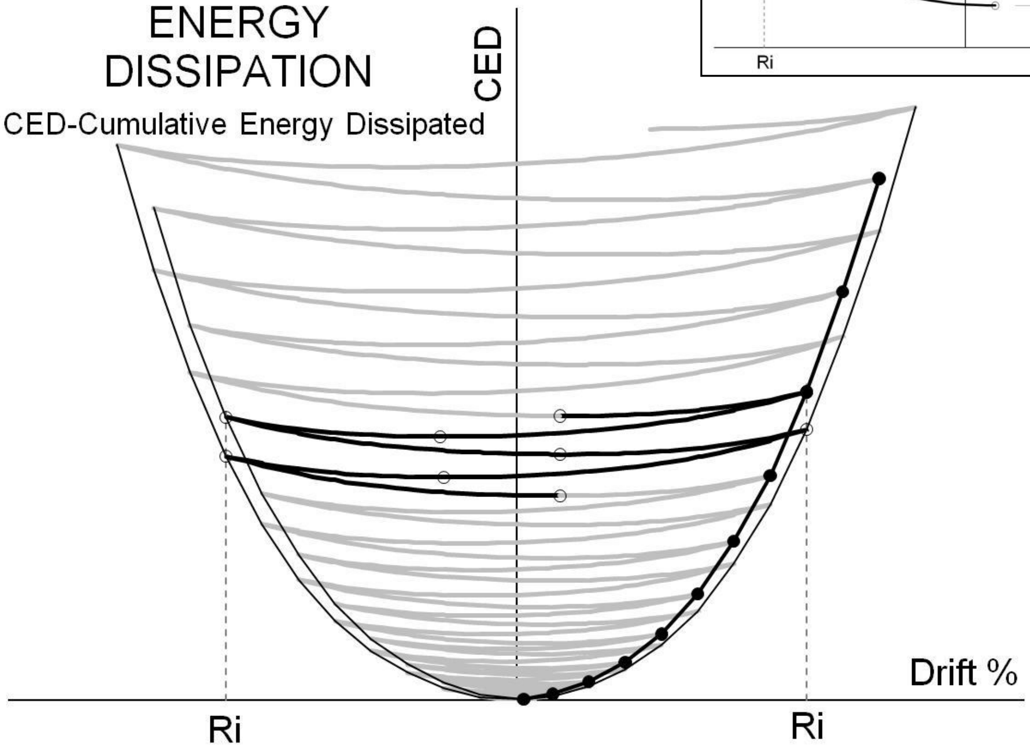
Characteristic points

Cyclic energy dissipation

Half-cycle energy dissipation

ENERGY DISSIPATION ENVELOPE

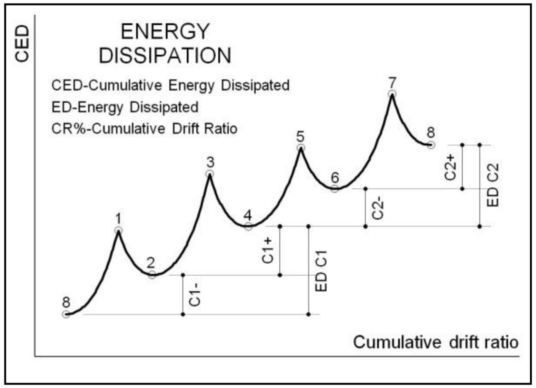


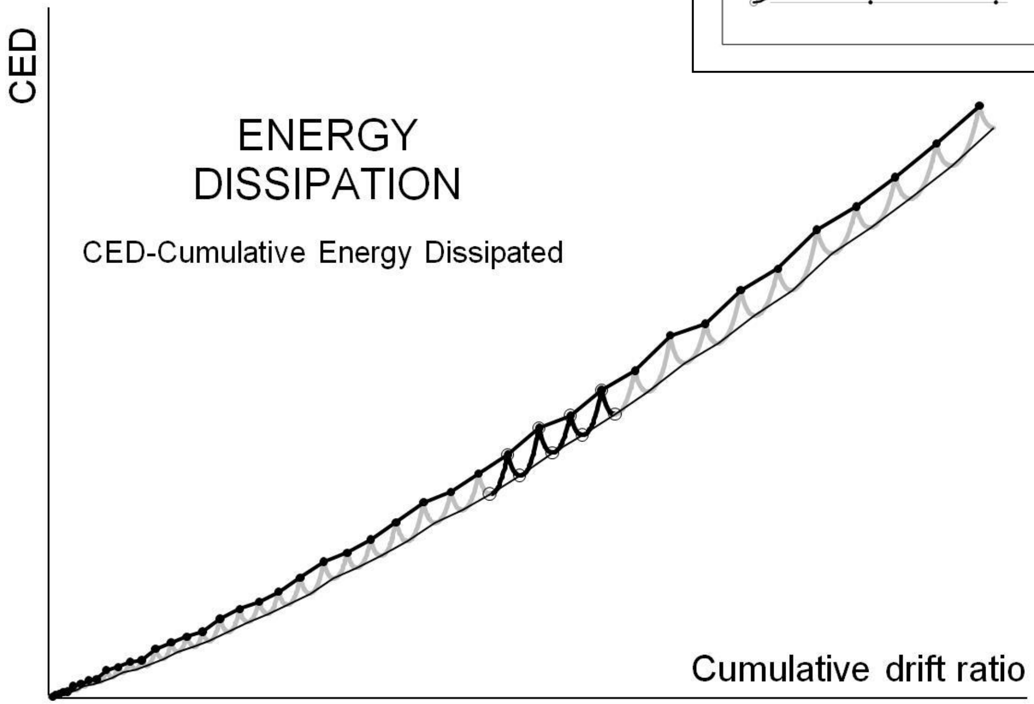


Four envelopes

Point 7 envelope was considered

