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PERFORMANCE-BASED APPROACH FOR THE RETROFIT OF URM WALL STRUCTURES BY RC WALLS

Alessandro PAPARO[1] and Katrin BEYER[2]

ABSTRACT

In several countries of moderated seismicity, with the re-evaluation of the seismic hazard most unreinforced masonry (URM) buildings with reinforced concrete slabs failed to satisfy the seismic design check. A possible seismically retrofit solution consists of adding RC walls to the existing structure or replacing selected critical URM walls with RC ones. Experimental and numerical studies have shown that this retrofit technique can be very effective since it modifies the global deformed shape of the structure, leading to an increase in the system's displacement capacity. The paper proposes a Displacement-Based Design methodology for the retrofit of URM structures by replacing selected URM walls by RC walls. The methodology follows the Direct Displacement-Based Design (DBD) approach by Priestley et al. (2007) and is based in particular on the DBD procedure for frame-wall buildings (Sullivan et al., 2005 and 2006). The design procedure consists of three main phases: *(i)* A preliminary design check of the URM building by means of the DBD approach. *(ii)* If the structure does not fulfil the design check and exhibits at the same time a dominant shear behaviour, replacing the critical URM wall or walls with RC ones leads to an improved system's behaviour. *(iii)* In the final phase, the DBD design of the mixed RC-URM wall structure, in which both the URM and the RC walls are taken into account, is carried out. The design methodology is then investigated through non-linear dynamic analyses of one case study.

1. INTRODUCTION

In recent years, several countries of moderate seismicity re-evaluated the seismic hazard and increased the acceleration and displacement design spectra. As a consequence, many residential buildings which have been constructed as unreinforced masonry (URM) structures with reinforced concrete slabs no longer fulfil the seismic design check and have to be retrofitted. A possible retrofit solution consists of adding RC walls to the existing structure or replacing selected URM walls with RC ones (Magenes, 2006). Recently, the authors have shown by means of experimental and numerical studies that this retrofit technique can be very effective since it modifies the global deformed shape of the structure, leading to an increase in the system's displacement capacity (Paparo and Beyer, 2014a, b). This technique is particularly beneficial when the URM walls display a dominant shear response rather than a rocking behaviour. New buildings can be conceived directly as mixed RC-URM wall structures since they show an improved seismic behaviour when compared to buildings with URM

[1] Doctoral assistant, Earthquake Engineering and Structural Dynamics (EESD), School of Architectural, Civil and Environmental Engineering (ENAC), École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, alessandro.paparo@epfl.ch

[2] Professor, Earthquake Engineering and Structural Dynamics (EESD), School of Architectural, Civil and Environmental Engineering (ENAC), École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, katrin.beyer@epfl.ch

walls only. At the same time, URM walls have better thermal and insulation properties at a lower construction cost than edifices with RC walls only.

The paper proposes a Displacement-Based Design methodology for the design of mixed RC-URM wall structures and retrofit of URM buildings by replacing or adding selected URM walls by RC walls. The methodology follows the Direct Displacement-Based Design (DBD) approach by Priestley et al. (2007) and is, with regards to several aspects, based on the DBD procedure for frame-wall buildings (Sullivan et al., 2005 and 2006). The design procedure consists of three main phases:

(i) A preliminary design check of the URM building by means of the DBD approach;

(ii) If the structure does not fulfil the design check and exhibits at the same time a dominant shear behaviour, replacing the critical URM wall or walls with RC ones leads to an improved system's behaviour. The objective is to develop in the structure the target displacement capacity for the smallest possible maximum storey drift demand.

(iii) In the final phase, the DBD design of the mixed RC-URM wall structure, in which both the URM walls and the RC walls are taken into account, is carried out. The shape of the displacement profile of the retrofitted structure is estimated using a simple mechanical model which represents the URM walls through an equivalent shear beam and the RC walls through an equivalent flexural cantilever.

Sec. 2 briefly describes the main characteristics of the seismic behaviour of mixed RC-URM wall structures. The mechanical model representing the interaction between shear dominated walls coupled to flexural dominated ones is presented in Sec. 3. Sec. 4 and 5 introduce the concepts of the DBD approach and develop its application for mixed RC-URM wall structures. The algorithm is then applied to one case study and validated against non-linear dynamic analyses in Sec. 6. The article closes with a summary of the main findings and an outlook for future improvements.

2. FEATURES OF MIXED RC-URM WALL STRUCTRES

URM walls have a dominant flexural or shear response depending on several parameters such as the vertical load ratio, the pier geometry or the coupling moment introduced by RC slabs or masonry spandrels. RC walls are designed to have a dominant flexural behaviour and a displacement capacity larger than that of URM walls.

Under lateral loading, URM buildings with walls deforming primarily in shear lead to larger inter-storey drifts at the bottom storeys than at the top ones. RC structures composed by flexural walls will present larger inter-storey drifts at top storeys. At the height of the RC slabs, URM and RC walls need to displace by the same amount. Hence, the deformed shape of mixed RC-URM wall structures lies in between that of a building with RC and URM walls alone. As a consequence, for such mixed structures the damage in the URM walls is not concentrated in the first storey – as for URM buildings – but it also spreads to the storeys above (Paparo and Beyer, 2014b).

