SEISMIC RETROFIT OF HISTORICAL AND EXISTING BUILDINGS

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ABSTRACT

RÖFIX SismaCalce, a new fiber-mortar composite applied on MASONRY walls**,** ignoring the steel reinforced concrete structure, is the perfect solution for **Earthquake protection.** Karlsruhe Institute of Technology (KIT) and RÖFIX has developed an anti-seismic reinforcement system consisting of *(1)* RÖFIX SismaProtect, a multi-axial hybrid high-tech tissue, synthetic and glass fibers, alkali- and corrosion- resistant, with *(2)* RÖFIX SismaCalce coating, a mineral mortar of NHL-Lime + white cement + polymer + bonder by penetrating chemical reaction agent.

Traditional stone and block masonry buildings have low ductility and are usually severely damaged during strong earthquakes. Their collapse could cause building destruction, occupants and passersby loss. Existing walls retrofitted with the new KIT and RÖFIX system, gain high ductility and low modulus of elasticity and adapt perfectly to the different requirements of new buildings, but also and especially of old and existing ones. During earthquake, the system improves the seismic stability of the global structure: retrofitted masonry walls becoming the main elements of building stability, working as sheer resistant walls holding the slabs. The earthquake-induced movements and energies in the masonry can be absorbed through the fiber mesh (Figure 1). Forces and force peaks distributed in the mesh are reduced by the special mortar (Figure 2). Although cracks and partial damages of the structure develop a complete collapse, however, can be prevented, saving human lives.

This innovative, economic and eco friendly system also offers thermal insulation and vapor diffusion permeability. It ensures safety, energy conservation, quality of life and property value. It is easy to handle and can be embedded on all masonry walls.

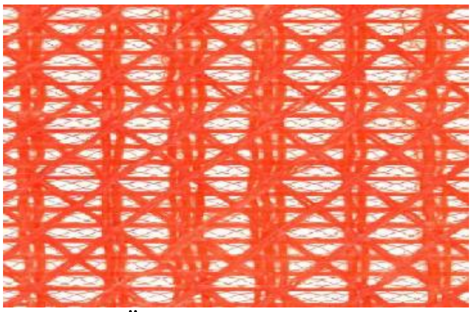


Figure 1. RÖFIX SismaProtect
Fibers overcome the shear strength

Figure 2. RÖFIX SismaCalce
Stone + mortar overcome the compression strengt

SISMA CALCE MATERIAL PROPERTIES CALCULATION - KIT

Professor Doctor-Engineer Lothar Stempniewski and Engineer Moritz Urban, Karlsruhe Institute of Technology, Germany, established calculations of material properties and fiber reinforcement.

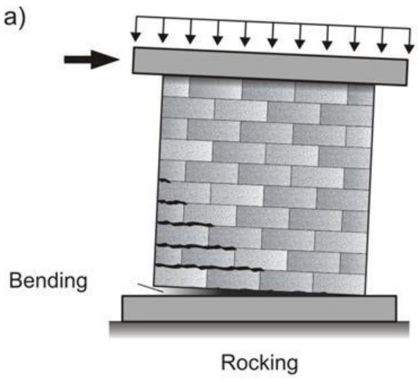
Parameters for in-plan shear :
With f_m = compressive strength masonry; f_{tk} = tensile strength masonry; f_d = designed compressive strength of masonry; p = average normal pressure in the wall;

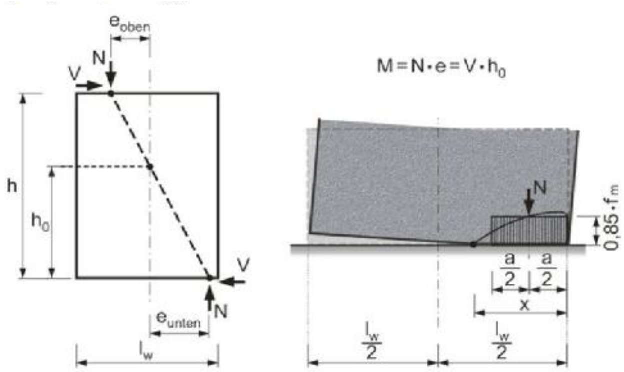
V_{Rd} = design value of shear resistance

d = wall thickness (mm)