ENERGY DISSIPATION ENVELOPE

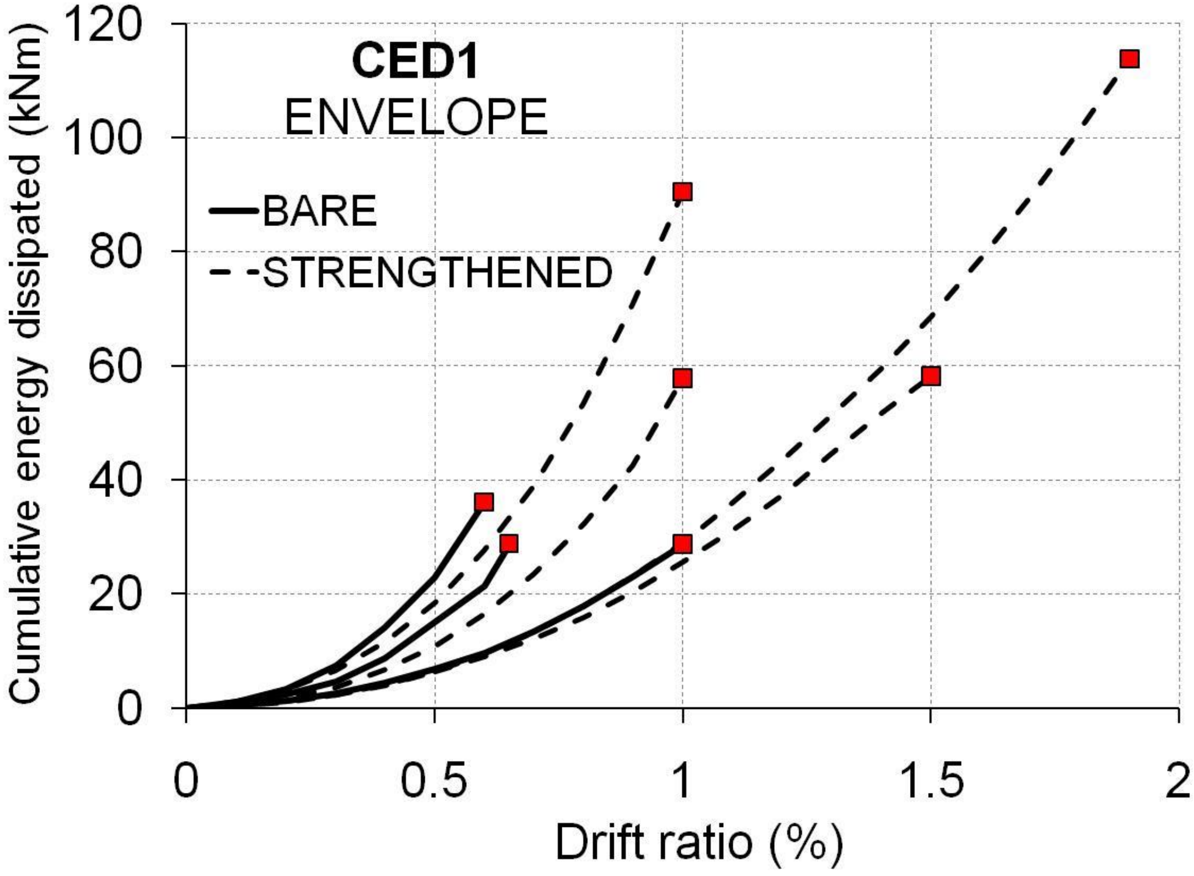




Two envelopes: upper and lower bound

Upper bound envelope was considered

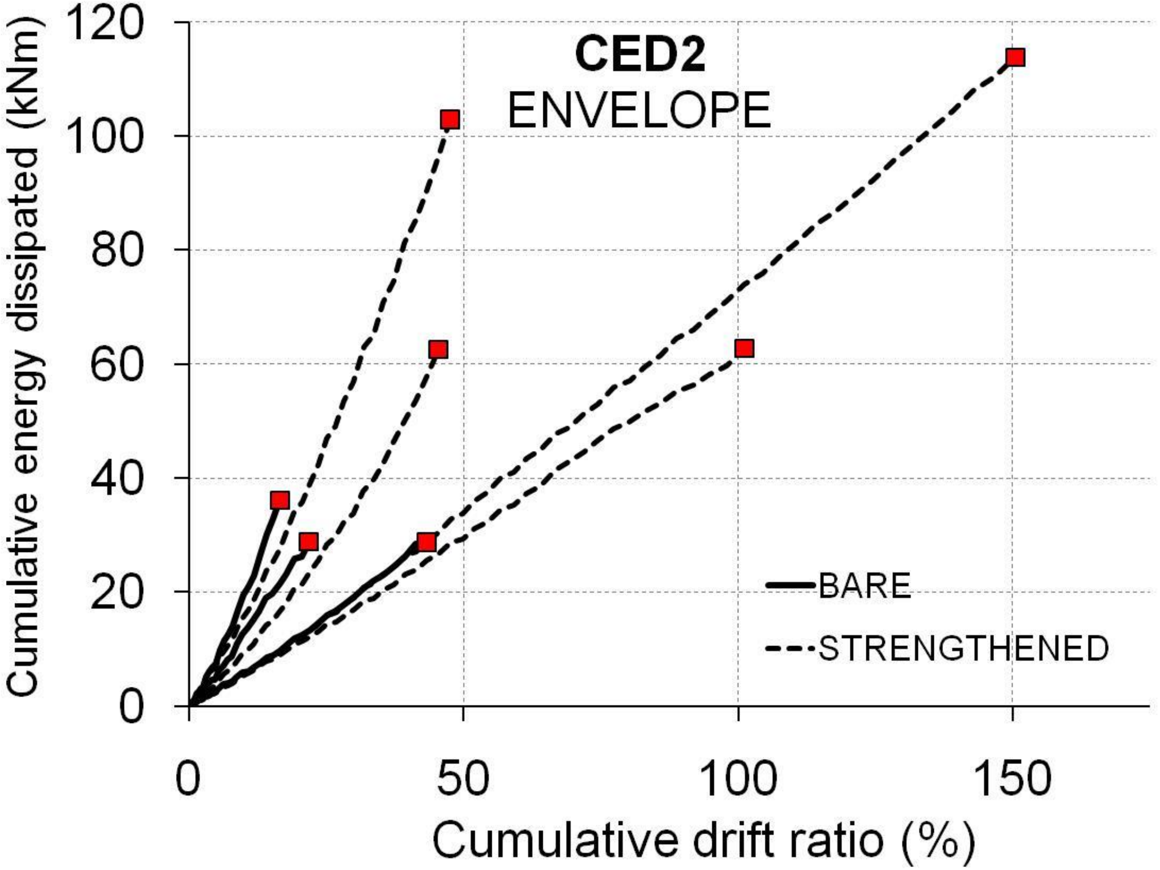
Energy Dissipation Analysis



Effect of cut-out condition

Effect of strengthening condition

