SEISMIC RETROFIT OF HISTORICAL AND EXISTING BUILDINGS
2015

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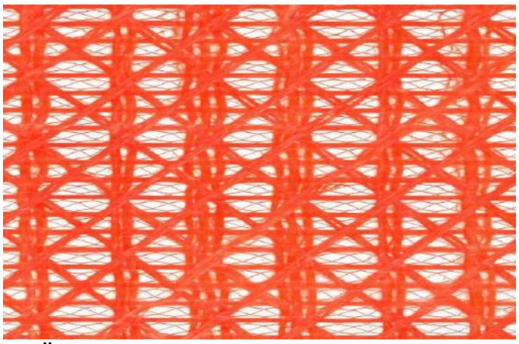
Keywords: *Earthquake Engineering, Retrofit, Old and New Buildings, Saves Lives, Eco-friendly*

RÖFIX SISMACALCE® ANTI-SEISMIC REINFORCEMENT SYSTEM

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), RÖFIX Germany and S Chemaly (MESC) 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 *(1)*. Forces and force peaks distributed in the mesh are reduced by the special mortar *(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.


RÖFIX SismaProtect *(1)*
Fibers overcome the shear strength


RÖFIX SismaCalce *(2)*
Stone+mortar overcome the compression strength

SISMA CALCE MATERIAL PROPERTIES CALCULATION - KIT

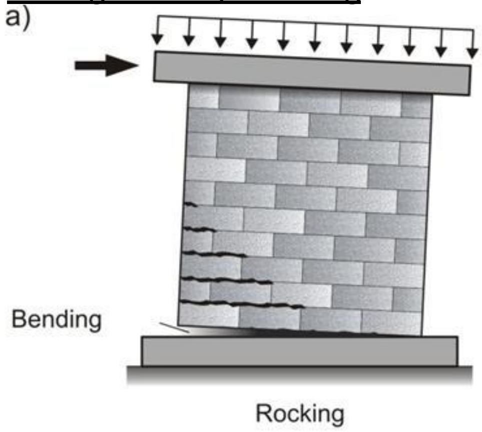
Professor Doctor-Engineer Lothar Stempniewski and Engineer Moritz Urban, Karlsruhe Institute of Technology, Germany, established **calculations of material properties and fiber reinforcement.**

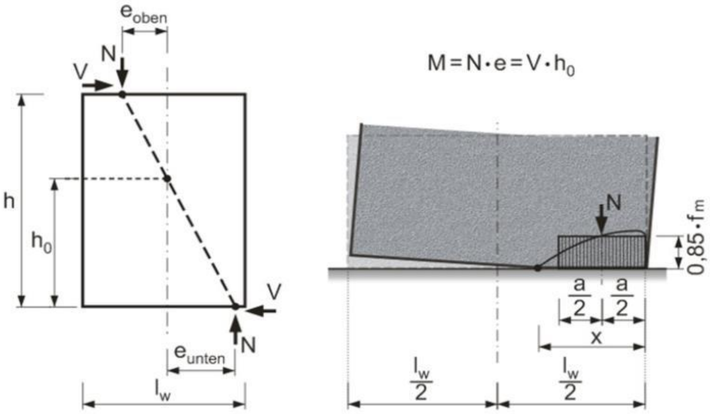
<u>Parameters for in-plan shear</u> :

With $\mathbf{f_m}$ = compressive strength masonry; $\mathbf{f_{tk}}$ = tensile strength masonry;
$\mathbf{f_d}$ = designed compressive strength of masonry; **p** = average normal pressure in the wall;
$\mathbf{V_{Rd}}$ - design value of shear resistance **d** = wall thickness (mm)

