# COST C26

Urban Habitat Constructions under Catastrophic Events
EARTHQUAKE RESISTANCE
WG 2 Session, March 30th

## Performance-based seismic retrofit of masonry and r.c. buildings

by:

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Workshop in Prague, 30-31 March 2007

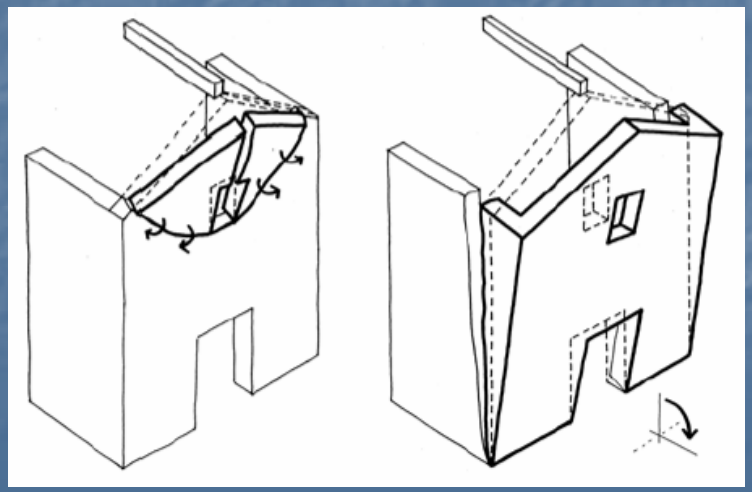
# FAILURE MECHANISMS OF MASONRY WALLS

**PRINCIPAL CAUSES**

- **lack of internal cohesion**
- **low effectiveness of both walls and floor-to-wall connections**

**Out-of-plane mechanism:**

- **turnover of walls**
- **local buckling of compressed members with material ejection**



**Giuffrè (1992)**

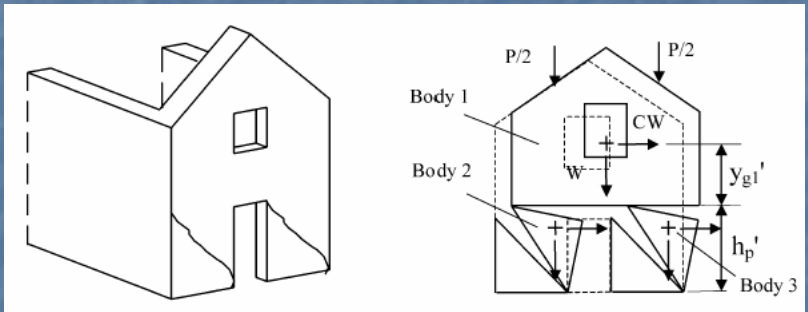
**Borri (1998)**

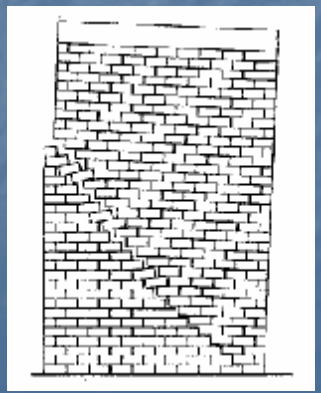
# FAILURE MECHANISMS OF MASONRY WALLS

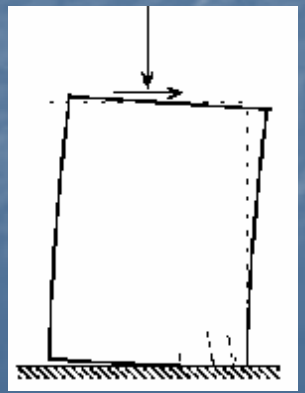
**Once the out-of-plane collapse mechanisms have been prevented, the structure reaction to seismic actions is entrusted to the in-plane strength of the masonry panel**

**In-plane mechanism:**

- **local cracking and overall wall rotation**
- **large cracks spread all over the wall**



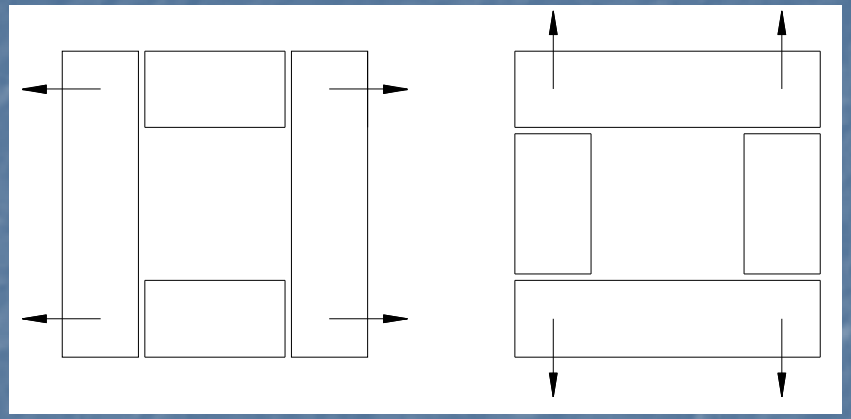


**Giuffrè (1992)**

**Borri (1998)**

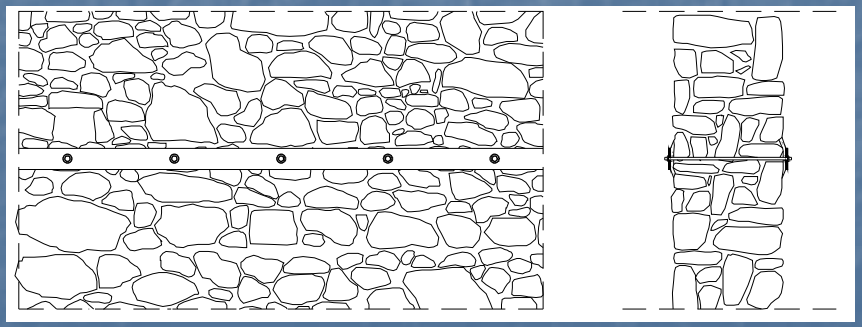
# THE INVESTIGATED TYING SYSTEM

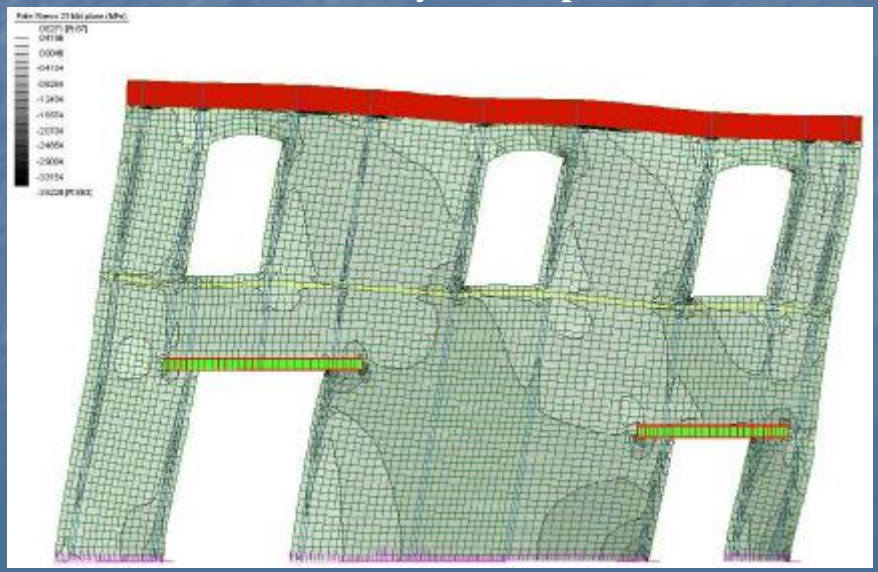
**Scheme of horizontal forces between wall connections.**



**Brick factory in Campobasso**

**Metal flat profiles in the opposite surfaces of the wall connected by properly spaced orthogonal bars**





**Advantages:**

- **full reversibility of the intervention**
- **simple installation and accessibility**
- **compatibility with all the type of masonry structures**

# FEMA 273 STRUCTURAL PERFORMANCE LEVELS

1. **Immediate Occupancy Performance Level (S-1)**

   the structural system of the building retains nearly the whole of its pre-earthquake strength and stiffness

   → minor spalling of plaster near openings without structural damage

2. **Life Safety Performance Level (S-3)**

   significant damage to the structures has occurred, but some margin against collapse remains after earthquake

   → extensive cracking and some crushing in walls
   extensive crushing and spalling of plaster

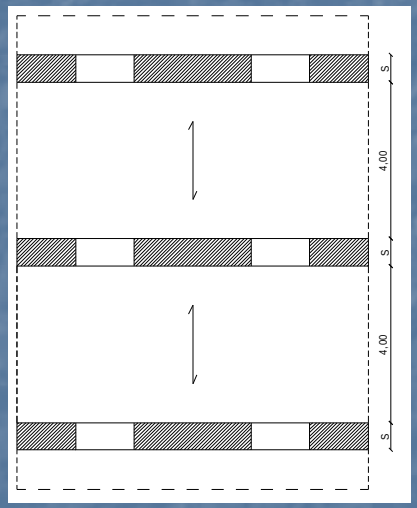
3. **Collapse Prevention Performance Level (S-5)**

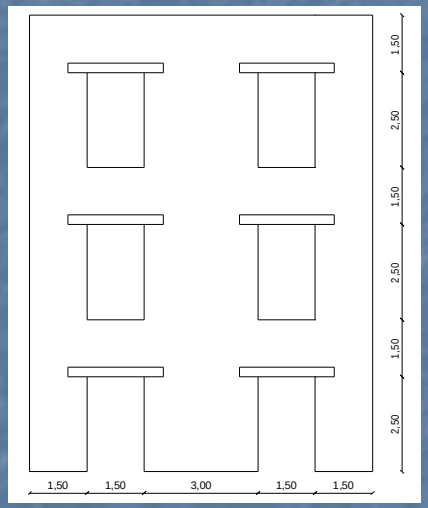
   a large damage to the structure has occurred with significant degradation in both stiffness and strength of the resisting system which, in any case, must continue to carry gravity loads.