Fig. 1 compares failure mechanisms of URM wall buildings where shear deformations prevail (a) and mixed RC-URM wall structures (b). The presence of the RC wall in the retrofitted configuration yields, for the same level of inter-storey drift δ^* at the ground floor, larger top displacements: $\Delta_2 > \Delta_1$. Consequently, the displacement capacity of mixed RC-URM wall structures is larger than that developed by buildings with URM walls only.

Mixed RC-URM wall structures present similarities to structures with RC walls and frames. Slender wall elements, which display mainly flexural deformations, are coupled to frames, whose behaviour can be approximated by that of a shear beam. As a consequence, and similar to mixed RC-URM wall structures, the deformed shape of coupled wall-frame buildings is different to that of walls or frames alone and tends to be rather linear over the height of the structure (Paulay and Priestley, 1992).

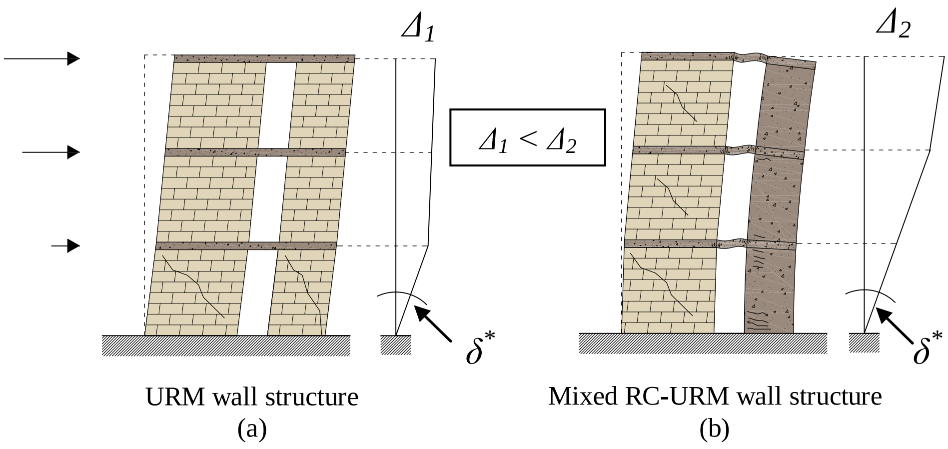

Figure 1. Deformation capacity, for the same level of inter-storey drift δ^*, of a URM wall structure (a) and a mixed RC-URM wall structure (b)

3. BENDING-SHEAR CANTILEVER MODEL

The interaction between walls with a dominant flexural behaviour coupled to ones which deform primarily in shear can be represented with a simple mechanical model. This consists of a pure bending cantilever which represents the totality of the RC walls and a pure shear cantilever which describes the totality of the URM walls. The two beams are continuously connected over the height by axially rigid links with zero moment capacity (Fig. 2a). Given EI the sum of the flexural stiffnesses of the concrete walls and GA the sum of shear stiffnesses of the masonry walls, the stiffness ratio α is obtained (Pozzati, 1980):

$$\alpha = H\sqrt{\frac{GA}{EI}} \tag{1}$$

where H is the height of the building. If the external load q is constant over the height of the structure, the overturning moment $OTM(x)$ has a parabolic shape and its maximum is at the base: $OTM(x=0) = -qH^2/2$. At any cross section at height x (Fig. 2a), the drift $\theta(x)$ can be calculated as the ratio between the shear carried by the shear cantilever, $V_1(x)$, divided by its shear stiffness GA, where $v(x)$ is the horizontal displacement of the system:

$$\theta(x) = \frac{dv(x)}{dx} = \frac{V_1(x)}{GA} \tag{2}$$

The shear $V_1(x)$ is the derivative of the moment carried by the shear cantilever $M_1(x)$ with respect to x and its derivative can be written as:

$$\frac{d^2v(x)}{dx^2} = \frac{1}{GA}\frac{d^2M_1(x)}{dx^2} \tag{3}$$

Since at any cross section the ratio $\frac{1}{GA}\frac{d^2M_1(x)}{dx^2}$ of the shear cantilever has to be equal to the curvature of the flexural one, it follows:

$$\frac{1}{GA}\frac{d^2 M_1(x)}{dx^2} = -\frac{1}{EI}M_2(x) = -\frac{1}{EI}(OTM(x) - M_1(x)) \tag{4}$$

