March 30-31, 2007 - Prague, Czech Republic

Full-scale cyclic tests of a real masonry-infilled RC building for seismic upgrading

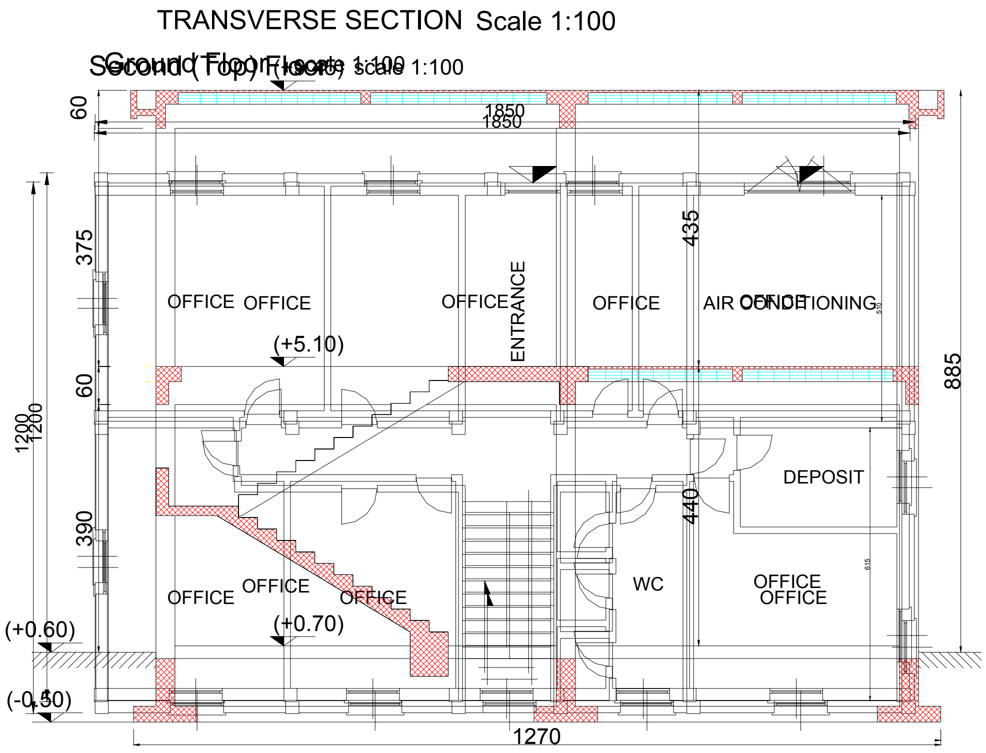
F.M. Mazzolani, Gaetano Della Corte, L. Fiorino, E. Barecchia

Department of Structural Engineering
University of Naples Federico II

Original building

BASIC DATA

- Construction period: end of ’70s
- Plan dimensions: 18.50m x 12.00m
- Floor area: 222 mq
- N° of floors: 2
- Total height on ground: 8.85 m
- Total volume: 1965 mc

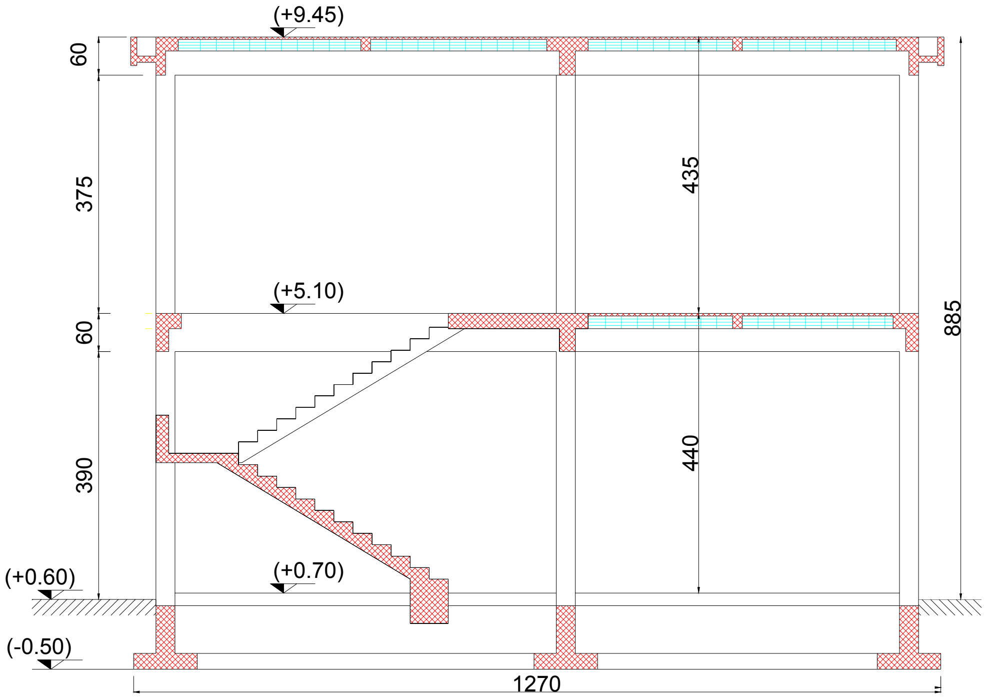


Original building

BASIC DATA

- Construction period: end of '70s
- Plan dimensions: 18.50m x 12.00m
- Floor area: 222 mq
- N° of floors: 2
- Total height on ground: 8.85 m
- Total volume: 1965 mc

TRANSVERSE SECTION Scale 1:100



Research objectives

Multi-task research

1. Experimental task:

Multi-step tests on a real masonry-infilled RC building

1.1 One “push-pull” test on the original building (next indicated as test #1)

1.2 One “push-pull” test on the building with MW_FRP (next indicated as test #2)

1.3 One “push-pull” test on the building with BRB

…

2. Numerical task:

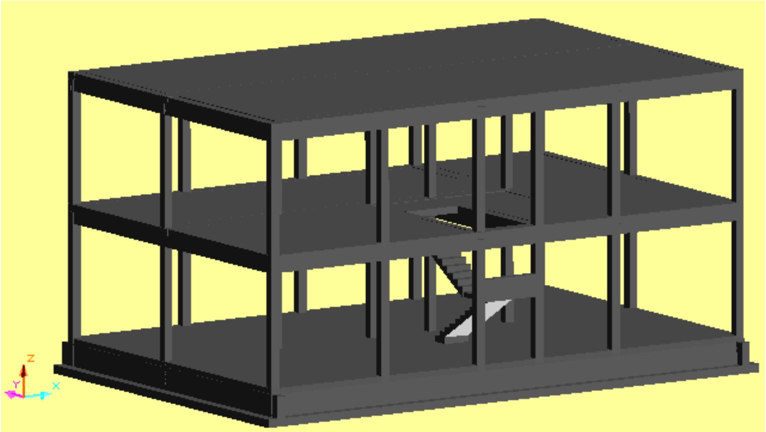
2.1 Development and calibration of numerical models

2.2 Vulnerability assessment

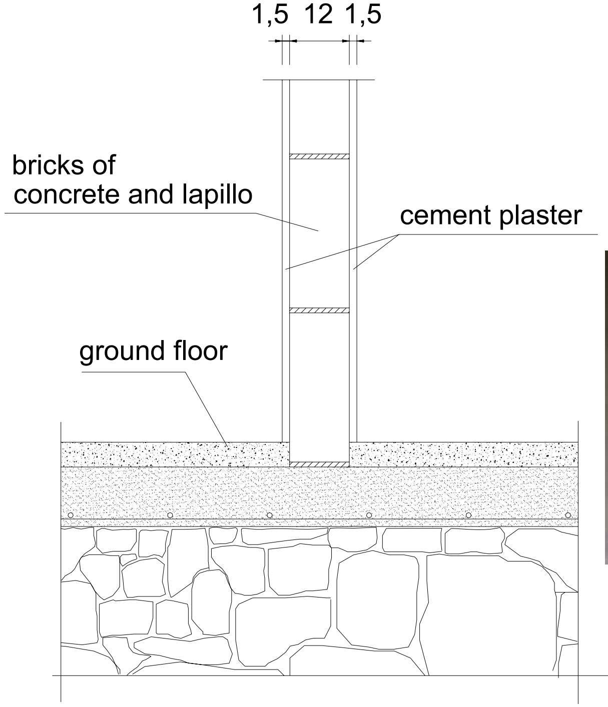
Original building

STRUCTURAL AND NON STRUCTURAL ELEMENTS

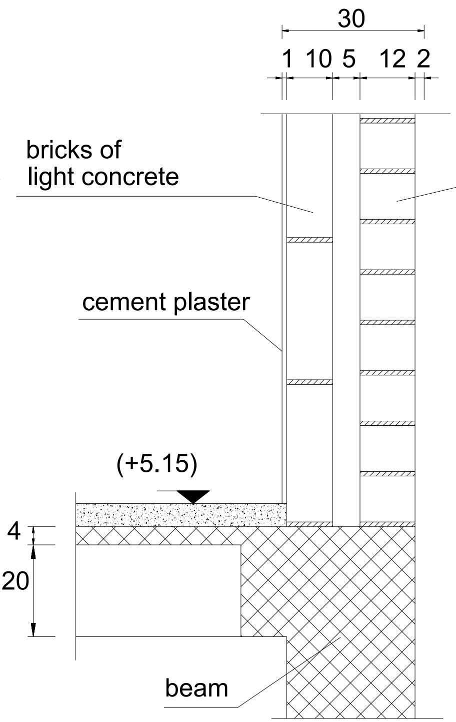
- Columns: 30x30cm
- Beams: 15x60cm; 20x60cm; 25x60cm
- First floor slab: mixed RC-hollow tiles H=20+4=24cm
- Second floor slab: mixed RC-hollow tiles H=18+4=22cm
- External claddings: two parts
  - internal part: concrete and lapillo blocks (s=10cm)
  - external part: semi-hollow clay blocks (s=12cm)
- Internal partitions: concrete and lapillo blocks (s=10cm)

