International Workshop:
"Role of research infrastructures in seismic rehabilitation"

Effects of local strengthening interventions on the global seismic performance of existing RC structures

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Introduction

Recent earthquake events have clearly shown the high vulnerability of existing reinforced concrete (RC) structures

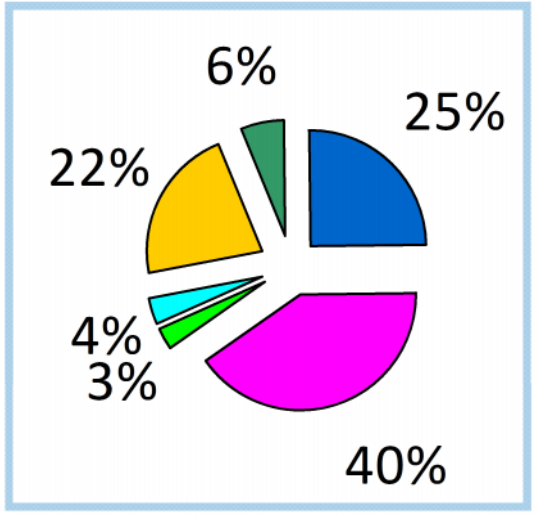
- poor concrete quality;
- design for gravity loads only or with reference to obsolete seismic provisions;
- lacking of adequate transverse steel reinforcement at members' ends and on partially confined beam-column joints;
- poor attention to details;

L'Aquila 2009

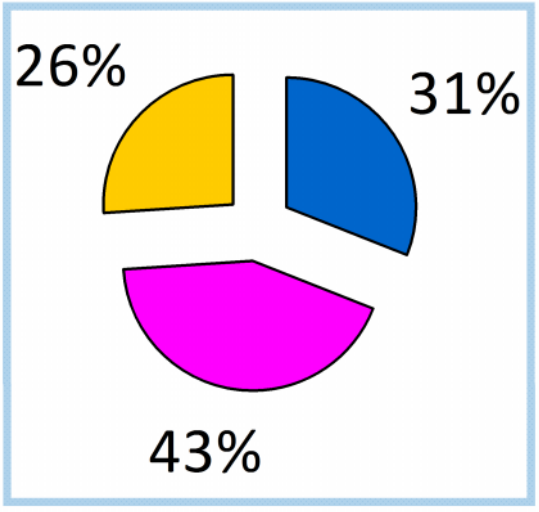
Introduction

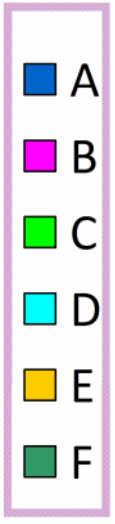
Aftermath L'Aquila earthquake in situ inspections to assess damages

On all types of construction



On RC structures





Rating **A**

No damage

A

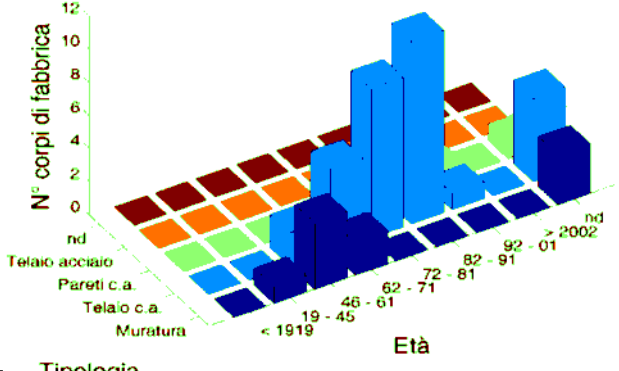
B

Rating **E**

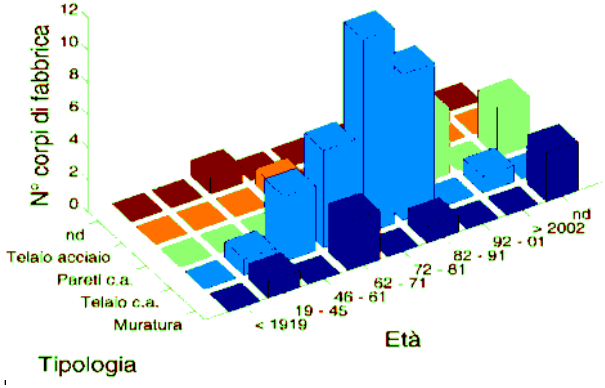
Exstensive damage

School buildings

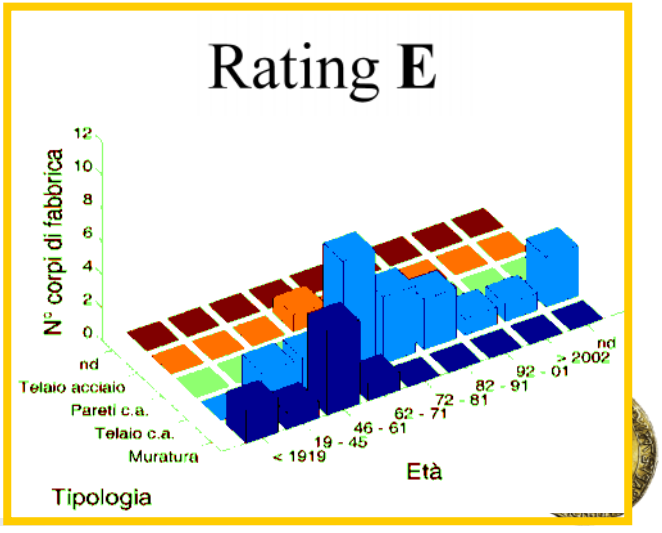
Rating **A**



Rating **B**

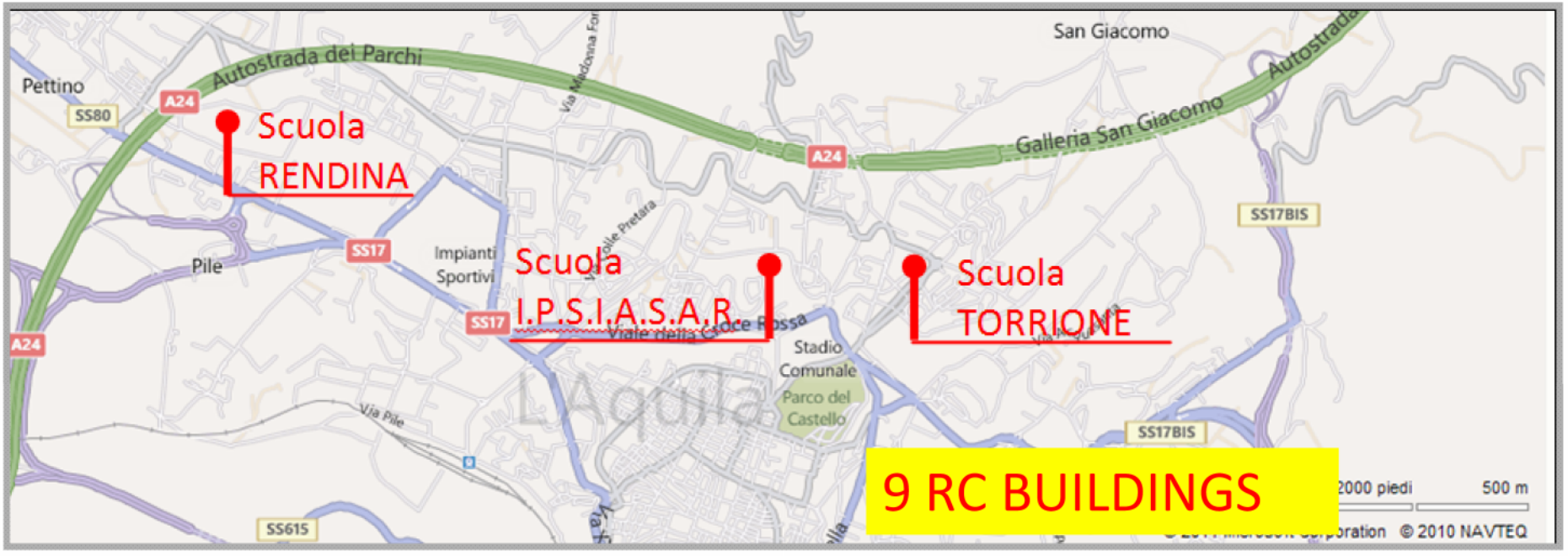


Rating **E**



Seismic assessment of school buildings

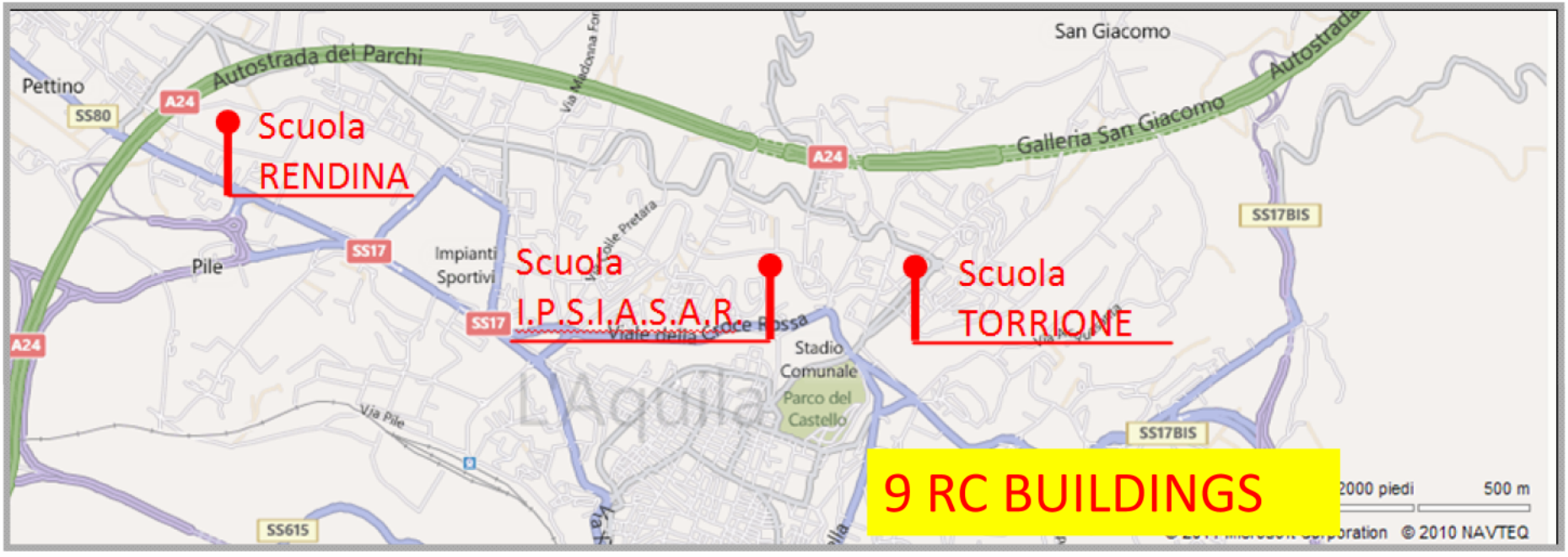
SEISMIC SAFETY ASSESSMENT OF SCHOOL BUILDINGS IN L'AQUILA



- TORRIONE school (1 building);
- I.P.S.I.A.S.A.R. “Leonardo da Vinci” school (2 buildings);
- RENDINA school (6 buildings);

