DESIGN SPECTRA FOR STRENGTHENING OF RC BUILDINGS

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ABSTRACT :

Seismic evaluation of the existing building stock has become a recognized priority after damage and collapse of many reinforced concrete structures during recent earthquakes. Today there is a concerted international focus on reduction of seismic risk through assessment and rehabilitation programs to upgrade buildings that are deemed inadequate with regards the level of the seismic protection they provide to the public. Establishing an optimum retrofit strategy is a complex procedure. Several alternative retrofit strategies may be possible for a specific project which should be evaluated before proceeding to the application of the most efficient solution. The objective of this paper is to present a retrofit assessment procedure that relates the characteristics of the intervention method to the demand imposed by the earthquake. A new type of spectrum representation is developed, the Retrofit Design Spectra (RDS), where the demand is related to the key design parameters of the intervention method. The methodology utilized for the derivation of the RDS is based on the Capacity Spectrum Method (ATC 40), as later modified in ATC 55/FEMA 440, where the Capacity Curve is described by relationships for global intervention methods that are parameterized in terms of fundamental response quantities. The proposed spectra provide a direct insight into the complex interrelation between the characteristics of the intervention method and the implications of retrofitting on demand. Alternative retrofit solutions are thus assessed in an efficient way that clearly links supply to demand.

KEYWORDS: Retrofit, rehabilitation, strengthening, spectra, reinforced concrete

1. INTRODUCTION

The majority of the existing building stock consists of structures that were built according to older generations of design codes where seismic detailing was not necessarily mandatory. These structures are susceptible to future earthquakes and therefore assessment and identification of their deficiencies are essential for seismic risk reduction. Alternative retrofit scenarios may apply depending on the performance objectives of the rehabilitation effort as well as on the available budget. Each retrofit scenario satisfies a performance objective which dictates the design and detailing of the intervention method. The design approach may be either force-based or displacement-based; in this regard, an efficient displacement-based retrofit design methodology of substandard reinforced concrete buildings has been developed by Thermou *et al.* (2006, 2007). A key step in that methodology is to eliminate damage localization through controlled modification of the lateral response shape of the building. To achieve a pre-selected target response shape that optimizes interstorey drift in all floors, a weighted distribution of stiffness increments along the building height is required. The final step in the retrofit process involves assessment of the retrofit solution.

The alternative retrofit strategies possible for any specific project need be evaluated before proceeding to the most efficient solution, where efficiency may be quantified by some performance index. Therefore a relatively fast and straightforward retrofit assessment procedure is required. The objective of this paper is to present a retrofit assessment procedure that relates the characteristics of the intervention method to the demand imposed by the design response spectrum. The procedure is also amenable for use in developing design scenarios. To this end, design charts that relate the characteristics of the intervention method to the spectral displacement demand of each retrofit scenario are developed. A new type of spectrum representation is developed where the demand is related to the key design parameters of the intervention method.

The proposed procedure for constructing the new retrofit design spectra (RDS) relies on the Capacity

Spectrum Method, described in ATC 40 (1996), as later modified in ATC 55/FEMA 440 (2005). A key feature is that the capacity curve of the retrofitted structure is expressed parametrically in terms of the intervention method characteristics. This allows derivation of closed-form expressions which enable estimation of the performance point as a function of the response characteristics of the retrofitted structure. Performance points corresponding to different retrofit scenarios may be utilized to construct the Retrofit Design Spectra (RDS), which adopt the Acceleration Displacement Response Spectrum (ADRS) representation. The RDS facilitate rapid assessment of the implications of each possible scenario which may combine different global interventions, because the engineer has full control of the key design parameters and is simultaneously aware of their effect on demand measures. In the present paper, a global intervention procedure (reinforced concrete jacketing) is used as a point of reference in order to illustrate practical implementation of the proposed methods. In the proposed methodology it is considered that local deficiencies will be corrected through local interventions, such as fiber reinforced plastic wraps (glass or carbon FRPs).