ENERGY DISSIPATION ENVELOPES

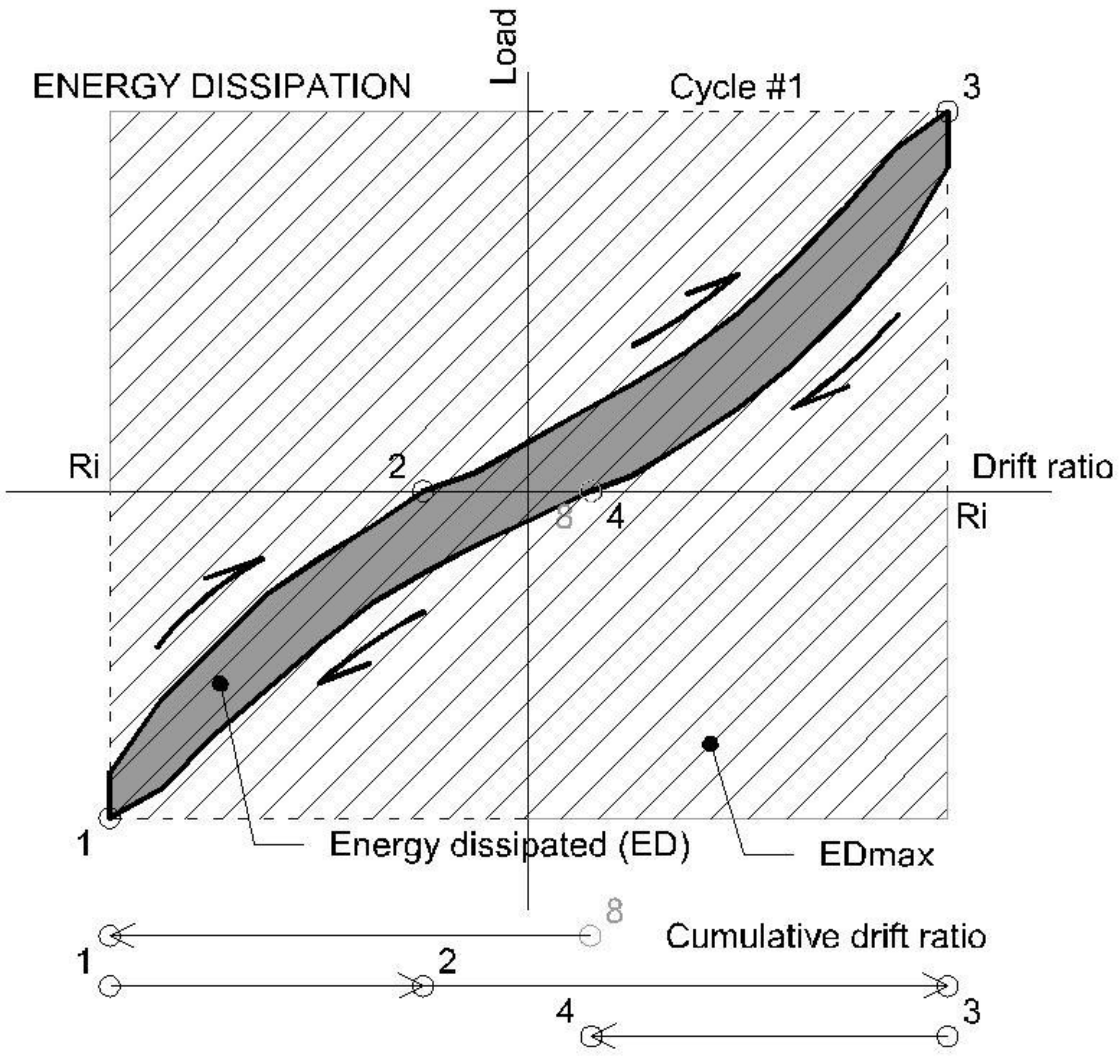


Effect of cut-out condition

Effect of strengthening condition

<u>Energy dissipation rate</u>
the ratio of the cumulative energy dissipated and the cumulative displacement (CED/CD, results in force unit)