Damage Case a): Rocking

$V_{RD} = l_w^2 \,.\, d \,.\, p \,.\, (1 - p / 0{,}85 \,.\, f_d) / 2 \,.\, h_0$





Damage Case b) Shear sliding

According to Mohr-Coulomb: $\tau = c + \mu \,.\, \sigma_v$

According to Euro Code 6: $f_{vk} = f_{vk0} + 0{,}4 \,.\, \sigma_v$

Wall capacity: $V_{Rd} = A_m \,.\, (f_{vk0} + 0{,}4 \,.\, \sigma_v)$

$f_{vk0} =$ initial shear strength of masonry under zero compressive strength

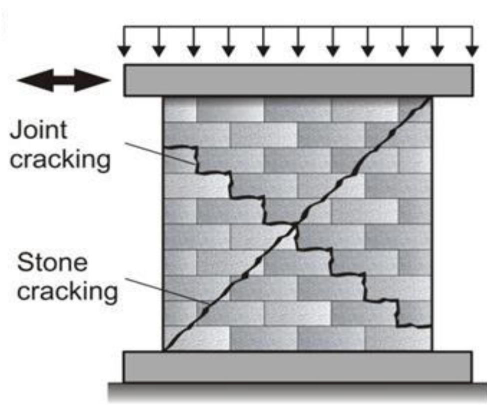
σ_v = compressive strenght perpendicular to shear

f_{vk} = shear strenght of masonry

V_{Rd} = design value of shear resistance

EC 6 : (Table 1)				f_{vk0} in N/mm^2	
in N/mm^2				*Thin layer of mortar (joints between 1 - 3 mm)*	*Light mortar*
2,5	5	10	20		
0,08	0,18	0,22	0,26	0,22	0,18

Damage Case c) Shear/Tension failure



Shear failure

f_{vk0} = initial shear strength according EC 6 (Table 1)

n = number of sisma calce layers being applied (1 or 2)

Ψ_f^{θ} = 0,433 for SismaCalce

$T_f^{\theta} = n \,.\, f_f^{\theta} \,.\, l_{netto} \,.\, \sin(\theta)$ with $f_f^{\theta} = 17{,}9\ N / mm^2$

θ = angle between brick & horizontal wall joint :

SismaCalce 30^o ; t = wall thickness (mm)

$l_{cal} = h_r \,.\, \tan(\varphi)$ with h_r = wall height (mm) &

φ = crack angle : "standard walls" ~ 25^o- 40^o, slender walls : 10^o - 20^o

$k_{eq} = 1 - \alpha_{gmax}$; Reduction of vertical acceleration due to max. vertical acceleration for earthquake used

σ_v = average pressure caused by vertical loads acting for seismic design (vertical earthquake acceleration not included)

$$V_{RK} = \min \{V_{RK}^{shear} ; V_{RK}^{tension} \}$$

$$V_{RK}^{shear} = f_{vk}^{mod} . l_{cal} . t + n . \Psi_f^{90} . T_f^{90}$$

$$f_{vk}^{mod} = (f_{vk0} + n .\Psi_f^{\theta} . T_f^{\theta} . \cos\theta / l_{cal} .t) + \mu (k_{eq} . \sigma_{v} + n. \Psi_f^{\theta} . T_f^{\theta} . \sin\theta / l_{cal} . t)$$

$$V_{RK}^{tension} = f_{bt,cal}^{mod} . l . t / 2{,}3 . (1 + \alpha_v) . e1 + N_{Rd} / f_{bt,cal}^{mod} . l . t$$

$$f_{bt,cal}^{mod} = f_{bt} + n . \Psi_f^{\theta} / t . (f_f^{90} . \cos^2 \varphi + f_f^{0} . \sin^2 \varphi + f_f^{0} . \cos^2 | \varphi - \theta |)$$

Damage Case d) Compression failure

According Schubert: $f_m = a . f_b^{b} . f_{mo}^{c}$

f_m = compressive strength of masonry
f_b = compressive strength of brick
f_{mo} = initial compression strength in masonry