2. PROPOSED METHODOLOGY FOR CONSTRUCTION OF THE RETROFIT DESIGN SPECTRA

For the requirements of the present work and without loss of generality, the capacity curve of a retrofitted structure is approximated by a tri-linear envelope. The three distinct regions thus defined, are separated by milestone points that correspond to specific limit states. Limit states selected are, global yield, attainment of peak base shear and ultimate deformation capacity, respectively (Figure 1a).

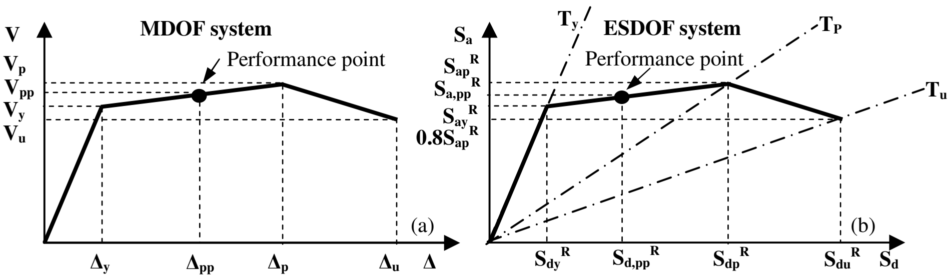

Figure 1 (a) Pushover curve of the retrofitted building; (b) Capacity curve of the retrofitted structure

The tri-linear Capacity Curve of the Equivalent Single Degree of Freedom (ESDOF) system (Figure 1b) is described in spectral ordinates (i.e. total acceleration and relative displacement) by the following equations:

For $0<T\le T_y$, $S_a^R = K_y S_d^R$; for $T_y<T\le T_p$, $S_a^R = K_y r_p S_d^R + (1-r_p)S_{ay}^R$ whereas,

For $T_p<T\le T_u$, $S_a^R = K_y r_p r_u S_d^R + \left(S_{ap}^R - K_y r_p r_u S_{dp}^R\right)$ (2.1)

where, $K_y(=S_{ay}^R/S_{dy}^R)$ is the initial elastic stiffness, $r_p(=S_{dy}^R(S_{ap}^R\text{-}S_{ay}^R)/S_{ay}^R(S_{dp}^R\text{-}S_{dy}^R))$ is the ratio of the post-yield stiffness up to peak to the initial elastic stiffness and $r_u(=-0.2S_{ap}^R(S_{dp}^R\text{-}S_{dy}^R)/(S_{ap}^R\text{-}S_{ay}^R)(S_{du}^R\text{-}S_{dp}^R))$ is the ratio of the post-peak stiffness up to ultimate to the post-yield stiffness. S_{ay}^R, S_{ap}^R, $S_{au}^R(=0.8S_{ap}^R)$ are the spectral ordinates at yield, peak and ultimate, S_{dy}^R, S_{dp}^R, S_{du}^R are the spectral abscissae at yield, peak and ultimate corresponding to the ESDOF model of the retrofitted building, respectively (Figure 1b) The milestone period values T_i where i=y, p, u associated with yield, peak and ultimate, respectively, are defined by $T_i=2\pi\sqrt{(S_{di}/S_{ai})}$.

The demand curve for linear elastic structures is given by the 5% damped ADRS response spectrum (Figure 2a). Elastic spectra with higher damping ratios are used to approximate inelastic response in spectral format (ATC 40 1996); the higher damping ratio is meant to account for the amount of hysteretic energy dissipation owing to the inelastic response excursion of the structure. Depending on the type of structure considered and the characteristics of the hysteretic model that describes the response of the retrofitted structure, the equivalent damping β_{eq} may be directly related to the displacement ductility demand, μ.