Seismic assessment of school buildings

SEISMIC SAFETY ASSESSMENT OF SCHOOL BUILDINGS IN L'AQUILA



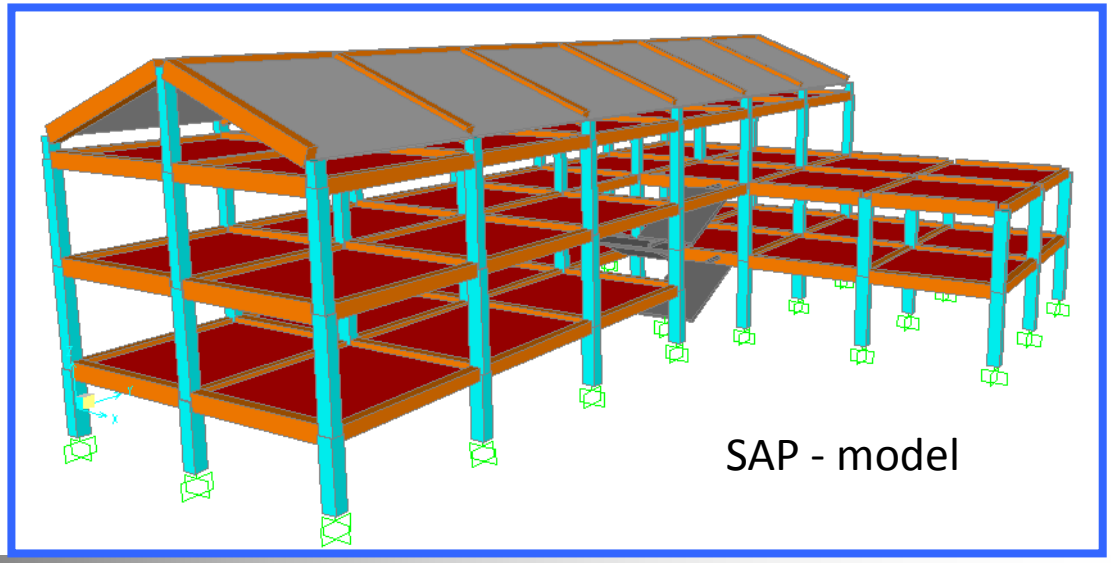
- TORRIONE school (1 building);
- I.P.S.I.A.S.A.R. “Leonardo da Vinci” school (2 buildings);
- RENDINA school (6 buildings);

How much FRP based local stengthening interventions (fast and easy to execute) could increase the global seismic capacity of existing RC structures?

Seismic assessment of school buildings

TORRIONE

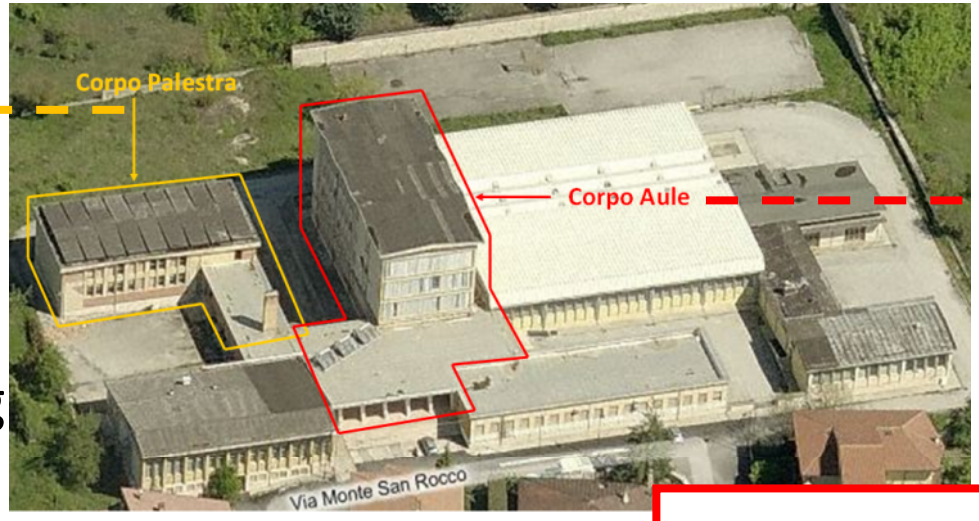
3 story building
Built in 1961



SAP - model

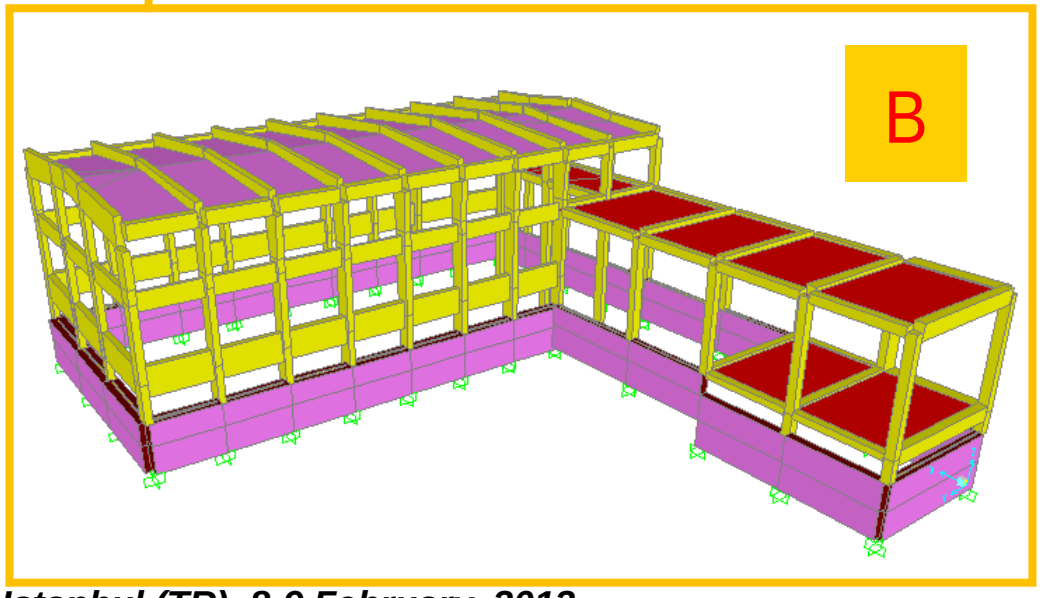
Seismic assessment of school buildings

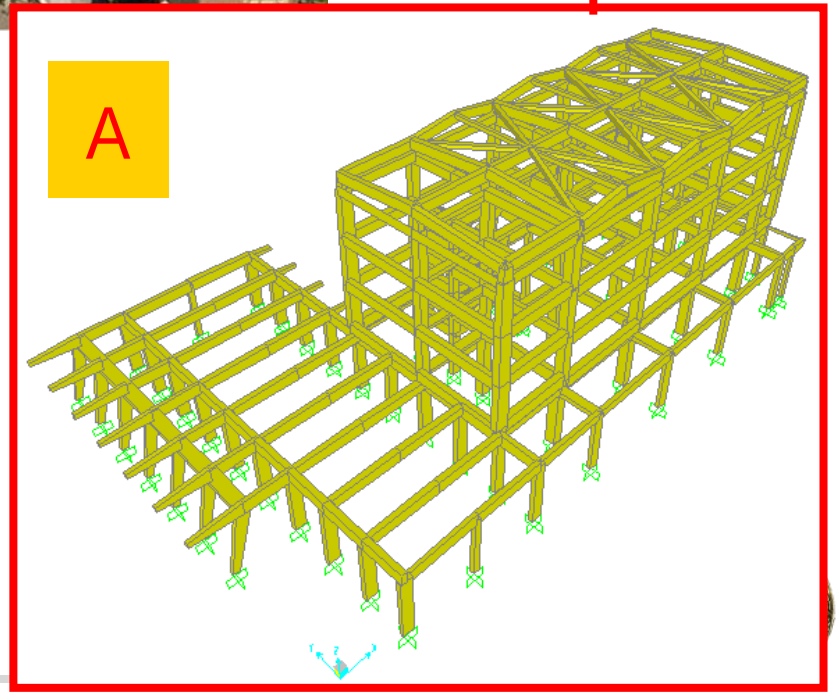
I.P.S.I.A.S.A.R.