   → extensive cracking and crushing with significant permanent drift

# ANALYSED STRUCTURE

**The geometry represents a typical scheme of a transverse load bearing wall of a masonry building**

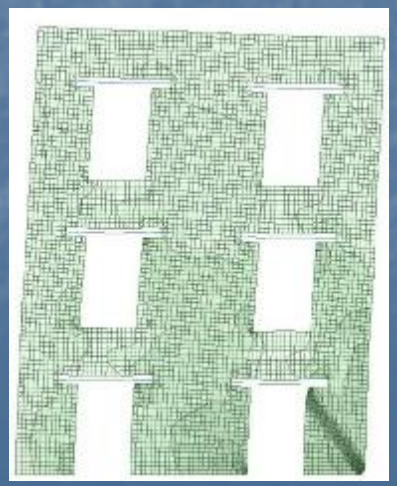


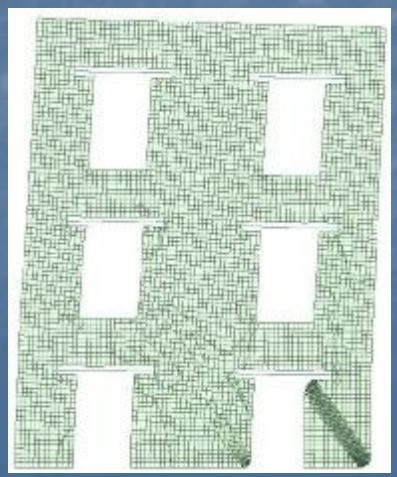

**Parameters assumed for masonry modelling**

| | Calcareous Stone Masonry | |
|---|---|---|
| Modulus of elasticity E | 2000 | MPa |
| Poisson's ratio | 0,25 | |
| Density | 2200 | kg/m$^3$ |
| Friction angle | 45° | |
| Compressive strength | 2,00 | MPa |
| Cohesion | 0,07 | MPa |

*a)*



*b)*

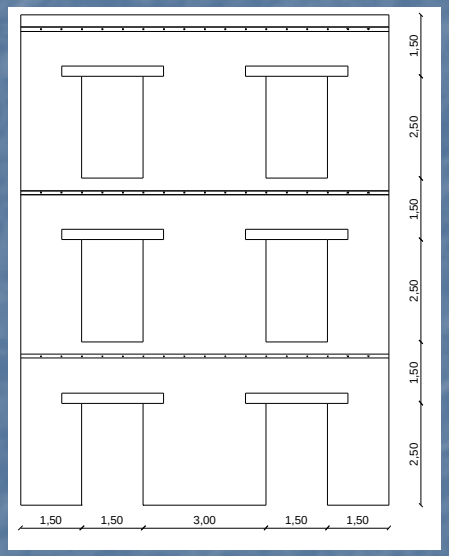


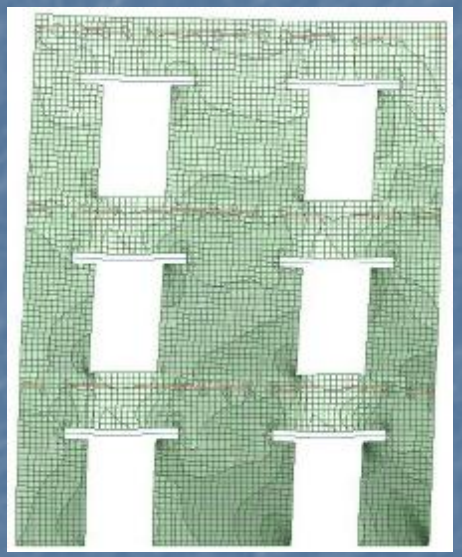
*c)*

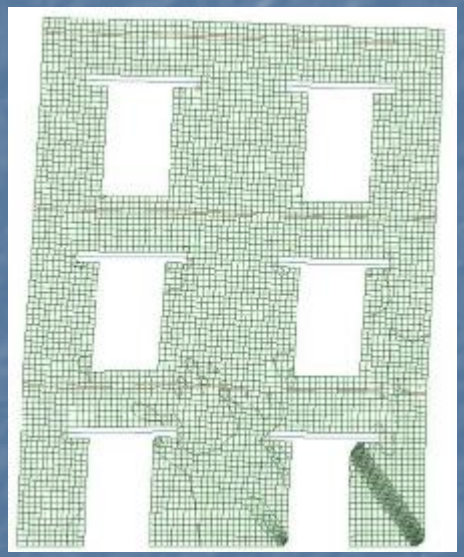
**Deformed shapes related to performance levels:**
**a) S-1**
**b) S-3**
**c) S-5**

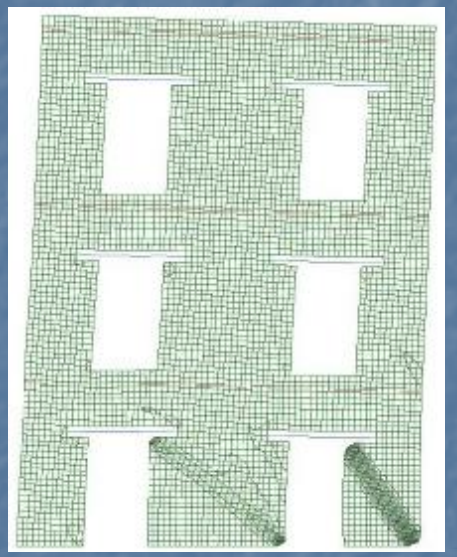
# INTERVENTION LEVEL 1

**wall fitted with horizontal ties at each floor**







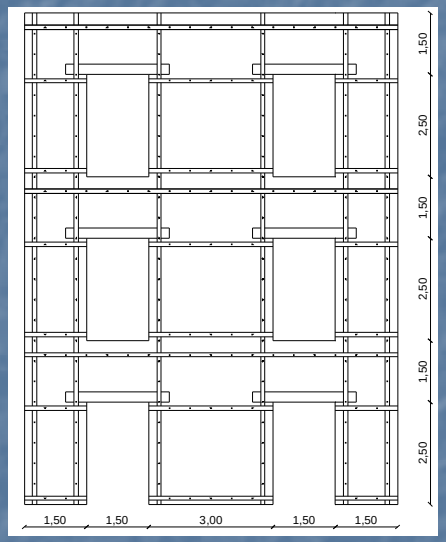
**a) S-1** **b) S-3** **c) S-5**

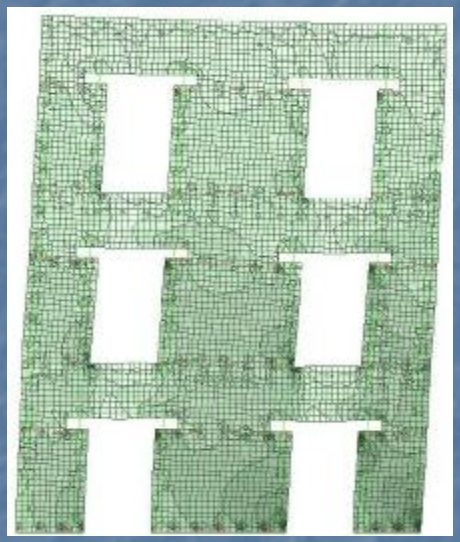
**Deformed shapes related to performance levels**

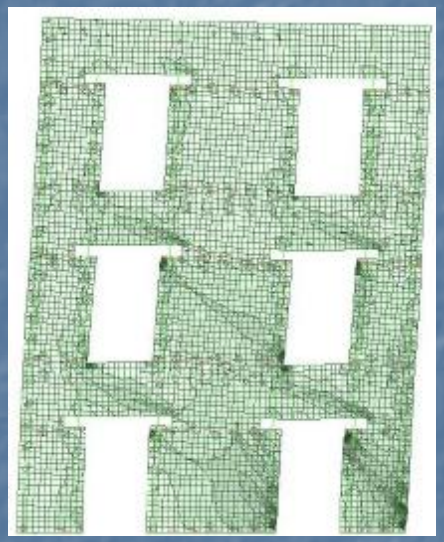
**Ties effect produces collaboration between all the sub-panels at each level, so that when one of these fails, the tie transfer the seismic action to the remaining ones**

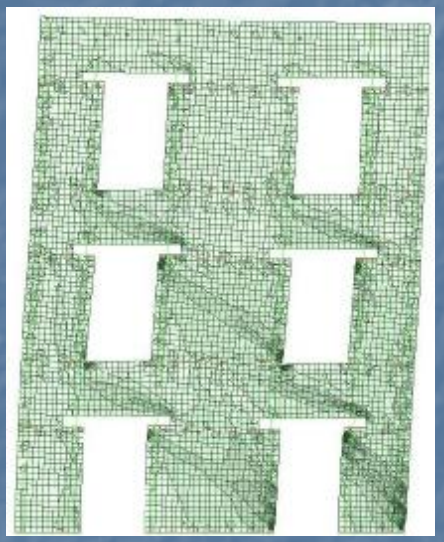
# INTERVENTION LEVEL 2

**wall fitted with horizontal ties at floors and at both base and top of each sub-panel between openings, together with vertical ties**