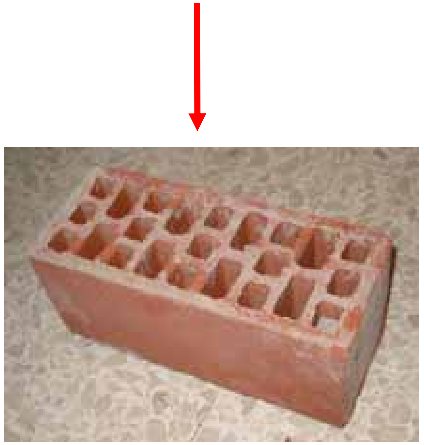


INTERNAL PARTITION WALLS



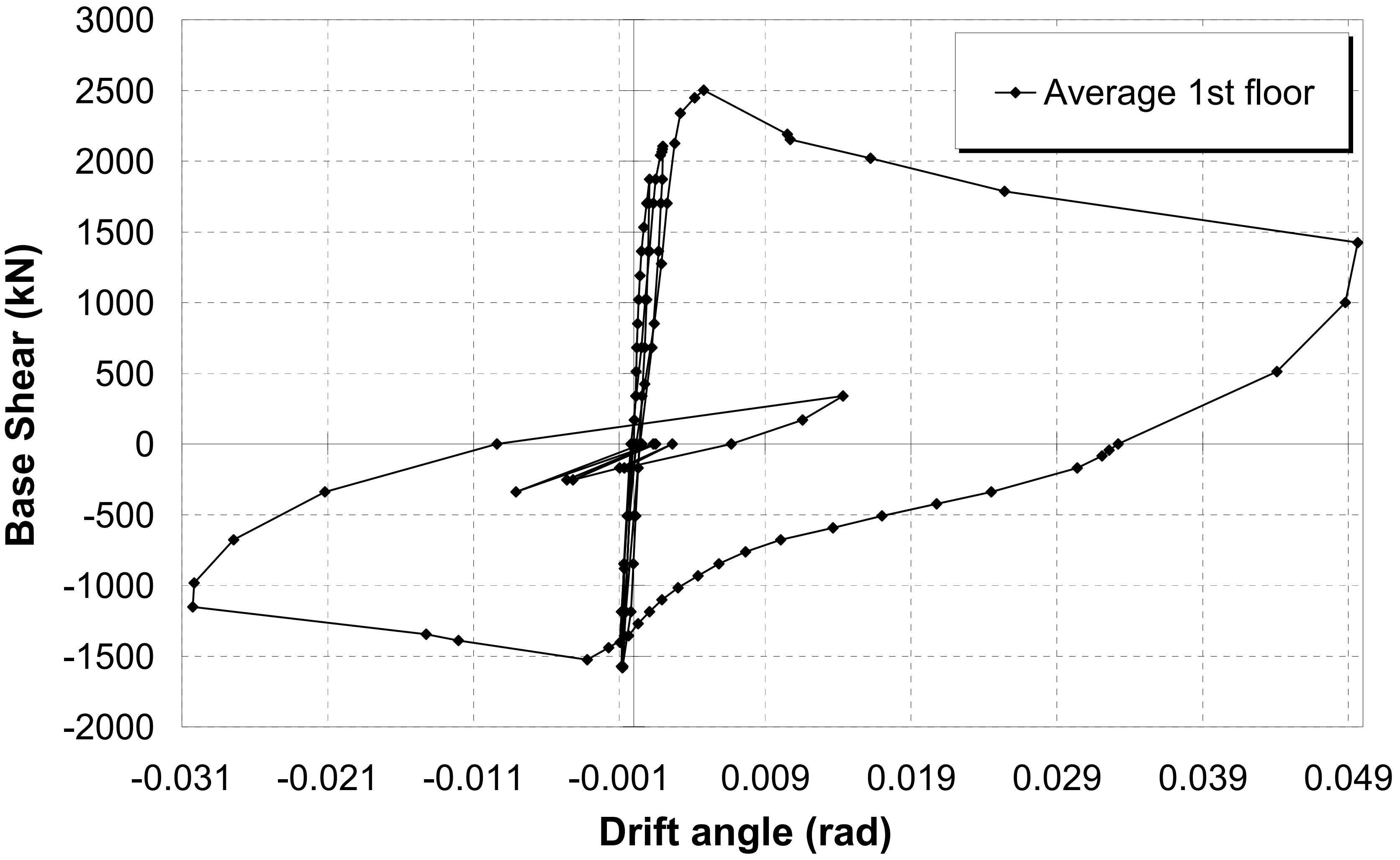
EXTERNAL CLADDING DETAIL



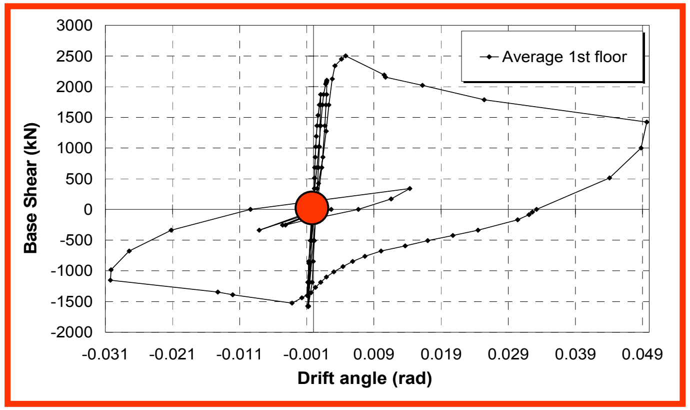


Test equipment

Test #1 - Summary

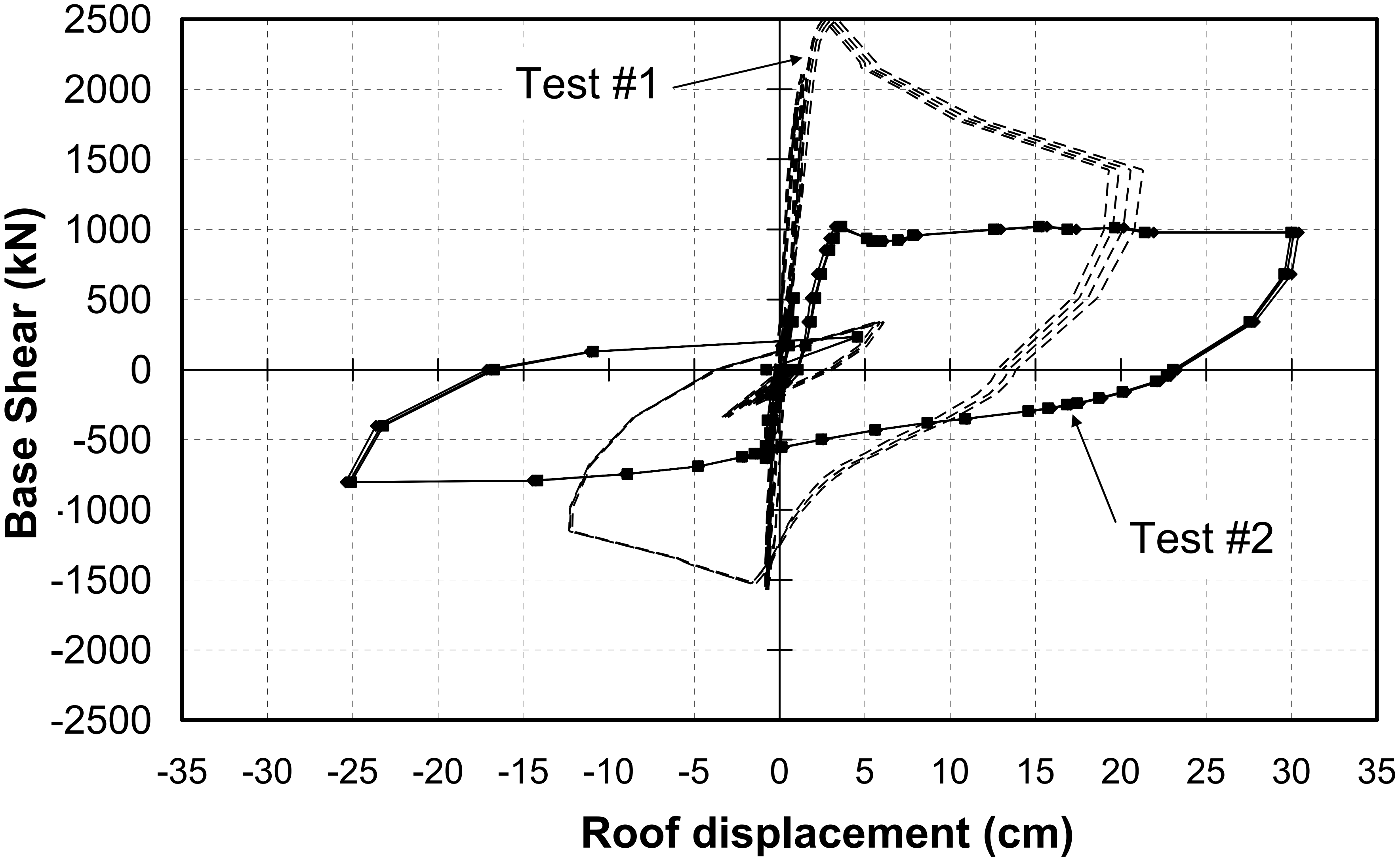


Test #1 - Summary

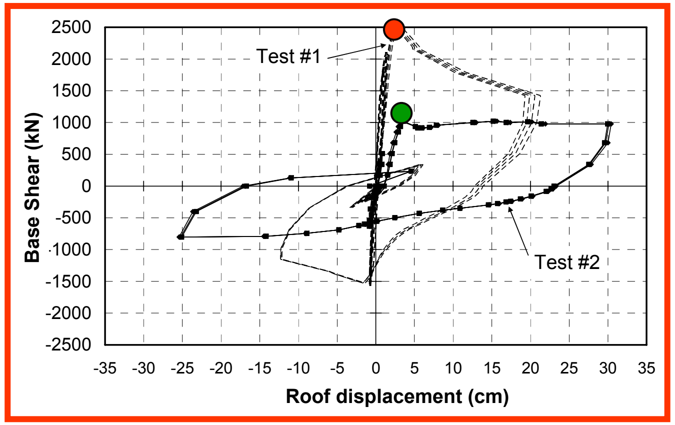


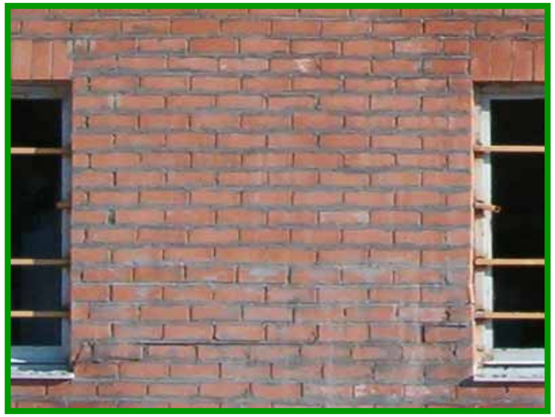
Reconstruction of perimeter infill panels and FRP structural repointing (NSM FRP bars in the bed joints)