DISSIPATION RATIO



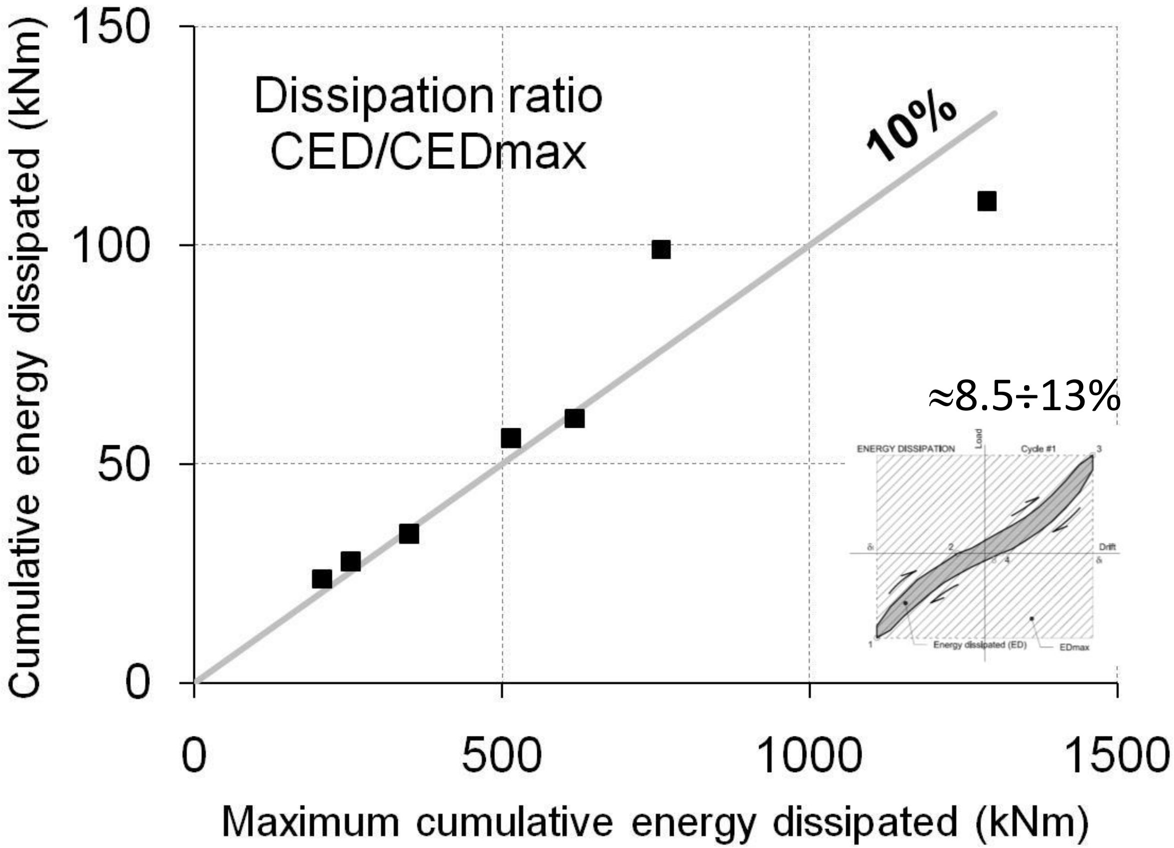
<u>Definition</u>

ED/ED_{max}

ED hysteretic energy

ED_{max} maximum energy dissipation (area of the peak to peak rectangle)

ULTIMATE DISSIPATION RATIO



In this experimental program ≈10%

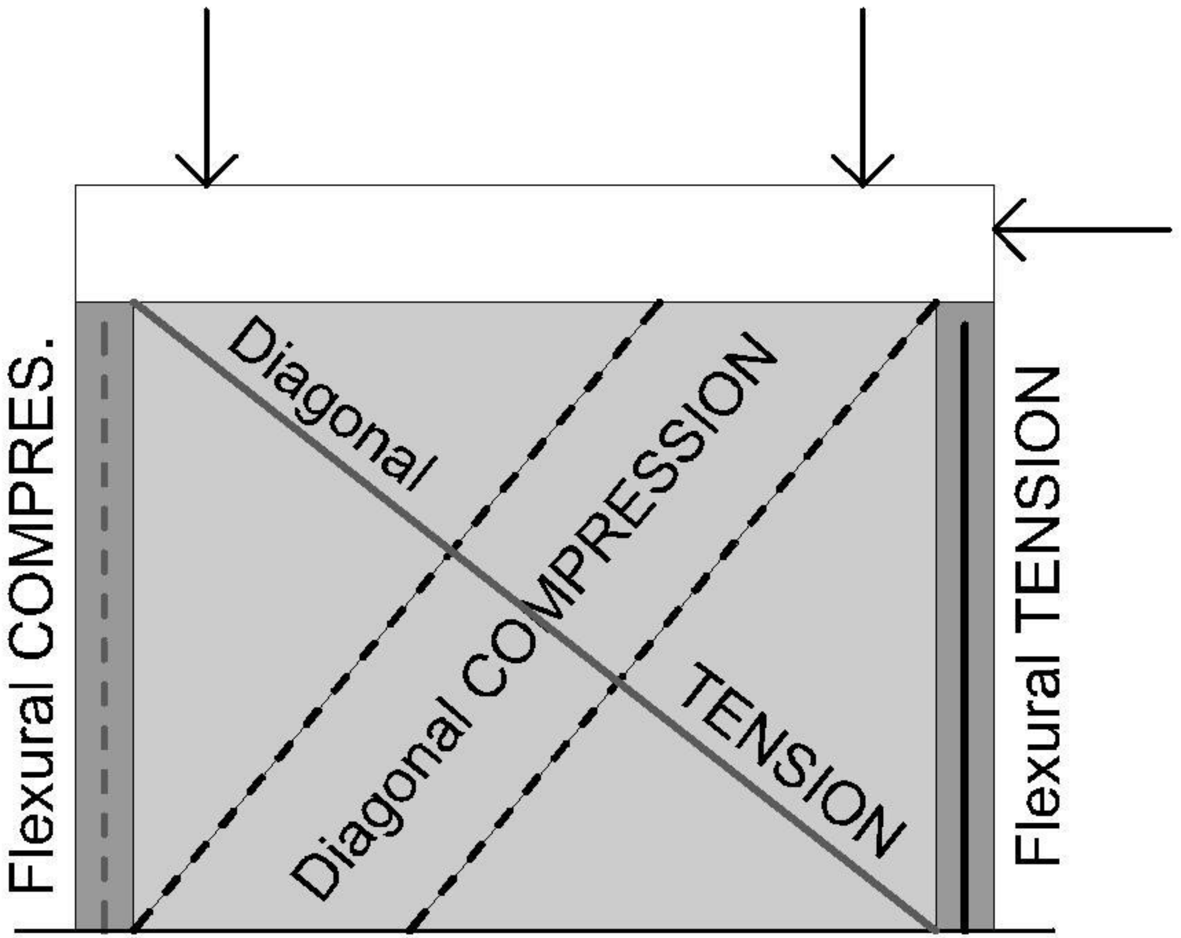
Seems to characterizes the boundary conditions (restrained rotation by variable axial loading)