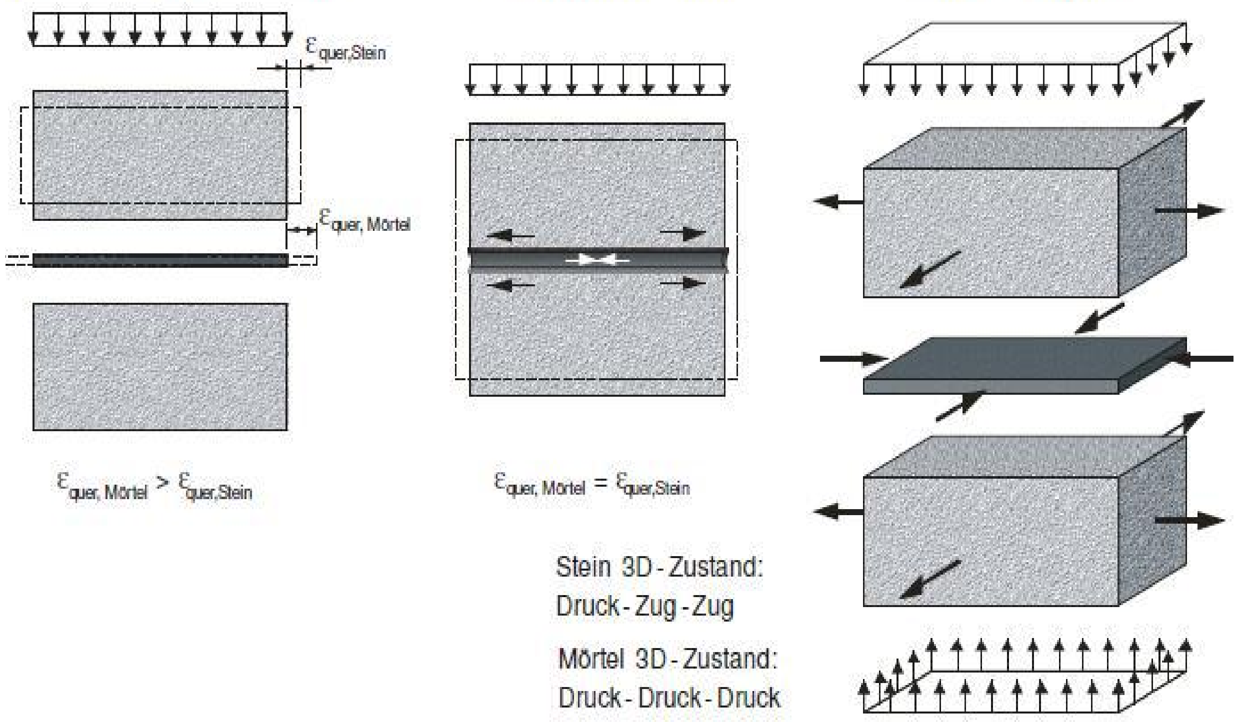
Stone	a	b	c
Solid stone	0,73	0,73	0,16
Hollow brick	0,55	0,56	0,46
Lime Sandstone	0,7	0,74	0,21

Important: Strength of mortar and brick:

Free transverse elongation of single element

Combining of elements

Tension state



Brick 3D – state:
Compression-pull of- pull of

Mortar 3D – state:
Compression-compression-compression

Calculation of missing properties

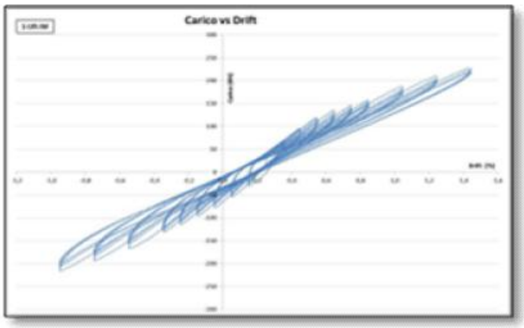
According Italian code Equation (1): $f_{tk} \approx 1{,}5.f_{vk0}$	Table EC6 :				
Equation (2) : $f_m \approx 0{,}7 \,.\, f_b$ Equation (3) : $f_{tk} \approx 1 / 15 \,.\, f_b$ Equation (4) : $f_m = a \,.\, f_b^{\,b} \,.\, f_{mo}^{\,c}$	f_{m0}	2,5	5	10	20
	f_{vk0}	0,08	0,18	0,22	0,26
	Interpolation	0,1268	0,21096	0,24208	Calculated
	Value f_m	3,67	8,87	15,52	To put in