**a) S-1** **b) S-3** **c) S-5**

**Deformed shapes related to performance levels**

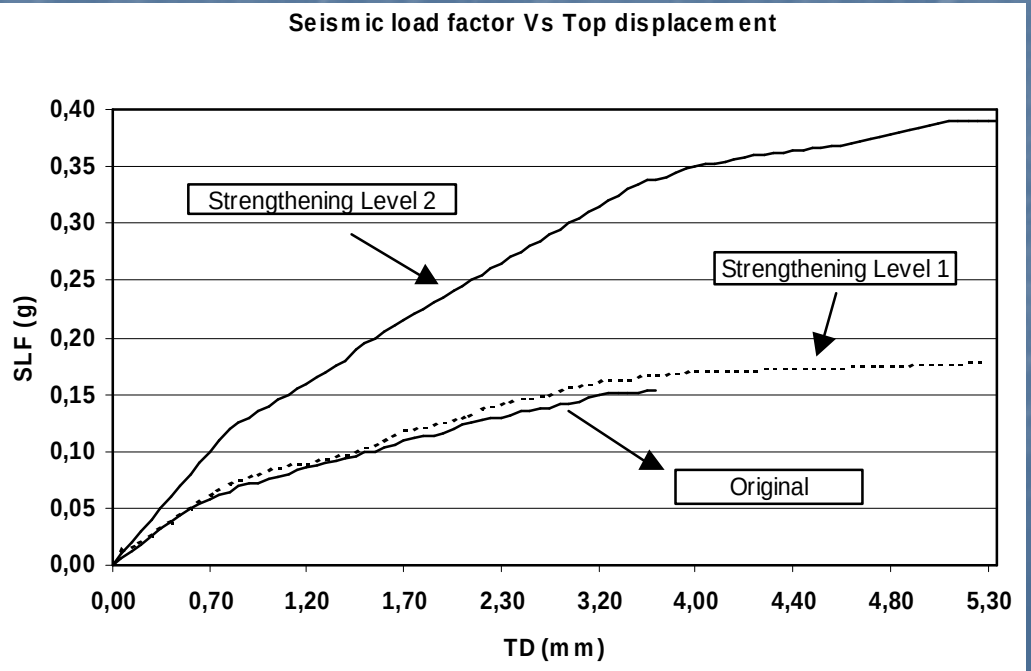
**Vertical ties improve the behaviour of each sub-panel, that can perform like compressed sloped struts, whereas horizontal ties installed at the base and the top of each sub-panel increase the compressive strength with their confinement action**

# RESULTS

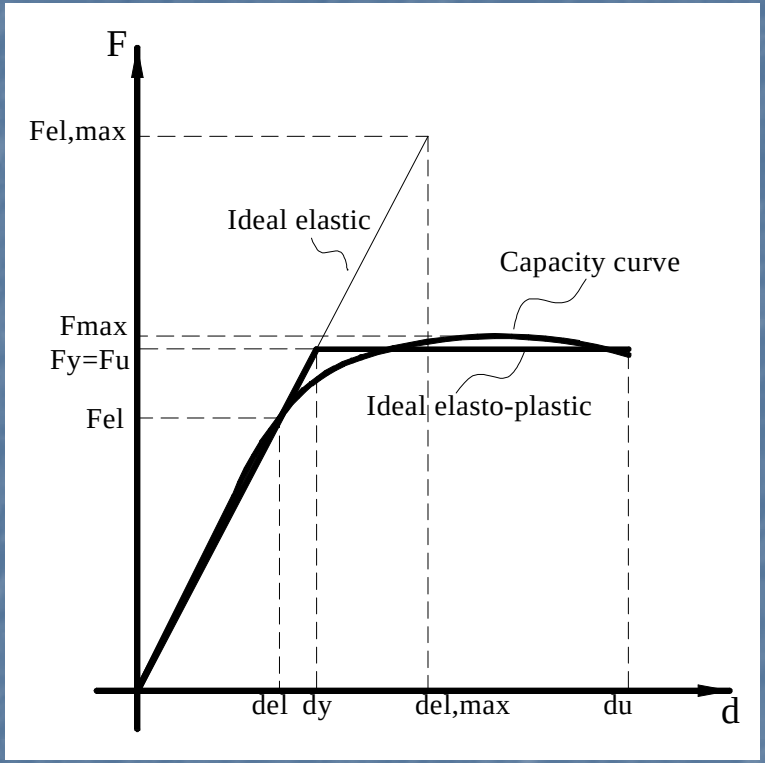
• the original resistance of the structure is very low and related to a poor global performance with low resistance and a brittle failure mechanism

• the wall reinforced by means of horizontal metal ties at each floor shows some improvement of global resistance but, most of all, a sensible increase of ductility of the structure

• the wall reinforced by means of both horizontal and vertical metal ties exhibits a significant increase of the seismic load factor for each Performance Level and, in particular, a remarkable increase of ultimate ductility of the structure



# RESULTS




| | Original Structure | Strengthening Level 1 | | Strengthening Level 2 | |
|---|---|---|---|---|---|
| Structural Performance Parameter | kN | kN | improvement (%) | kN | improvement (%) |
| Fel | 148 | 172 | 16 | 451 | 205 |
| Fy | 203 | 238 | 17 | 630 | 210 |
| Fmax | 216 | 253 | 17 | 684 | 216 |
| Fel,max | 307 | 447 | 46 | 1166 | 280 |

| | Original Structure | Strengthening Level 1 | | Strengthening Level 2 | |
|---|---|---|---|---|---|
| Structural Performance Parameter | mm | mm | improvement (%) | mm | improvement (%) |
| del | 1,6 | 1,9 | 19 | 3,3 | 106 |
| dy | 2,2 | 2,6 | 17 | 4,6 | 110 |
| du | 3,6 | 5,8 | 61 | 10,2 | 183 |

| | Original Structure | Strengthening Level 1 | | Strengthening Level 2 | |
|---|---|---|---|---|---|
| Structural Performance Parameter | | | improvement (%) | | improvement (%) |
| $q_0$ | 1,51 | 1,88 | 24 | 1,85 | 23 |
| OSR | 1,37 | 1,38 | 1 | 1,40 | 2 |
| q | 2,07 | 2,60 | 25 | 2,58 | 25 |
| $pga_{co}$ (g) | 0,078 | 0,091 | 17 | 0,263 | 238 |

$$q = q_0 \cdot OSR$$

$$q_0 = \frac{F_{el,\max}}{F_y}, \quad OSR = \frac{F_y}{F_{el}}$$

# RESULTS

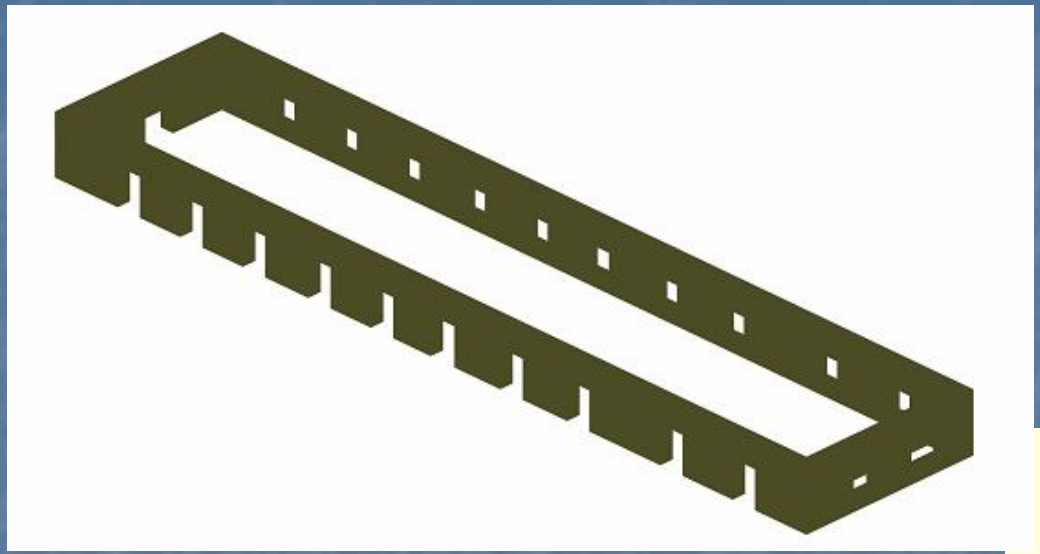
## Seismic load factor related to Performance Levels

| | Original Structure | Strengthening Level 1 | | Strengthening Level 2 | |
|---|---|---|---|---|---|
| Structural Performance Level according to FEMA 273 | Seismic load factor (g) | Seismic load factor (g) | improvement (%) | Seismic load factor (g) | improvement (%) |
| IO S-1 | 0,075 | 0,097 | 29 | 0,120 | 60 |
| LS S-3 | 0,150 | 0,172 | 15 | 0,345 | 130 |
| CP S-5 | 0,153 | 0,180 | 18 | 0,393 | 157 |

## Displacement related to Performance Levels

| | Original Structure | | Strengthening Level 1 | | Strengthening Level 2 | |
|---|---|---|---|---|---|---|
| Structural Performance Level according to FEMA 273 | Top displacement (mm) | Ductility factor | Top displacement (mm) | Ductility factor | Top displacement (mm) | Ductility factor |
| IO S-1 | 1,0 | 3,6 | 1,4 | 3,9 | 0,9 | 6,0 |
| LS S-3 | 3,2 | | 4,2 | | 3,9 | |
| CP S-5 | 3,6 | | 5,4 | | 5,4 | |

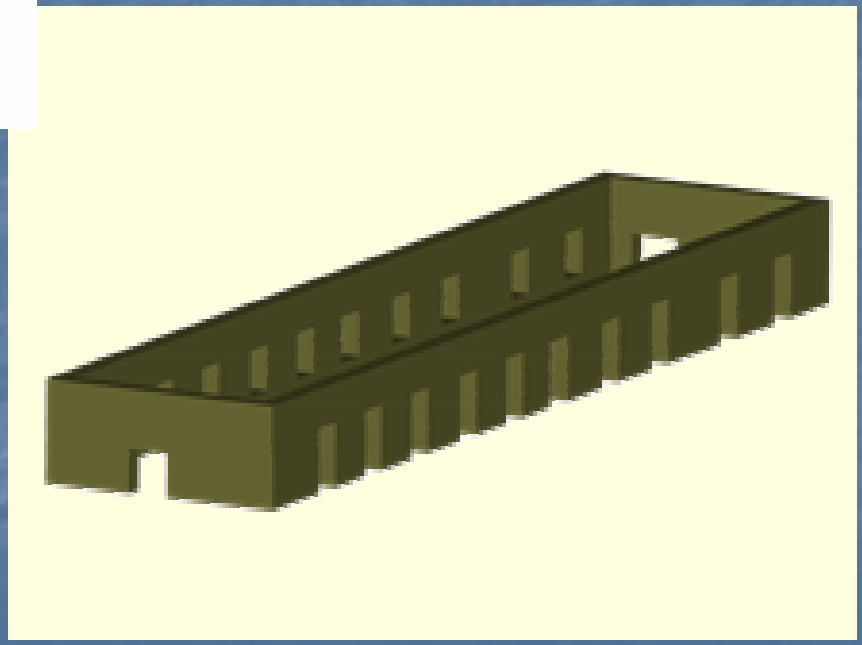
# *LONG-BAY BUILDING – STRUCTURAL MODEL*