Test #2: experimental results

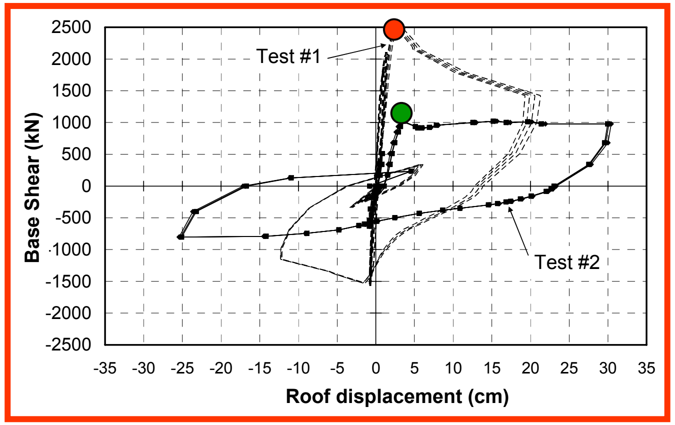


Test #2: experimental results

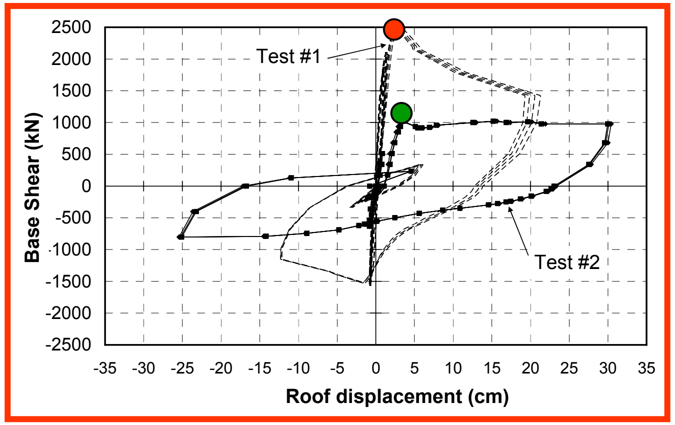




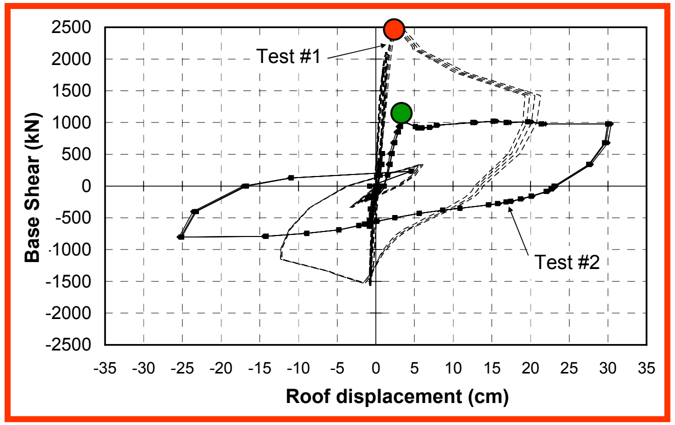
Test #2: experimental results



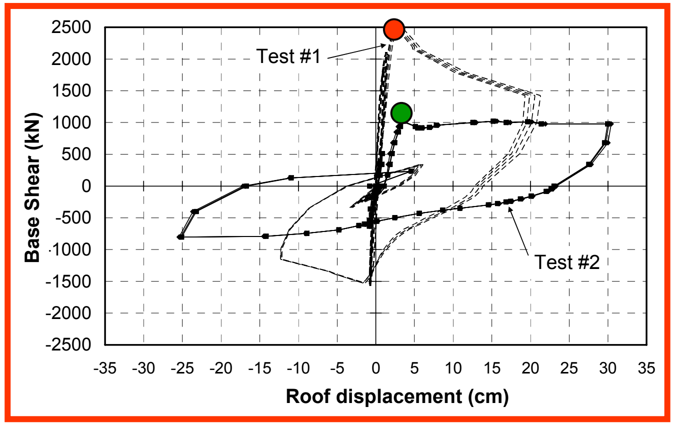
Test #2: experimental results



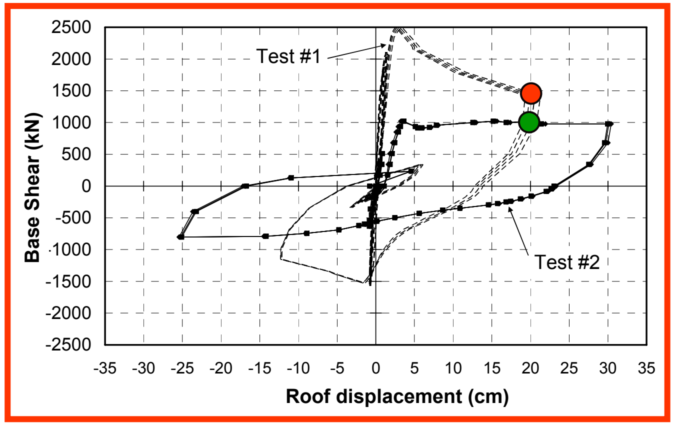
Test #2: experimental results

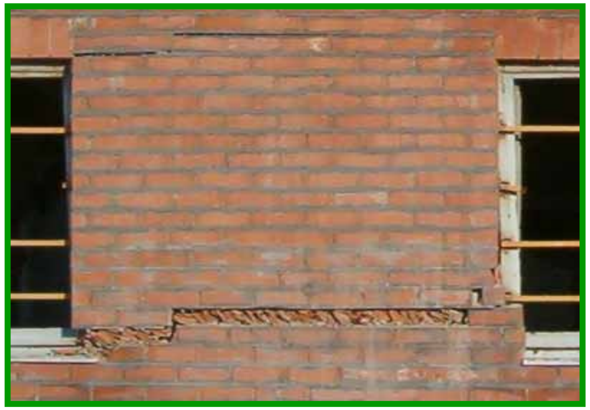


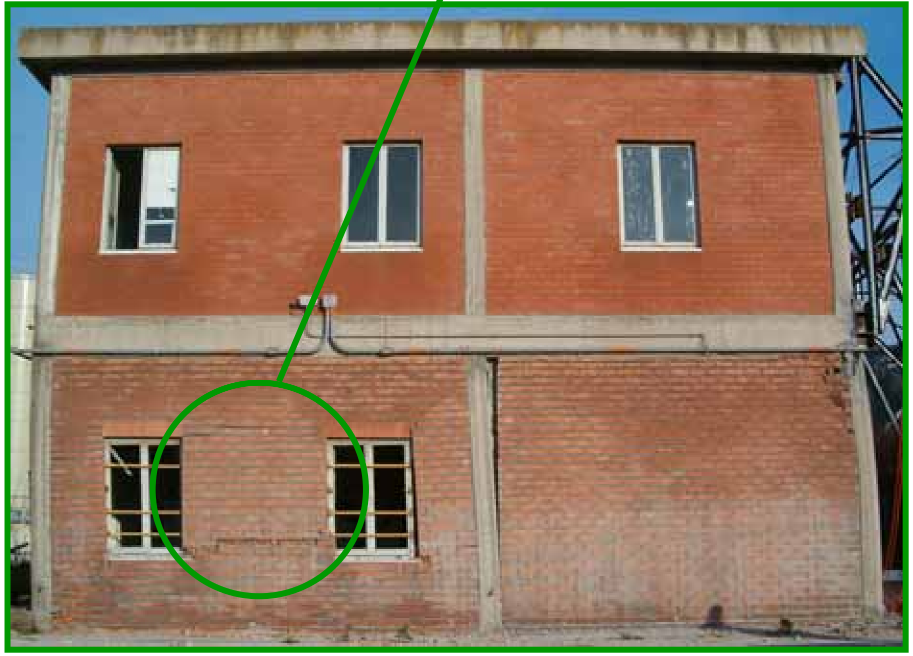
Test #2: experimental results



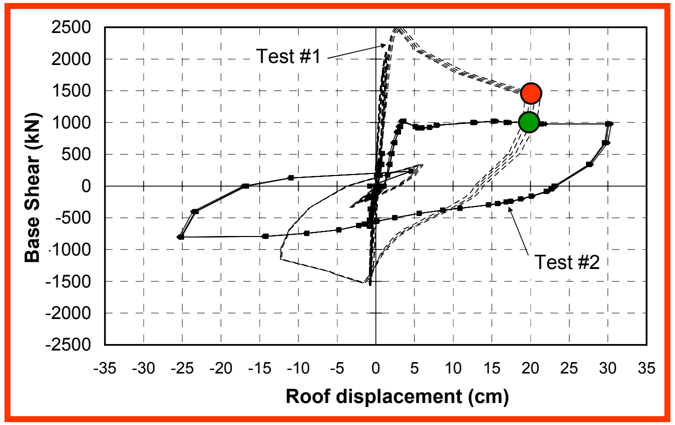
Test #2: experimental results

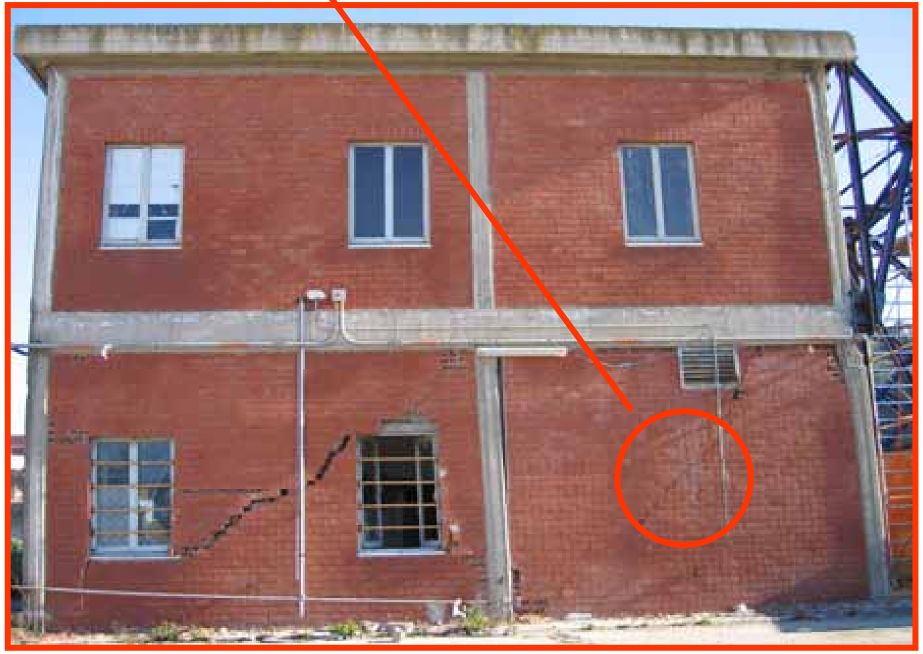




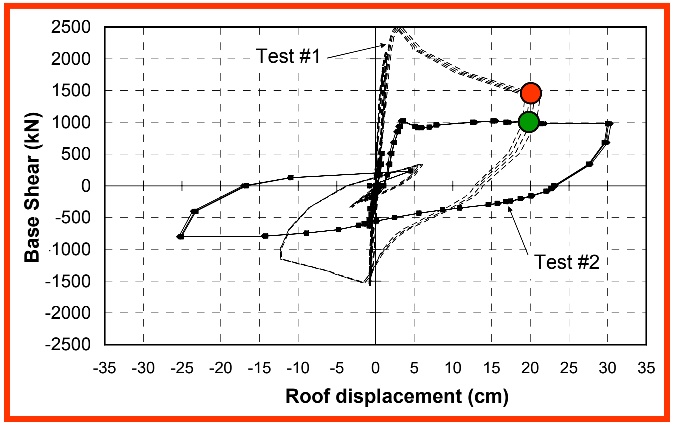


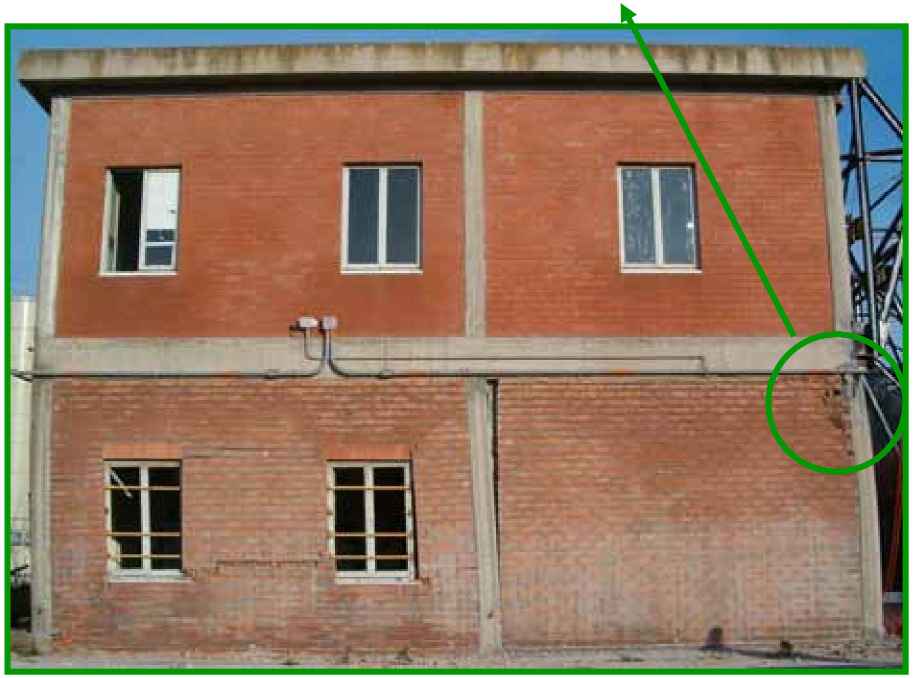
Test #2: experimental results



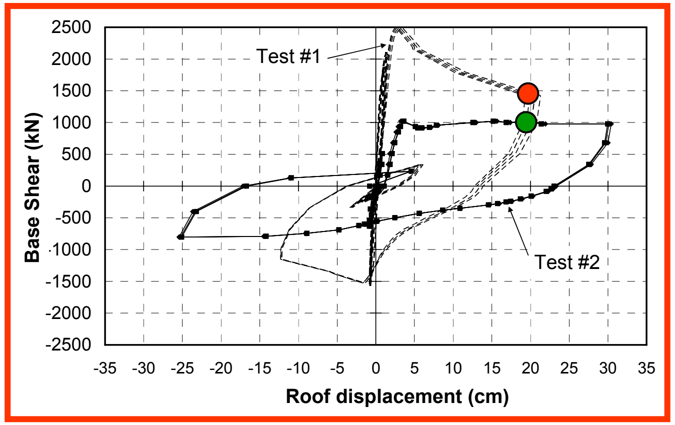


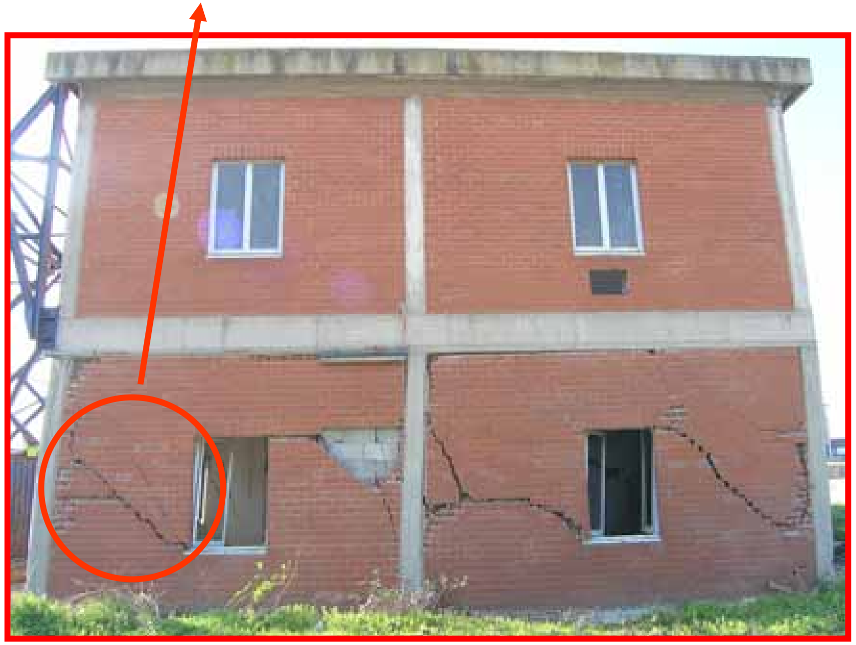
Test #2: experimental results



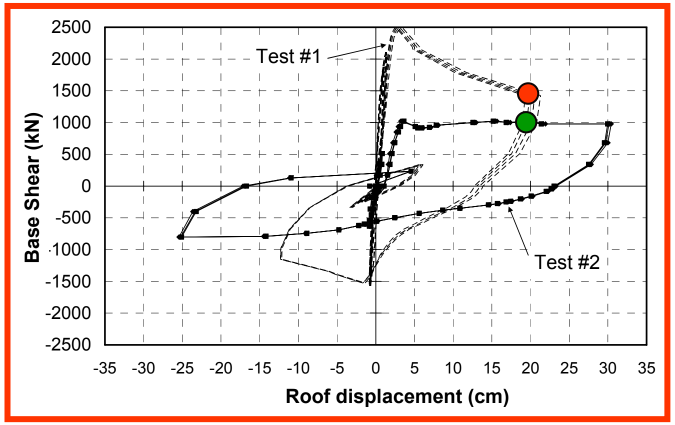


Test #2: experimental results

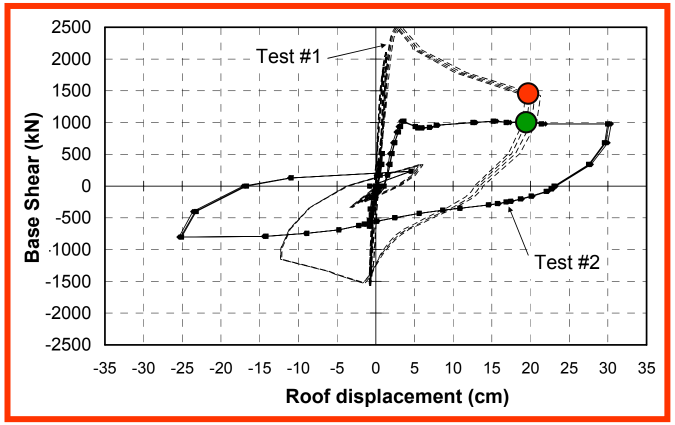




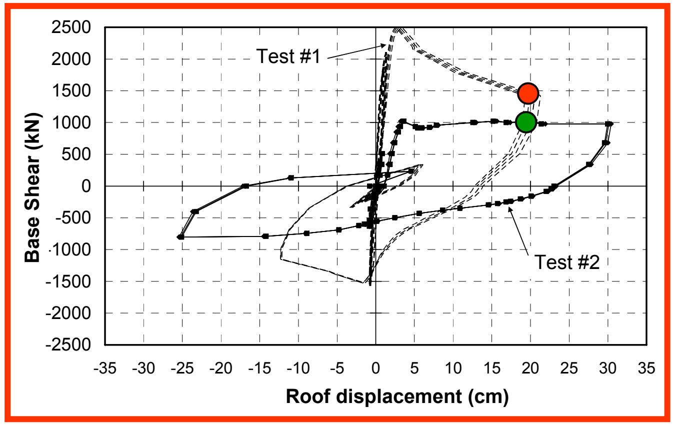
Test #2: experimental results



Test #2: experimental results



Test #2: experimental results



Experimental results - comments

Components contributing to lateral resistance

Test #1: one fully-reversed load cycle into inelastic range (degradation)

1. **RC columns**
2. **Staircase structure**
3. **Perimeter MWs** **(two-sided: clay + light concrete bricks)**
4. **Internal MWs** **(single-sided: light concrete bricks)**

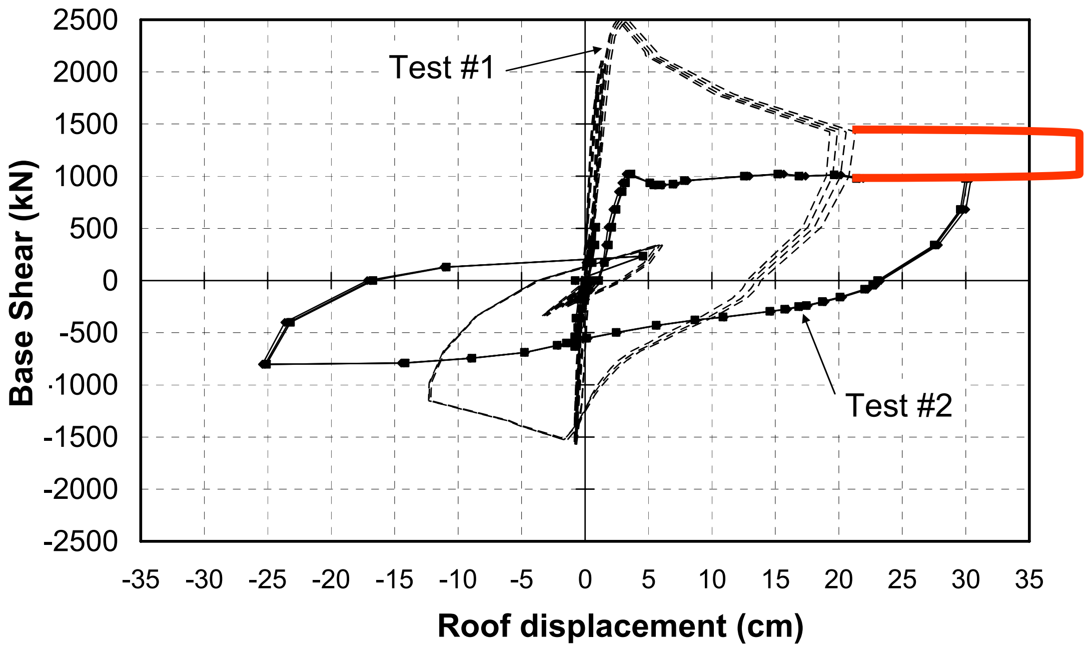
Test #2: lack of contribution of staircase and internal MWs