According to ATC 55/ FEMA 440 (2005), the reduced elastic response spectra that correspond to higher than 5% values of critical damping are obtained from the 5% damped elastic spectrum through pertinent spectral reduction factor, SR (Figure 2a). The reduction factor is given as a function of the equivalent viscous damping, β_{eq}:

$$SR = 1/B = 0.25 \cdot \left(5.6 - \ln(\beta_{eq})\right) \tag{2.2}$$

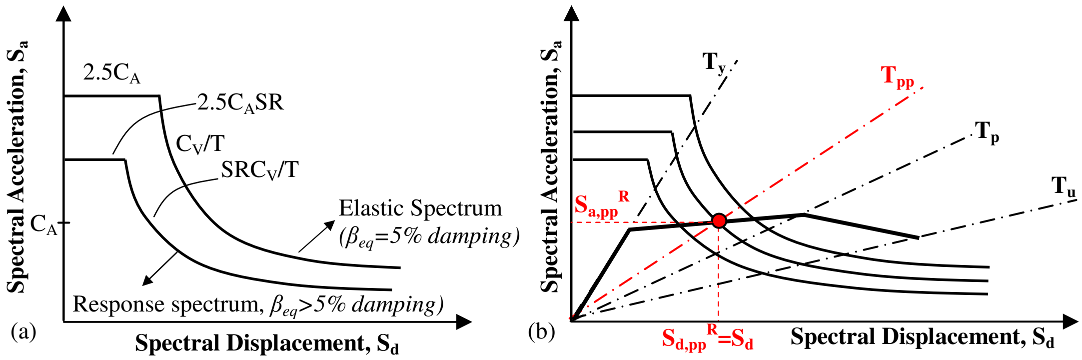

Figure 2 (a) Acceleration-Displacement Response Spectrum (ADRS) for definition of demand; (b) Equilibrium between demand and supply – Definition of performance point ($S_{d,pp}^R$, $S_{a,pp}^R$)

The 5% damped elastic spectrum, used here as a reference for derivation of the RDS, is that recommended by ATC 40 (1996), where spectral displacement S_d is calculated from the structural period (Figure 2a):

For $0 < T \le T_c$: $S_d = 0.063\, C_A\, SR\, T^2$; whereas for $T_c < T$, $S_d = 0.025\, C_V\, SR\, T$ (2.3)

where, C_A, C_V are the site-specific seismic coefficients (ATC 40, 1996) and T_c is the period value corresponding to the end of the constant acceleration range. In Eqn. (2.3), C_A is the effective peak ground acceleration, whereas the ratio C_V / T defines the acceleration response in the velocity domain. By setting the supply equal to the demand (Figure 2b), $S_{d,pp}^R = S_d$, the following expressions are derived:

$$0 < T_{pp} \le T_c, \quad S_{a,pp}^R - C_A \left(3.48 - 0.62 \ln(\beta_{eq})\right) = 0 \tag{2.4a}$$

$$T_c < T_{pp}, \quad \left(S_{d,pp}^R S_{a,pp}^R\right)^{0.5} - C_V \left(0.22 - 0.04 \ln(\beta_{eq})\right) = 0 \tag{2.4b}$$

where, $S_{d,pp}^R$, $S_{a,pp}^R$ are the spectral abscissa and ordinate, respectively, of the performance point, C_A, and C_V are the site-specific seismic coefficients and β_{eq} is the equivalent viscous damping. Eqns. (2.4a) and (2.4b) may be expanded further if the spectral ordinate of the performance point, $S_{a,pp}^R$, is substituted according to Eqns. (2.1). In case the performance point lies in the region between the yield and peak spectral displacement (S_{dy}^R and S_{dp}^R), then the following expressions apply:

$$\text{If } T_y < T_c \le T_p \text{ and } 0 < T_{pp} \le T_c: \; K_y\, r_p\, S_{d,pp}^R + (1 - r_p) S_{ay}^R - C_A \left(3.48 - 0.62 \ln(\beta_{eq})\right) = 0 \tag{2.5a}$$

$$\text{If } T_y < T_c \le T_p \text{ and } T_c < T_{pp}: \; \left(K_y\, r_p\, {S_{d,pp}^R}^2 + (1 - r_p) S_{ay}^R S_{d,pp}^R\right)^{0.5} - C_V \left(0.22 - 0.04 \ln(\beta_{eq})\right) = 0 \tag{2.5b}$$