**TRIDIMENSIONAL VIEW OF THE STRUCTURE**

***Masonry mechanical features***

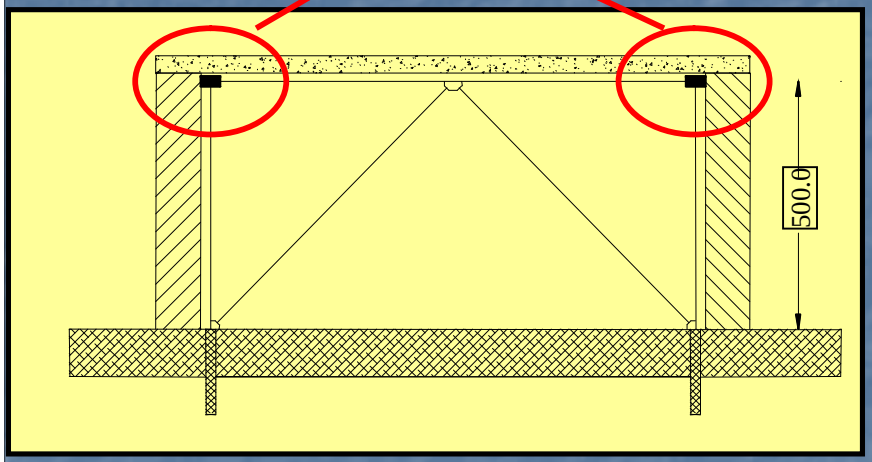
- Modulus of Young, *E = 2000 MPa*
- Shear modulus G = *300 MPa*
- Unit weight $\rho$ = *1800 kg/m$^3$*