The general solution of Eq. 4 is:

$$M_1 = A\cosh\left(\alpha\frac{x}{H}\right) + B\sinh\left(a\frac{x}{H}\right) + M_{tp}(x) \tag{5a}$$

$$M_2(x) = OTM(x) - M_1(x) \tag{5b}$$

where $M_{tp}(x)$ is the particular solution which, for constant horizontal load q, is:

$$M_{tp}(x) = OTM(x) - q\left(\frac{H}{\alpha}\right)^2 \tag{6}$$

The two constants A and B of Eq. 5a are found by assigning two boundary conditions. In order to account for the formation of the plastic hinge at the base of the RC wall, the flexural cantilever is modelled with a pinned base condition. A base moment ($M_{RC,base} = \beta_{RC}\, OTM(x=0)$) corresponding to its yielding moment is then applied as force to the RC wall base hinge in addition to the externally applied horizontal load q. The parameter β_{RC} describes the ratio between the base moment $M_{RC,base}$ provided by the flexural (RC) wall and $OTM(x=0)$. The second constant can be derived using the static boundary condition that the top the moment of the flexural beam has to be equal to zero ($M_1(x=H) = 0$). The shears $V_1(x)$ and $V_2(x)$ are found as the derivate of the moments $M_1(x)$ and $M_2(x)$ with respect to x. Finally, the displacement Δ_i at each storey is calculated as the integral of the drift $\theta(x)$ between the base and the height of the storey h_i:

$$\Delta_i = \int_0^{hi}\theta(x)\,dx \tag{7}$$

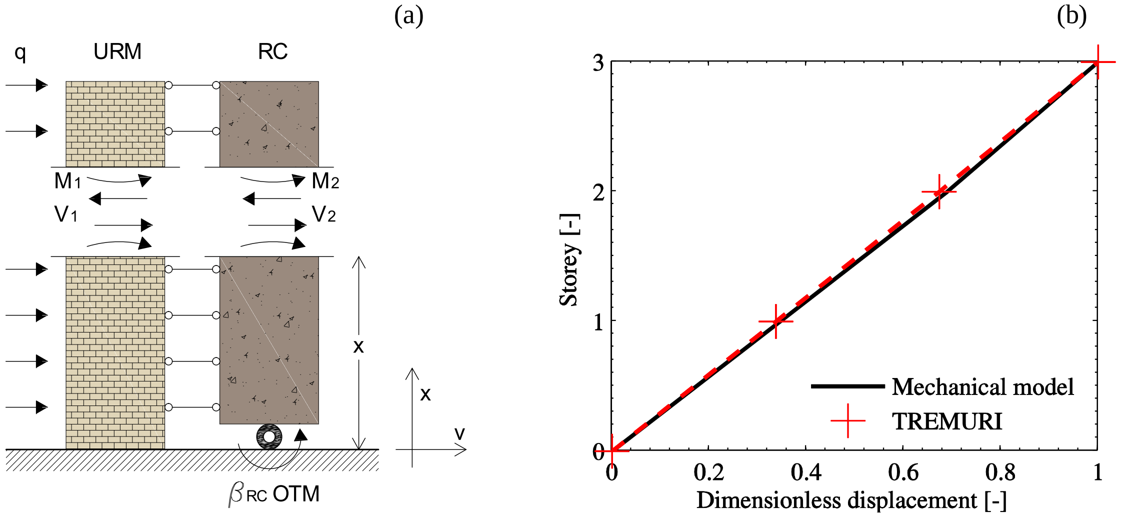

Figure 2. Mechanical model: (a) Definition of the reference system and of the internal forces; (b) Displacement profile of a three storey mixed RC-URM wall structure: comparison between the mechanical model and the TREMURI model (Penna et al., 2013; Lagomarsino et al., 2013) at an average drift of 0.4%.

The mechanical model yields insights into the interaction of URM and RC walls. For instance, the inter-storey drift profile over the height can be evaluated. Pushover analyses carried out with

TREMURI (Penna et al., 2013; Lagomarsino et al., 2013) have confirmed that the mechanical model estimates well the displacement profile over the height of the structure (Fig. 2b).

4. GENERAL DIRECT DISPLACEMENT-BASED DESIGN PROCEDURE

The fundamentals of the Direct Displacement-Based Design procedure by Priestley et al. (2007) are illustrated in Fig. 3. A multi-degree-of-freedom (MDOF) structure is converted to a single-degree-of-freedom (SDOF) system with an effective mass m_e and an effective height h_e (Fig. 3a). The bilinear envelop of the SDOF system is characterised by defining the yield displacement Δ_y and the design displacement Δ_d. This allows finding the displacement ductility demand μ_Δ (Fig. 3b). In the third step, the ductility demand μ_Δ is used to determine an equivalent viscous damping ratio (ξ_e), representing the combined elastic damping and the hysteretic energy absorbed by the structure during inelastic deformations (Fig. 3c). As can be seen, the equivalent viscous damping ξ_e depends on the level of ductility demand and the type of structural system. In the last part (Fig. 3d) the design displacement spectrum, reduced according to the equivalent viscous damping, is used to find the effective period of the structure T_e which corresponds to the design displacement Δ_d defined in (Fig. 3b). From T_e the effective stiffness of the structure and, subsequently, the design base shear force V_{base} can be derived:

$$K_e = 4\pi^2 m_e / T_e^2 \tag{8}$$

$$V_{base} = K_e \Delta_d \tag{9}$$

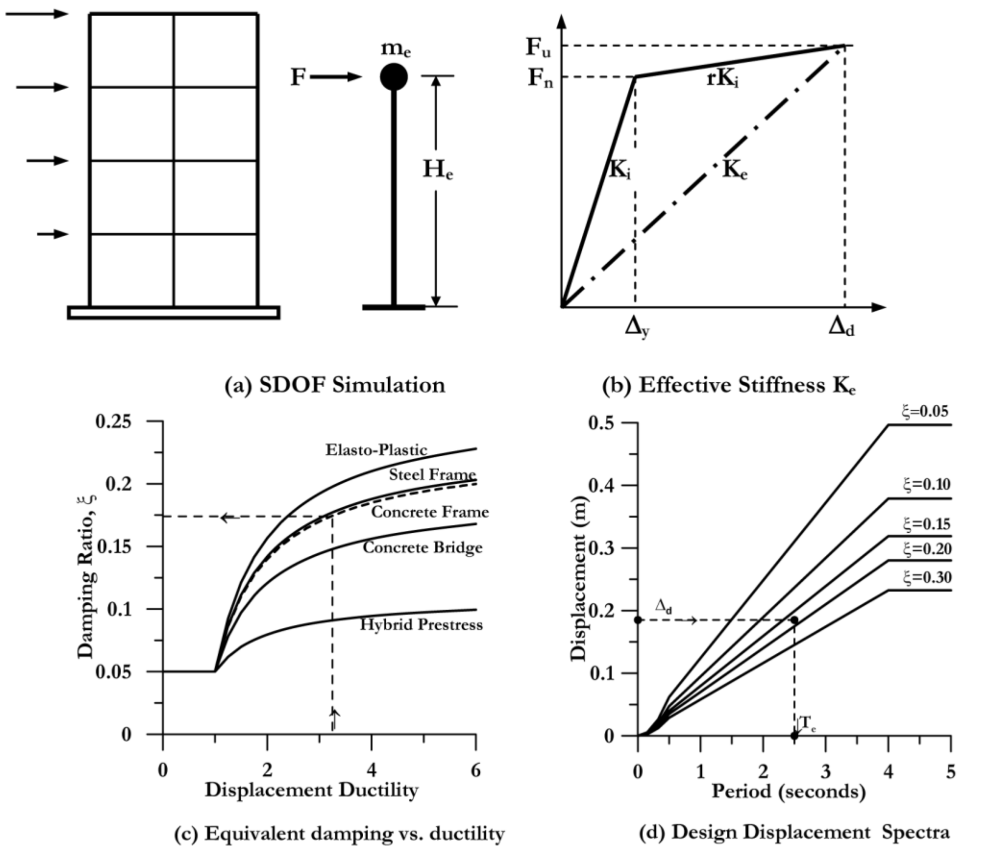

Figure 3. Fundamentals of Direct Displacement-Based Design (from Priestley, 1998)

5. PROPOSED DBD METHODOLOGY FOR MIXED RC-URM WALL BUILDINGS

The fundamental DBD procedure described in Sec. 4 has been applied by Sullivan et al. (2005 and 2006) to regular RC frame-wall buildings. Having in mind that the structural behaviour of mixed RC-URM wall structures is similar to the one of RC frame-wall buildings, the main scope of this paper is to extend the procedure developed by Sullivan et al. for designing mixed RC-URM wall structures.

The procedure to convert the MDOF system to a SDOF system is the standard one adopted by DBD (Priestley et al., 2007) and is not repeated here. The conversion is based on the displacement profile which is here assumed to be linear over the height. At the end of the procedure this hypothesis will be counter-checked with the mechanical model described in Sec. 3. As it was observed in Paparo and Beyer (2014b), in mixed RC-URM wall structures the significant damage (SD) limit state - as well as the near collapse (NC) - is always controlled by the URM walls which fail for smaller drift demands than that of RC members. As a consequence, the drift limits assumed are the ones used for URM walls. In the following, the DBD process has been broken down into a step-by-step procedure:

Step 1 – Preliminary design check of the URM wall building according to the DBD approach

The design approach starts by considering a URM structure composed of URM walls connected at each storey by RC slabs. If the structure does not fulfil the DBD design check (Priestley et al., 2007) and exhibits at the same time a dominant shear behaviour, one or more URM walls can be replaced by RC ones. Once the base shear V_{base} is known, the OTM demand (OTM_{dem}) is found (h_e is the effective height of the SDOF system):

$$OTM_{dem} = V_{base} h_e \tag{10}$$

Step 2 – Replacement/addition of RC walls

The designer chooses the URM walls to be replaced by RC ones. No calculations are needed in this step. Note that neither the dimensions nor the strength of the RC walls are yet defined. Because of the assumption of the linear displacement profile over the height of the structure, the maximum roof displacement (Δ_{top}) can be calculated as the design drift (δ_d) multiplied by the total height of the structure *H*.