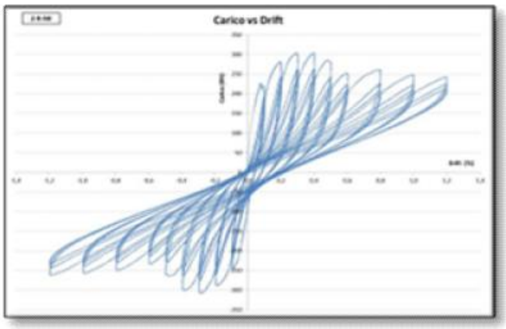
EXPERIMENTAL TESTS - PADOVA (ITALY), AND IZIIS (SKOPJE, MACEDONIA)

"Out of plan" tests

Non-reinforced wall

Walls Reinforced with Sisma Calce



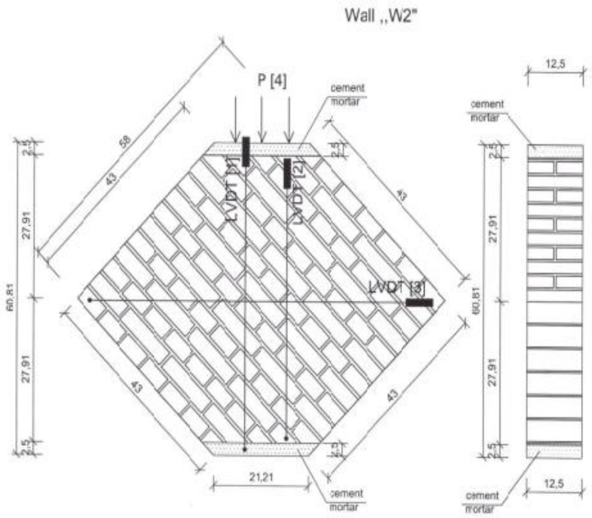


Resistance for "out of plain" by reinforced wall has demonstrated increasing of resistance for approximate 54% and increasing of maximum deformation for 35%.

IN- PLAN STRENGTH TEST

Testing results of W2 type wall elements to diagonal compression up to failure

Giving Shear and Tensile strengths
Case of Non Retrofitted Wall



Wall element	Date of testing	Cross-section A (cm^2)	Maximum axial force P_{max} (kN)	Comprehensive strength $\sigma_c = \tau_u = P_{max} \cos45^o / A$ (kPa)	Tensile strength F_t (kPa)
W2-1	16.04.13	725	51	497	307
W2-2	24.04.13	725	43	419	259
W2-3	25.04.13	725	48	468	289

Testing results of W2R type Retrofitted wall elements to diagonal compression up to failure

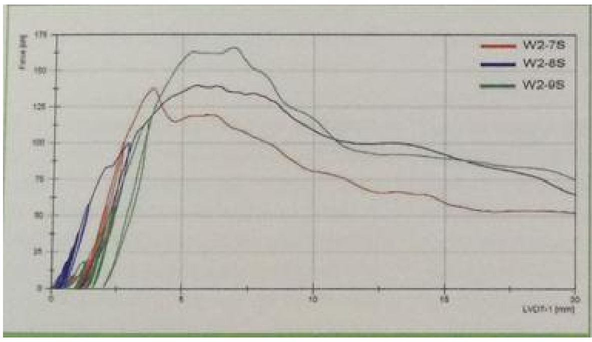
Wall element	Date of testing	Maximum axial force P_{max} (kN)	Comprehensive Shear Stress $\sigma_c = \tau_u = P \cos45^o / A$ (kPa)	Tensile strength F_t (kPa)	Ductility capacity
W2-4R	22.08.13	150	1462	903	5.1
W2-5R	23.08.13	128	1248	771	5.9
W2-6R	27.08.13	97	946	584	7.1

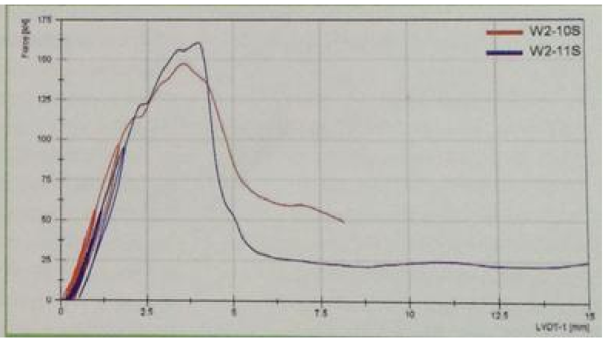
Testing results of W2S type Retrofitted wall elements to diagonal compression