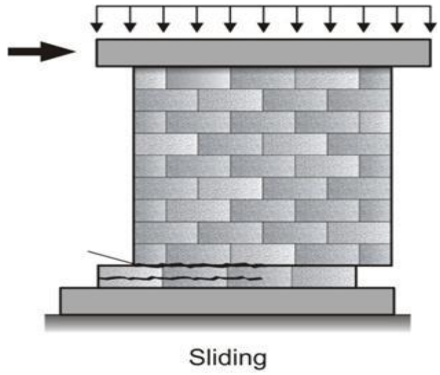
Damage Case a): Rocking

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





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

with

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

σ_v = compressive strenght perpendicular to shear

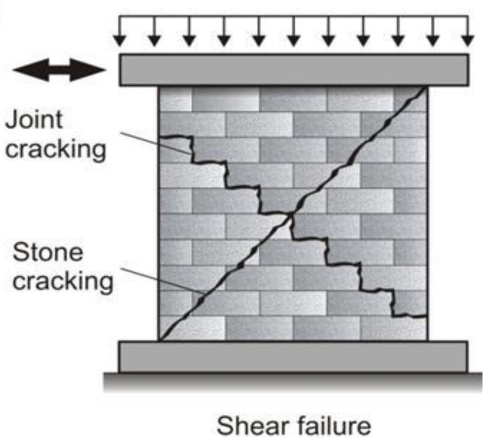
f_{vk} = shear strenght of masonry

V_{Rd} = design value of shear resistance

A_m = Horizontal wall section

EC 6 : (Table 1) $\underline{f_{vk0}}$ in N/mm^2					
Normal mortar with Compressive Strength f_{m0} 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



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 Sisma calce

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

θ = angle between brick cracks & horizontal wall joint :
for Sisma calce: 30^o **;**

t = wall thickness (mm)

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

φ = Mortar crack angle: "standard walls" ~ 25^o- 40^o,
slender (thin) 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)

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

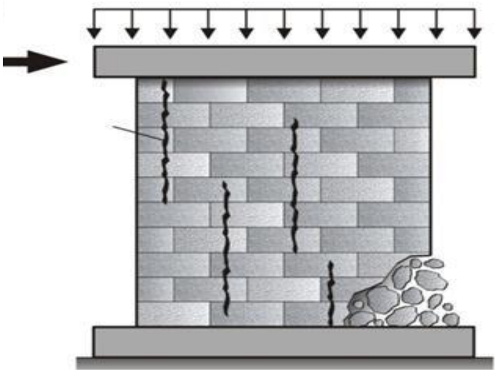
$$\mathbf{V_{RK}^{shear} = f_{vk}^{mod} \,.\, l_{cal} \,.\, t + n \,.\, \Psi_f^{90} \,.\, T_f^{90}}$$

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

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

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

Damage Case d) Compression failure



According Schubert: $\mathbf{f_m = a \,.\, f_b^{\,b} \,.\, f_{mo}^{\,c}}$
According EC6 : $\mathbf{f_m = k \,.\, f_b^{\,b} \,.\, f_{mo}^{\,c}}$
$\mathbf{f_m}$ = compressive strength of masonry
$\mathbf{f_b}$ = compressive strength of brick
$\mathbf{f_{mo}}$ = initial compression strength in masonry
k value from EC6 table

Schubert Table:

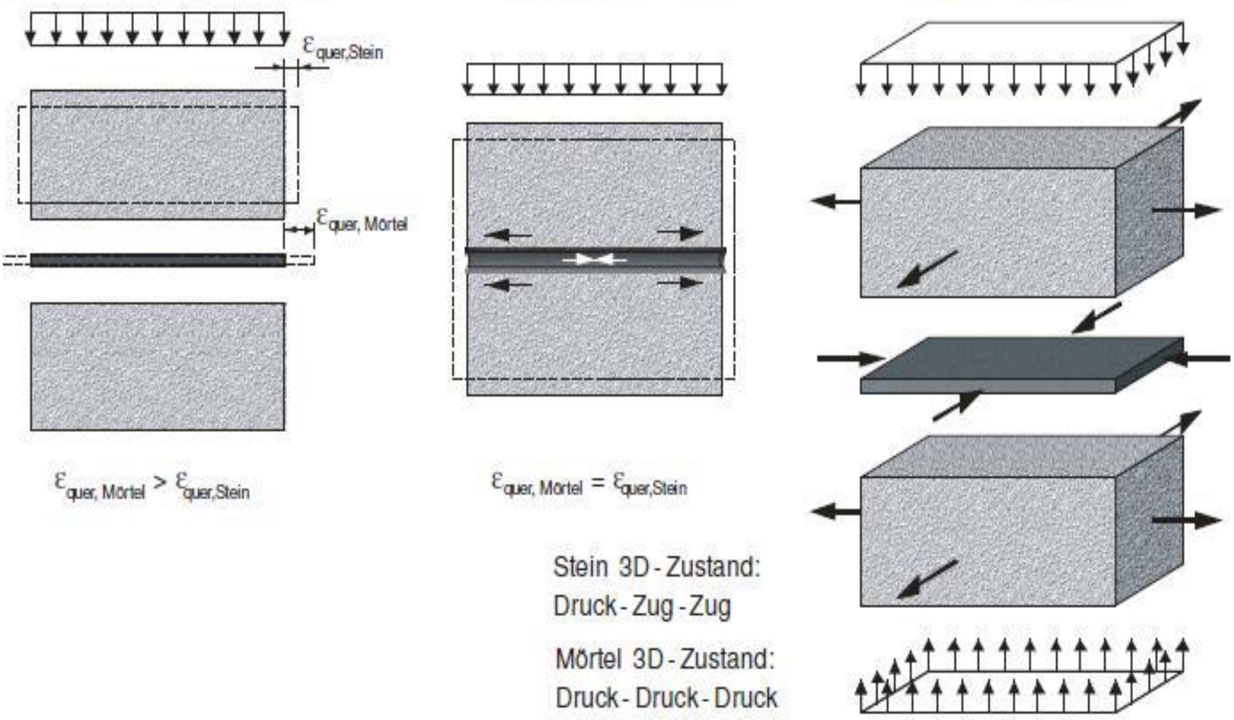
Stone	**a**	**b**	**c**
Solid stone	0,73	0,73	0,16
Hollow brick	0,55	0,56	0,46
LimeSandstone	0,7	0,74	0,21

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

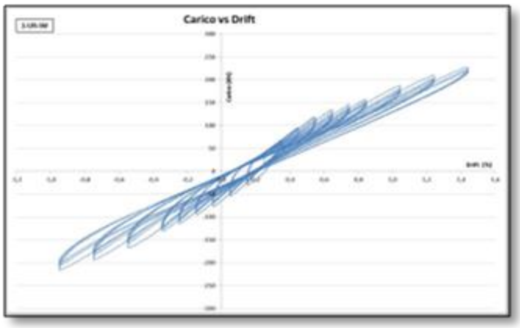
According Italian code Equation (1): $f_{tk} \approx 1{,}5.f_{vk0}$	Table EC6 :				
Equation (2) : $f_m \approx 0{,}7\ .\ f_b$ Equation (3) : $f_{tk} \approx\ f_b\ /15$ Equation (4) : $\mathbf{f_m = a\ .\ f_b^{\ b}\ .\ f_{mo}^{\ c}}$	f_{m0}	2,5	5	10	20
	f_{vk0}	0,08	0,18	0,22	0,26
	Interpolation	0,1268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

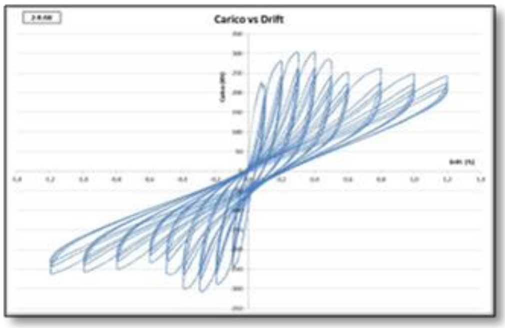
EXPERIMENTAL TESTS - PADOVA (ITALY), AND IZIIS (SKOPJE, MACEDONIA)