Step 3 – Estimation of the moment capacity of the mixed RC-URM wall structure (OTM_{cap})

By means of a non-linear pushover analysis carried out up to the maximum roof displacement (Δ_{top}), the moment at the base of the URM walls (M_{URM}), as well as the moment due to the presence of the coupling beams (M_{CB}) can be estimated. The moment capacity of the structure (OTM_{cap}) is the sum of these two contributions (the contribution of the RC walls is not accounted here and will be calculated in Step 5 as the required strength of the RC walls):

$$OTM_{cap} = M_{URM} + M_{CB} \tag{11}$$

Step 4 – Calculation of the equivalent viscous damping ξ_{sys} and the reduction factor R

The equivalent viscous damping of the system ξ_{sys} is obtained by averaging the damping of the three different structural systems:

$$\xi_{sys} = \beta_{CB}\,\xi_{CB} + \beta_{URM}\,\xi_{URM} + \beta_{RC}\,\xi_{RC} \tag{12}$$

where ξ_{CB}, ξ_{RC} and ξ_{URM} are the damping associated with coupling beams, RC walls and URM walls. ξ_{CB}, ξ_{RC} have to be chosen accordingly to the expected level of ductility and ξ_{URM} can be assumed equal to 15% (Priestley et al., 2007). The ratios of the base moments provided by the different structural systems can be evaluated by considering the OTM demand (OTM_{dem}) found in Step 1:

$$\beta_{CB} = M_{CB} / OTM_{dem} \tag{13a}$$

$$\beta_{URM} = M_{URM} / OTM_{dem} \tag{13b}$$

$$\beta_{RC} = 1 - \beta_{CB} - \beta_{URM} \tag{13c}$$

From the equivalent viscous damping ξ_{sys}, the reduction factor R, used to compute the spectrum for the desired ξ_e from the 5% damped displacement spectrum, is calculated:

$$R = \left(\frac{0.07}{0.02 + \xi_{sys}} \right)^{0.5} \tag{14}$$

Step 5 – Evaluation of the strength demand (OTM_{dem}) and of the required strength of the RC walls (M_{RCreq})

The effective period T_e is found by entering the reduced displacement spectrum with the design displacement Δ_d. The effective stiffness K_e and the base shear V_{base} are consequently determined accordingly to Eq. 8 and 9. Then the new overturning moment demand OTM_{dem} is estimated by multiplying the base shear V_{base} to the effective height h_e (Eq. 10). The required strengths of the RC walls (M_{RCreq}) can then be estimated:

$$M_{RCreq} = OTM_{dem} - OTM_{cap} \tag{15}$$

Step 6 – Calculation of the contra-flexure height of the RC walls (H_{CF})

The contra-flexure height H_{CF} of the RC walls can be estimated by imposing $M_2(x)$ (Eq. 5b) equal to zero. Pushover analyses carried out with the software TREMURI (Penna et al., 2013; Lagomarsino et al., 2013) have confirmed that the mechanical model estimates well the contra-flexure height H_{CF}.

Step 7 – Definition of the ductility of the RC walls ($\mu_{\Delta RC}$)

The designer chooses the level of ductility which the RC walls will undergo. Quasi-static and dynamic tests on mixed RC-URM wall structures (Paparo and Beyer, 2014a; Tondelli et al., 2013) have shown that the RC walls experience very small inelastic deformations when the URM walls failed. Hence it is reasonable to conceive that, at the design displacement, the RC walls exhibit displacement ductility $\mu_{\Delta RC}$ within the range of 1 and 2.

Step 8 – Definition of the length of the RC walls (l_{RC})

From Step 7 the yielding displacement at the effective height is known ($\Delta_{yi} = \Delta_d / \mu_{\Delta RC}$) and from Eq. 16a and 16b the yield curvature of the RC walls (φ_{yRC}) can be found:

For $h_e < H_{CF}$

$$\phi_{yRC} = \Delta_{yi} \left(\frac{h_e^2}{2} - \frac{h_e^3}{6 H_{CH}} \right)^{-1} \tag{16a}$$

For $h_e > H_{CF}$

$$\phi_{yRC} = \Delta_{yi} \left(\frac{H_{CF} h_e}{2} - \frac{H_{CF}^2}{6} \right)^{-1} \tag{16b}$$

Recalling the correlation between yield curvature and wall length, it is possible to define the design RC wall length (l_{RC}):

$$l_{RC} = \frac{2\varepsilon_y}{\phi_{yRC}} \tag{17}$$

Step 9 – Cycles to find a stable solution

Cycle Steps 3 to 8 until a stable solution is found. For instance the variation of the required strength of the RC walls (M_{RCreq}) can be checked.

Step 10 – Ascertain the displacement profile of the structure

This DBD procedure relies on the assumption of a linear displacement profile over the height of the structure. To check this assumption the mechanical model described in Sec. 3 can be adopted. For instance, the profile over the height of the structure can be assumed linear if the ratio between the inter-storey drift of the first storey (δ_1) and the inter-storey drift of the second one (δ_2) is within the range of 0.80 and 1.20:

$$\frac{\delta_1}{\delta_2} \in [0.80 - 1.12] \tag{18}$$

If the ratio δ_1/δ_2 is not between 0.80 and 1.20, the designer have two options: *(i)* choose a different number of URM walls to be replaced by the RC ones and re-check the procedure from Step 2 or *(ii)* change the level of ductility ($\mu_{\Delta RC}$) of the RC walls defined in Step 7.