# *STRENGHTENING OPTIONS*

**OPTION 1: Concentric brace with viscous devices**

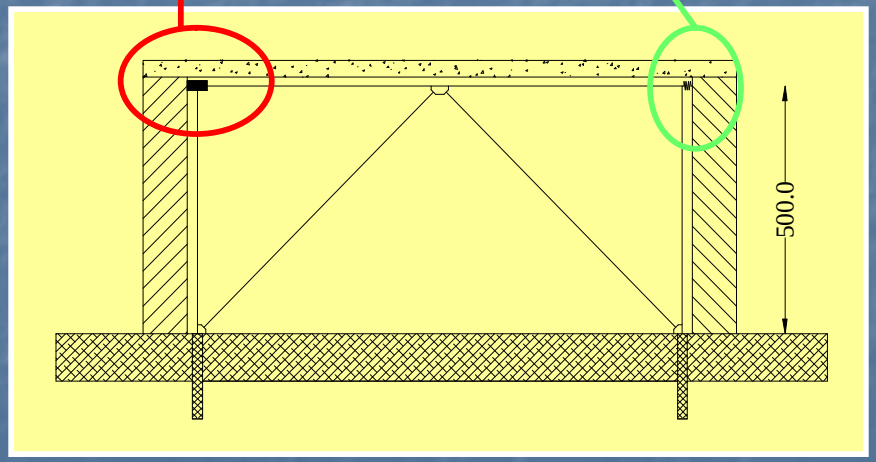
**Viscous devices**




**OPTION 2: Concentric brace with viscous and yielding device**

**Viscous devices**

**Plastic threshold devices**

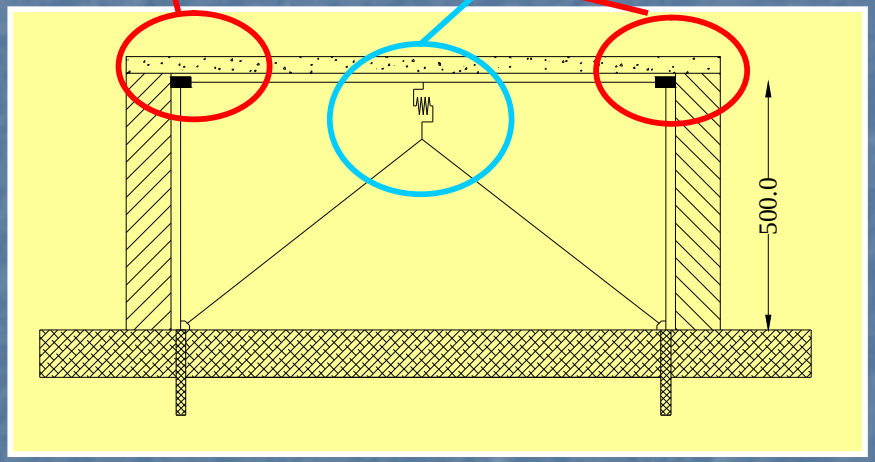


# *STRENGHTENING OPTIONS*

**OPTION 3: Eccentric brace with viscous devices**

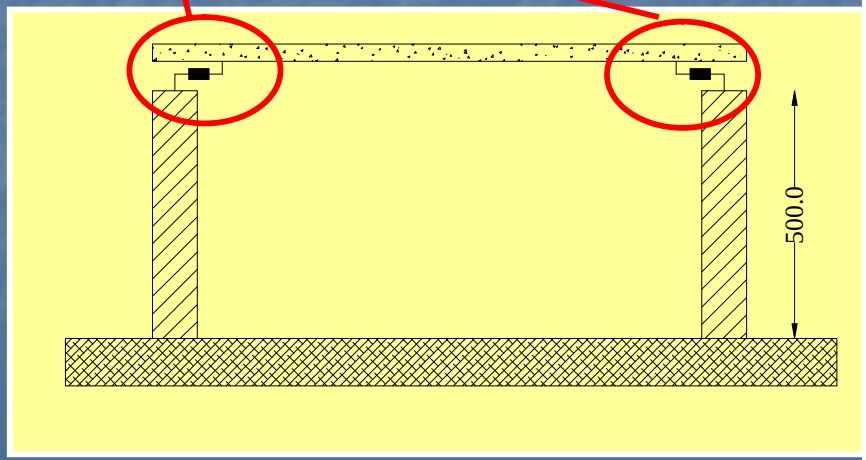
**Viscous devices**

**Link**



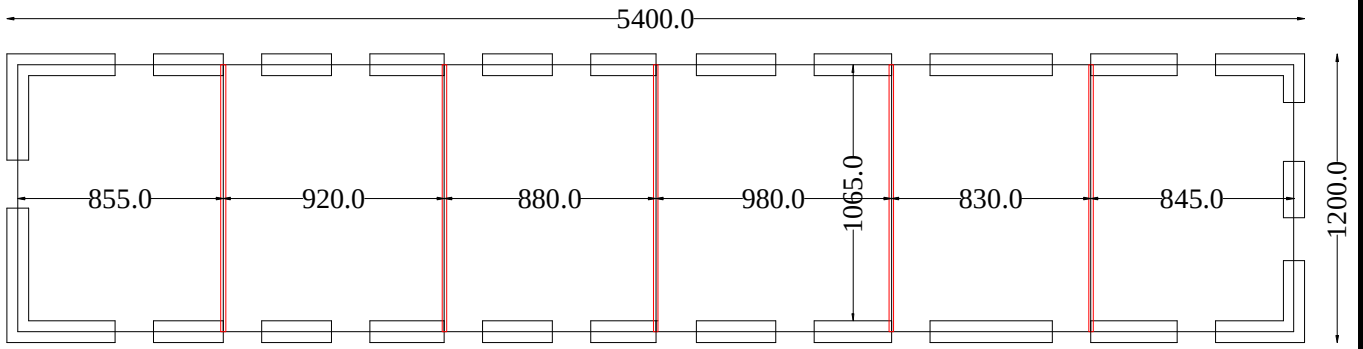

**OPTION 4: Floating deck**

**Viscous devices**

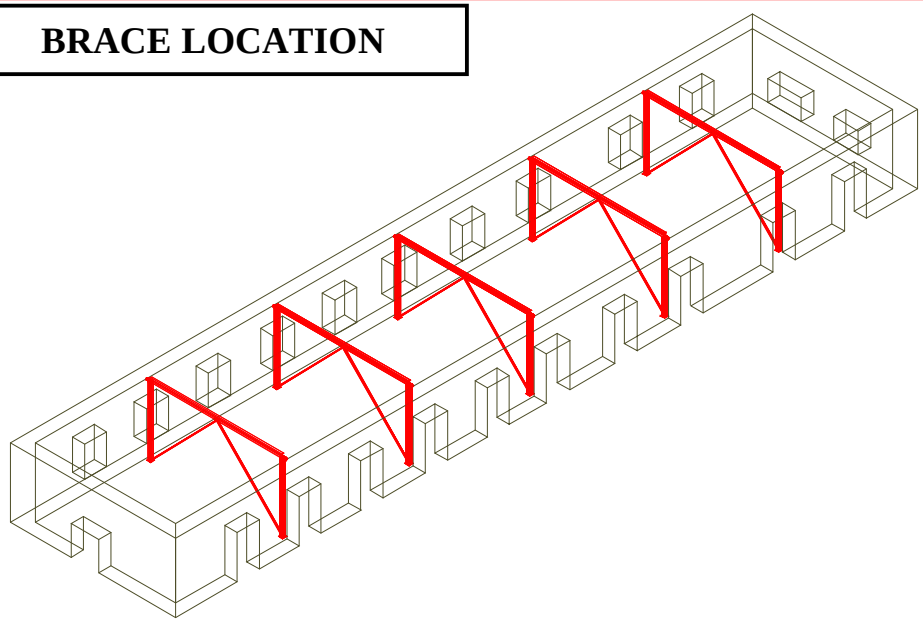


# INTERVENTION DETAIL

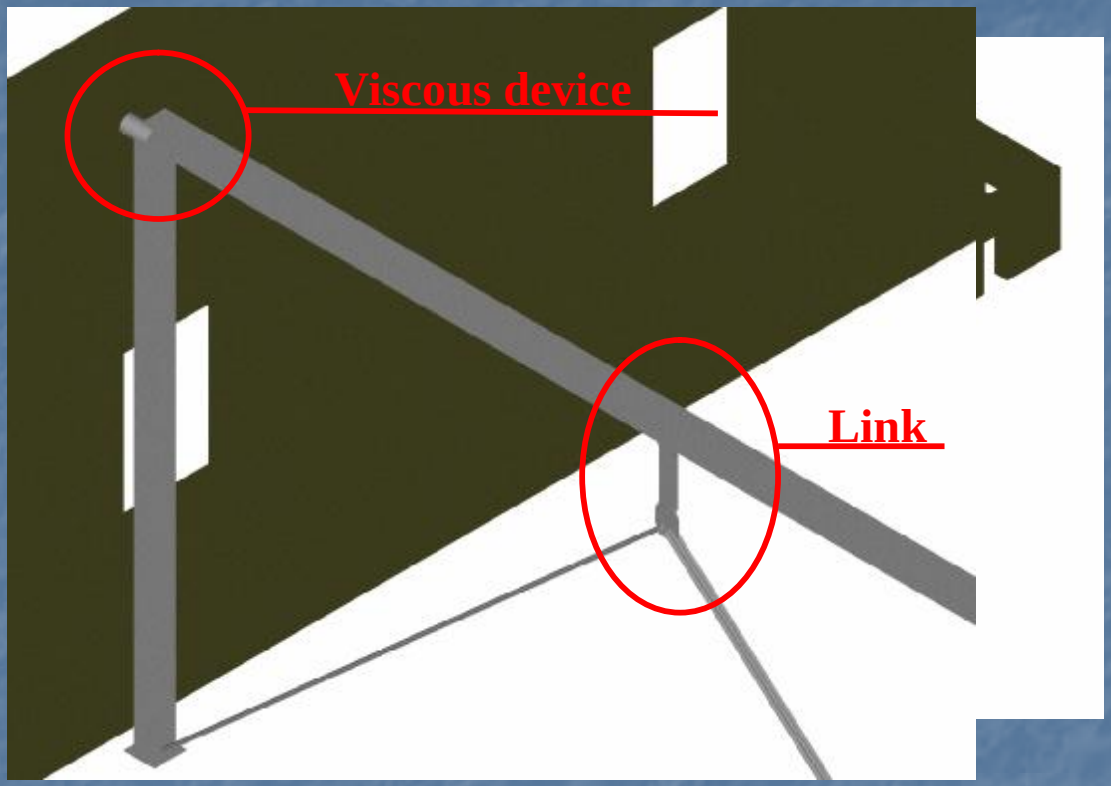
**BRACE LOCATION**




**BRACE LOCATION**

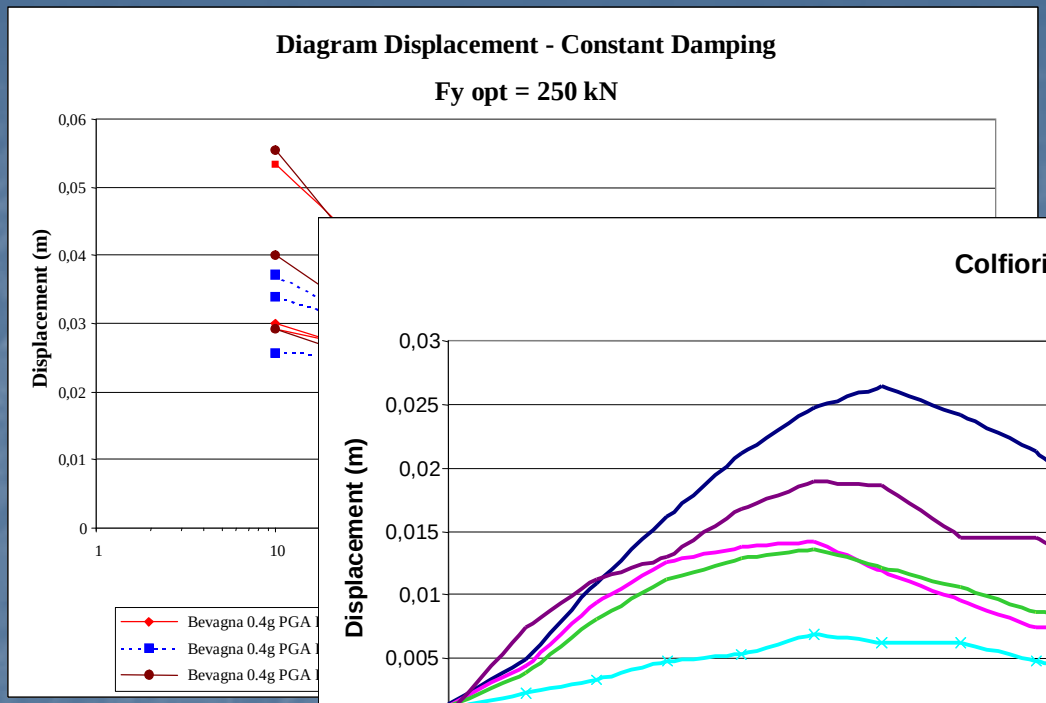


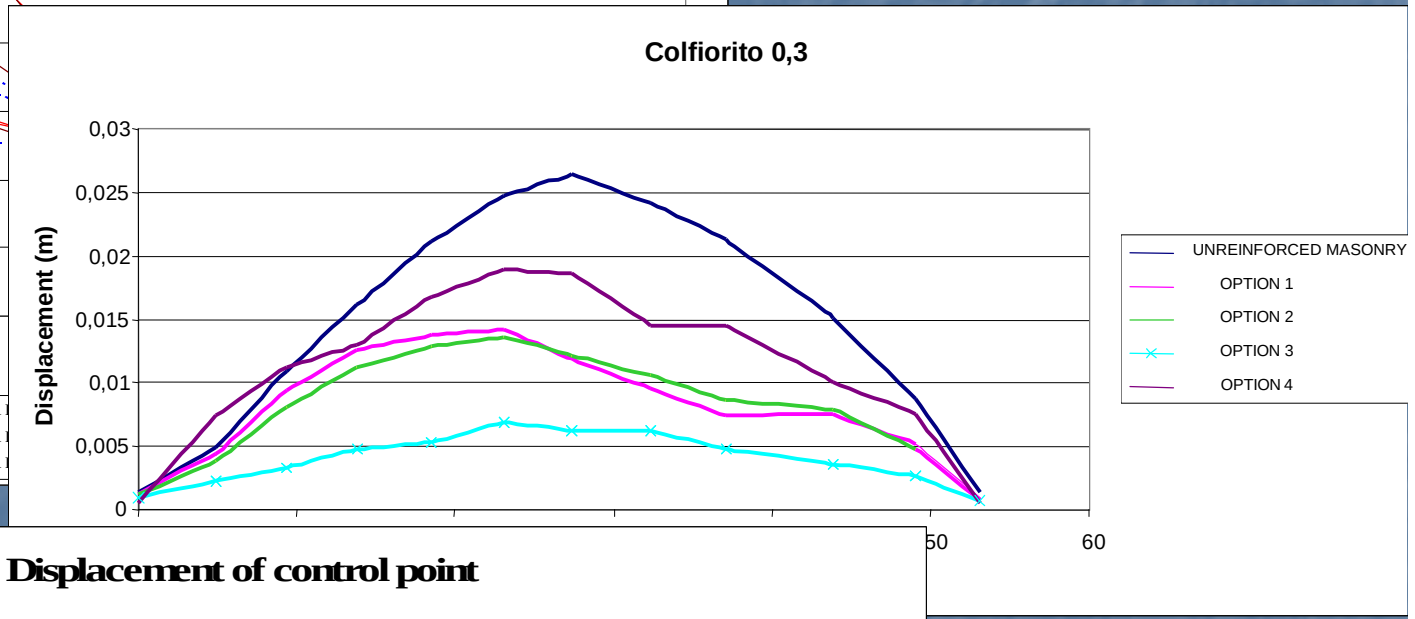
# *INTERVENTION DETAIL*

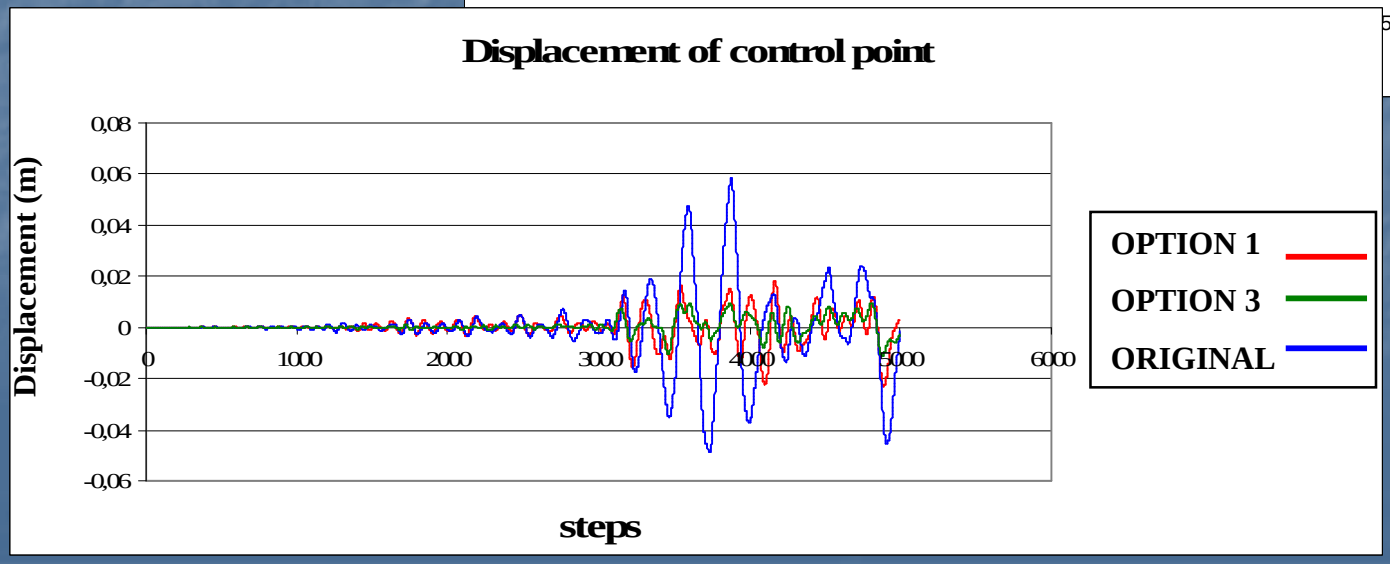



**BRACE DETAILS**

# RESPONSE IN TERMS OF DISPLACEMENT

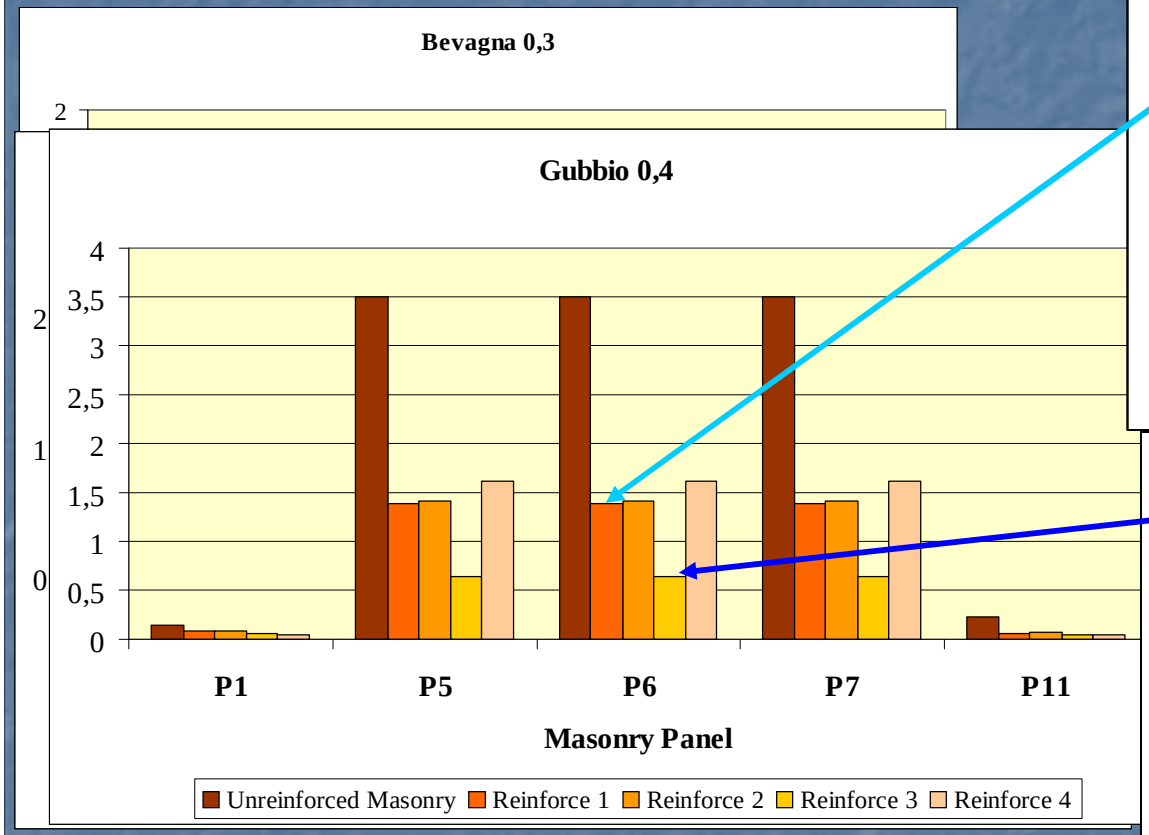


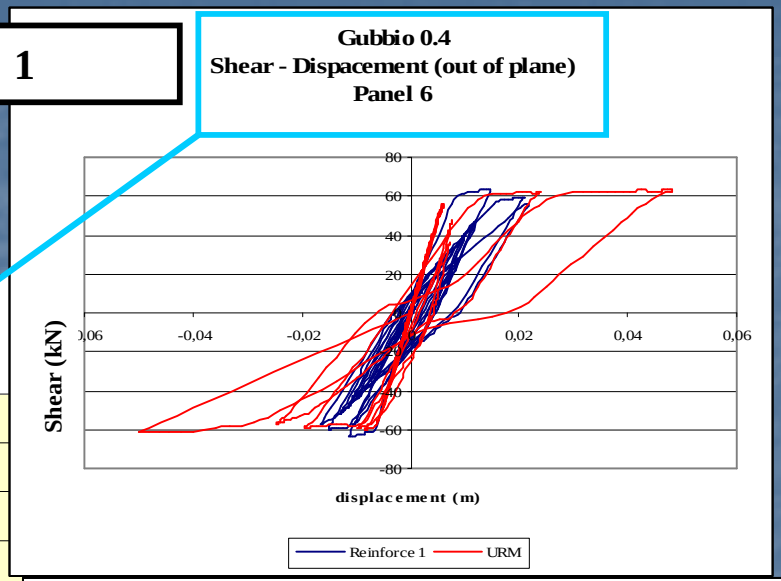



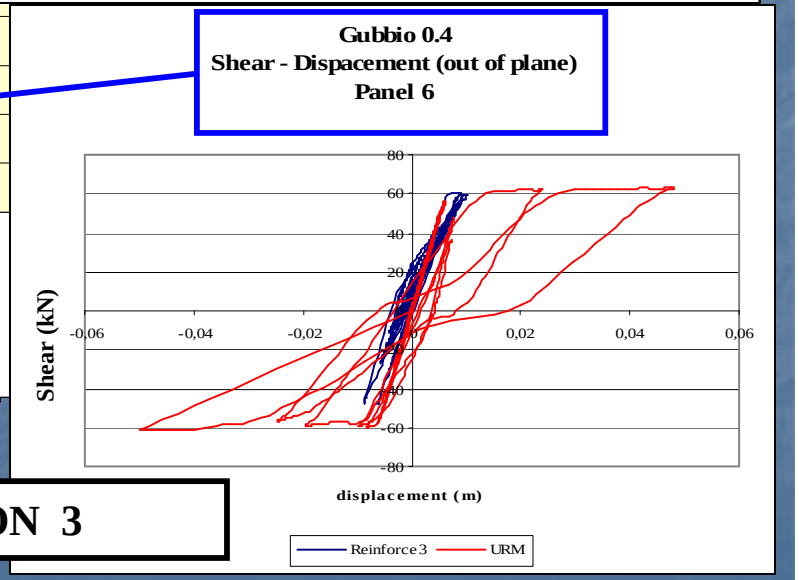