2 story building
Built in 1969

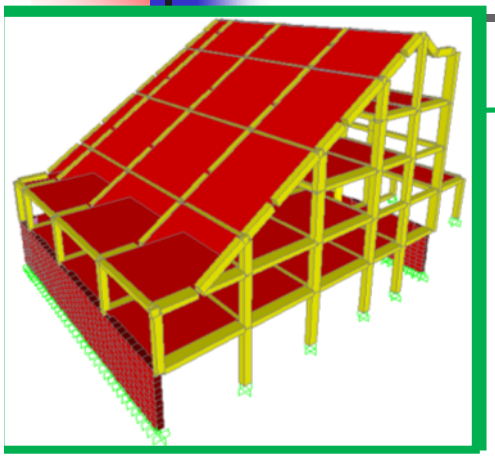
4 story building
Built in 1969

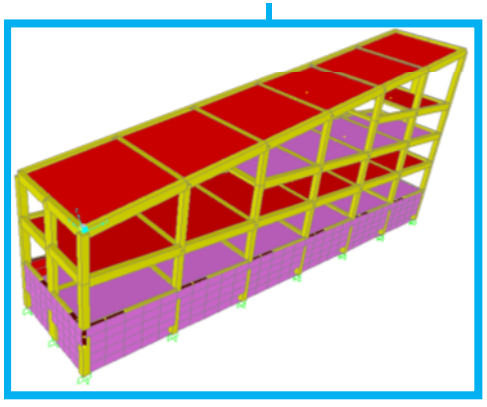


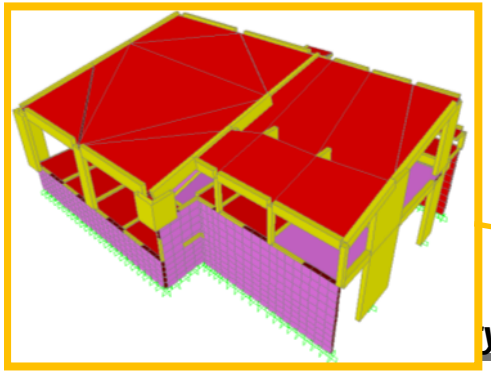


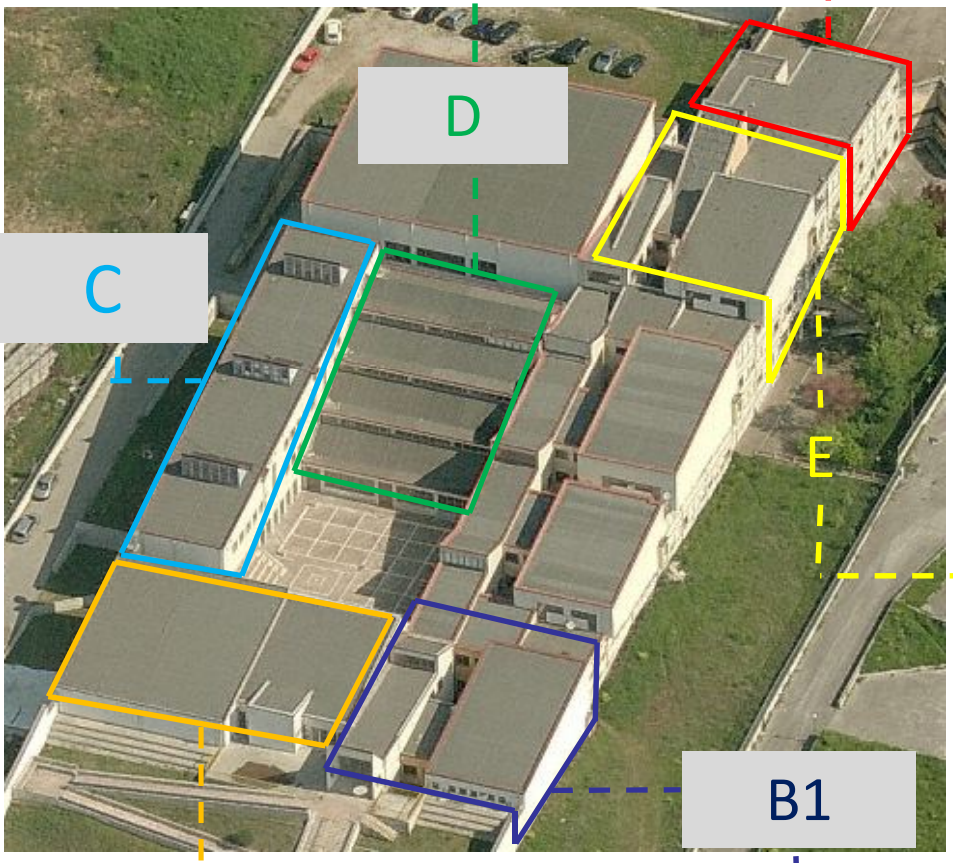
Seismic assessment of school buildings

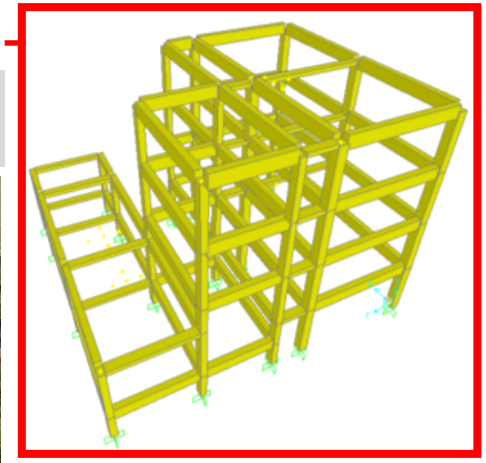
6 buildings, Built 1982-1999

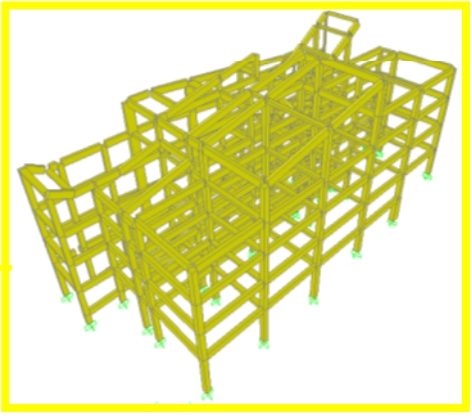


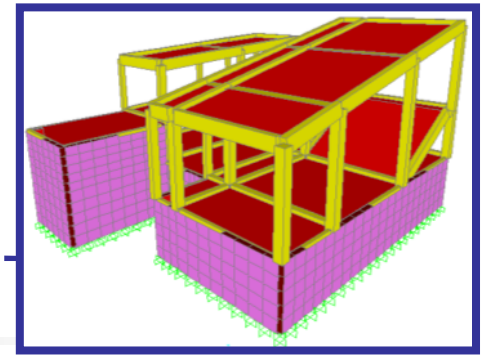












G

D

C

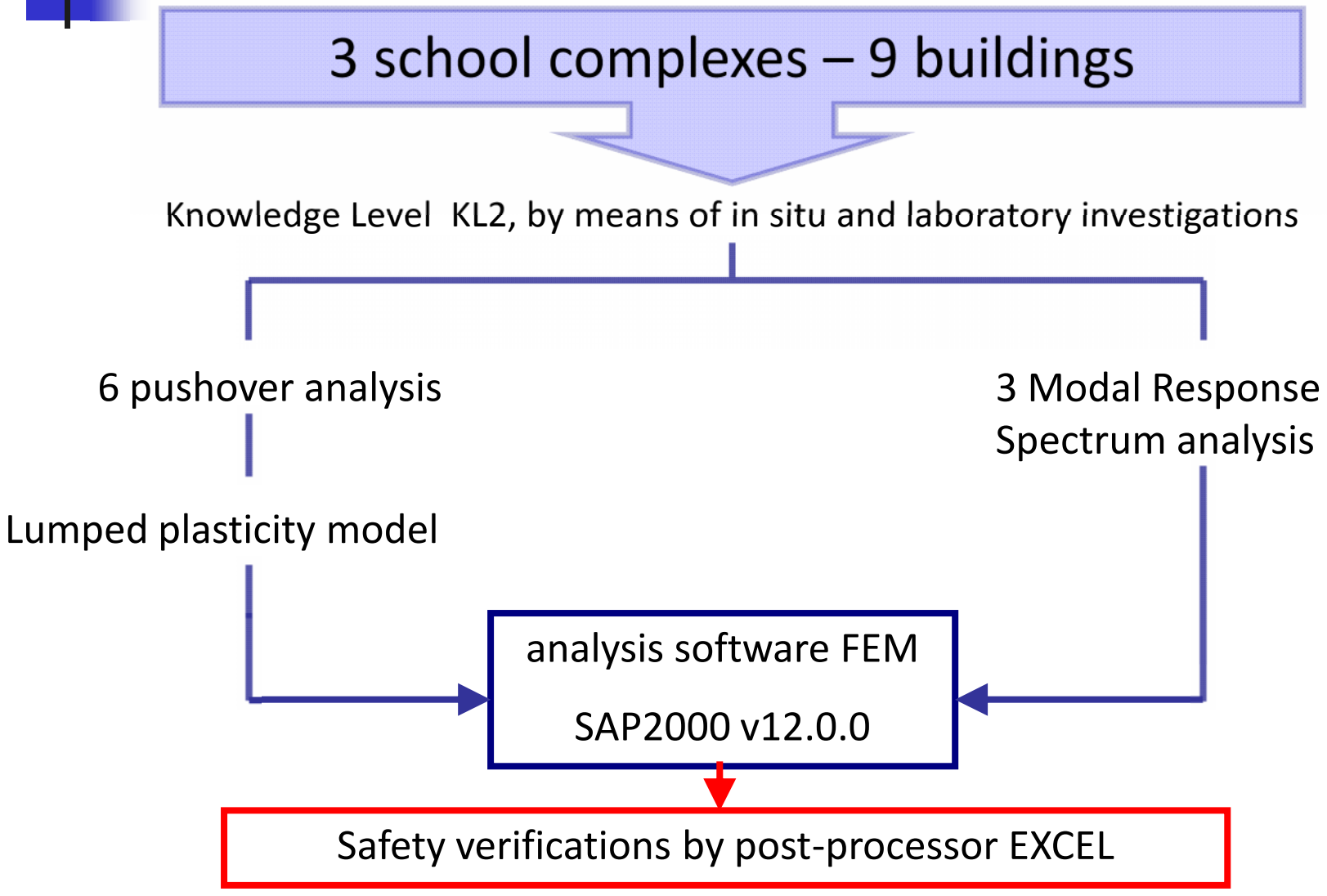
E

B1

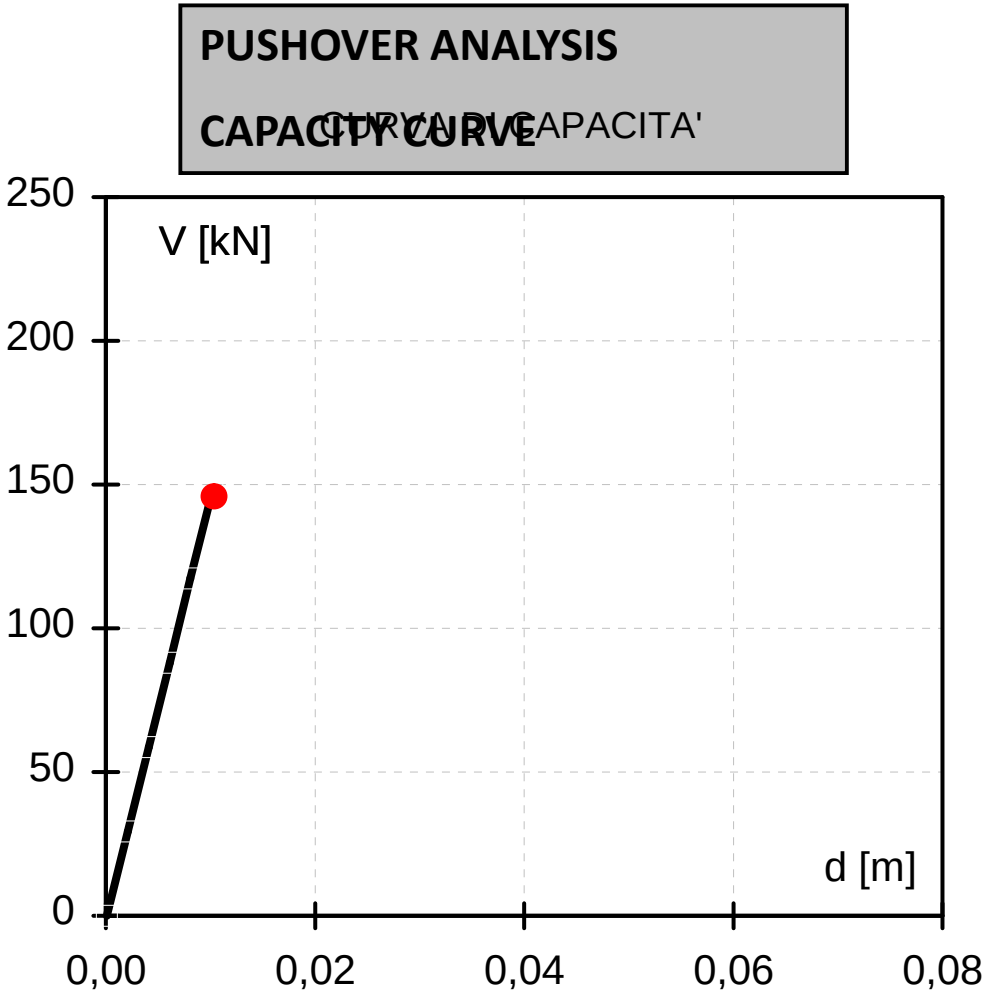
B2

RENDINA

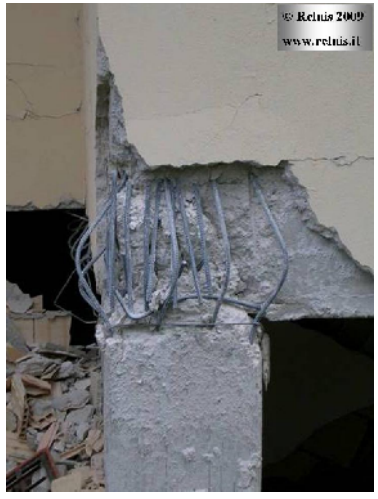
Seismic assessment of school buildings



Capacity curve and progressive failures



First brittle failure on joint (tensile stress)



$$p_t = 0.30\sqrt{f_c}$$

$$p_t = \left| \frac{f_a}{2} - \sqrt{\left(\frac{f_a}{2}\right)^2 + v_j^2} \right| \le k\sqrt{f_c}$$