Eqns. (2.5a) and (2.5b) relate directly the response characteristics of the retrofitted structure (S_{ay}^R, S_{ap}^R, S_{dy}^R, S_{dp}^R) with the spectral displacement at the performance (demand) point, $S_{d,pp}^R$.

The equivalent damping ratio, β_{eq}, should be taken to reflect the hysteretic characteristics of the retrofitted structure. Here, the equivalent damping as defined in ATC 55/FEMA 440 (2005, Eqn. (6-4)) is selected for demonstration of the methodology (Figure 2(b) - the abscissa at ultimate (S_{du}) coincides with that of the performance point ($S_{d,pp}^R$)). Thus, the hysteretic damping expressed in percent of critical damping is defined as a function of the ductility demand $\mu_{pp}(=S_{d,pp}^R/S_{d,y}^R)$:

$$\beta_{eq} = \beta_o + 5 = 4.9(\mu_{pp} - 1)^2 - 1.1(\mu_{pp} - 1)^3 + 5 \tag{2.6}$$

Alternative hysteretic models may be utilized for the definition of the hysteretic damping, β_o. A detailed description of this aspect of the methodology is given in Thermou (2007).

2.1. Performance point as a function of the characteristics of the retrofit solution

Estimation of the performance point refers to a definition of spectral demand. Eqns. (2.5a) and (2.5b) define performance according to the design spectrum of ATC 40 (1996). Using the expressions derived for equivalent damping (e.g. the closed-form expressions derived by substitution of Eqn. (2.6) in Eqns. (2.5a) and (2.5b)) enables estimation of the performance point ($S_{d,pp}^R$, $S_{a,pp}^R$) as a function of the response characteristics of the retrofitted structure (S_{ay}^R, S_{ap}^R, S_{dy}^R, S_{dp}^R):

For $T_y < T_c \le T_p$ and $0 < T_{pp} \le T_c$

$$K_y\, r_p \mu_{pp} + (1-r_p)K_y - \frac{C_A}{S_{dy}^R}\left(3.48 - 0.62\,ln\left(4.9(\mu_{pp}-1)^2 - 1.1(\mu_{pp}-1)^3 + 5\right)\right) = 0 \tag{2.7a}$$

For $T_y < T_c \le T_p$ and $T_c < T_{pp}$

$$\left(K_y\, r_p \mu_{pp}^2 + (1-r_p)K_y \mu_{pp}\right)^{0.5} - \frac{C_V}{S_{dy}^R}\left(0.22 - 0.04\,ln\left(4.9(\mu_{pp}-1)^2 - 1.1(\mu_{pp}-1)^3 + 5\right)\right) = 0 \tag{2.7b}$$

For each retrofit scenario, Eqns. (2.7a) and (2.7b) provide a direct estimation of the ductility demand, μ_{pp}, and hence of the abscissa of the performance point $S_{d,pp}^R$ $(=\mu_{pp} S_{dy}^R)$.