→ the cut-outs and the strengthening condition are not affected significantly the dissipation ratio

CONTENT

1. INTRODUCTION
2. EXPERIMENTAL PROGRAMME
3. EXPERIMENTAL ELEMENT
4. **TEST SET-UP**
5. **LOADING STRATEGY**
6. **INSTRUMENTATION**
7. **DAMAGE ASSESSMENT AND STRENGTHENING**
8. **EXPERIMENTAL RESULTS**
9. **CONCLUSIONS**

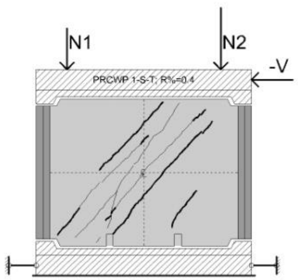
SHEAR MECHANISMS

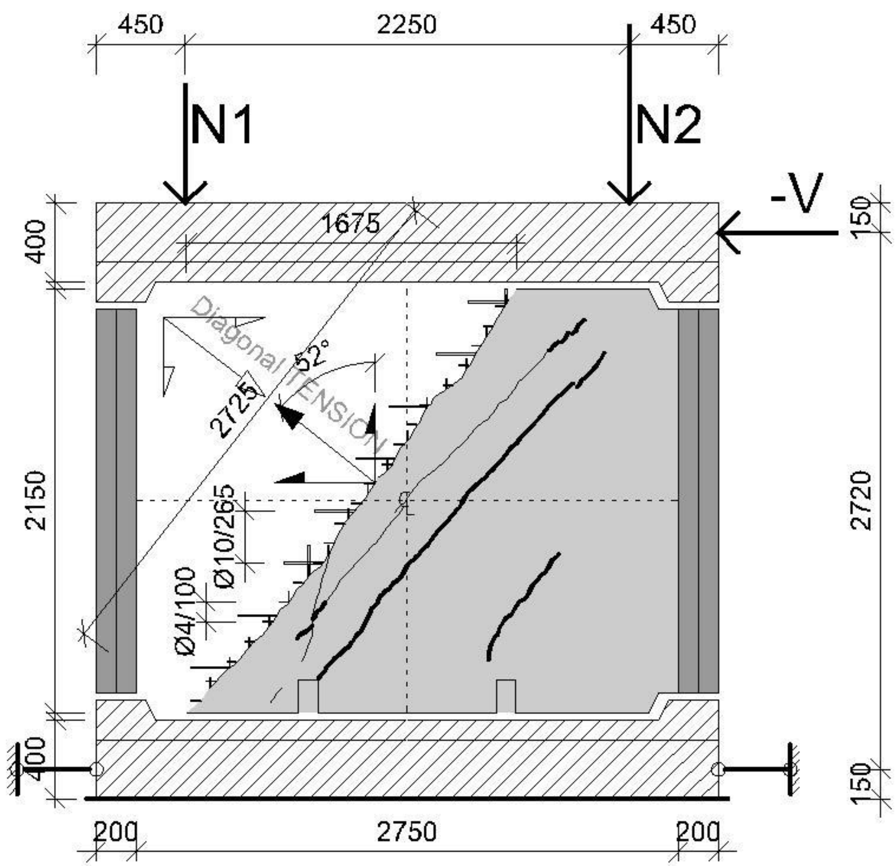


Shear transferred along diagonal load paths:
DIAGONAL COMPRESSION
and/or
DIAGONAL TENSION

Proportion between shears carried by the two load paths:
stiffness
loading conditions
boundary conditions