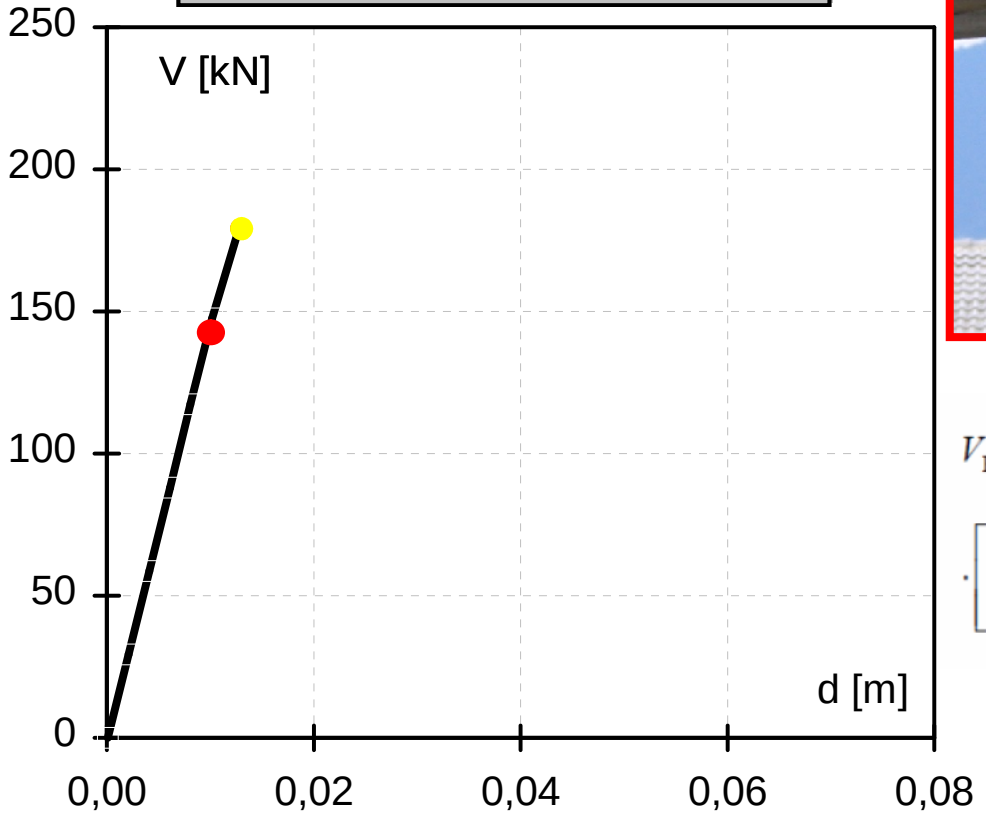
$$f_a = \frac{N_c}{b_j \cdot h_c} \qquad v_j = \frac{V_{jh}}{b_j \cdot h_c}$$

Capacity curve and progressive failures

- First brittle (shear) failure on columns

PUSHOVER ANALYSIS

CAPACITY CURVE CURVA DI CAPACITA'



$$V_R = \frac{1}{\gamma_{el}}\left[\frac{h-x}{2L_V}\min(N;\,0{,}55A_c f_c)+\left(1-0{,}05\min\left(5;\,\mu_\Delta^{pl}\right)\right)\cdot\right.$$

$$\left.\cdot\left[0{,}16\max(0{,}5;\,100\rho_{tot})\left(1-0{,}16\min\left(5;\frac{L_V}{h}\right)\right)\sqrt{f_c}A_c+V_w\right]\right]$$

$$\mu_\Delta^{pl} = \mu_\Delta - 1.$$

min = 0

max = 5

Capacity curve and progressive failures

Displacement capacity

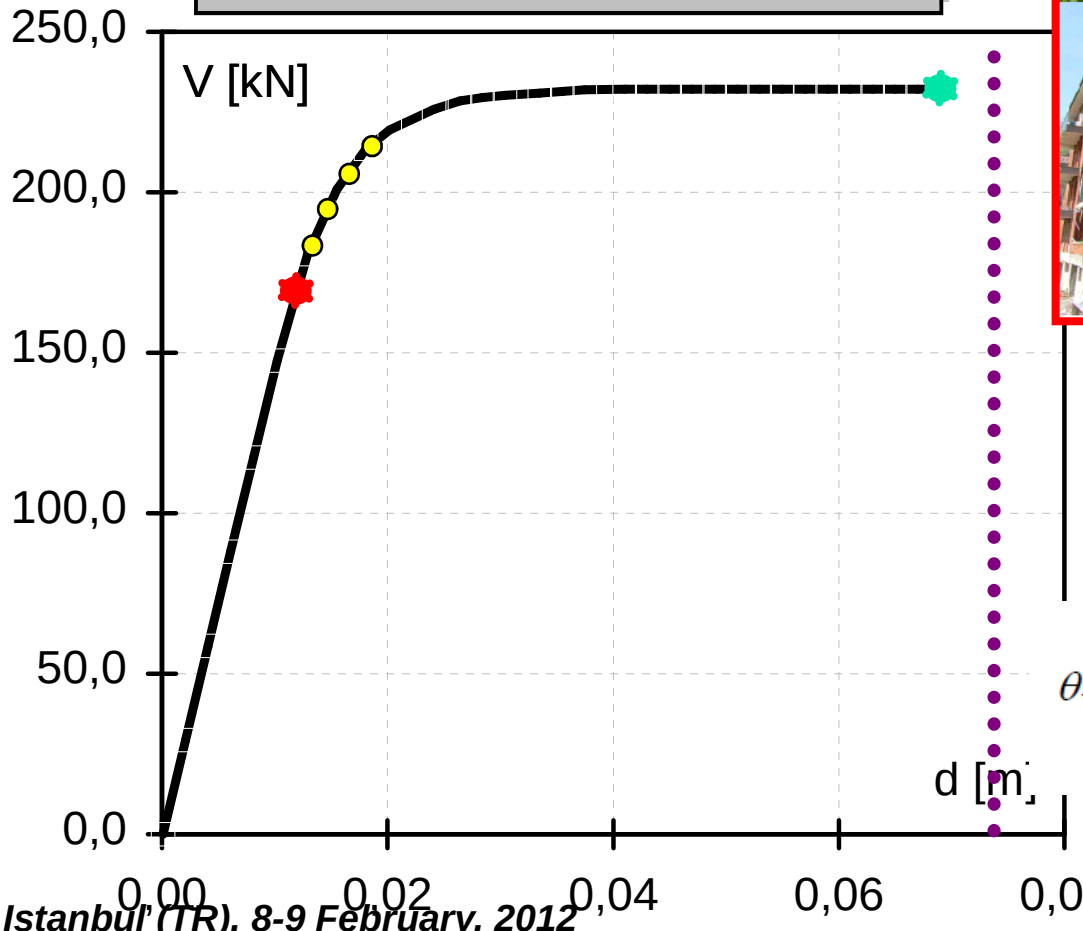
LS Significant damage; (plastic hinge $3/4\theta_u$)

Displacement demand

PUSHOVER ANALYSIS

CAPACITY CURVE

CURVA DI CAPACITA'



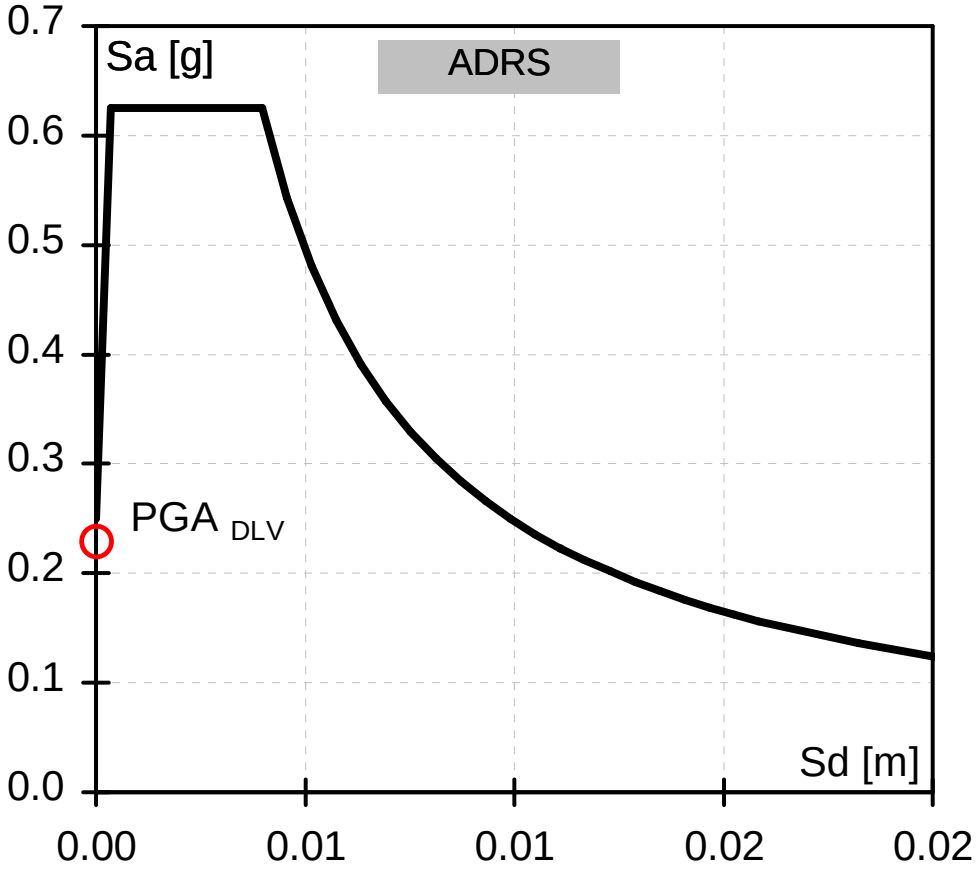
$$\theta_{um} = \frac{1}{\gamma_{el}}\left(\theta_y + (\varphi_u - \varphi_y)L_{pl}\left(1 - \frac{0{,}5L_{pl}}{L_V}\right)\right)$$