6. CASE STUDY

6.1. Description of the retrofit design

The procedure described above was applied to retrofit one URM wall structure by replacing the central URM wall with a RC wall. Fig. 4a and 4b shows the plan before and after the retrofit design. The original structure consists of 5 four-storey URM walls coupled by RC slabs. The thickness of the walls is always 30 cm, and the URM wall's length and height is always 300 cm. The total height of the structure is 1200 cm. Since two-dimensional simulations are carried out, RC beams 25x90 cm represent the slabs. The longitudinal reinforcement ratio of the RC beams is equal to 0.5%. The thickness of the RC beams is three times that of the walls (Priestley et al., 2007) and the free span is 100 cm. The axial stress ratio σ_0/f_m at the base of the URM walls is around 0.05. All RC beams (and the RC wall in the retrofitted configuration) are designed such that the URM walls fail before any RC element. The total mass of the building is 143 t. The objective of the replacement of the central URM wall with one RC one is to avoid that deformations concentrate in the first storey and provide an almost linear displacement profile over the height of the building. The structure is located in a moderate seismicity area, with the input ground motion represented by a displacement spectrum with a corner period at 2 s and a corresponding corner displacement demand equal to 18.8 cm.

The RC wall was designed to respond elastically for the selected seismic intensity ($\mu_{\Delta RC}$ = 1). Also the RC beams responded elastically (this feature was checked at each iteration of the design process through pushover analyses carried out with TREMURI). At the end of the design procedure, the mechanical model ascertained that the ratio δ_1/δ_2 resulted equal to around 0.95. This means that the assumed displacement profile is correct (see Eq. 18).

The key outputs from the DBD are listed in Table 1. Since both RC wall and coupling beams respond elastically, around 80% of the OTM_{dem} is provided by elastically responding (RC) members. As a consequence, the equivalent viscous damping ξ_e is rather small.

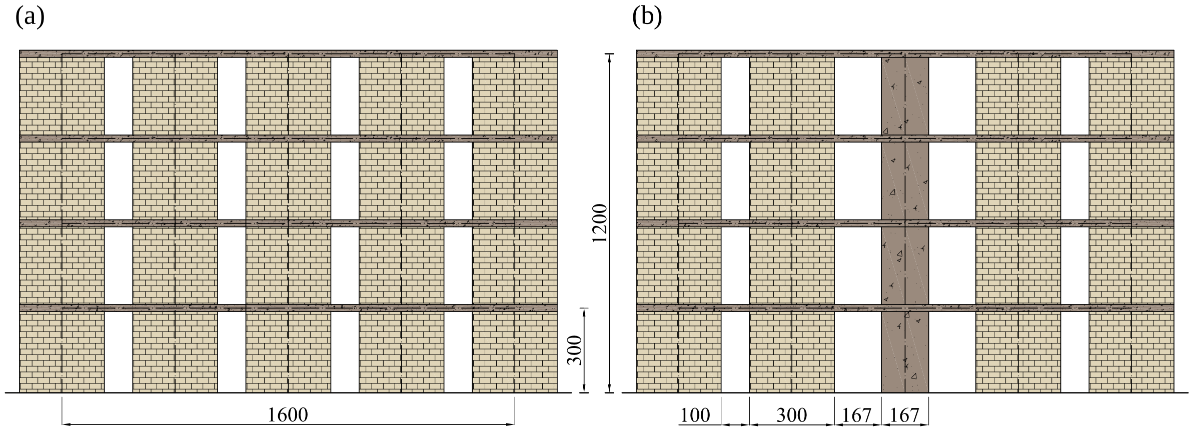

Figure 4. Retrofit design of one masonry structure: (a) Original URM wall building. (b) Retrofitted configuration. All dimensions in cm.

Table 1. Key design outputs from DBD

Maximum drift	δ	0.4 %
Total base shear	V_{base}	646 kN
Overturning moment demand	OTM_{dem}	5820 kNm
Required moment capacity of the RC wall	M_{RC}	1082 kNm
Effective period	T_e	0.51 s
Mean longitudinal reinforcement ratio in the RC wall	ρ_{RC}	0.38%
Length of the RC wall	l_{RC}	1.67 m
OTM_{dem} provided by the coupling beams	β_{RC}	0.19
OTM_{dem} provided by the URM walls	β_{URM}	0.19
OTM_{dem} provided by the RC wall	β_{CB}	0.62
Equivalent viscous damping	ξ_e	0.069

6.2. Modelling and analysis

To assess the retrofit design, the case study was modelled and analysed through inelastic time history analyses (ITHA) performed with TREMURI (Penna et al., 2013; Lagomarsino et al., 2013). In the software, each structural member (walls and beams) is modelled as single elements which are then assembled to an equivalent frame (equivalent frame approach). The macro-element developed by Penna et al. (2013) is used to describe the behaviour of masonry walls. The non-linear macro-element model is representative of a whole masonry panel and allows for the representation of the two main in-plane failure mechanisms (i.e. shear and bending-rocking). The macro-element is divided into three parts: a central body in which shear deformations occur and the two extremities where the bending-rocking behaviour is concentrated. For the shear-damage behaviour, the model accounts for non-linear plastic deformations in the pre-peak response, as well as non-linear plastic deformations in the post peak response with stiffness and strength degradation. The bending rocking behaviour is represented by no-tension springs in the two extremities of the panel. Non-linear elastic deformations, corresponding to the partialisation of the section, are accounted for. The macro-element takes also into account the effect of the limited compressive strength of the masonry. Timoshenko beams, characterized by Takeda model law and plasticity concentrated at the extremities, represent RC members. For further details of the software, the reader is referred to Penna et al. (2013) and Lagomarsino et al. (2013).