The fundamental steps of the proposed methodology for the construction of the Retrofit Design Spectra (RDS) are summarized in Figure 3. After the definition of the alternative retrofit scenarios, the capacity curve of the retrofitted frame is expressed parametrically in terms of the intervention method characteristics (Step A). The performance point for each retrofit scenario is defined by utilizing closed-form expressions similar to those of Eqns. 2.7 (Step B). This is an essential element of the procedure since it provides direct estimation of the performance point, thus avoiding the iterative procedures adopted in the Capacity Spectrum Method (ATC 40, ATC 55/FEMA 440). Step B requires the definition of (i) the response shape of the retrofitted structure for the transformation of the MDOF to the ESDOF system, (ii) the hysteretic model representative of the response of the retrofitted frame, and (iii) the demand through elastically damped spectra. Step C involves the construction of the Retrofit Design Spectra (RDS), which follows the ADRS spectrum representation. The RDS may be utilized for assessment of the optimum retrofit scenario, thus providing direct relationship between Step A and Step C.

3. PARAMETERIZED PUSHOVER CURVE OF THE RETROFITTED BUILDING

The basic premise of the proposed methodology is that the pushover curve of the retrofitted structure is given explicitly in terms of the technological details of the retrofit scenario, so that the parametric dependence of the strength, stiffness and ductility terms may be immediately assessed by inspection. However, what is available so far from the mechanics of reinforced concrete are explicit expressions that describe these relationships at the individual element level (for example the response curve of a well designed RC-jacketed column may be quantified with confidence). To transfer this information to the global scale on the pushover curve of the entire structure, it is necessary to perform a transformation from the level of the member to the structural entity. A key tool in this regard is the assumed shape of lateral vibration of the structure during dynamic response, as the shape identifies the distribution of interstorey drift along the height of the structure, which, in conjunction with information about storey stiffness and strength may identify the occurrence of a milestone event (such as yielding of some elements).

It is common practice at least in the phase of preliminary design to consider a single mode of response for typical frame buildings. For example, in ATC 40 (1996) the fundamental mode shape is utilized, thus, it is assumed that the elastic response shape remains the same in the post-elastic regime (up to the peak). The methodology proposed by the authors for seismic retrofit strategy development, builds on the premise that globally the retrofit scheme will target a modified lateral response shape so as to manage the distribution of damage (through control of interstorey drift, Thermou *et al.* 2006, 2007); local deficiencies will be corrected through local interventions.