1. **RC columns** **(only few external columns repaired)**
2. **Perimeter MWs** **(two-sided: clay + light concrete bricks)**

⇩

It explains the strength reduction in the second test

Experimental results - comments



Strength contribution from: (columns + staircase + M~~W~~s) – (columns + M~~W~~s/FRP) = staircase (at large displacements, strength contribution from MWs vanishes and the FRP contribution is considered negligible)

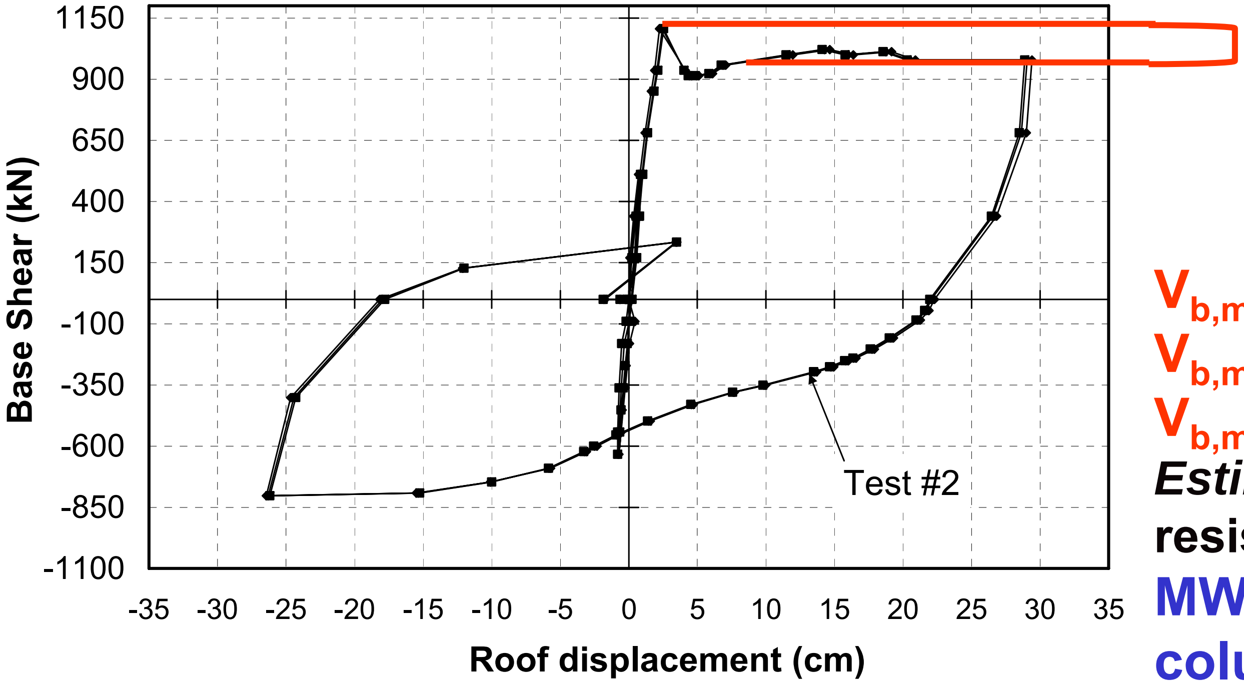
At u_{roof} = 20cm, Test #1 gives: $V_{b,1}$ = 1425kN
Test #2 gives: $V_{b,2}$ = 1000kN

Hence: $V_{b,2}$ - $V_{b,1}$ = 425kN

***Estimated* contributions to resistance:**

Staircase structure → 425/1425=0.30
RC columns + MWs → 1000/1425=0.70

Experimental results - comments



Strength contribution from MWs/FRP

$V_{b,max}$ = 1106kN

$V_{b,min}$ = 978kN (at 30cm)

$V_{b,max} – V_{b,min}$ = 128kN

***Estimated* contributions to resistance:**

MWs/FRP → 978/1106=0.12

columns →1000/1425=0.88

Back-analysis of building response during both test #1 and test #2 will help in quantifying the percentage contribution to strength of different sources

Numerical models must be set-up and calibrated against experimental data

Seismic performance criteria

🟩	*0. - 0.0025 rad*	*Fully Operational*	
🟩	*0.0025 – 0.005 rad*	*Immediate Occupancy*	
🟨	*0.005 – 0.01 rad*	*Moderate damage*	*Life safe*
🟧	*0.01 – 0.02 rad*	*Severe damage*	
🟥	*> 0.02 rad*	*Life danger*	

S_d : T = 475 years (severe damage)

RC frame + MW

$1.5S_d$: T ≈ 1600 years (collapse)

θ_{max} (rad)	Soil A	Soil B,C,E	Soil D
Zone 1	0.007	0.011	0.018
Zone 2	0.005	0.008	0.012
Zone 3	0.003	0.005	0.007
Zone 4	0.001	0.002	0.002

θ_{max} (rad)	Soil A	Soil B,C,E	Soil D
Zone 1	0.011	0.017	0.027
Zone 2	0.008	0.012	0.019
Zone 3	0.005	0.007	0.011
Zone 4	0.002	0.002	0.003

Simplified analysis of seismic demand - results

RC frame + MW

S_d : T = 475 years
(severe damage)

θ_{max} (rad)	Soil A	Soil B,C,E	Soil D
Zone 1	0.007	0.011	0.018
Zone 2	0.005	0.008	0.012
Zone 3	0.003	0.005	0.007
Zone 4	0.001	0.002	0.002

$1.5S_d$: T ≈ 1600 years
(collapse)

θ_{max} (rad)	Soil A	Soil B,C,E	Soil D
Zone 1	0.011	0.017	0.027
Zone 2	0.008	0.012	0.019
Zone 3	0.005	0.007	0.011
Zone 4	0.002	0.002	0.003

RC frame

S_d : T = 475 years
(severe damage)

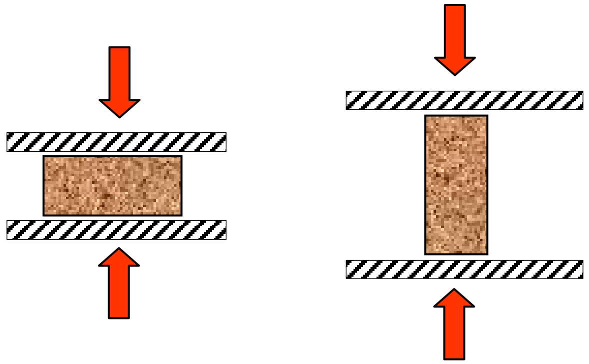
θ_{max} (rad)	Soil A	Soil B,C,E	Soil D
Zone 1	0.010	0.016	0.027
Zone 2	0.007	0.012	0.019
Zone 3	0.004	0.007	0.011
Zone 4	0.001	0.002	0.003

$1.5S_d$: T ≈ 1600 years
(collapse)

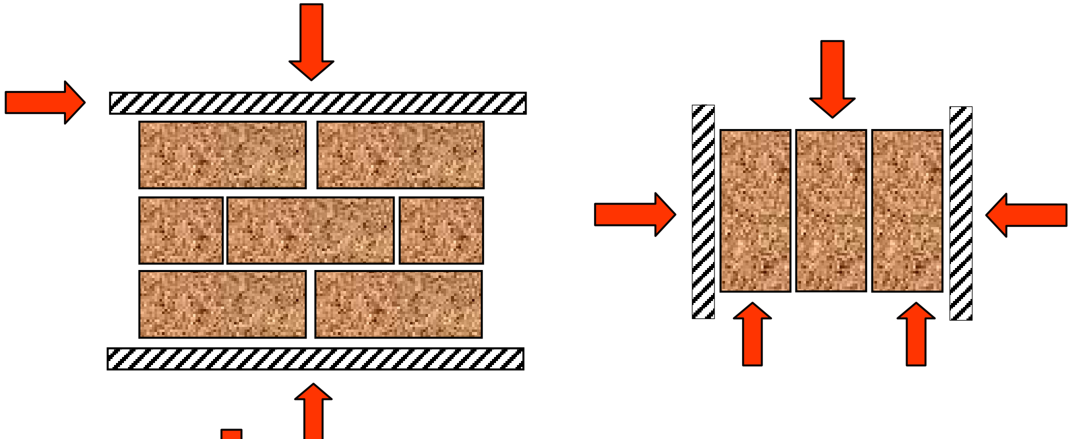
θ_{max} (rad)	Soil A	Soil B,C,E	Soil D
Zone 1	0.016	0.024	0.041
Zone 2	0.011	0.017	0.029
Zone 3	0.007	0.010	0.017
Zone 4	0.002	0.003	0.005

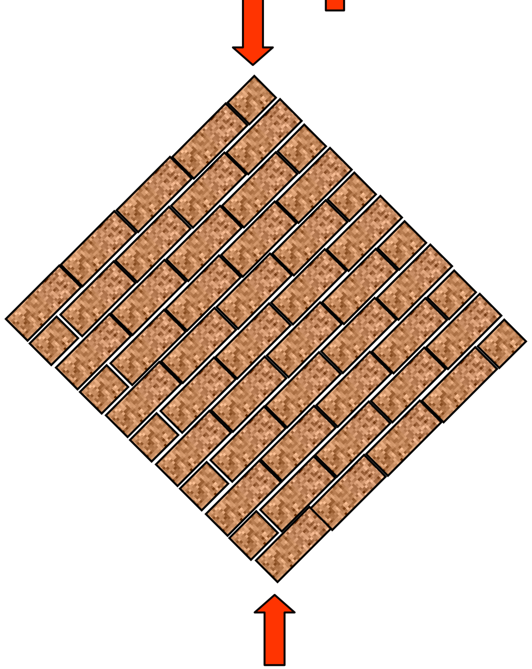
Tests on masonry specimens

Tests on single blocks

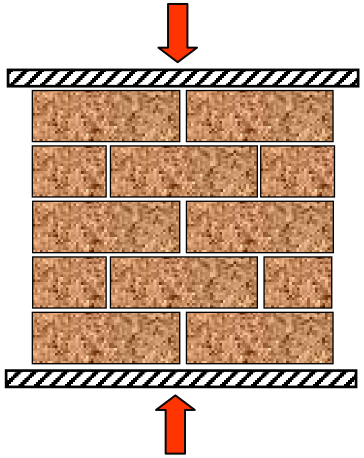


Shear tests on sub-assemblages





Compression tests on sub-assemblages



Tests on masonry specimens - results

Original masonry (test #1)

Bricks: $f_{b,m}$ = 17.1MPa; $f_{b,k}$= 10.0MPa ← **Experimental results (6 specimens)**

Mortar: $f_{m,m}$ = 2.5MPa (Italian standard M4)

Masonry: $f_{m,m}$ = 6.6MPa

Bricks: $f_{b,m}$ = 3.1MPa ← **Only 3 specimens**

Mortar: $f_{m,m}$ = 2.5MPa (Italian standard M4)

Masonry: $f_{m,m}$ = 1.4MPa

Masonry:

$$f_w = 0.9\frac{f_b\left(f_{bt}+\alpha f_m\right)}{U\left(f_{bt}+\alpha f_b\right)}$$

$$\alpha = \frac{h_m}{4.1 h_b} \qquad U = 2 - f_m/34.5 \qquad f_m < 27.6$$

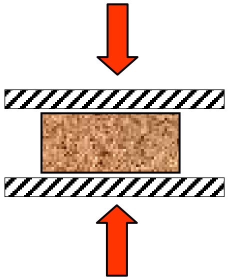
Non-uniform stress distribution factor

f_m → mortar compression strength
f_b → brick compression strength
f_{bt} → brick tensile strength
h_m → mortar joint depth
h_b → brick depth

Hilsdorf (Paulay & Priestley, 1992)

Tests on masonry specimens - results

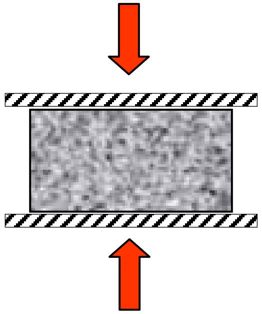
Original masonry (test #2)



Bricks: $f_{b,m}$ = 20.7MPa; $f_{b,k}$= 9.5MPa ← Experimental results (6 specimens)

Mortar: $f_{m,m}$ = 8.0MPa (Italian standard M2)

Masonry: $f_{m,m}$ = 6.6MPa



Bricks: $f_{b,m}$ = 3.1MPa

Mortar: $f_{m,m}$ = 8.0MPa (Italian standard M2)

Masonry: $f_{m,m}$ = 1.4MPa

Masonry:

$$f_w = 0.9 \frac{f_b \left(f_{bt} + \alpha f_m \right)}{U \left(f_{bt} + \alpha f_b \right)}$$

$$\alpha = \frac{h_m}{4.1 h_b} \qquad U = 2 - f_m / 34.5$$

$$f_m < 27.6$$

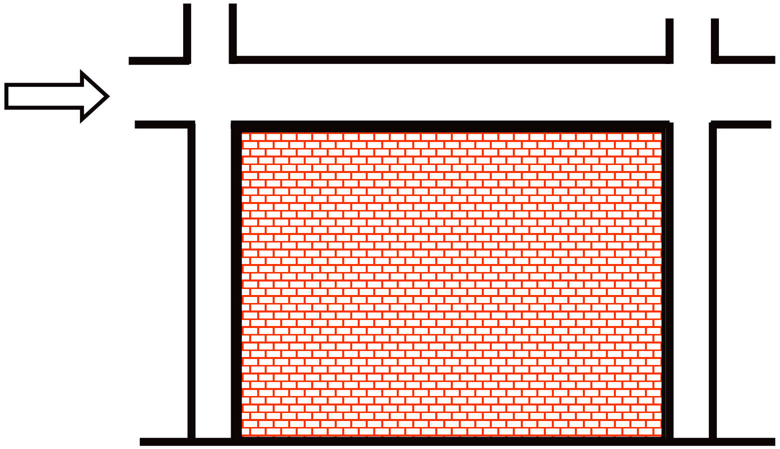
Non-uniform stress distribution factor

f_m → mortar compression strength
f_b → brick compression strength
f_{bt} → brick tensile strength
h_m → mortar joint depth
h_b → brick depth