Safety index: PGA capacity/demand ratio

THE PARAMETER α HAS BEEN ADOPTED TO COMPUTE THE CAPACITY DEMAND RATIO

$$\alpha = \frac{PGA_{CLV}}{PGA_{DLV}}$$

PGA_{DLV} = peak ground acceleration on type A ground with a reference probability of exceedance P_{NCR} = 10 % (no collapse requirement) in 50 years (reference return period T_{NCR} = 475 years)



PGA_{DLV} = L'Aquila = 0.261g

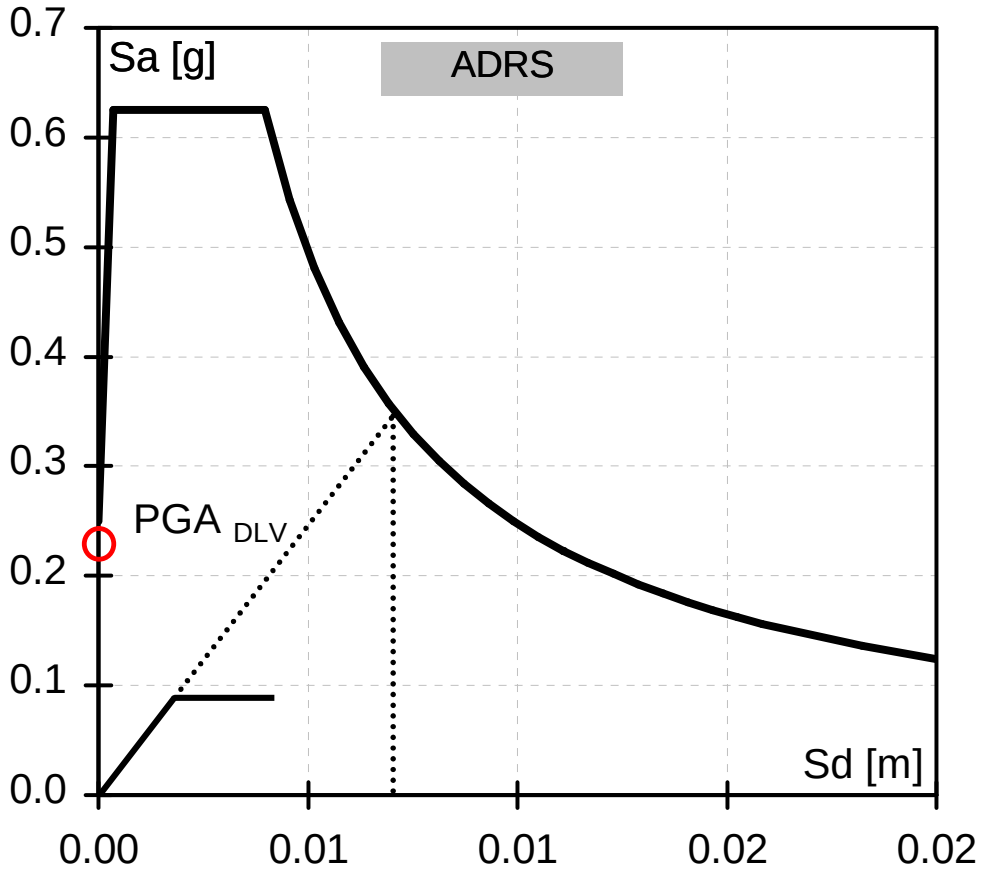
Safety index: PGA capacity/demand ratio

THE PARAMETER α HAS BEEN ADOPTED TO COMPUTE THE CAPACITY DEMAND RATIO

$$\alpha = \frac{PGA_{CLV}}{PGA_{DLV}}$$

PGA_{DLV} = accelerazione orizzontale massima su sito di riferimento rigido orizzontale che ha una probabilità di essere superato pari al 10% (P_{Vr}=10%) in un tempo pari al periodo di riferimento dell'opera

PGA_{CLV} = peak ground acceleration on type A ground which can be sustained by the structure at Limit State of Significant Damage (LSSD)



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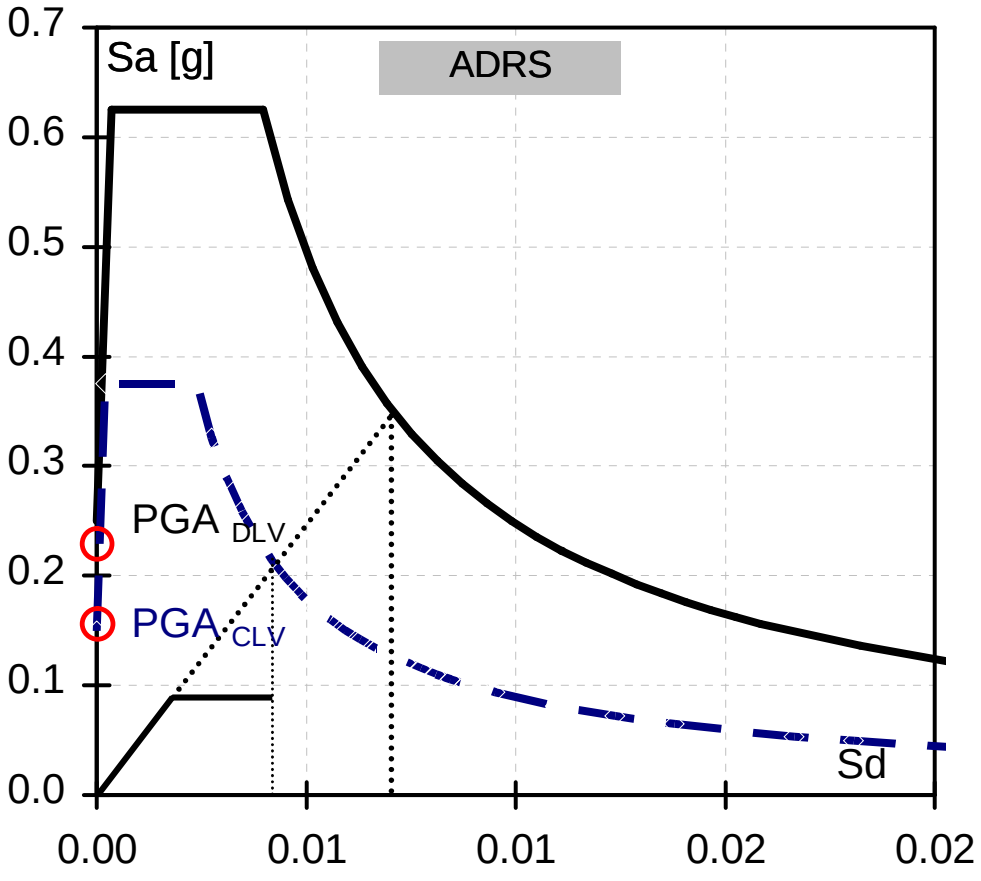
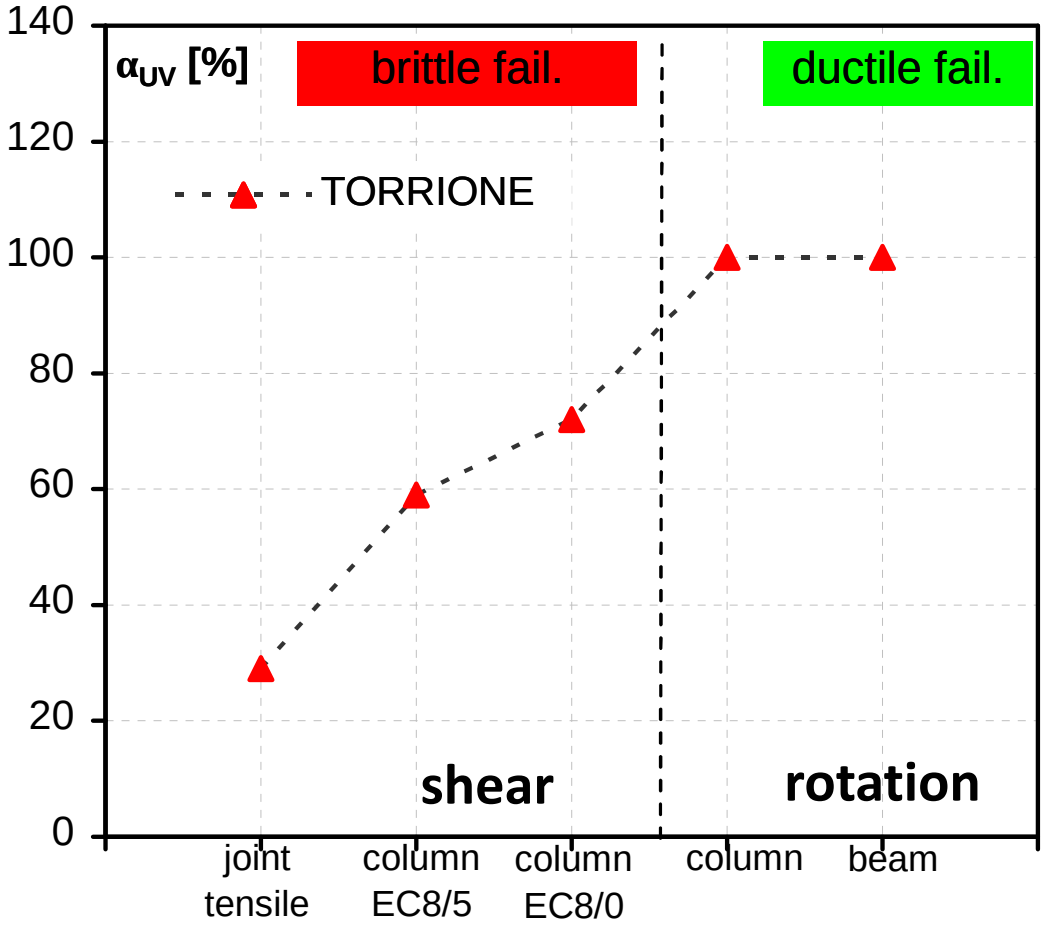