SHEAR MECHANISMS





Diagonal tension

$V_{DT}=nA_s\sigma_s$

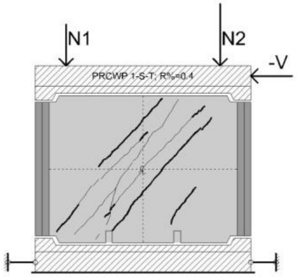
Predicted/Measured ratio

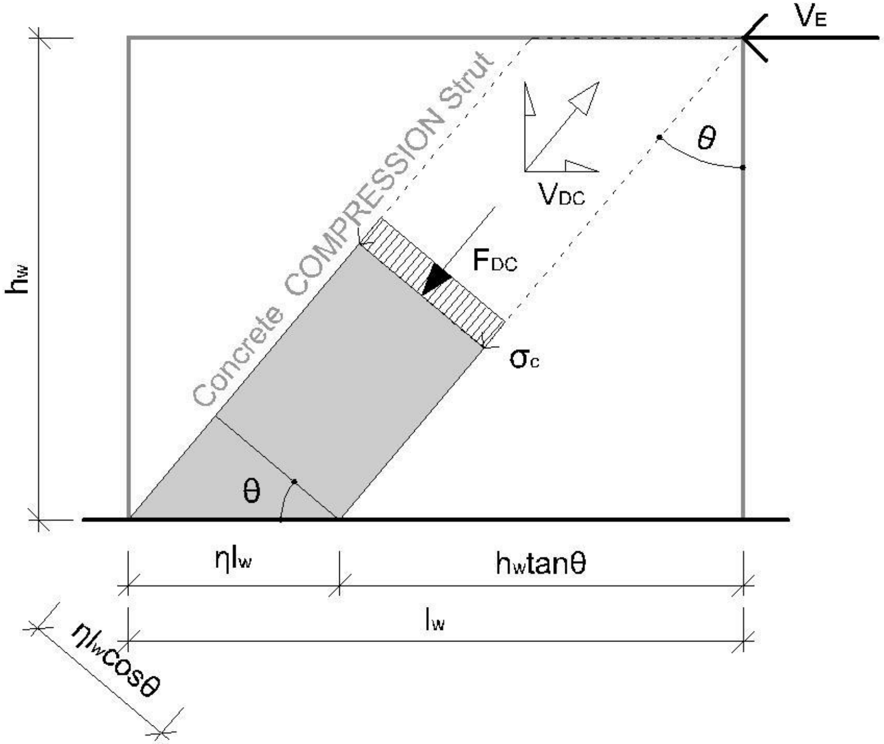
at R=0.4%
$V_{P/M}=300/940=0.32$

at ultimate
$V_{P/M}=446/1210=0.37$

Excessive underestimation

SHEAR MECHANISMS





Diagonal compression

$V_{DC}=F_{DC}\sin\theta$

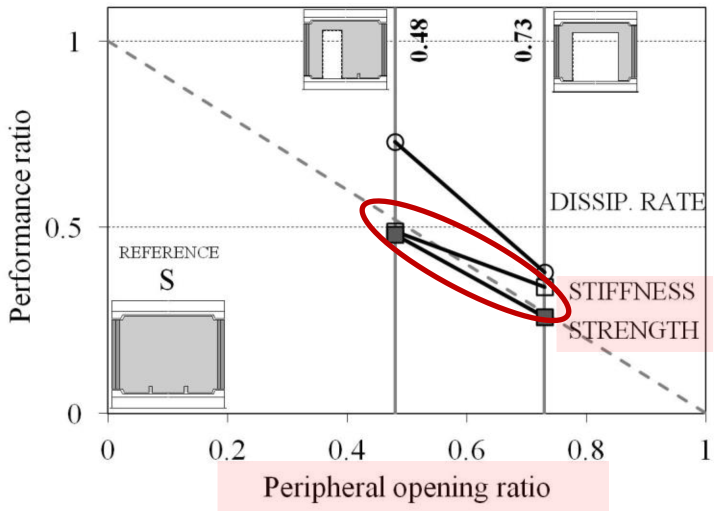
Predicted/Measured ratio

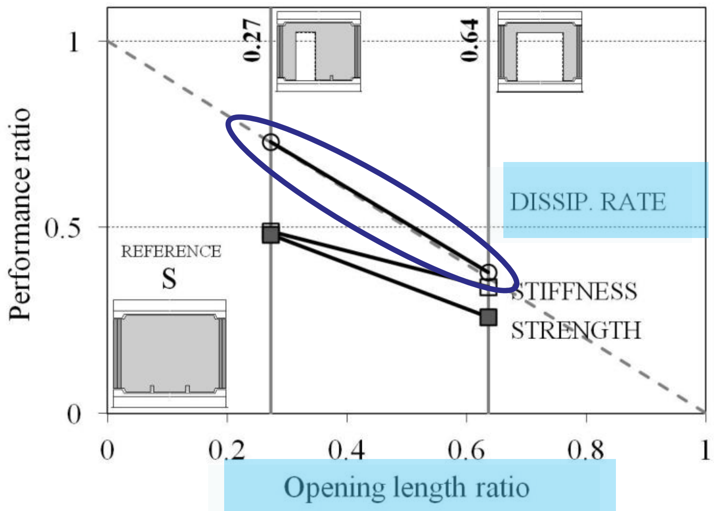
at R=0.4%
$V_{P/M}$=652/940=0.7

at ultimate
$V_{P/M}$=990/1210=0.82

Slight underestimation

WEAKENING EFFECT OF THE CUT-OUT OPENINGS





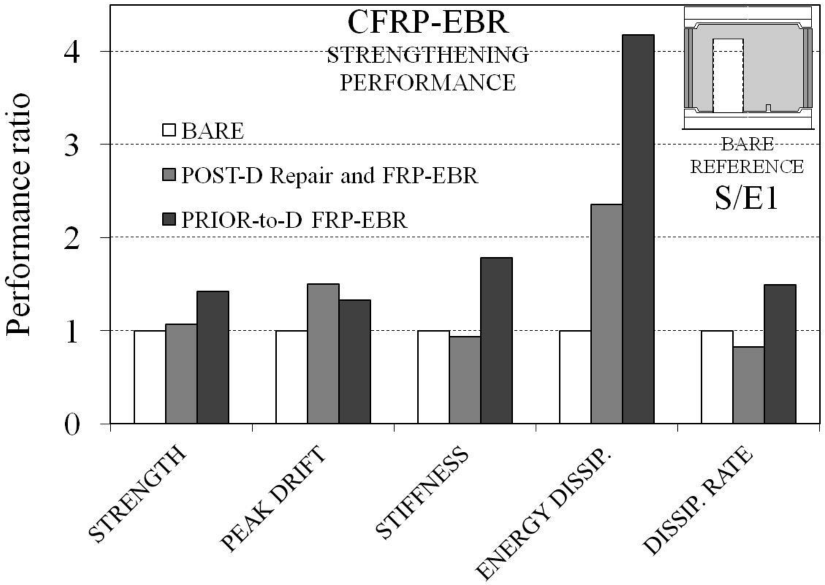
$$R_{weak} = R_{solid} \cdot \alpha_p$$

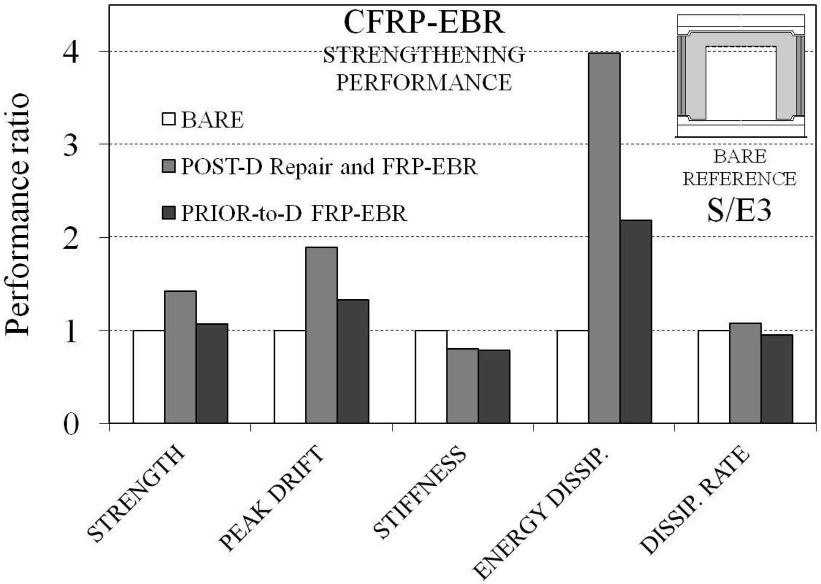
where the performance ratio $\alpha_p = 1 - \eta$
and the opening ratio