Hilsdorf (Paulay & Priestley, 1992)

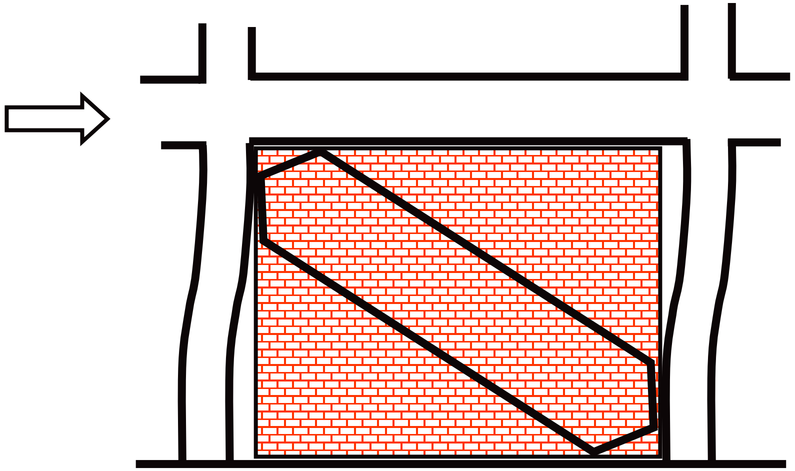
MW modelling (without openings)

Basic concepts

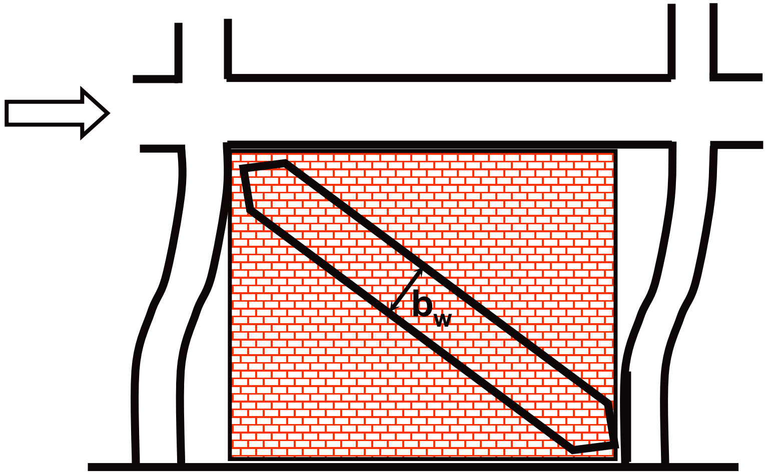


Initial stiffness → composite shear wall

(with partial interaction because of micro-cracking, initial separation,…)



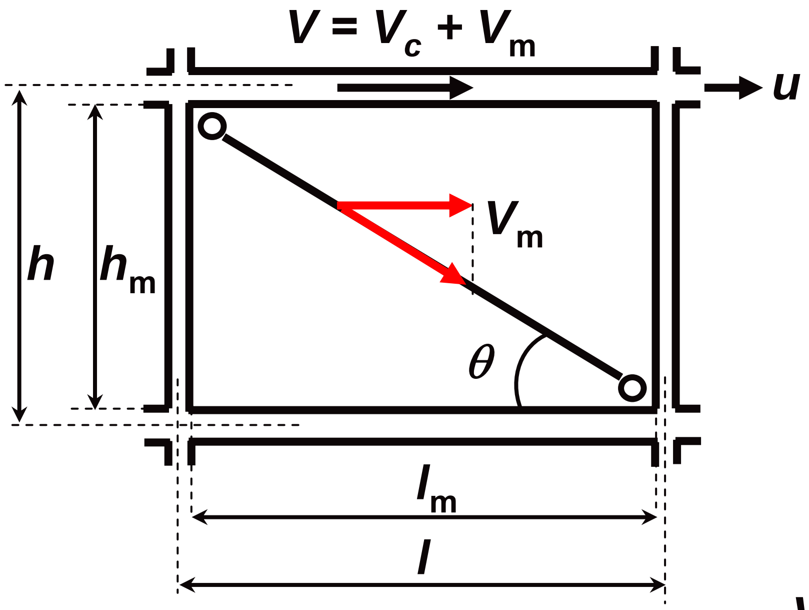
Strength → equivalent strut

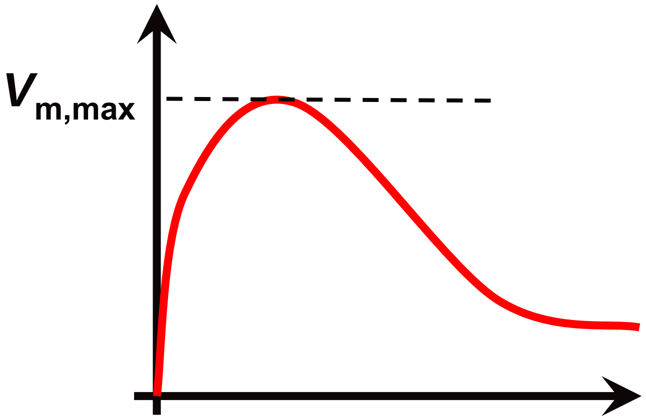


The equivalent strut width (contact area) reduces as far as the displacement increases.

MW modelling (without openings)

Basic features





$$V_{m,max} = min \begin{cases} \textit{Sliding failure} \\ \textit{Compression failure (crushing of the equivalent strut)} \\ \textit{Diagonal tension failure} \end{cases}$$

Diagonal tension failure

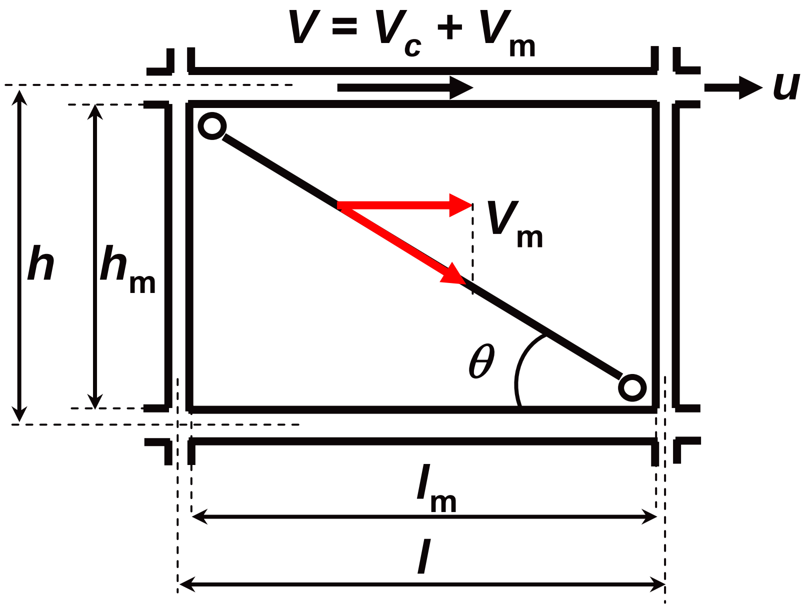
$$V_{m,T} = \frac{S_s l t}{0.6}$$ ***(Stafford Smith et al., 1978)***

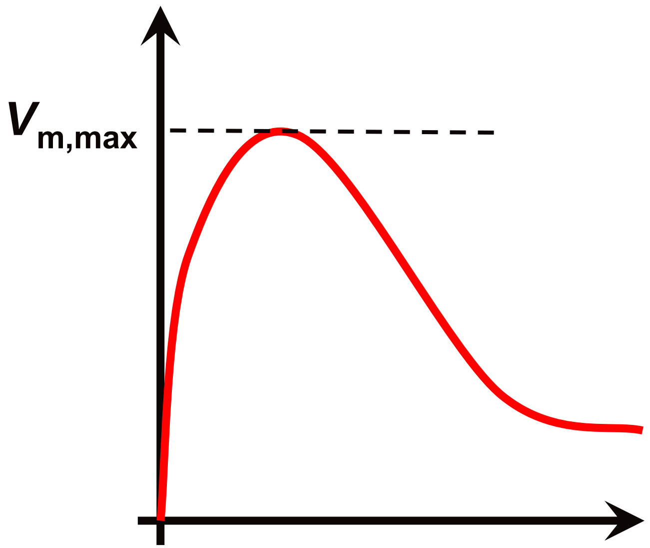
Sliding failure $$V_{m,s} = \tau_0 l_m t + \mu N$$

$$N = E_m l_m t \left(\frac{u}{h} \right)^2$$ ***(FEMA 306, 1998)*** $$\tau_0 = 0.04 f_m (kg_f / cm^2)$$ ***(Paulay & Priestley, 1992)***

MW modelling (without openings)

Basic features





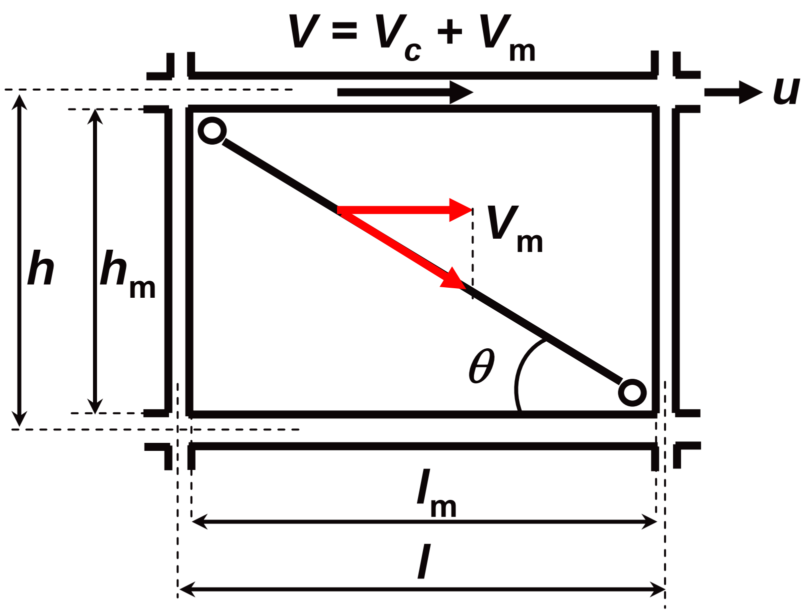
Compression failure $V_{m,cr} = atf_m \cos\theta$

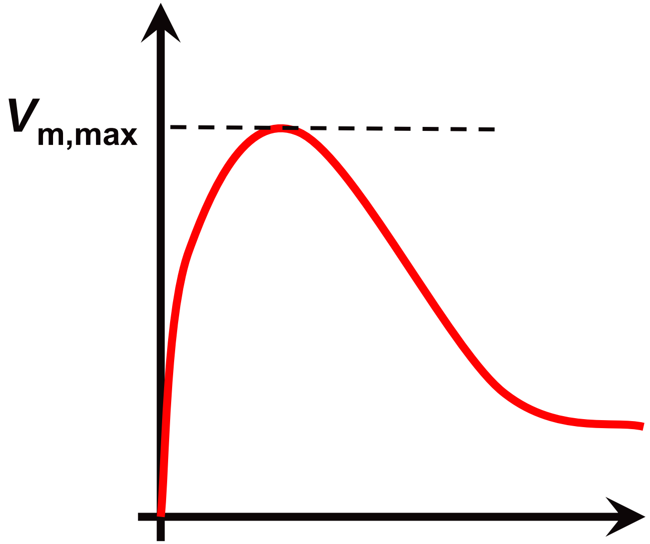
$$a = 0.175(\lambda h)^{-0.4} d_m \qquad d_m = \sqrt{l_m^2 + h_m^2} \qquad \lambda = \left(\frac{E_m t \sin 2\theta}{4E_c I_g h_m}\right)^{1/4}$$

Stafford Smith et al. 1966; Mainstone, 1974; Klingner & Bertero, 1978 ; FEMA 306, 1998)

MW_FRP modelling (without openings)

Basic features





Diagonal tension or sliding failure

$$V_{mf,cr} = V_m + f_f A_f k_{\varpi}$$

Compression failure

$$V_{MW\_FRP,cr} = 1.6 V_{MW,cr}$$

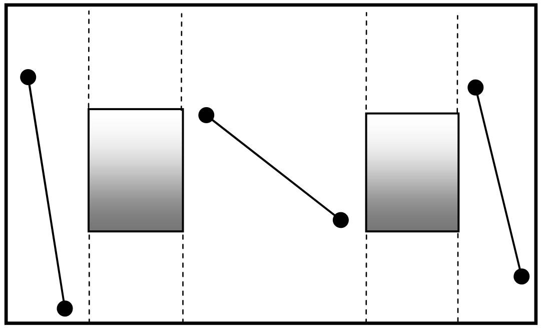
(test results by Grando, 2002)

Design guidelines for the strengthening…using FRP systems – University of Missouri-Rolla, March 2005

MW_FRP modelling (with openings)

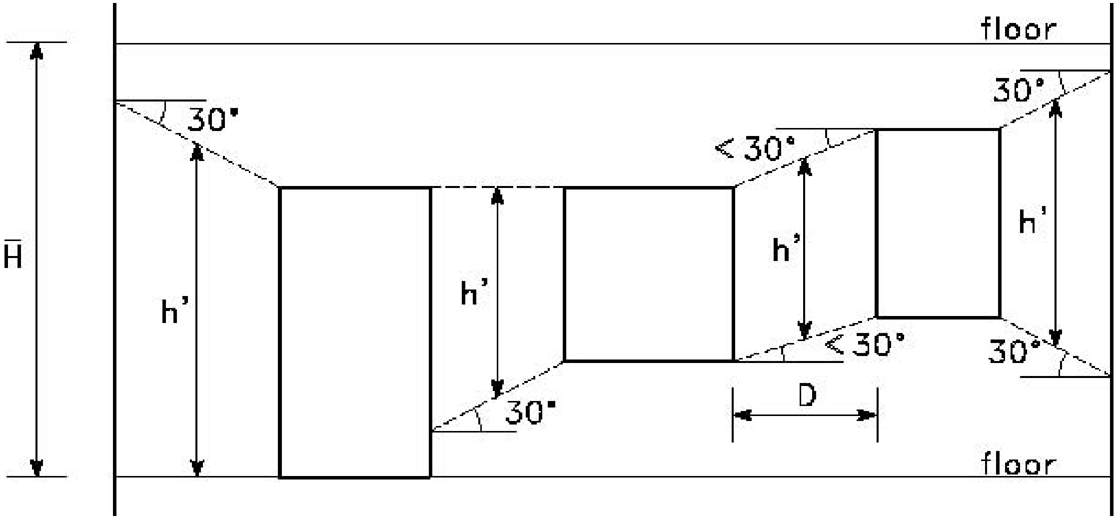
Basic features

⟺



Each sub-panel is substituted by an equivalent strut. The height of the sub-panel is obtained by a suggestion given by Dolce (1989).