"Out of plan" tests



Non-reinforced wall **Walls Reinforced with Sisma Calce**



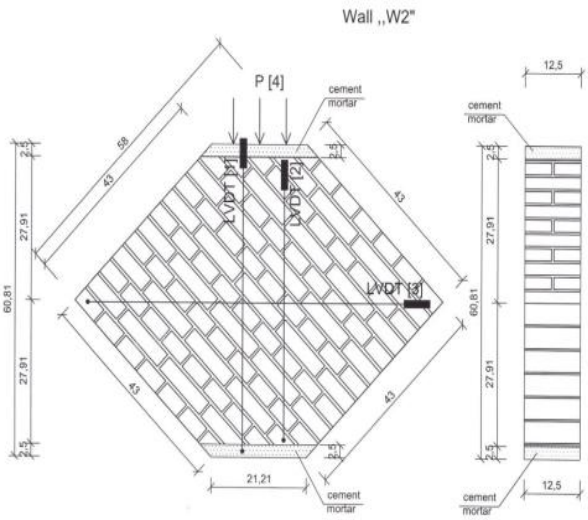


Resistance for "out of plain" by reinforced wall has demonstrated increasing of resistance for approximate 54% and increasing of maximum deformation for 35%.

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° / 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

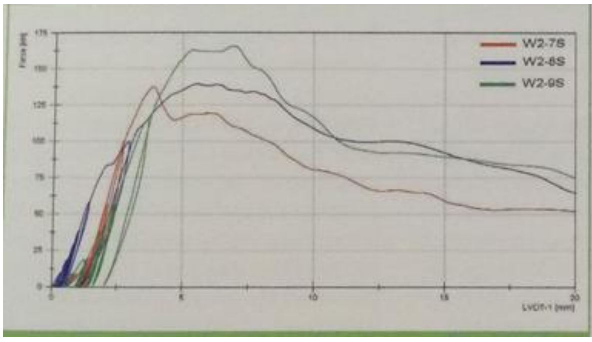
Testing results of W2R type **Retrofitted wall** elements to diagonal compression up to failure

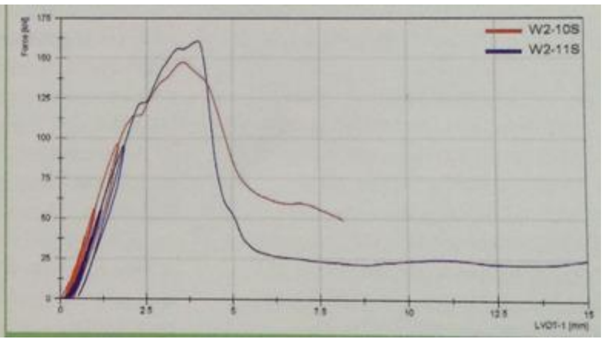
Wall element	**Date of testing**	**Maximum axial force P_{max} (kN)**	**Comprehensive Shear Stress $\sigma_c = \tau_u$ = P cos45° / A (kPa)**	**Tensile strength F_t (kPa)**	**Ductility capacity**
W2-4R	22.08.13	150	1462	903	5.1
W2-5R	23.08.13	128	1248	771	5.9
W2-6R	27.08.13	97	946	584	7.1

Testing results of W2S type **Retrofitted wall** elements to diagonal compression