# RESPONSE IN TERMS OF DAMAGE INDEX

**OPTION 1**




$$DI = \frac{\delta_{max}}{\delta_u} + \beta \cdot \frac{\int dE}{F_y \cdot \delta_u}$$

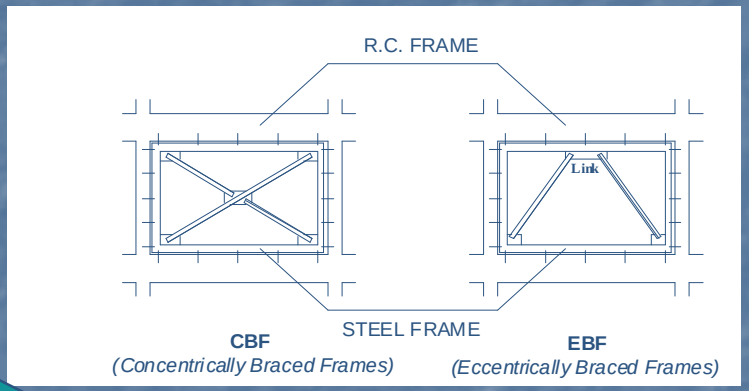
**OPTION 3**

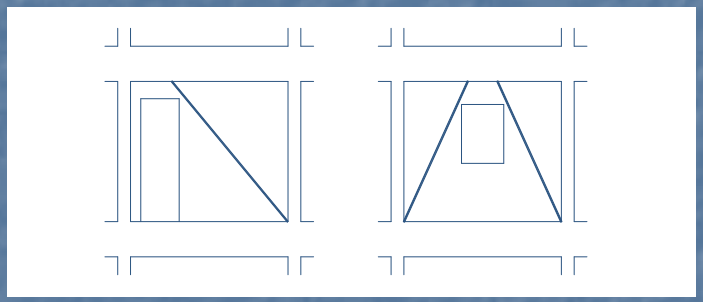
# *OBJECTIVES OF THE STUDY ON R.C. FRAMES*

- A DAMAGE-CONTROLLED PROCEDURE FOR PERFORMANCE-BASED ASSESSMENT OF REINFORCED CONCRETE STRUCTURES WITH DISSIPATIVE BRACING SYSTEMS IS PRESENTED.
- THE PROCEDURE IS BASED ON THE CAPACITY SPECTRUM METHOD, THE INELASTIC DEMAND RESPONSE SPECTRA AND THE ESTIMATION OF THE DURATION-RELATED DAMAGE WHICH IS A FUNCTION OF THE ENERGY ABSORBED IN THE STRUCTURE.
- THE PARK & ANG DAMAGE INDEX AND THE INTERSTORY DRIFT INDEX WERE USED AS CONTROL PARAMETERS TO CHECK THE ATTAINMENT OF THE PERFORMANCE LEVELS OF THE BUILDING FOR A GIVEN EARTHQUAKE GROUND MOTION (FULL OPERATIONAL LEVEL (FO), OPERATIONAL LEVEL (O), LIFE SAFETY LEVEL (LS), COLLAPSE PREVENTION LEVEL (CP)).
- FINALLY, THE SEISMIC PERFORMANCE OF REHABILITATED RC FRAMES DURING VARIOUS LOADING SCENARIOS IS INVESTIGATED AND THE ACCURACY OF THE PROPOSED PROCEDURE WHEN COMPARED WITH STEP-BY-STEP DYNAMIC ANALYSIS IS DISCUSSED.