Wall element	Date of testing	Maximum axial force P_{max} (kN)	Comprehensive Shear Stress $\sigma_c = \tau_u = P \cos45^o / A$ (kPa)	Tensile strength F_t (kPa)	Ductility capacity
W2-7S	29.08.13	138	1345	831	5.1
W2-8S	30.08.13	140	1365	843	5.5
W2-9S	02.09.13	165	1579	976	7.5

Two side retrofitted wall element

One side retrofitted wall element





Appearing of high ductility (3 times higher)

Increasing of shear resistance for 300%

Damages on non-retrofitted model (0,35 g)

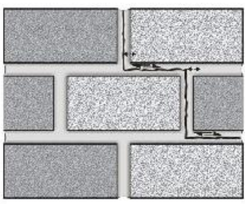
Damages on SismaCalce retrofitted model (1,22 g)

Experimental values of tested Earthquake : Results comparison for both models

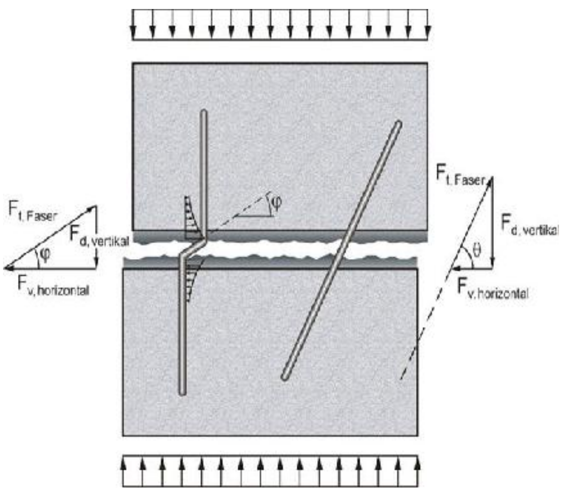
Earthquake	Span %	acc^{inp}_{ut} (g)	BM - Non Retrofitted Wall			Damages	BM - SR - Sisma Calce Retrofitted Wall			**Damages**
			acc^{top} (g)	LP^{top} (mm)	LP^{top} - $LP^{foun.}$ (mm)		acc^{top} (g)	LP^{top} (mm)	LP^{top} - $LP^{foun.}$ (mm)	
Petrovac	36	0,16	0,26	6,4	0,34		0,25	5,7	0,29	
Northridge	16	0,18	0,34	13,5	0,26		0,21	12,8	0,21	
Petrovac	40	0,18	0,29	6,9	0,58		0,28	6,4	0,52	
El Centro	75	0,21	0,35	16,4	0,91	Initial fine cracks	0,32	15,9	0,86	
Petrovac	45	0,20	0,32	7,8	0,77		0,30	7,0	0,73	
Northridge	20	0,21	0,42	17	0,98		0,28	15,8	0,62	
El Centro	80	0,27	0,52	11,6	1,20	Further propagation of initial cracks	0,37	10,9	1,11	
Northridge	25	0,23	0,47	21	1,04		0,33	20	0,79	
Petrovac	50	0,22	0,41	8,9	1,14	Damages development	0,36	8,4	0,94	Initial fine cracks
Petrovac	70	0,32	0,61	12,2	1,29		0,55	11,9	1,60	
Petrovac	75	0,35	0,71	13,9	1,54		0,51	12,2	1,64	
Petrovac	100	0,51					0,91	16,9	2,80	
Petrovac	120	0,60					1,09	20,3	2,98	Further propagation of initial cracks
El Centro	100	0,31					4,41	21,7	1,35	
Petrovac	150	0,82		---------			1,29	23,9	4,26	
Petrovac	180	0,92					1,58	28,9	11,40	Damages development
Petrovac	220	1,035					1,76	36,99	20,10	
Petrovac	260	1,22					2,1	44,7	26,40	
							Additional resistance for retrofitted model			

CALCULATIONS AND MATERIAL PROPERTIES

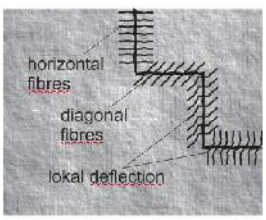
Mortar joint cracking



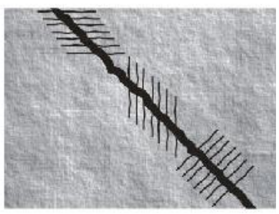
Stone cracking



Behavior of composite material



Behavior of stone



CALCULATION OF FIBER REINFORCEMENT DAMAGE CASES:

Modification of shear strength with SismaCalce:

$$f_{vk}^{reinforced} = f_{vk0} + (n / t) \cdot \Psi_f^{30} \cdot f_f^{30} \cdot \cos 30^o$$

n = fibres layers number ; t = wall thickness (mm); Ψ_f^{30} = bonding efficiency factor for SismaCalce

43,3% ; f_f^{30} = Strength of fibres; f_f^{90} = 1960 N / 50mm ; f_f^{0} = 1817 N / 50mm ; f_f^{30} = 895 N / 50mm

Modification of tensile strength with SismaCalce:

$$f_{bt,cal}^{mo} = f_{bt,cal} + n \,.\, \Psi_f^{\theta} /t.\ (f_f^{90}\ .\ \cos^2 \varphi + f_f^{0}\ .\ \sin^2 \varphi + f_f^{0}\ .\ \cos^2 | \varphi - \theta |)$$

Easy equations:

Modification of shear strength with Sisma Calce:

$$f_{vk}^{strength} = f_{vk0} + (n / t) \,.\, f_{SC,shear} / t = f_{vk0} + n \,.\, 6{,}71\ N/ mm \,.\, t$$

Modification of tensile strength with Sisma Calce:

$$f_{bt}^{strength} = f_{bt} + (n / t).\ f_{SC,tension} \,.\, (h / l)$$

Height / Length (h /l)	4	2	1	0,5
$f_{SC,tension}$	19,55 N / mm	21,37 N / mm	23,58 N / mm	24,44 N / mm

Calculation of fiber reinforcement (Example)

Type of wall	Non-reinforced f_{vk0} (N / mm^2)	One side reinforced f_{vk0} (N / mm^2)	Two side reinforced f_{vk0} (N / mm^2)	Non-reinforced f_{bt} (N / mm^2)	One side reinforced f_{bt} (N / mm^2)	Two side reinforced f_{bt} (N / mm^2)
Solid brick 200 mm	0,11	0,143	0,177	You must establish these values experimentally		
Solid brick 250 mm	0,11	0,137	0,164			
Hole brick 200 mm	0,23	0,263	0,297	0,97	1,24	1,51
Hole brick 250 mm	0,23	0,257	0,284	0,97	1,188	1,406

Material Properties of different Stones. In Laboratories. Unit: **(MN / m^2) = MPa**

Material	f_{tk}	f_{vk0}	f_m	f_{bm}	f_{bk}	w (kN/m^3)
Hollow brick	0,3 (1)	Norm: 0,2?	7,35 (2)	10,5	7,35	
Hollow brick Isoledil	1,93 (3)	0,2 (N)	20,3 (2)		29	7,2
Solid brick	1,26 (3)	0,1 (N)	13,3 (2)	15	19	17
Hollow brick before 1970	0,8 (3)	0,2 (N)	8,4 (2)	12		
Hollow rick after 1970	1 (3)	0,2 (N)	10,5 (2)	15		
Solid brick before 1970	1 (3)	0,1 (N)	10,5 (2)	15		
Solid brick after 1970	1,33 (3)	0,1 (N)	14 (2P)	20		
Aquila natural stone	11,73	0,12 (EC6)	40,14 (4)	164,5		26
Lime sandstone KA 2DF	1,53	0,11	7,72 (4)	20,57		20

EARTHQUAKE-RESISTANT PROTECTION RÖFIX SISMACALCE SYSTEM BENEFITS

- Saves human lives
- Improves buildings stability and ductility, a considerable deformation of the building can be achieved
- Increases the load-bearing capacity of masonry and protects the non-bearing walls at the limit load against damages, therefore cracks and partial damages cannot provoke a general structural collapse, which reduces the cost of eventual reconstruction
- Ensures a uniform distribution of stresses in walls
- Sustainable and eco-friendly material: energy consumption reduction; elimination of thermal bridges; breathable walls therefore healthy and comfortable room climate without condensation or mold
- The retrofitting system impresses with its easy use and low cost