$$\eta = \begin{cases} P = \sqrt{A_0/A_w} & for\ R: shear\ resistance\ (V)\ and\ stiffness\ (K) \\ l_0/l_w & for\ R: dissipation\ rate \end{cases}$$

Practicing engineers can use the experimental results to evaluate the performance ratios in terms of strength, stiffness and energy dissipation rate.

CONTRIBUTION OF THE CFRP-EBR STRENGTHENING

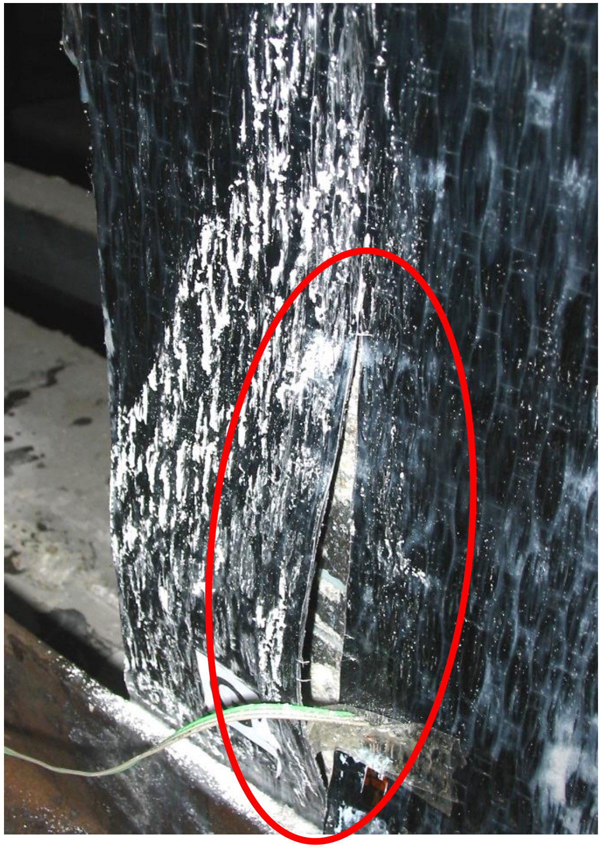




- the shear strength increases in average by 25%
- the peak drift increases by 50%
- the initial stiffness and the energy dissipation rate remain roughly the same
- the cumulative energy dissipation at ultimate increases by 2÷4 times

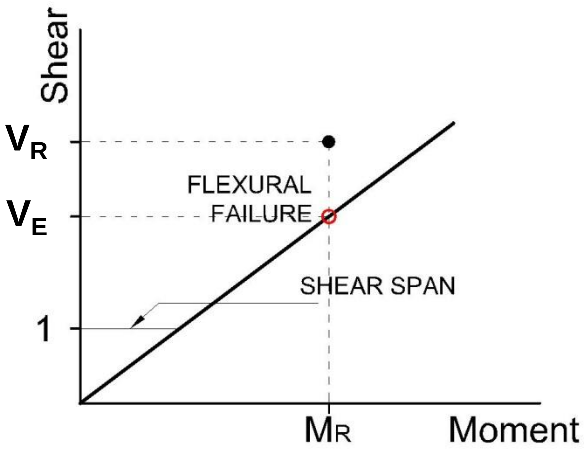
CFRP-EBR RETROFIT LIMITATION

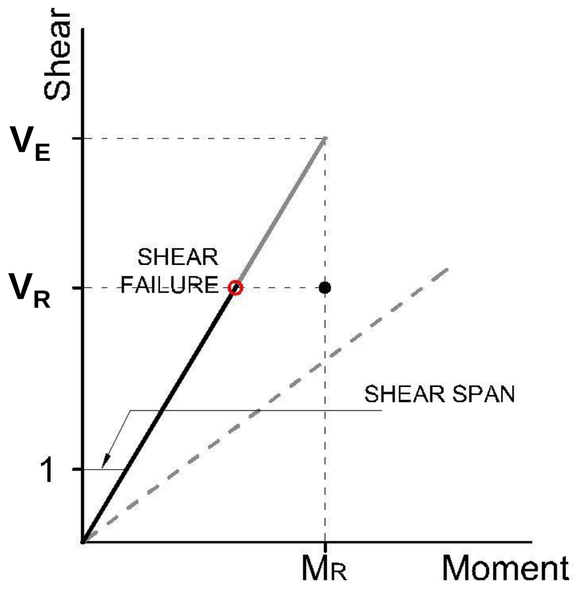
In reversed cyclic applications the flexural CFRP-EBR is susceptible to **premature failure** → recommended to use a **safety coefficient for flexural FRP ≈ 3**
→ further subject-oriented investigations are necessary on this issue.