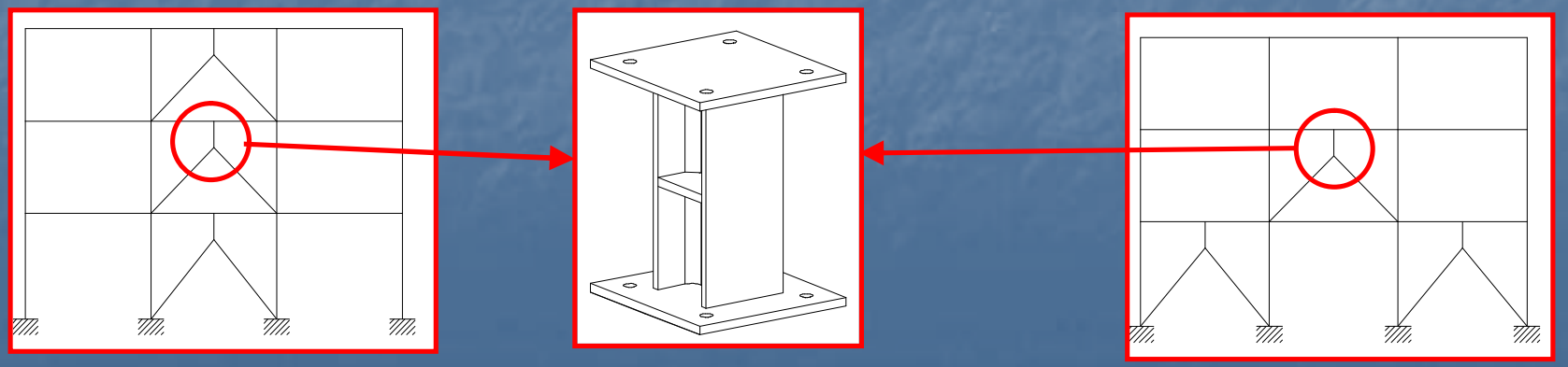
# *Seismic retrofit of r.c. frames with steel braces*

- A CONVENTIONAL RETROFIT STRATEGY CONSISTS OF ADDING STEEL BRACES OR MOMENT FRAMES. BOTH OF THESE SOLUTIONS TEND TO INCREASE THE STIFFNESS OF THE STRUCTURE AND MAY PRODUCE A GREAT INCREASE OF SEISMIC DEMAND TO HIGH FREQUENCY SHAKINGS.

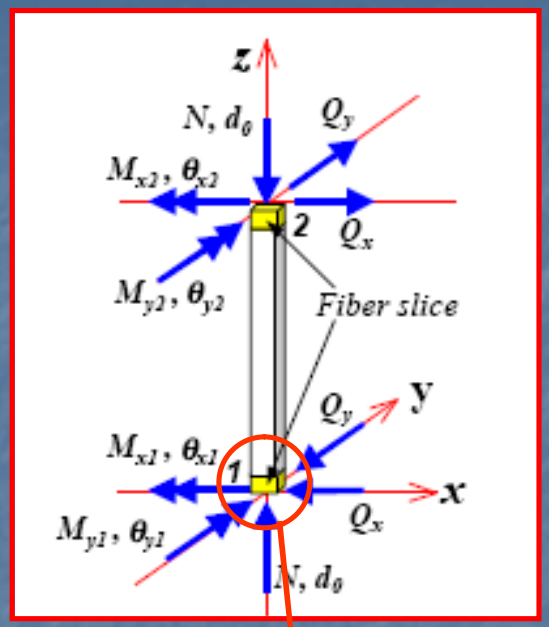


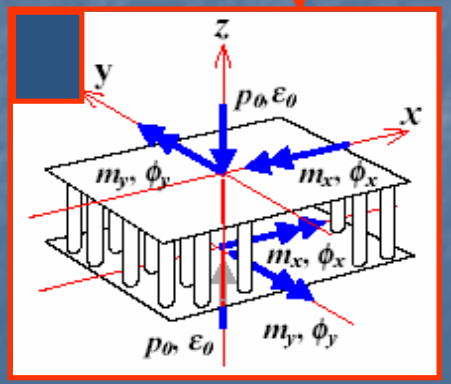
- HIGH DAMPING BUT LIMITED INCREASE OF LATERAL STIFFNESS MAY BE OBTAINED WITH A VERTICAL SHEAR LINK WHICH ACT AS A FUSE BY DISSIPATING ENERGY AND PREVENTING BUCKLING OF THE BRACES.