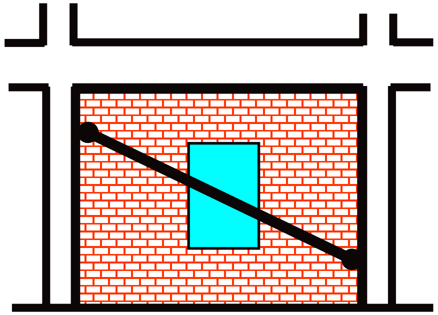
$$H_{eff} = h' + \frac{1}{3} D \frac{(\bar{H} - h')}{h'}$$



MW_FRP modelling (with openings)

Basic features

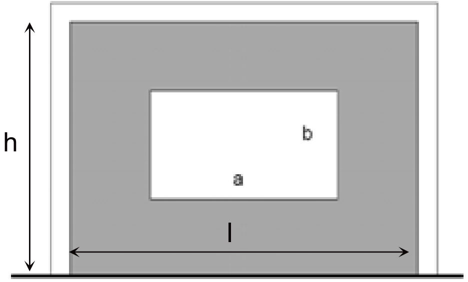
Al-Chaar, 2002



$$R = 0.6\left(\frac{A_{open}}{A_{panel}}\right)^2 - 1.6\left(\frac{A_{open}}{A_{panel}}\right) + 1$$

$$A_{open} \leq 60\%\ A_{panel}$$

GNDT (National Italian Team for Seismic Protection)



$$A_a = 100(ab)/(hl);\ A_c = 100(a/l)$$

Unstrengthened $\text{NR: } r_{ac} = 0.78e^{-0.322 \ln A_a} + 0.93e^{-0.762 \ln A_c}$

Intermediate $\text{SR: } r_{ac} = 1.04e^{-0.322 \ln A_a} + 1.51e^{-0.762 \ln A_c}$

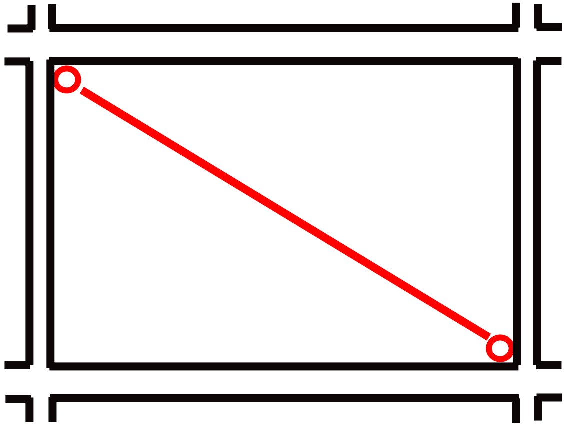
Strengthened $\text{RE: } r_{ac} = 1.25e^{-0.322 \ln A_a} + 1.97e^{-0.762 \ln A_c}$

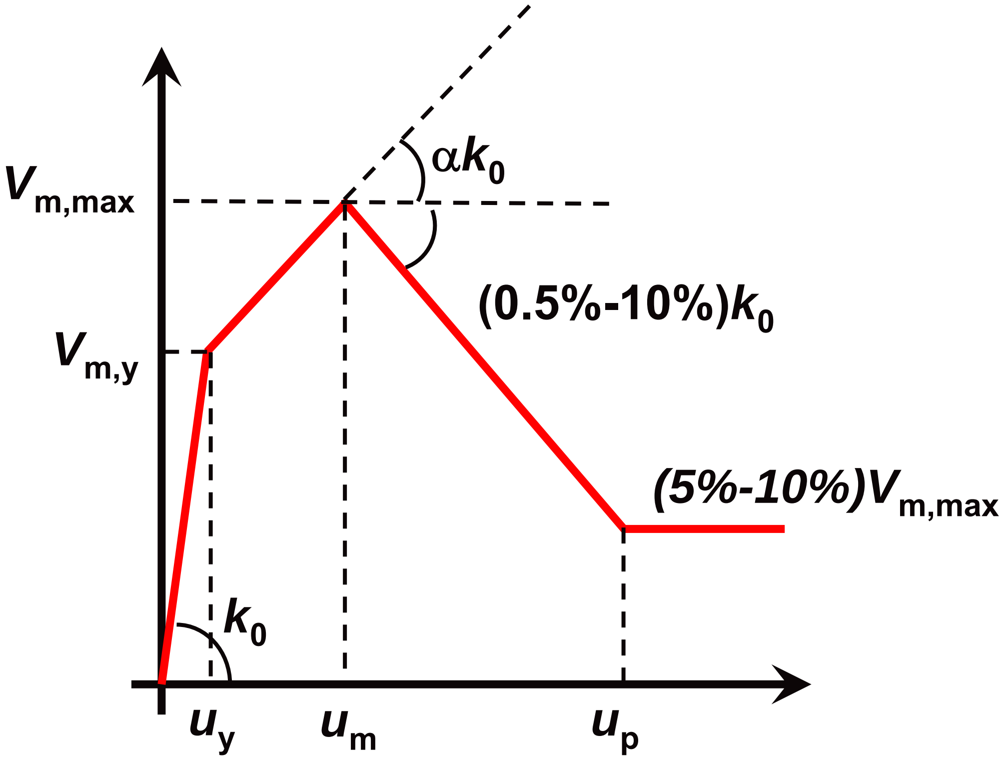
$r_{ac} \leq 1$; $A_a \leq 25\%$; $A_v \leq 40\%$

If a = l then the panel contribution is neglected

MW modelling

Panagiotakos & Fardis, 1994





$$k_0 = \frac{G_m t_m l_m}{h_m} \qquad V_{m,y} = f_{ms} t_m l_m$$

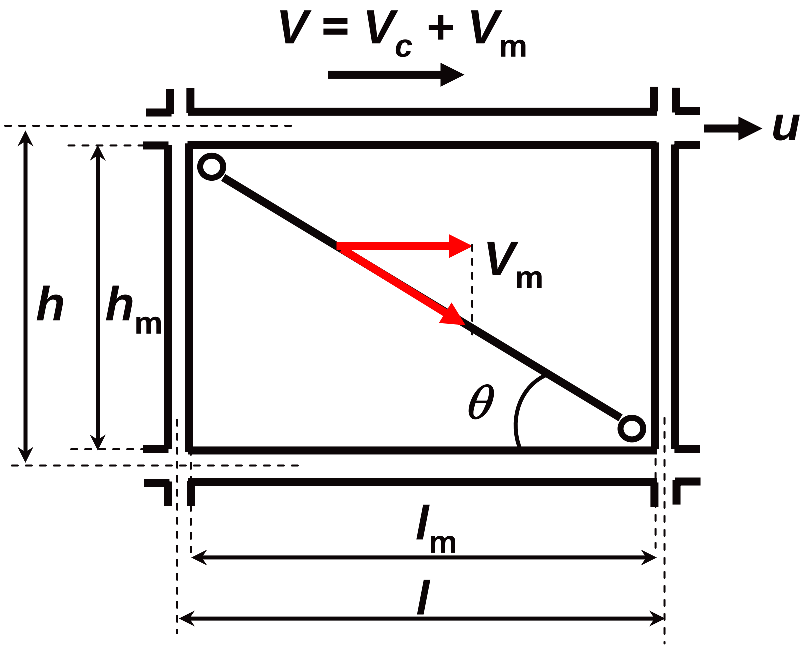
f_{ms} = shear strength according to diagonal compression test

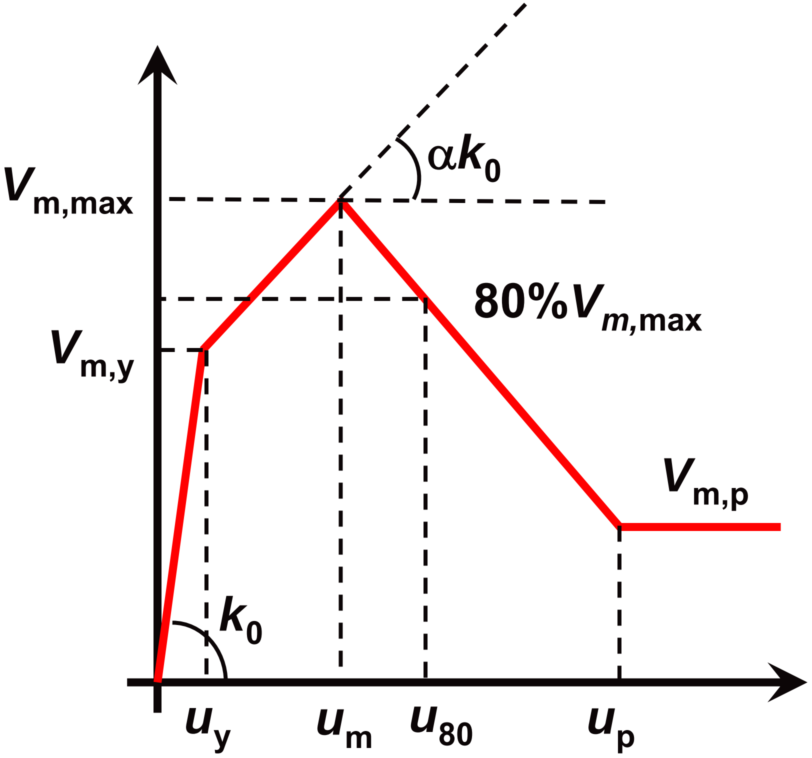
$$\alpha k_0 = \frac{E_m t_m a}{d_m} \cos^2 \theta \qquad V_{m,max} = 1.30 V_{m,y}$$

Openings empirically taken into account by reducing the strut width

MW modelling

Mostafaei & Kabeyasawa, 2004





$V_{m,max}$ = maximum strength of the wall = *min*

- ***Sliding failure***
- ***Compression failure***
  (of the equivalent strut)

$$u_m = \frac{\varepsilon_m d_w}{\cos\theta}$$

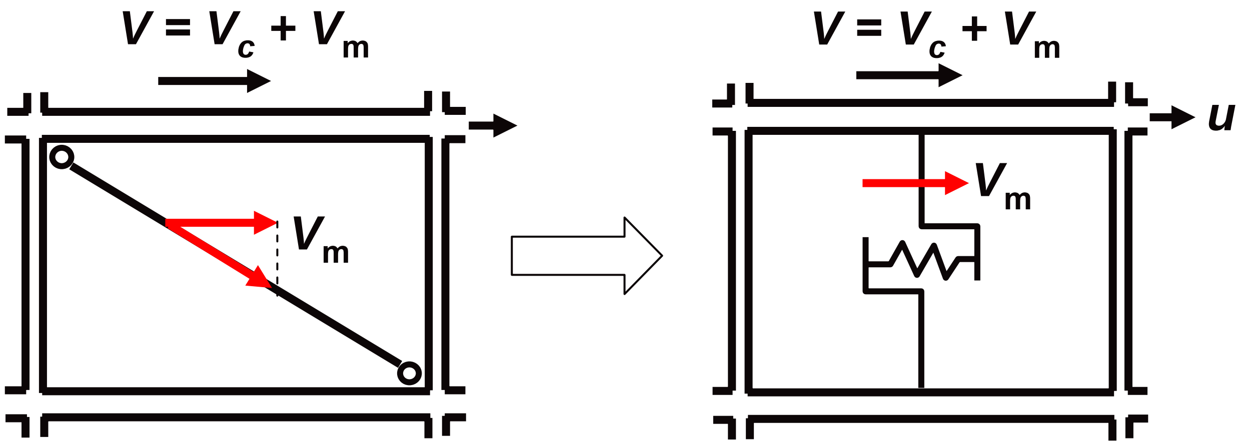
ε_m = compression strain of the equivalent strut at maximum stress

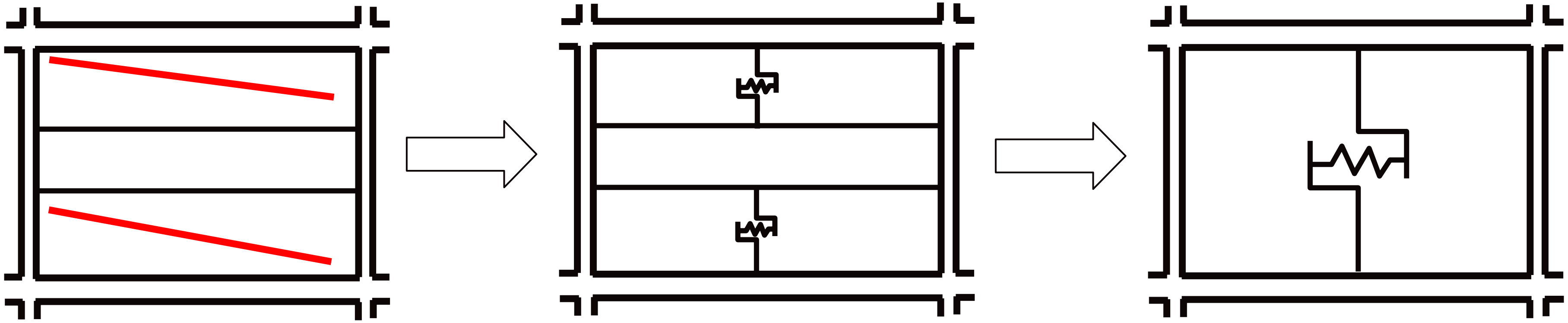
$$\theta = arctg\left(\frac{h_w}{l_w}\right) \quad d_w = \sqrt{l_w^2 + h_w^2}$$

$$k_0 = 2\frac{V_{m,max}}{u_m};\ \alpha = 0.20 \ \Longrightarrow V_{m,y} = \frac{V_{m,max} - \alpha k_0 u_m}{1-\alpha} = 0.75 V_{m,max} \ (V_{m,max} = 1.33 V_{m,y})$$