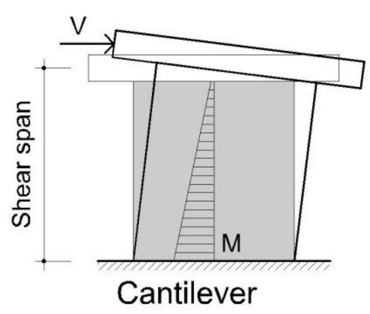


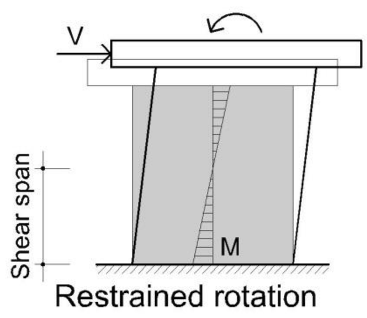
(2003) (2010)

SHEAR SPAN CONDITIONS







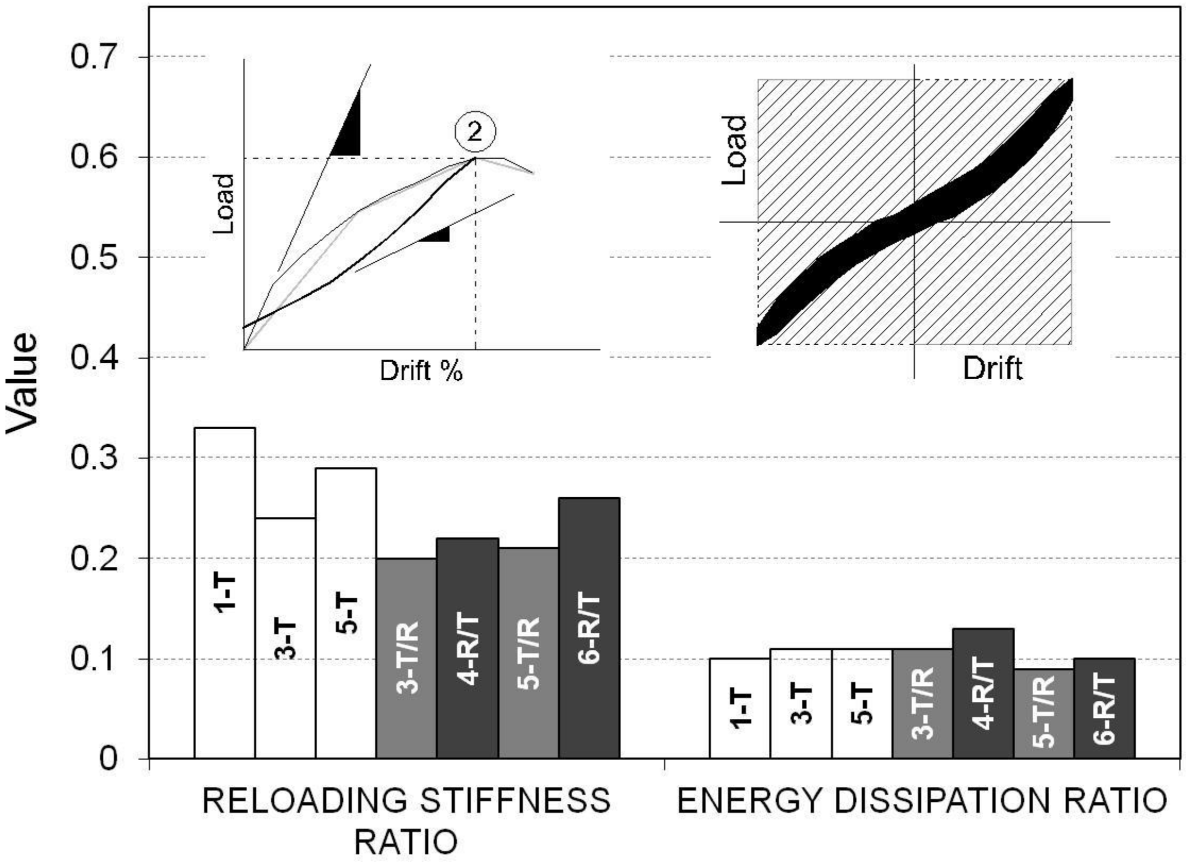


Laboratory investigations on cantilever walls tend to overestimate the shear span conditions relative to the as-built situation.

A reduced shear span condition may change the failure mode from flexural to shear for the same specimen.

Further investigations are necessary on this topic

RESPONSE CHARACTERISTICS

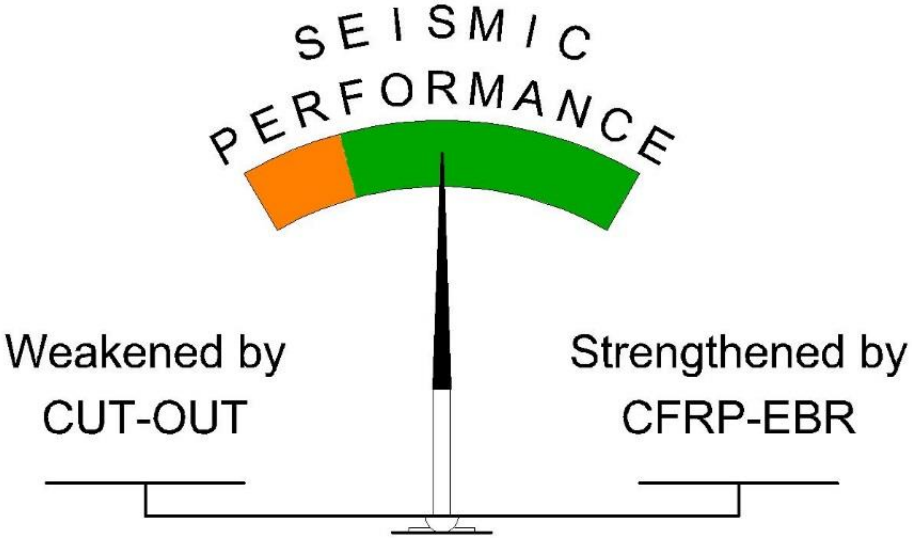


Diagonal compression dominated shear response

Reloading stiffness ratio: 0.2÷0.33

Energy dissipation ratio: 10%

THANK YOU FOR YOUR ATTENTION!



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Wall tests videos on:
-*PRCWP 5-S/E3-T*
-*PRCWP 3-S/E1-T/R*
-*PRCWP 1-S-T*
-*PRCWP 3-S/E1-T*