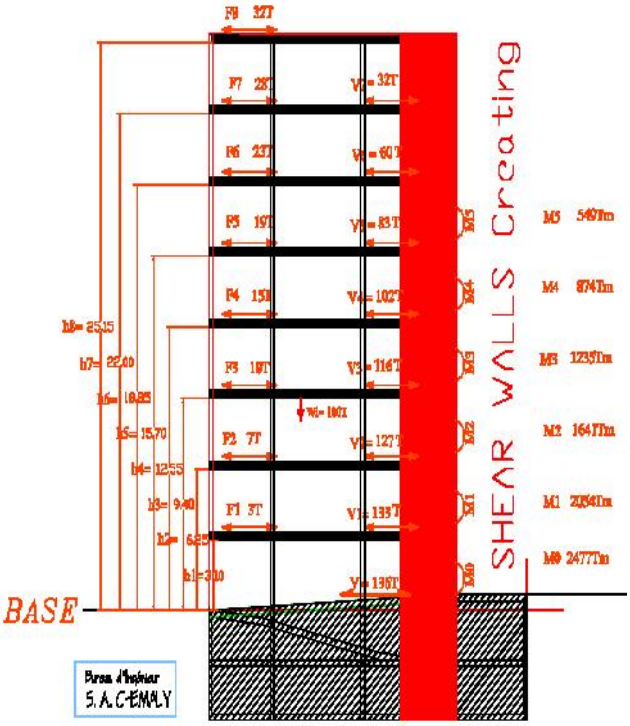
APPLICATION ON A BUILDING OF GROUND FLOOR +7 FLOORS

Building structure composed by Columns and Slabs of Steel reinforced Concrete. The partition walls are hollow block masonry walls.

SEE 7

Four chosen masonry walls were retrofitted, two in each direction X and Y, by simply applying one Fiber reinforced SismaCalce System.

The application of the System transformed these masonry walls into shear walls.



The hollow block Masonry walls problem is that they are FRAGILE like glass; they brake and crumble suddenly due to the lack of Elasticity and Plasticity.

Reinforced Sisma Calce system, is to bind to the wall to become "one body" with it, and to impart DUCTILITY to the wall, giving it Elastic and Plastic properties.

The seismic Forces and displacements design using simple Force Method give the Base Shear Strength, **V** =1360 KN in each directions X and Y, and all other strengths and stresses.

When masonry walls are (superposed) from top to foundations, for example the external walls, these walls are considered load bearing walls holding part of the vertical load: tiles and secondary partitions; let us say 2 KN/m2 as minimum load.

The vertical load in the wall by linear meter, for one floor is **p**, minimum = 12 KN / lm / floor, and In the ground floor masonry wall, under 7 floors loads: **p**, minimum= 84 KN /lm. If the wall thickness **t** is 20cm. The vertical weight stress in the wall is $\sigma_v =$ 0.42 MPa.

In the above table: "Material Properties of different Stones", $\mathbf{f_{vk0}}$ = 0.2 MPa for 20cm concrete hollow block, see above "Damage Case b) Shear sliding".

Before Sisma Calce Coating:
Initial shear stress resistance in the bloc, using Mohr circle equation: $\mathbf{f_{vk} = f_{vk0} + 0.4\ \sigma_v}$

After Sisma Calce Coating on one side of the wall (n=1):
$f_{Rvk0} = f_{vk0} + n\ 6.71 / t = 0.263$
and the Shear stress resistance in the wall,
$f_{Rvk} = f_{Rvk0} + 0.6\ \sigma_v = 0.515$ MPa

In the Ground Floor, in X direction, **L,** being needed one face retrofitted wall Length. Base Shear Strength V = 1360 KN < = f_{Rvk} . t . L . 2 (2 retrofitted walls), give L > = 6.6 m
If we can make the coating on the 2 faces of the walls, L > = 3.3 m.
The same issue in Y direction.

If the height of the walls is 3 m, the total coated area in Ground Floor to be retrofitted: 80 m2.
The same calculation for the 6th floor gives 60 m2 of coated walls area to be retrofitted.

Traditional Old Houses

Let us consider a house composed by a Ground Floor + 2 upper floors, built with bearing walls of natural stones. Usually the walls of these houses are high (4m for ex). The same calculations as above, with **fvk0** = 0.12 MPa for natural stone, gives L> 8m (1 face) / direction, or L>4m (double coats).