PGA_{DLV} = L'Aquila = 0.261g

Torrione: Assessment

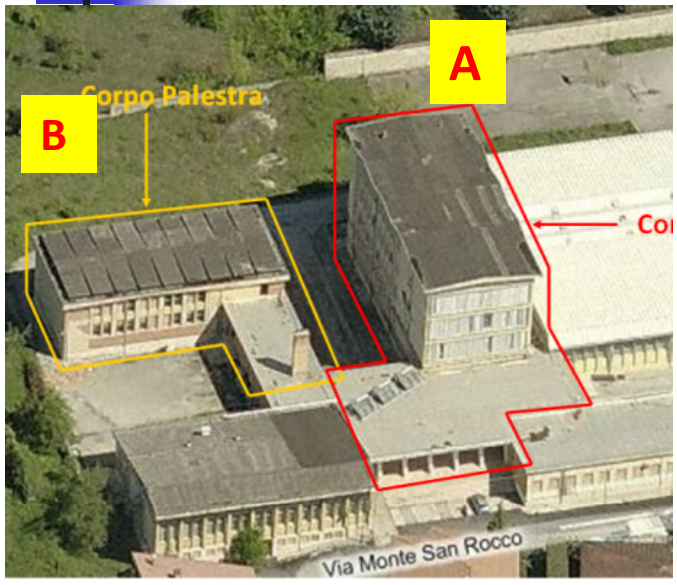
Pushover

N. story	3
f_{cm} [MPa]	14
f_{ym} [MPa]	320
Rebars Type	Plain
year	1961

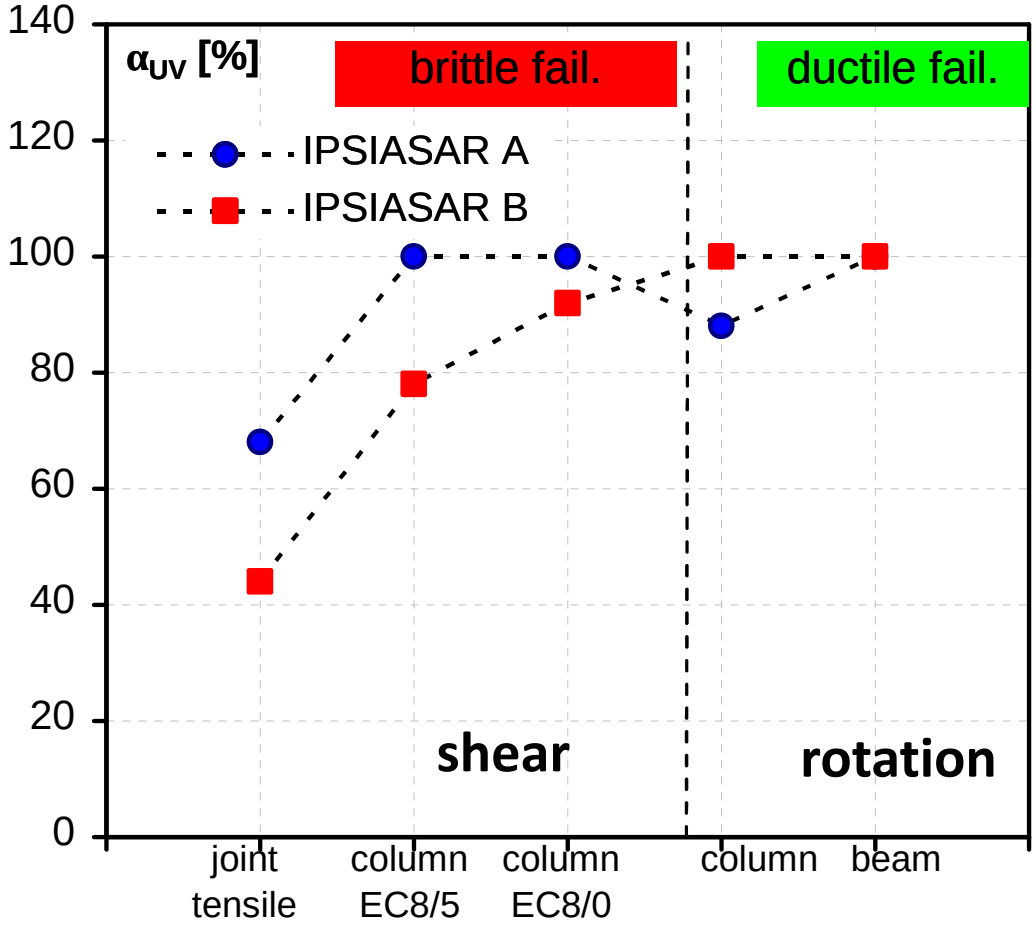


I.P.S.I.A.R.: Assessment

Pushover

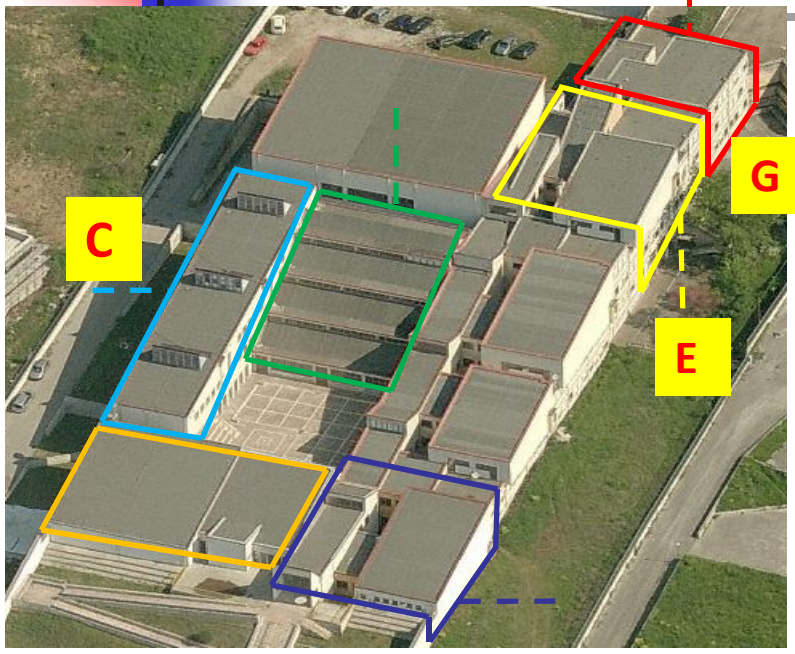


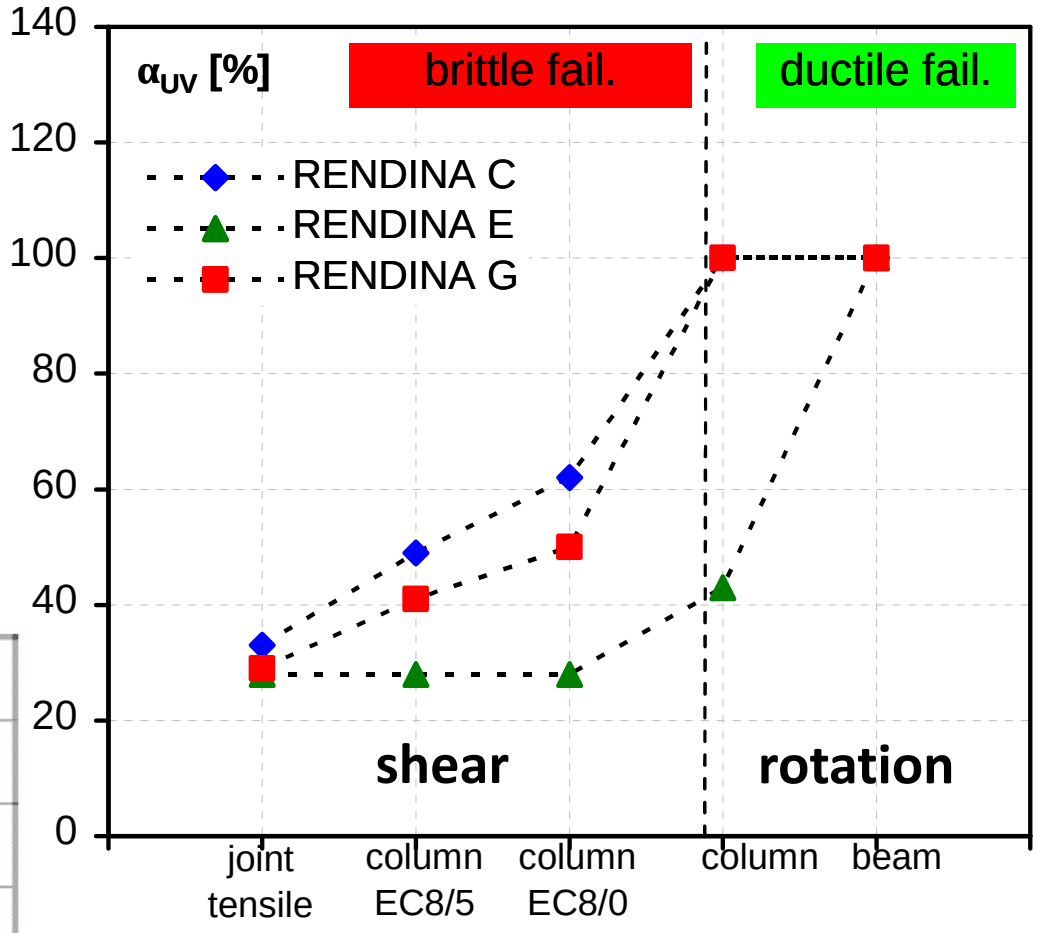
Building	A	B
N. story	4	2
f_{cm} [MPa]	16.6	16.7
f_{ym} [MPa]	320	320
Rebars Type	plain	plain
year	1969	1969



Rendina: Assessment

Pushover

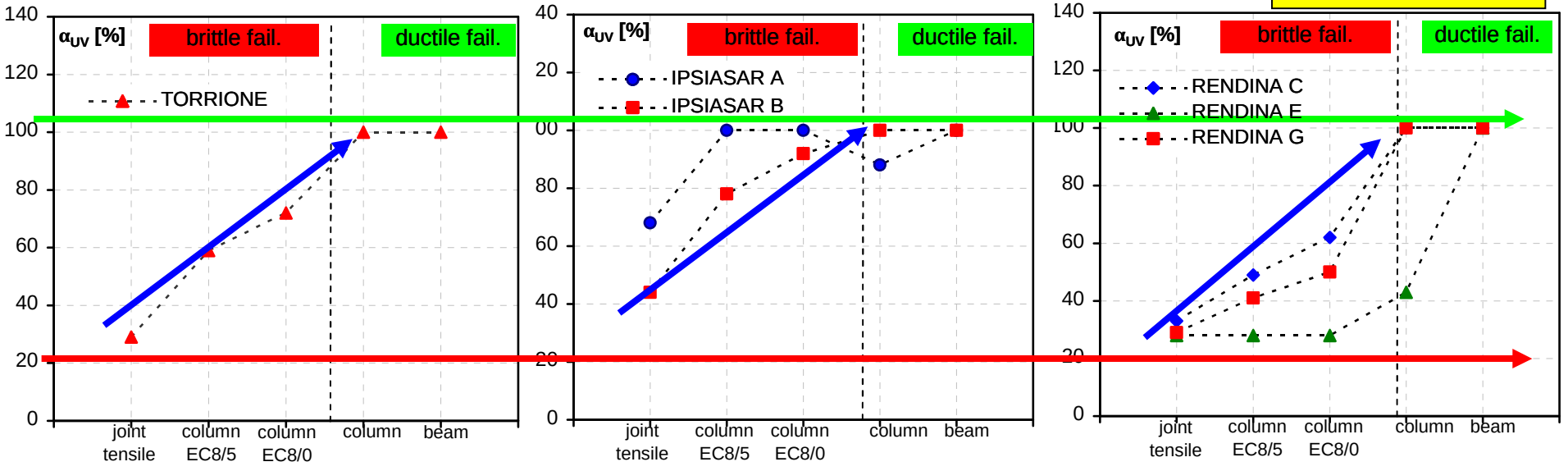




Building	C	E	G
N. story	4	4	3
f_{cm} [MPa]	33.3	21.4	23.5
f_{ym} [MPa]	480	375	375
Rebars Type	def.	def.	def.
year	1999	1982	1982

How much FRP based local stengthening interventions could increase the global seismic capacity of existing RC structures?