Concerning the material properties adopted and the construction of the equivalent frame model, the indications presented in Paparo and Beyer (2014b) were followed. Table 2 provides the assumed material properties. E_e is a reduced Young's modulus which accounts for cracking of the RC walls. The reduction is taken into account by considering the effective stiffness EI_e as proposed by Priestley et al. (2007):

$$EI_e = \frac{M_N}{\varphi_y} \tag{19}$$

where M_N is the nominal yielding moment, calculated considering the axial force acting at the base of the wall before applying the horizontal load, and Φ_y is the nominal yielding curvature, which is equal to $C\varepsilon_y/l_{RC}$. C is a constant depending on the geometrical properties of the section; ε_y is the yielding strain of the longitudinal reinforcing bars and l_{RC} is the length of the wall.

The model was subjected to a suite of 5 artificial spectro-compatible accelerorgrams. Details of the records are shown in Fig. 5. The accelerograms were scaled to a PGA equal to 0.25 g to match the design displacement spectrum adopted in the design procedure.

A Rayleigh viscous damping is implemented in the TREMURI program. The damping matrix C for a MDOF system can be written as:

$$C = a_1 M + a_2 K \tag{19}$$

Where M and K are the mass and the linear stiffness matrices of the structure when the initial tangent stiffness is used. The coefficients a_1 and a_2 are defined to give a damping of 5% at the first elastic period (T_1) and at the secant period (T_e).

Table 2. Adopted material properties for the simulations

Materials	Material properties		Model parameters
URM members	Equivalent friction	μ^* [-]	0.19
	Equivalent cohesion	c^* [MPa]	0.06
	Masonry compressive strength	f_m [MPa]	6.30
	E-modulus of masonry panels subjected to compression orthogonal to bed-joints	E_{mx} [GPa]	5.10
	Masonry shear modulus	G_m [GPa]	0.54
	Non-linear shear deformation parameter	Gc_t [-]	1
	Softening parameter	β [-]	0.1
RC members	RC member's Young's modulus	E_c [GPa]	E_e (1st storey & beams) 18 (above storeys)
	RC member's shear modulus	G_c [GPa]	E_e/2.4 (1st storey & beams) 7.5 (above storeys)
	Reinforcing bars yielding tensile strength	f_y [MPa]	550

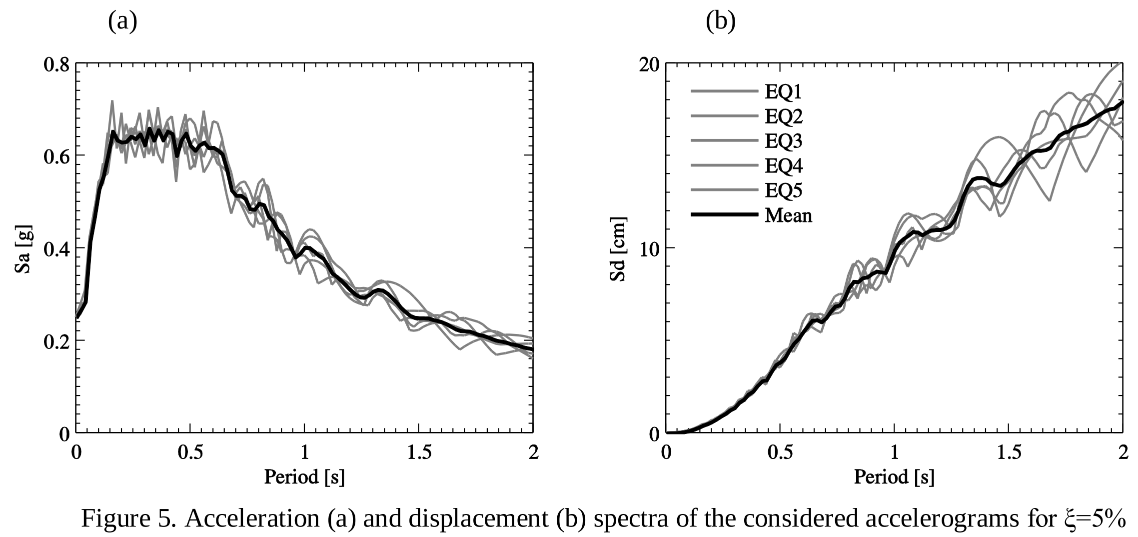

Figure 5. Acceleration (a) and displacement (b) spectra of the considered accelerograms for ξ=5%