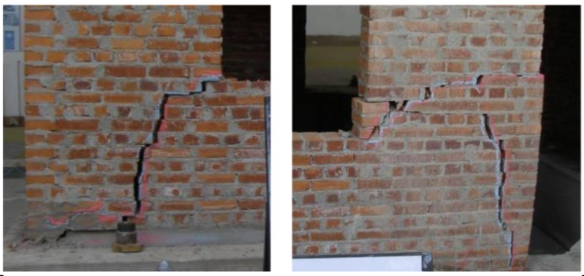
Wall element	**Date of testing**	**Maximum axial force P_{max} (kN)**	**Comprehensive Shear Stress $\sigma_c = \tau_u$ = P cos45° / A (kPa)**	**Tensile strength F_t (kPa)**	**Ductility capacity**
W2-7S	29.08.13	138	1345	831	5.1
W2-8S	30.08.13	140	1365	843	5.5
W2-9S	02.09.13	165	1579	976	7.5

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)

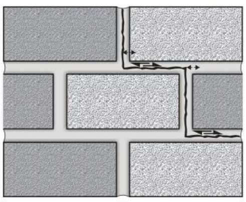
Damages on Sisma Calce retrofitted model (1,22 g)

Experimental values of tested Earthquake : Results comparison for both models

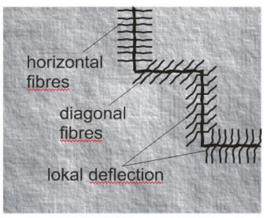
Earthquake	Span %	Acc input (g)	BM - Non Retrofitted Wall acc top (g)	LP top (mm)	LP top - LP foun. (mm)	Damages	BM - SR - Sisma Calce Retrofitted Wall acc top (g)	LP top (mm)	LP top - LP foun. (mm)	Damages
Petrovac	36	0,16	0,26	6,4	0,34		0,25	5,7	0,29	
Northridge	16	0,18	0,34	13,5	0,26		0,21	12,8	0,21	
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					1,41	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	1,03					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

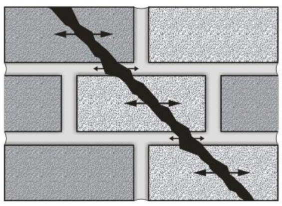
Mortar joint cracking



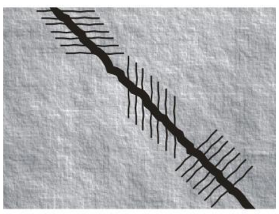
Behavior of composite material

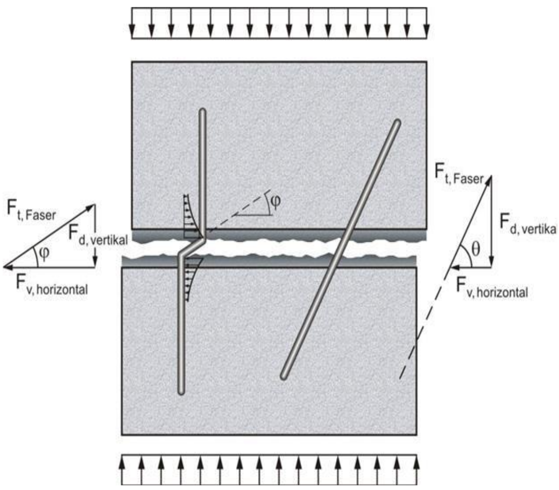


Stone cracking



Behavior of stone





CALCULATION OF FIBER REINFORCEMENT DAMAGE CASES:

Modification of shear strength with Sisma Calce:

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

n =fibre layers number; **t** =wall thickness (mm); $\mathbf{\Psi_f^{30}}$ =bonding efficiency factor for SismaCalce=43,3%;

$\mathbf{f_f^x}$ =Strength of fibres : $\mathbf{f_f^{90}}$ = 1960 N / 50mm ; $\mathbf{f_f^{0}}$ = 1817 N / 50mm ; $\mathbf{f_f^{30}}$ = 895 N / 50mm

Modification of tensile strength with SismaCalce:

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

Easy equations:

Modification of shear strength with Sisma Calce:

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

Modification of tensile strength with Sisma Calce:

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

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 Unit: (N / mm²)	Non-reinforced f_{vk0}	One side reinforced f_{vk0}	Two side reinforced f_{vk0}	Non-reinforced f_{bt}	One side reinforced f_{bt}	Two side reinforced f_{bt}
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 / m²) = MPa**