Pushover



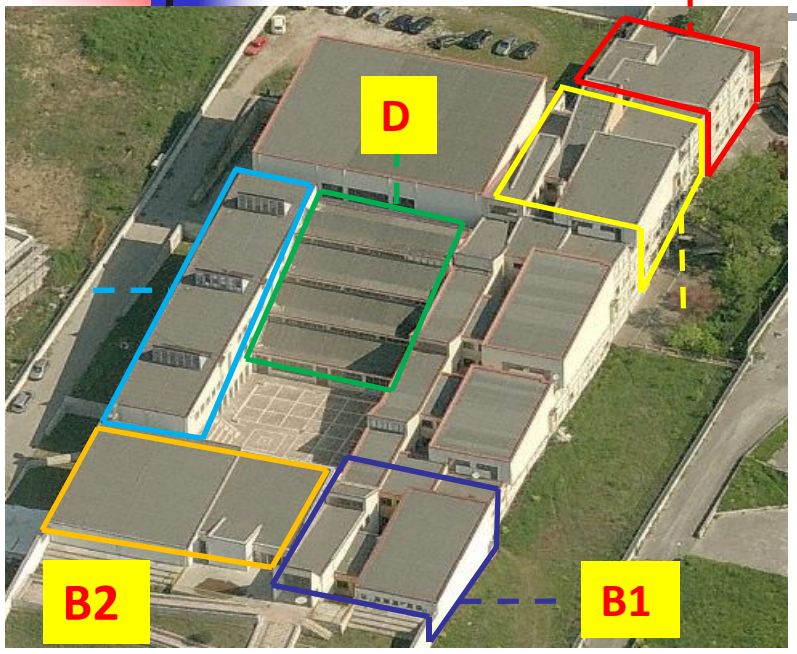
Rehabilitation

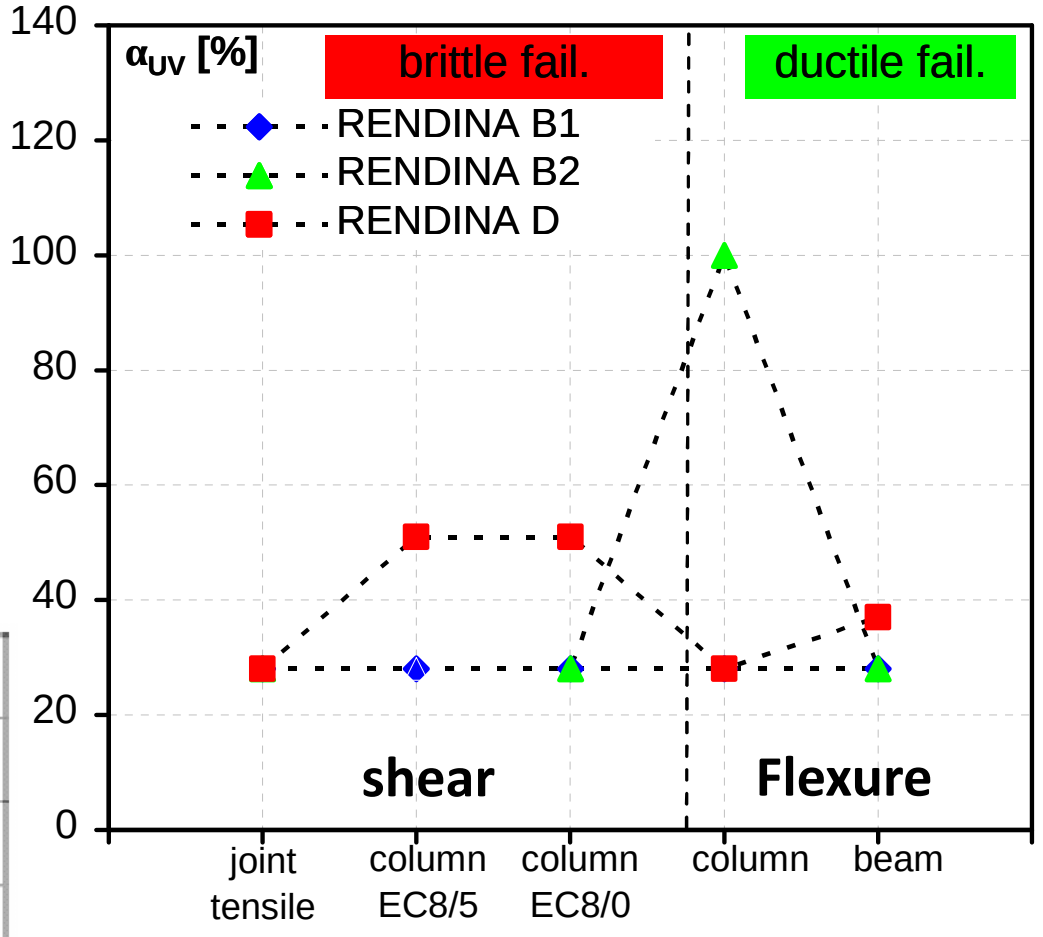
Removing brittle failure mechanisms

Minimum Safety level

Rendina: Assessment

Linear Analysis





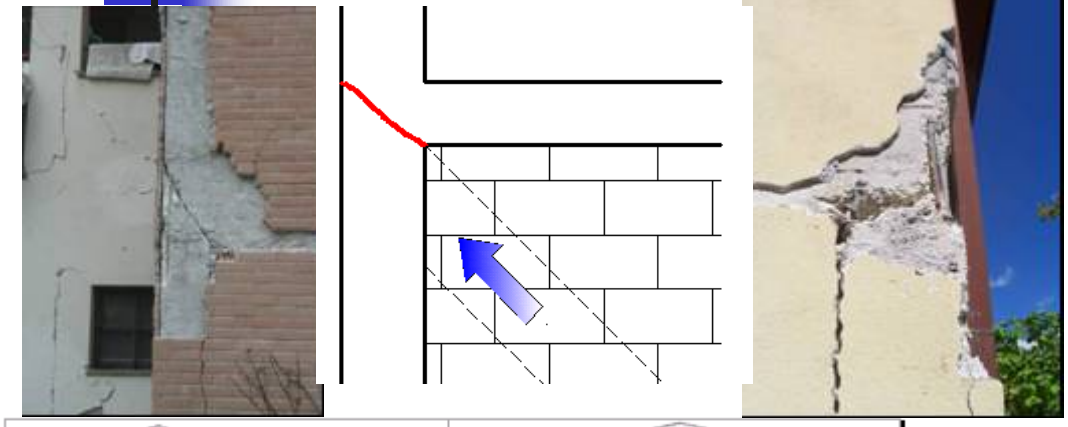
Building	B1	B2	D
N. story	2	2	4
f_{cm} [MPa]	35.5	35.5	29.6
f_{ym} [MPa]	480	480	480
Rebars Type	def.	def.	def.
year	1999	1999	1995

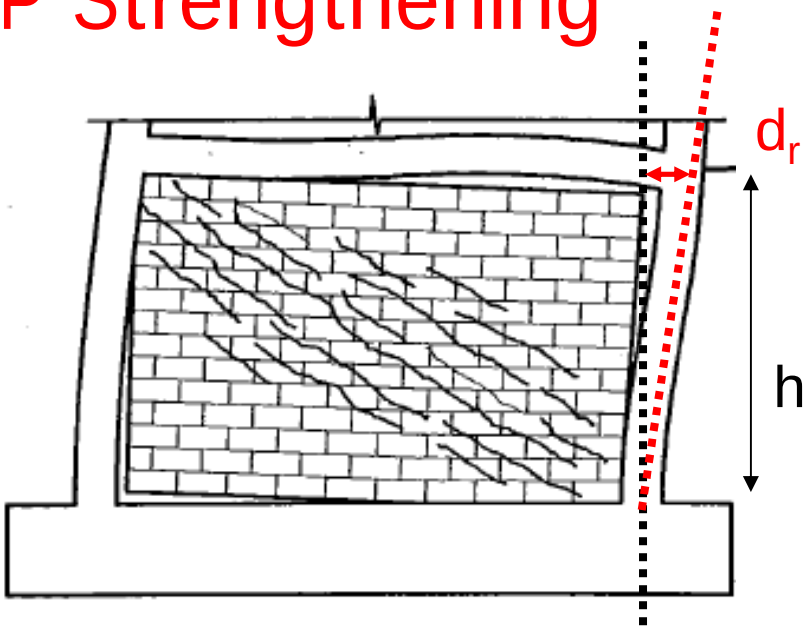
Local intervention: FRP Strengthening

According to theoretical results and to the experiences gained from examining the performances of RC structures after seismic events it was decided to design a local FRP based strengthening intervention on partially confined beam columns joints to quickly strengthen the RC building of L'Aquila