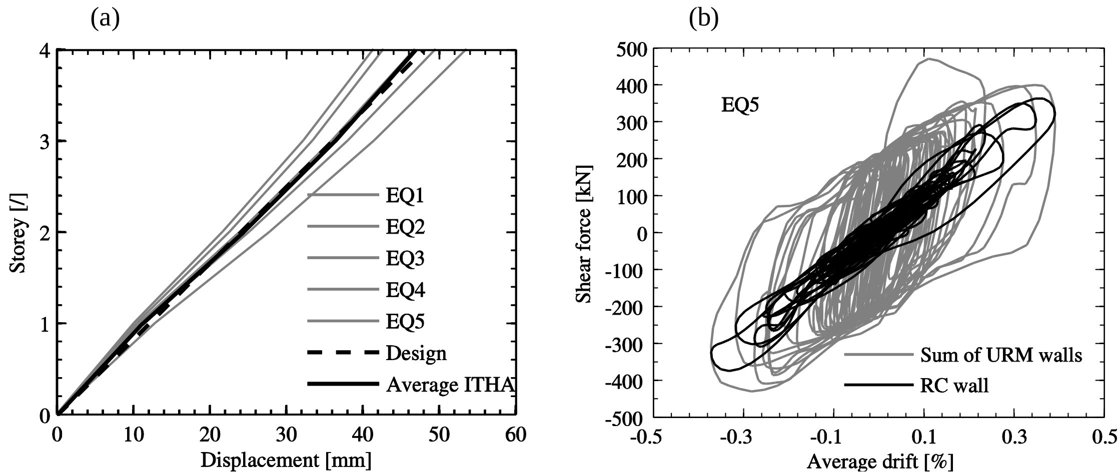

Figure 6. Time-History response for the case study. (a) Displacement profiles; (b) Hysteretic behaviour of the structure subjected to record 5

Comparing the design displacement profile with the actual displacement response (Fig. 6a), very good agreement was found. The displacement profile indeed is almost linear over the height of the structure, as it was assumed in the design. Also the average maximum displacement is well estimated. Fig. 6b shows the hysteretic behaviour of the RC wall for the structure subjected to record 5. EQ5 was selected since the displacement profile from this record is the closest to the average displacement profile from ITHA. It is possible to appreciate that the RC does not undergo plastic deformations, as it was defined during the design. Furthermore, the sum of the base shear absorbed by the URM walls is plotted, showing the large energy dissipated by the URM walls. This feature is typical of masonry walls with shear response and guarantee that they did feature shear (and no rocking-bending) behaviour.

7. CONCLUSIONS AND OUTLOOK

After the re-evaluation of the seismic hazard, in several countries of moderate seismicity, most unreinforced masonry (URM) buildings with reinforced concrete slabs failed to satisfy the seismic design check. A possible seismically retrofit solution consists of adding RC walls to the existing structure or replacing selected critical URM walls with RC ones. Experimental and numerical studies have shown that this retrofit technique can be very effective since it modifies the global deformed shape of the structure, leading to an increase in the system's displacement capacity. New buildings can be conceived directly as mixed RC-URM wall structures since they show an improved seismic behaviour when compared to buildings with URM walls only. At the same time, URM walls have better thermal and insulation properties at a lower construction cost than edifices with RC walls only.

The paper proposed a Displacement-Based Design methodology for the retrofit of URM structures by replacing selected URM walls by RC walls. The methodology follows the Direct Displacement-Based Design (DBD) approach by Priestley et al. (2007) and is based in particular on the DBD procedure for frame-wall buildings (Sullivan et al., 2006). The design procedure consists of three main phases: *(i)* A preliminary design check of the URM building by means of the DBD approach. *(ii)* If the structure does not fulfil the design check and exhibits at the same time a dominant shear behaviour, replacing the critical URM wall or walls with RC ones leads to an improved system's behaviour. *(iii)* In the final phase, the DBD design of the mixed RC-URM wall structure, in which both the URM and the RC walls are taken into account, is carried out. The shape of the displacement profile of the retrofitted structure is estimated using a simple mechanical model which represents the URM walls through an equivalent shear beam and the RC walls through an equivalent flexural cantilever.

The methodology has been checked by designing a case study and comparing its structural performance through ITHA. Five artificial spectro-compatible accelerorgrams were used. The design procedure effectively controlled the horizontal deformations and the insertion of the RC wall prevented a concentration of deformations at the lowest storey of the structure, typical feature for

URM wall buildings. In addition, the retrofitted configuration exhibited a displacement profile almost linear over the height of the structure, as it was assumed in the design. Also the choice that the RC wall responded elastically was respected.

Future studies will propose mechanical models for the estimation of the contribution to the overturning moment from the RC beams (M_{CB}) and the URM walls (M_{URM}) as, for the moment, these quantities are estimated through non-linear pushover analyses. In addition, application of the design methodology to a wider range of case studies will be necessary for further validations of the procedure. Structures raging form 3 to 5 storeys will be designed and gauged through ITHA. Also configurations with URM walls with different lengths will be investigated.

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