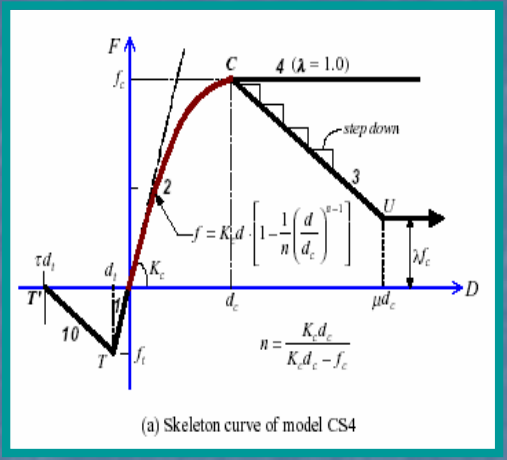
# NONLINEAR MODELLING OF RC MEMBERS

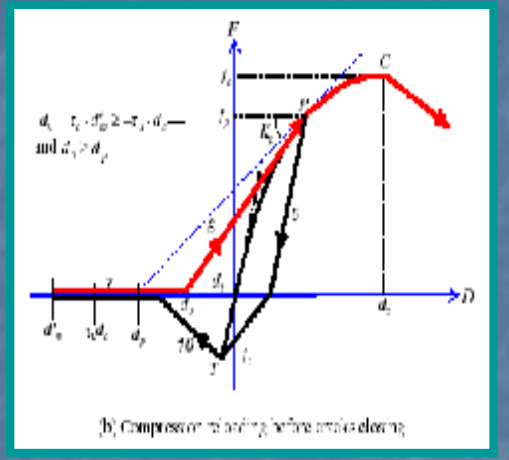



**FIBER MODEL (Canny 99)**

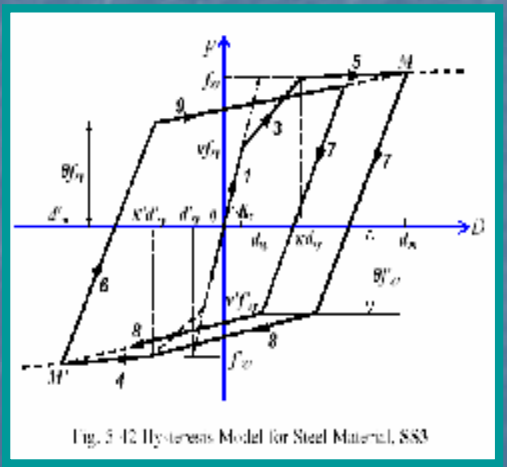


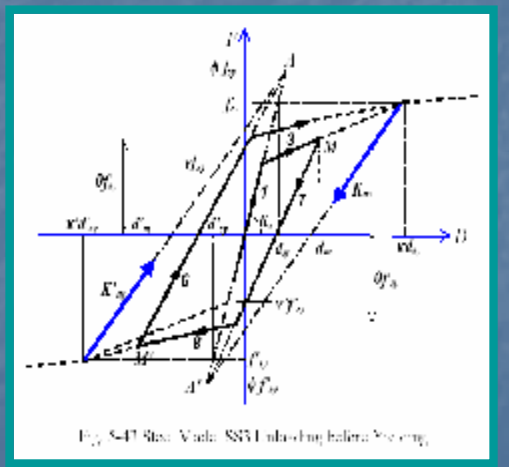

## CONCRETE



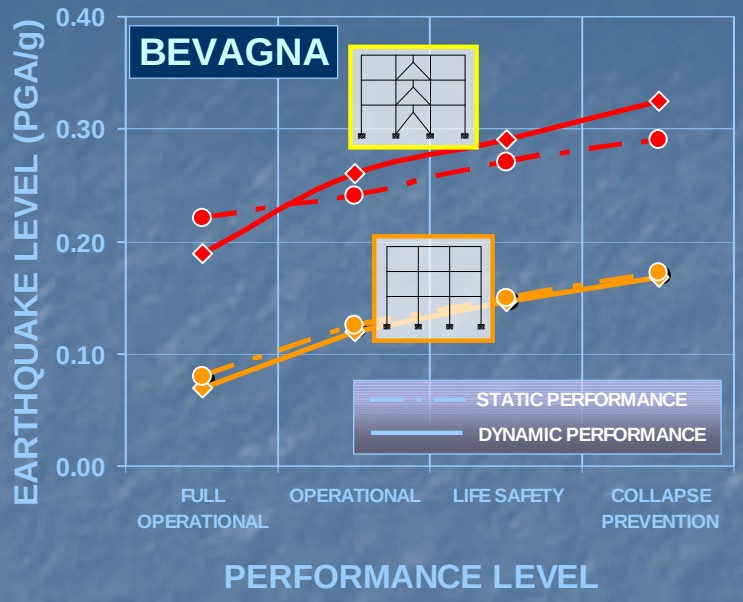

## STEEL

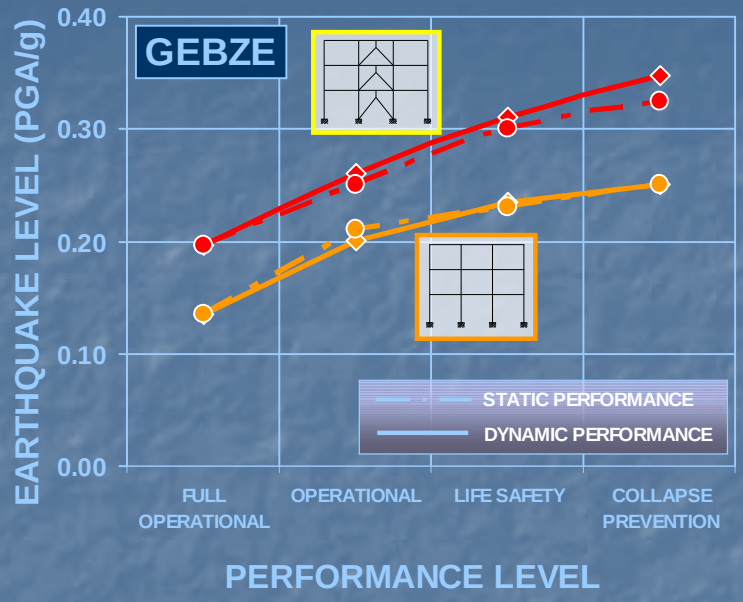


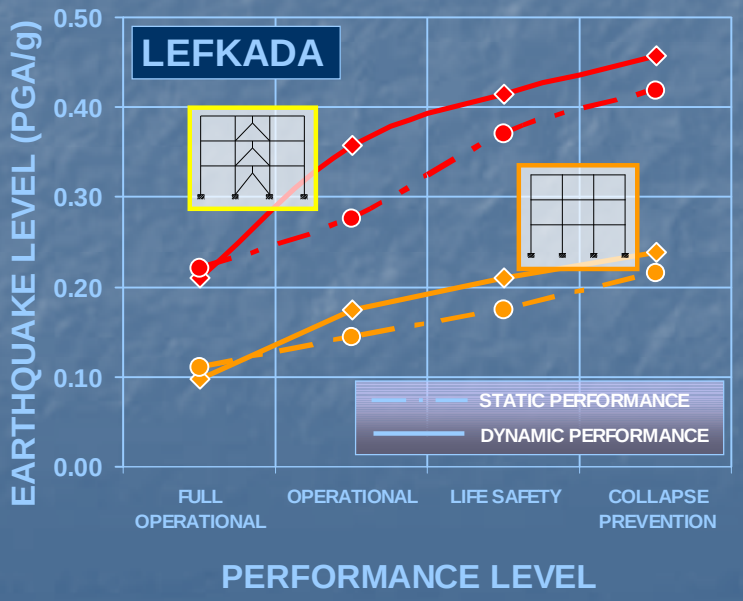



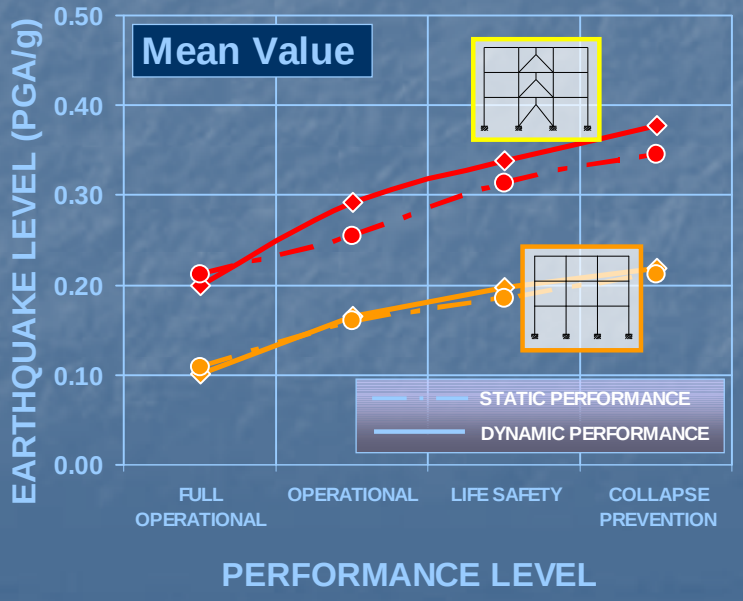
**LINK** → **BILINEAR – Vu/Vp=1.5**

# PERFORMANCE MATRIX



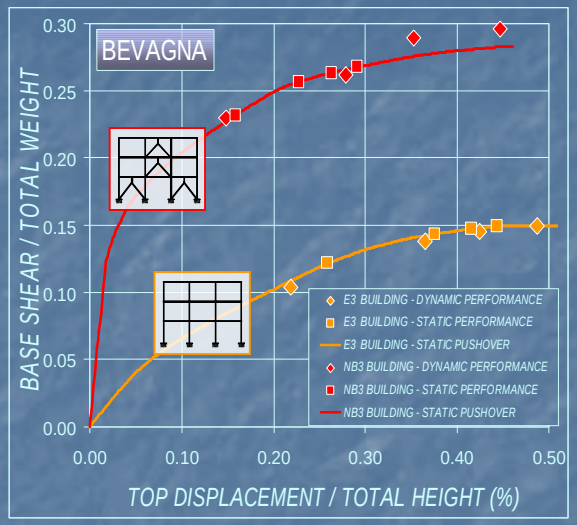



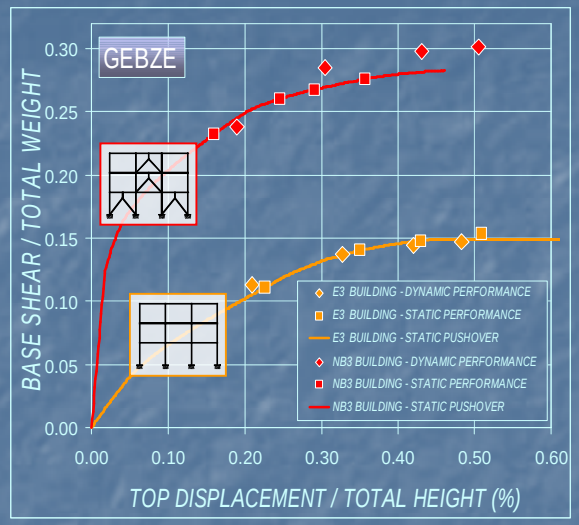



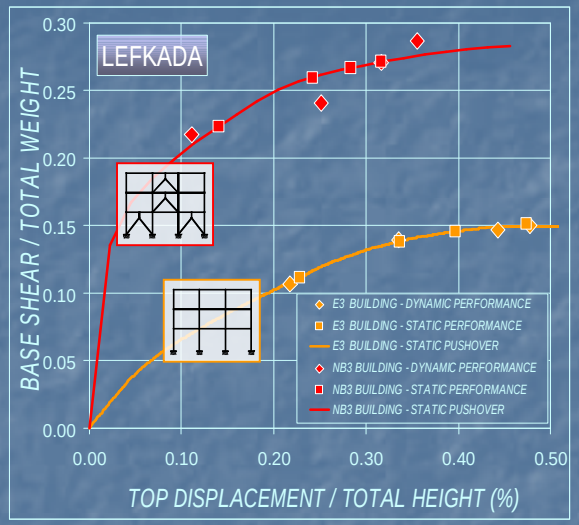



# NON-UNIFORM DISTRIBUTION OF BRACING SYSTEM OVER THE HEIGHT

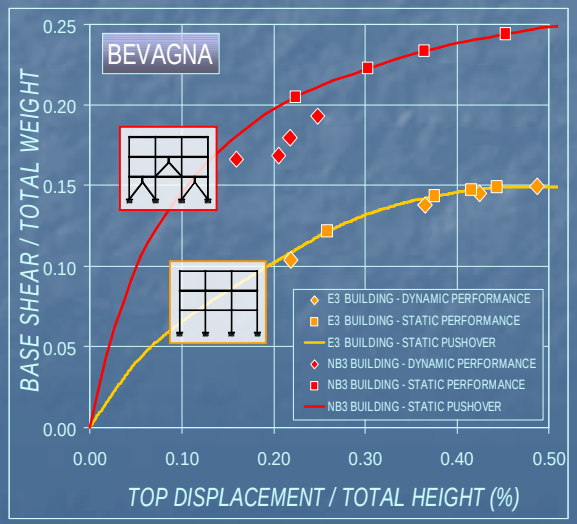
## RC FRAME STRENGHTENED WITH NON-UNIFORM DISTRIBUTION OF STEEL BRACES (NB3-1)

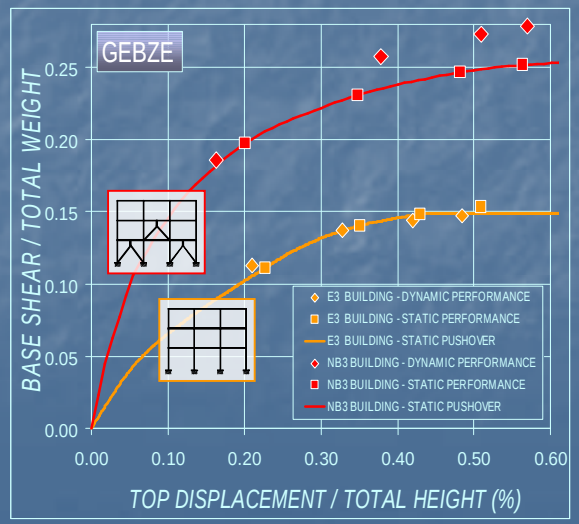


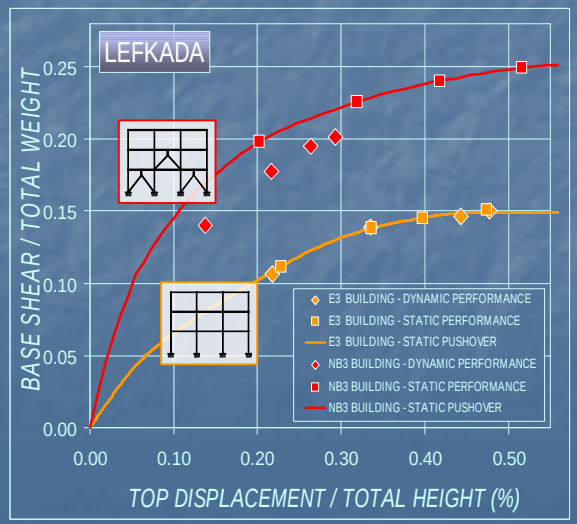




## RC FRAME STRENGHTENED WITH NON-UNIFORM DISTRIBUTION OF STEEL BRACES (NB3-2)



*THANK YOU VERY MUCH FOR YOUR ATTENTION!*