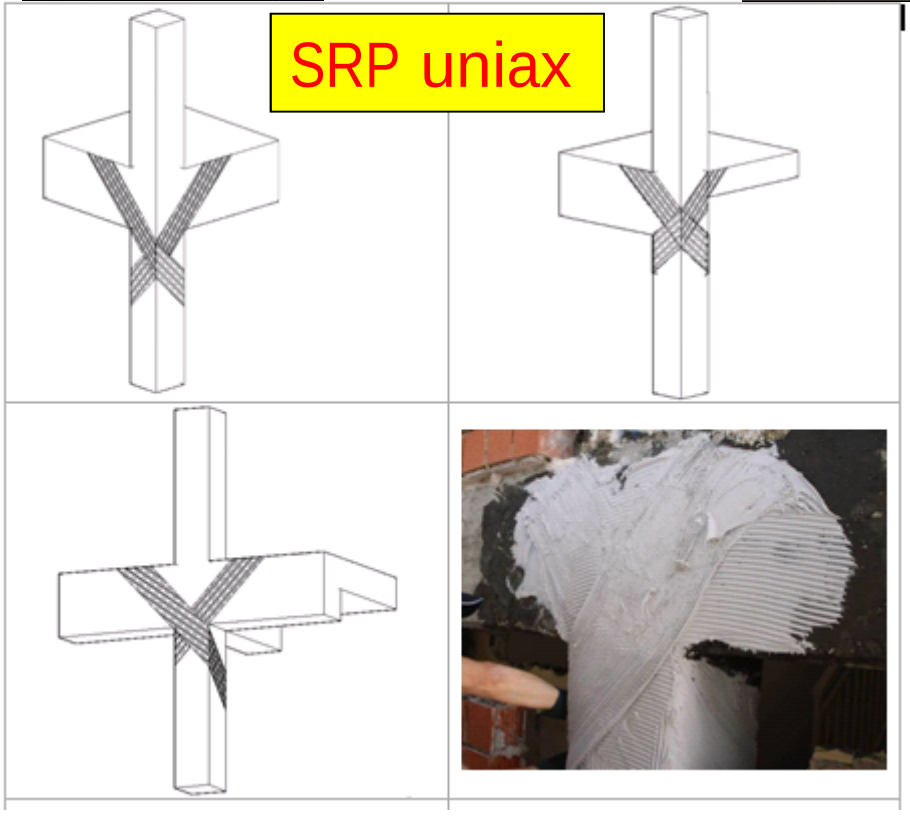
SPEAR structure

Local intervention: FRP Strengthening



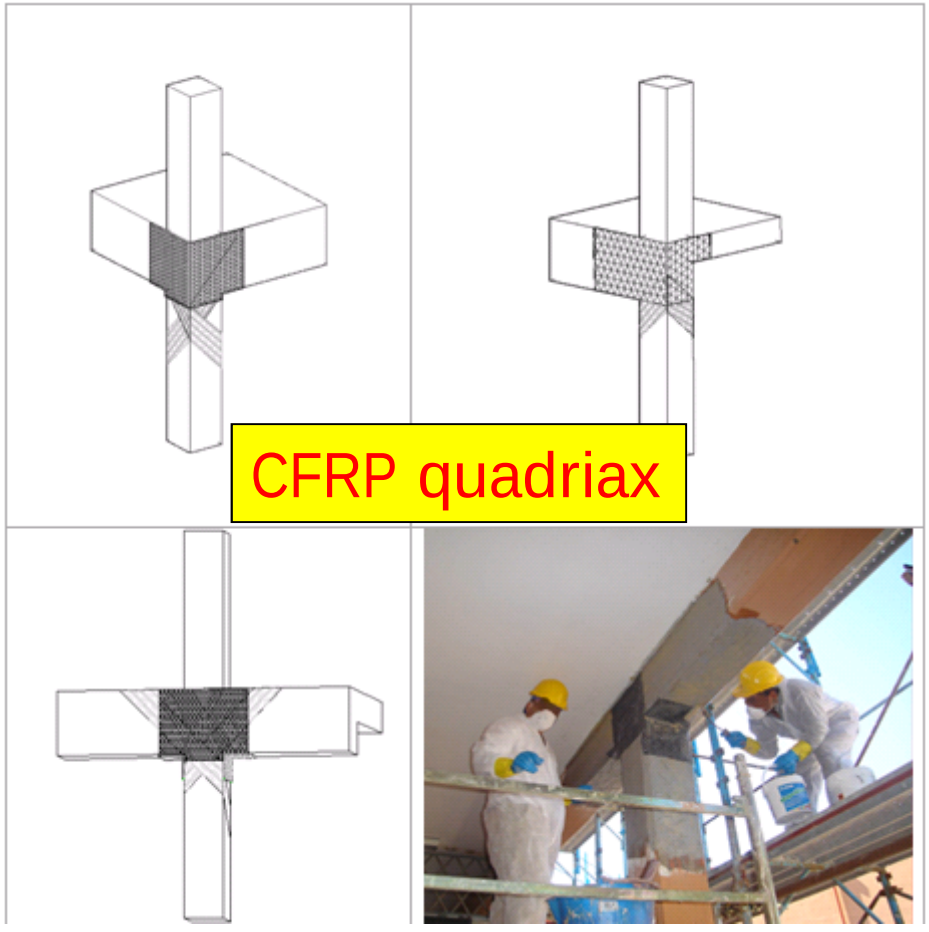


SRP uniax



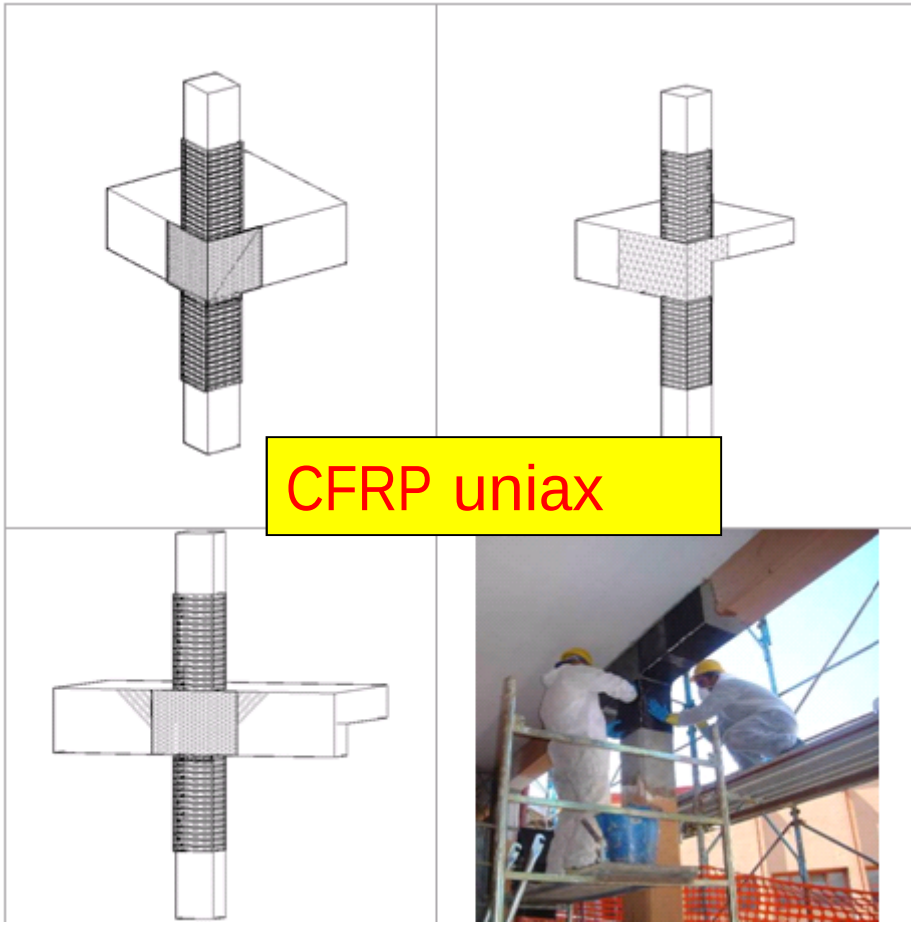
In order to withstand the horizontal component of the infill strut force, **SRP composites in the form of uniaxial systems** can be installed around the beam-column joint both in the case of corner or exterior joints

Local intervention: FRP Strengthening



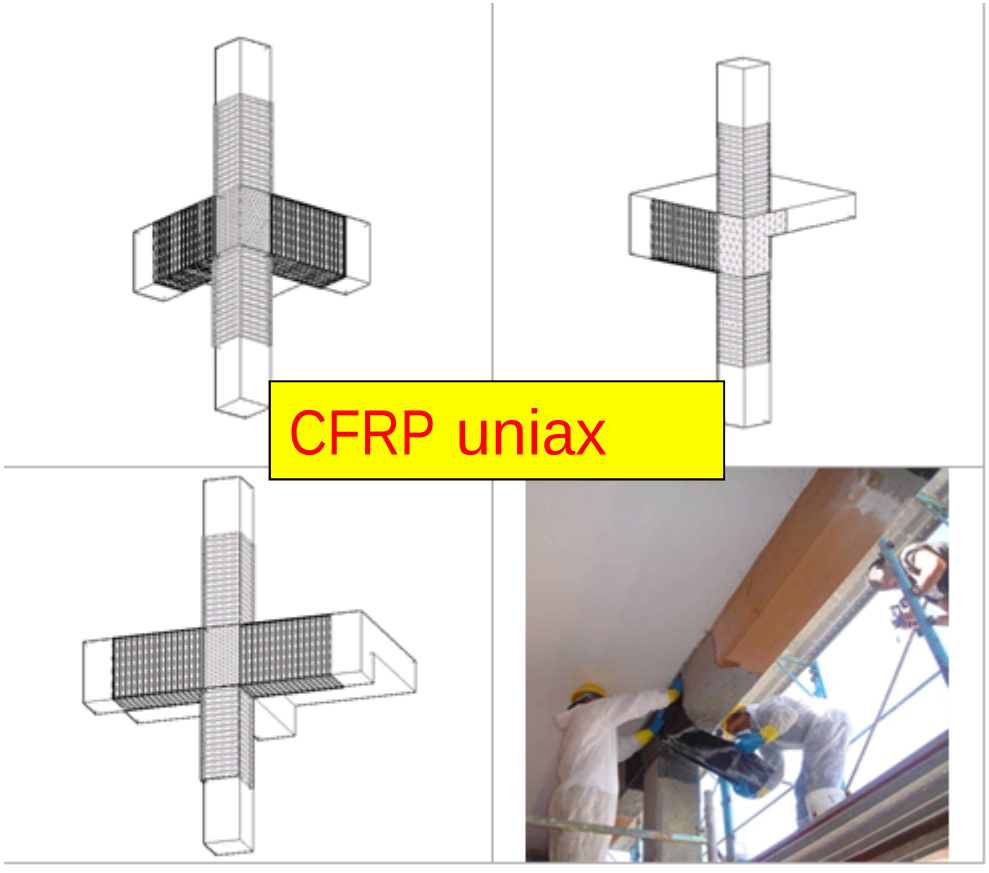
shear capacity increase of beam – column joint panel: the shear increase of beam column joint can be achieved through the application of composites with fibers placed along the principal tensile stresses (i.e. quadriaxial FRP laminates) for a corner joint and for an exterior one

Local intervention: FRP Strengthening



column's ends confinement: to significantly increase the deformation capacity in plastic hinges zones with a corresponding enhancement of global structural ductility. The confinement is also effective to prevent longitudinal bars buckling and to sustain the shear action, at the top of the column, due to the infill strut force.

Local intervention: FRP Strengthening



shear capacity increase of beams:

the use of U-wrap FRP laminates can increase the beams' end shear capacity (in the zone of maximum shear demand in case of seismic action) and at the same time can be very useful in order to provide a mechanical anchorage to the quadriaxial FRP panel sheet applied on the joint; they allow to prevent the premature debonding of such panel and thus the effectiveness of the whole strengthening scheme.

Local intervention: FRP Strengthening

Local intervention: FRP Strengthening

Conclusions

- Experiences gained from examining the performances of RC structures after seismic events indicate that most common brittle collapse mechanisms result from shear failure of partially confined beam-column joints and columns.
- In the aftermath of the April 2009 L'Aquila earthquake, local retrofitting works based on FRP were strongly executed to increase the seismic capacity of public and private buildings and to quickly allow their opening.

No stiffness and mass increase ➔ no global analysis is required

However, no standard provisions are still provided by international codes and guidelines related to the FRP strengthening of partially confined joints.