Material	f_{tk}	f_{vk0}	f_m	f_{bm}	f_{bk}	w (kN/m³)
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

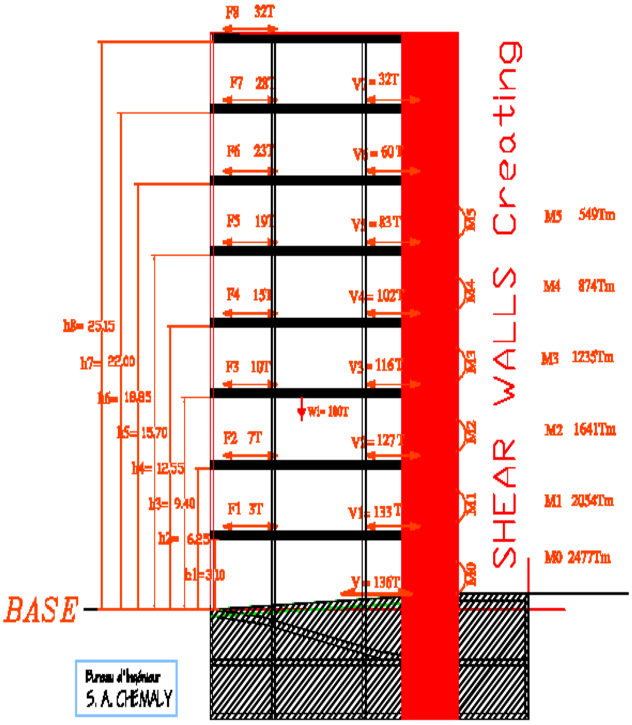
- Saves human lives
- Improves buildings stability and ductility, a considerable deformation of the building can be achieved
- Increases the load-bearing capacity of masonry and protects the non-bearing walls at the limit load against damages, therefore cracks and partial damages cannot provoke a general 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
- This 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.

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

σ_v = 0.42 MPa.

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

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

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

In the Ground Floor, in X direction,
<u>L</u> : the length of the wall we need to retrofit.
(for 1 layer of Sisma Calce coating).

Base Shear Strength **V** = 1360 KN < = $\mathbf{f_{Rvk}}$ **. 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.
(NB.: the SismaCalce retrofitting for each apartment, cost # 3000 $ approx.)

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 layer) / direction, or L>4m (double layers).

Span is intensity of input earthqake
Span% is percentage of earth excelaration
Those are the datas, which comes from earthqake platform.

I_{cal} depends on the wall height h_v, but V_{Rk} (shear and tension) must depend also on the length of the wall

$l_{cal} = h_v \cdot \tan\varphi$

The failure angle φ depends on the dimensions of the wall and especially on the ratio of the height *h* and the length *l*.

μ is the friction coefficient in the characteristic sliding shear strength of the masonry (Mohr-Coulomb formula $f_{vk} = f_{vk0} + \mu\sigma_v$)

α_{gmax} in **k_{eq}**? $\kappa_{eq} = \frac{g - a_{vertikal,\max}}{g}$ coefficient that takes into account the effect of the vertical acceleration of the earthquake $a_{vertikal,\ max}$ on the average normal stress due to vertical loads σ_v (g acceleration of gravity).

In case the vertical component of the earthquake isn't taken into account, $\kappa_{eq} = 1$;

In **$V_{RK}^{tension}$** formula:

- $\alpha_V = \frac{M}{V_{Rd} \cdot l} = \frac{N_{Rd} \cdot e}{V_{Rd} \cdot l}$ is the shear ratio, where N_{Rd} is the design axial force acting on the wall with the eccentricity *e* and V_{Rd} is the design shear force;
- l is the length of the wall;
- $\frac{N_{Rd}}{l \cdot t}$ is the average vertical stress;
- t is the thickness of the wall.