MW modelling

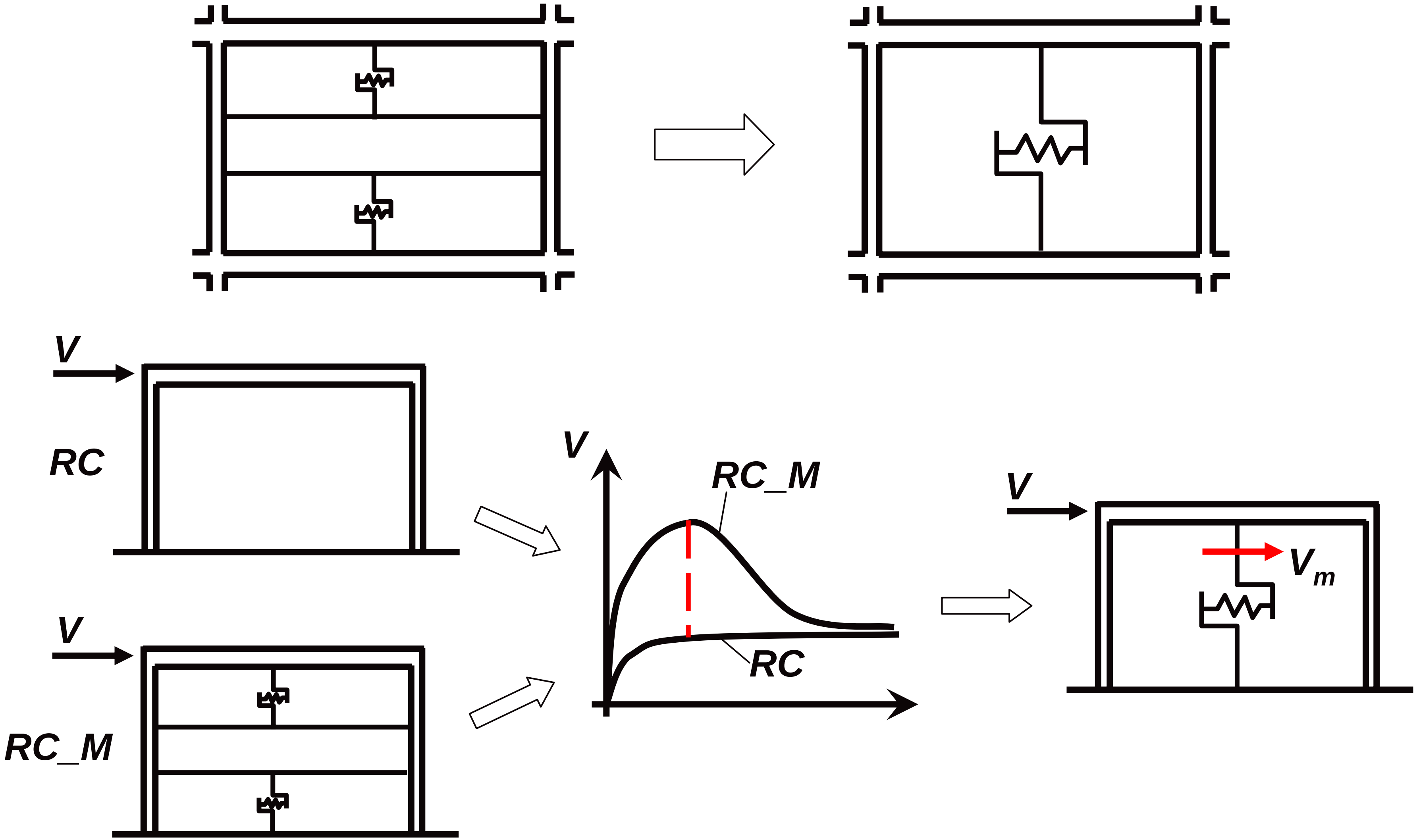
Mostafaei & Kabeyasawa, 2004





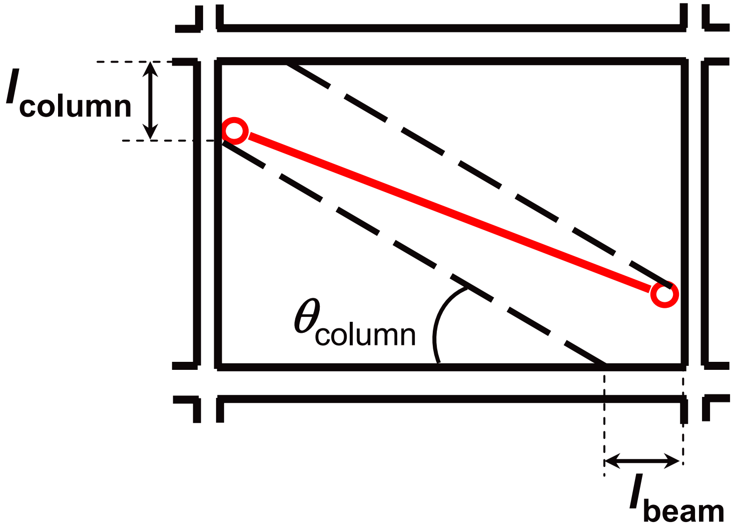
MW modelling

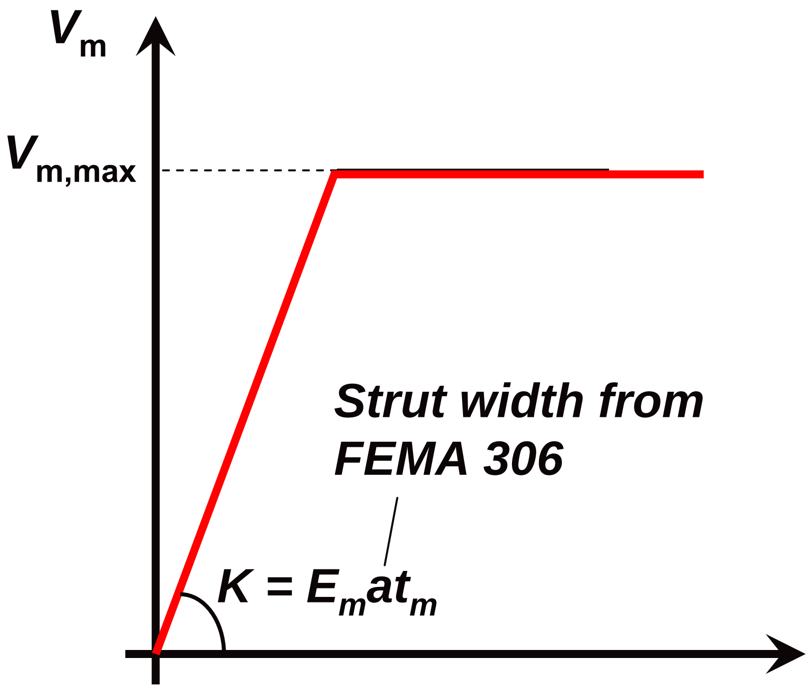
Mostafaei & Kabeyasawa, 2004



MW modelling

Al-Chaar, 2002





Strut width from FEMA 306

$$l_{column} = \frac{a}{\cos\theta_{column}} \qquad tg\theta_{column} = \frac{h - \frac{a}{\cos\theta_{column}}}{l}$$

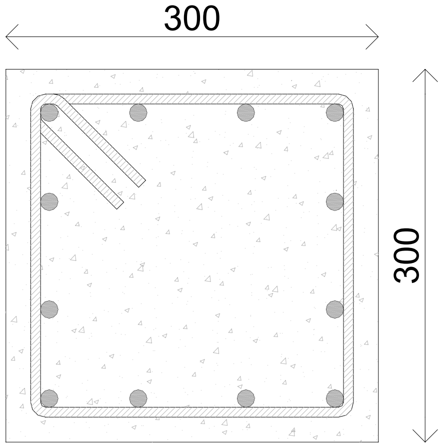
Openings and existing infill damage are considered by reducing the diagonal strut width

$$a_{red} = aR_1R_2 \qquad R_1 = 0.6\left(\frac{A_{open}}{A_{panel}}\right)^2 - 1.6\left(\frac{A_{open}}{A_{panel}}\right) + 1 \qquad R_2$$

Table from FEMA 306

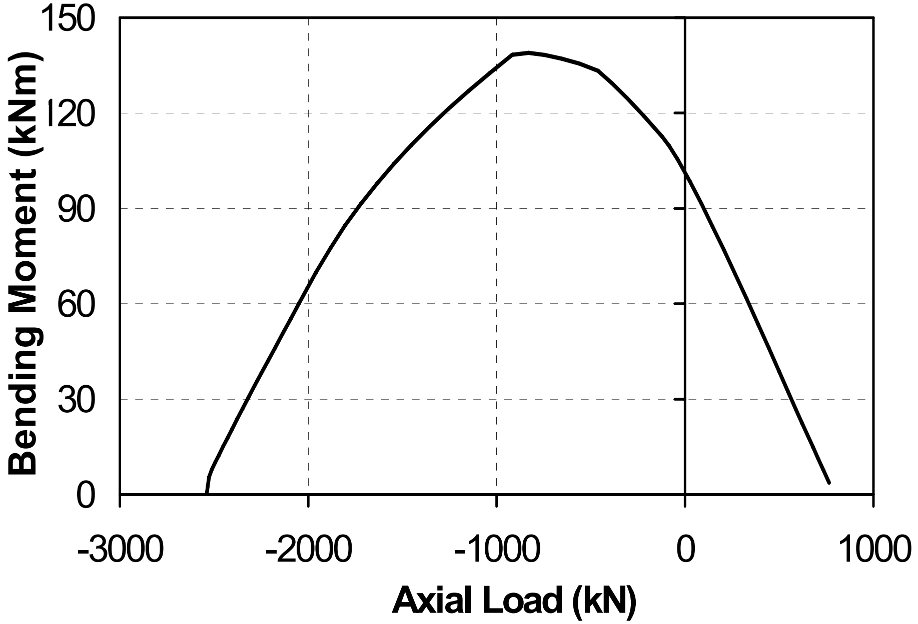
RC modelling

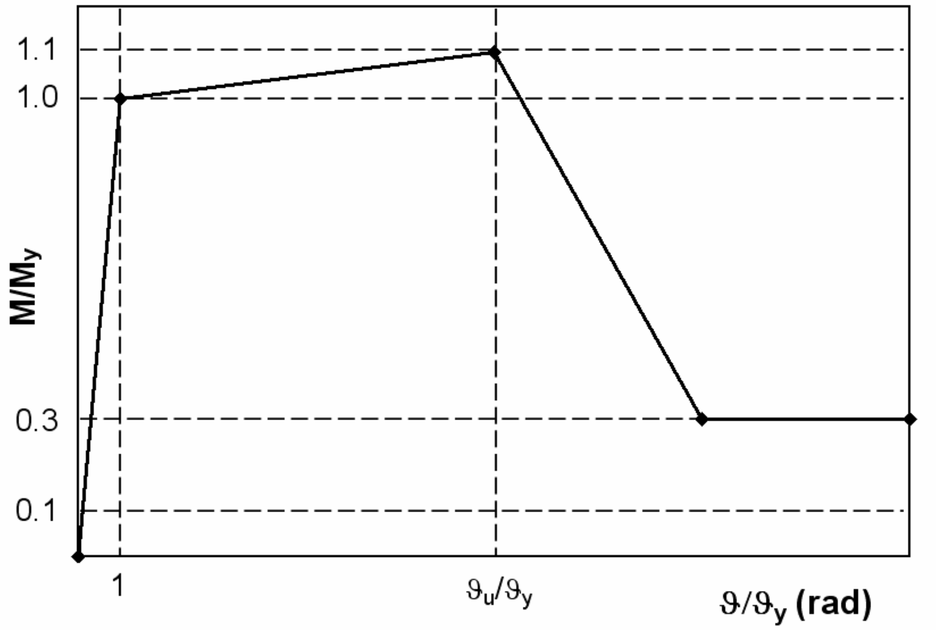
Column cross section



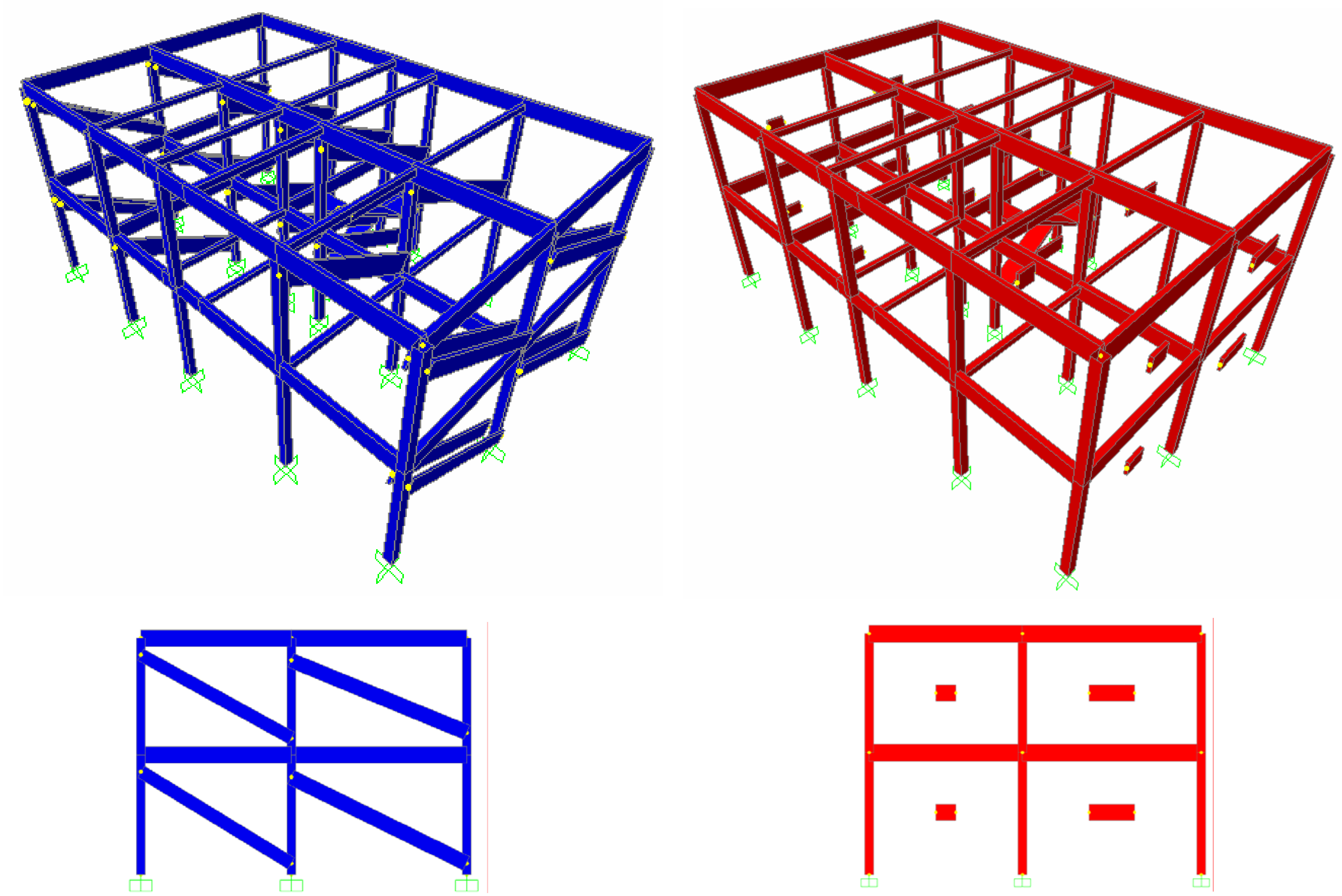
Long 14mm
St. 20cm

Plastic domain

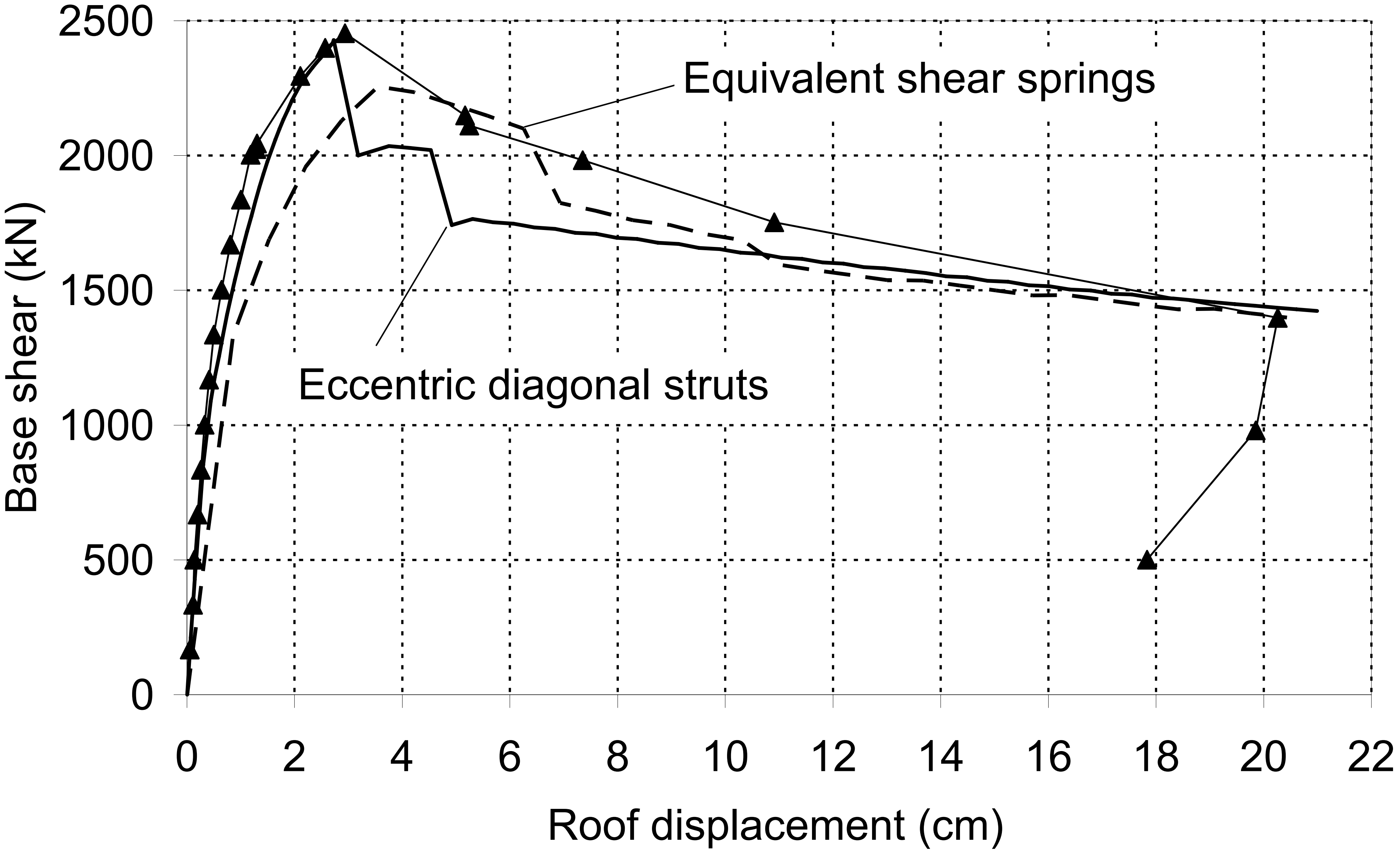




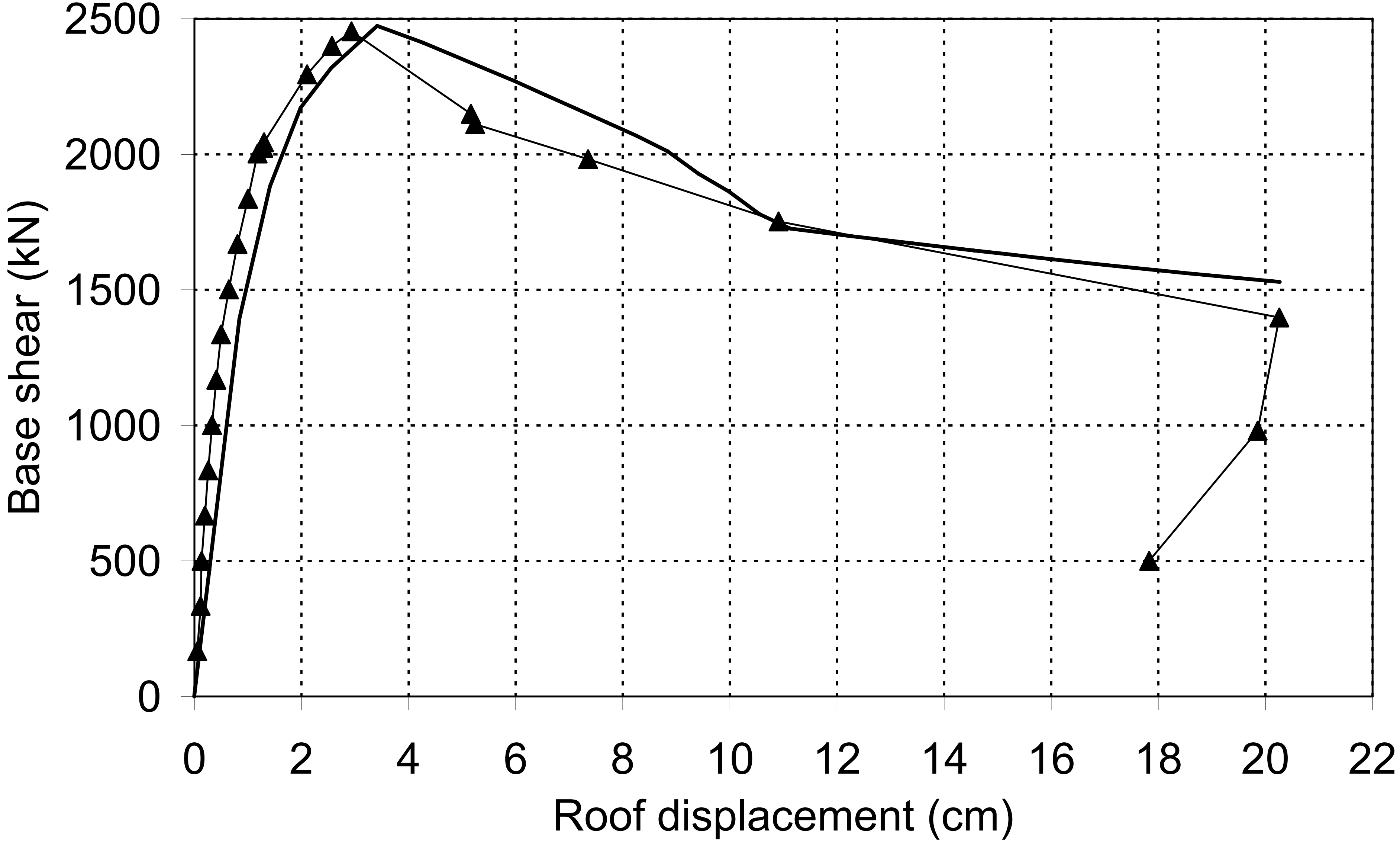
Numerical modelling – test #1



Numerical modelling – test #1

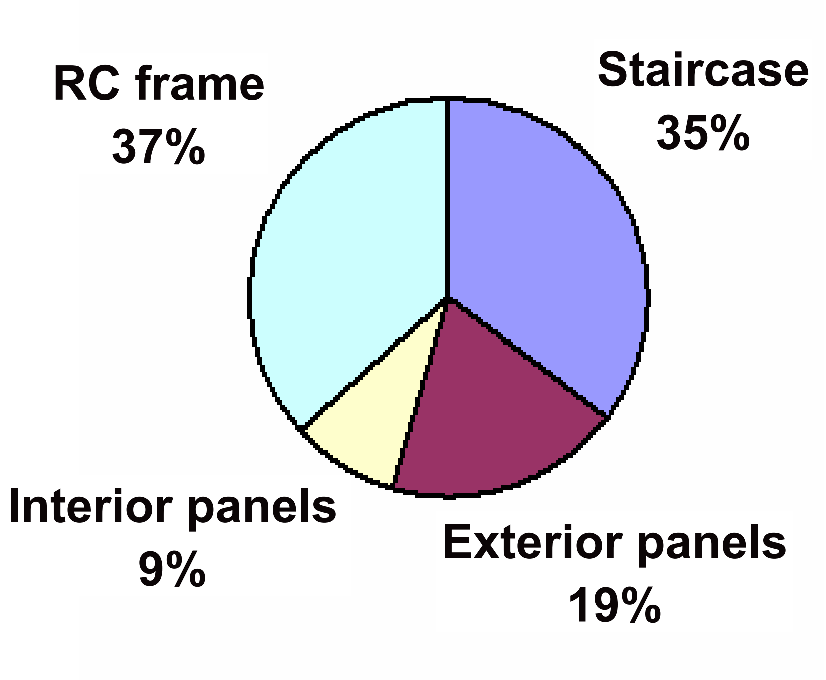


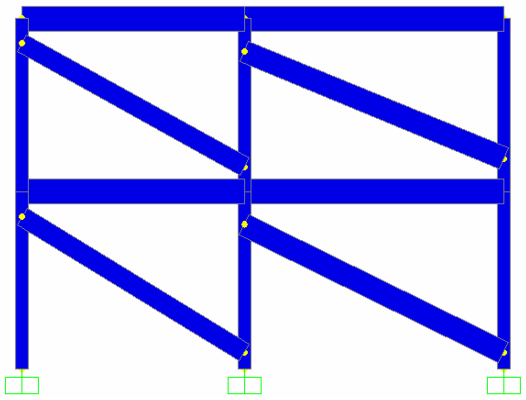
Numerical modelling – test #1



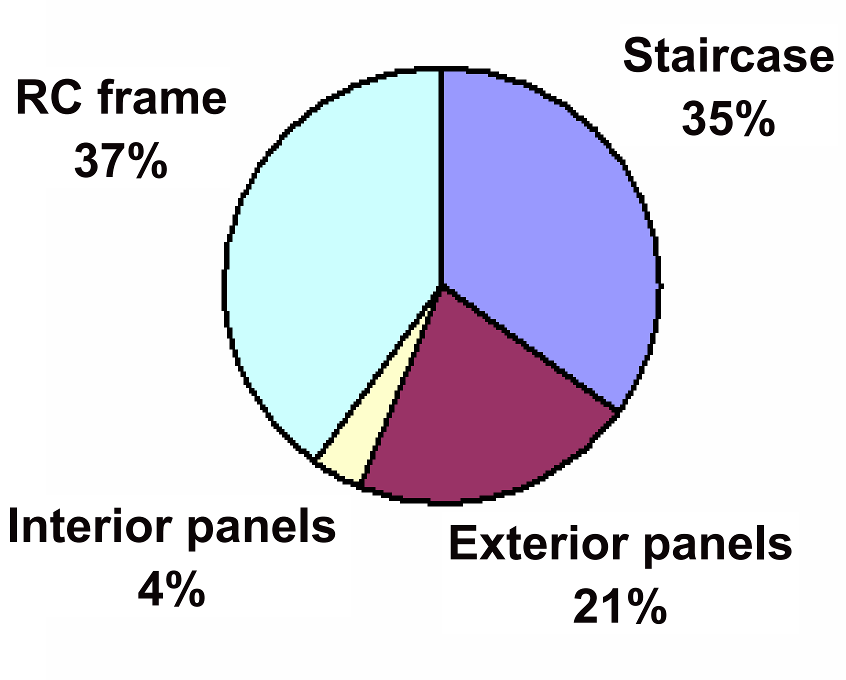
Numerical modelling – test #1

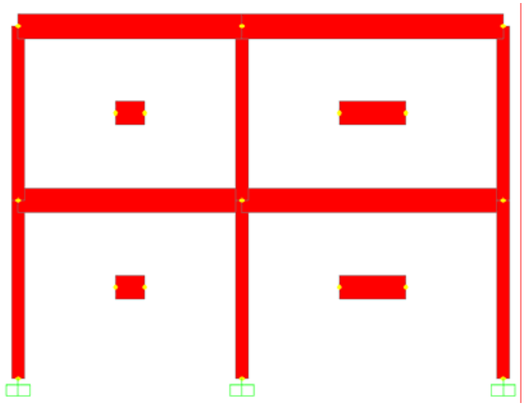
Diagonal struts





Shear springs





Numerical modelling – test #2