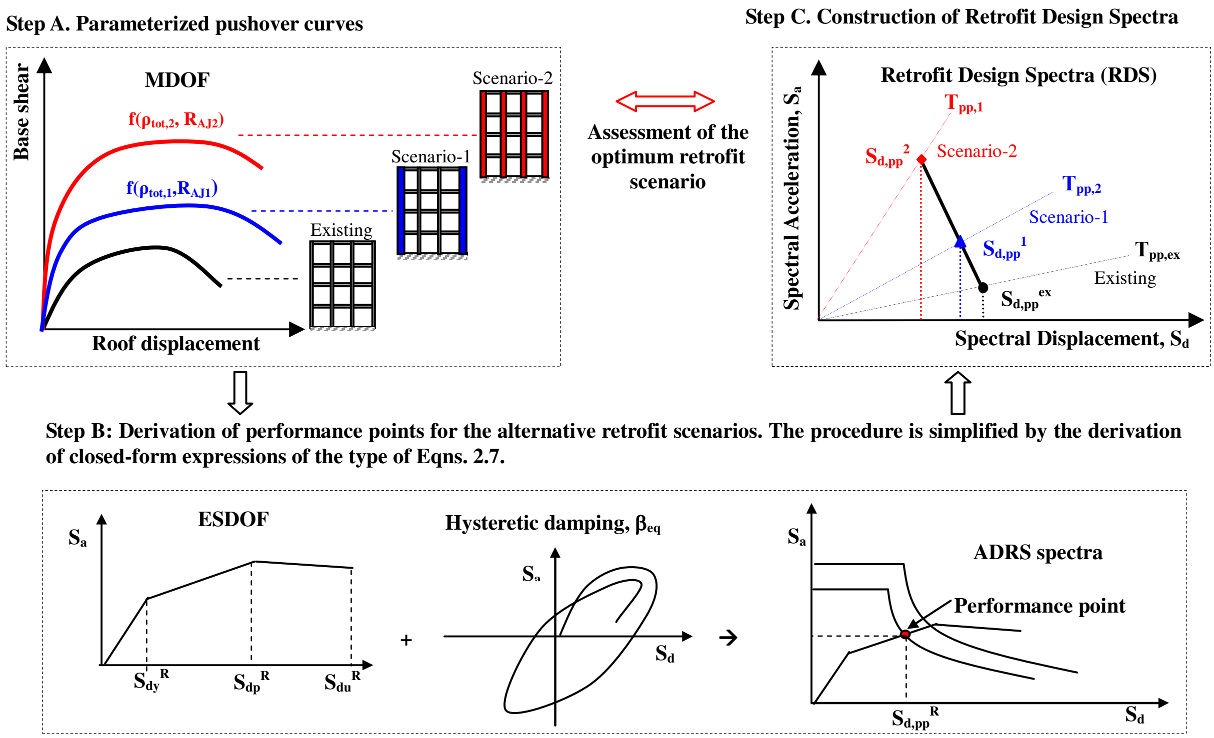

Figure 3 Conceptual framework of Retrofit Design Spectra (RDS).

In this paper, in order to construct the pushover curve of the retrofitted structure from the response curves of the individual components it is assumed that such an initial step has already been made, so that a stable hysteretic response without damage localization may be targeted for the retrofitted structure.

The basic element of the pushover curve of a frame structure is the response curve (i.e., shear versus relative displacement) of its individual storeys. (The response curve of a single storey is obtained by direct summation of the response curves of the individual vertical elements of the floor, assuming they all undergo the same interstorey drift). The response curve of the complete structure may be obtained from the response curves of the individual storeys: thus, for a given top storey displacement, the interstorey drifts are estimated using the targeted shape of vibration of the structure after retrofit, Φ; storey shears associated with the estimated storey drifts are obtained from the response curves of the individual storeys. This procedure implicitly relies on the rigid-diaphragm assumption; this could, in cases of excessive stiffening of the columns through retrofit, lead to overestimation of storey strength and stiffness, as it neglects the contribution of beam action to the total drift. Although this assumption at the preliminary design phase is justified for monolithic frame structures with floor slabs (due to the inherent slab participation to beam flexure), it is not an essential step in the simplified procedure detailed above; to improve accuracy by relaxing this assumption, the column interstorey drift need be multiplied by the ratio $\lambda/1+\lambda$, where λ the average storey column to beam flexural stiffness ratio; ($\lambda=EI_cL_b/EI_bh_{st}$, EI_c the average retrofitted column sectional stiffness, EI_b the average beam sectional stiffness, and h_{st} and L_b the respective average storey height and average span length in the structure). As an example, consider a given lateral displacement Δ at the top of the structure. Then, the i-th floor columns experience a relative drift of:

$$ID_i = \lambda_i \frac{(\Phi_i - \Phi_{i-1})}{h_i}\Delta \; ; \quad \text{and for the first storey:} \quad ID_1 = 0.67\lambda_1 \frac{\Phi_1}{h_1}\Delta \qquad (3.1)$$

In Eqn. 3.1 h_i and h_1 the storey height of the i-th and the first floors, respectively. Thus, the base shear $V_{base}(\Delta)$ of the structure, associated with top displacement Δ, is the sum of the first storey shears of the individual columns, associated with a relative displacement of the column ends equal to $0.67\lambda_1\Phi_1\Delta$.

3.1. Global intervention methods – The case of RC jacketing

In the context of the proposed methodology, the pushover curve of the retrofitted structure is uniquely determined by the response curves of the individual floor elements particularly those undergoing retrofit. Here, the milestone points of these response curves, denoted by δ_y, δ_u, F_y, F_u, are related to the technological parameters of the intervention method through closed form expressions. This enables rapid inspection of the practical implications on structural drift, effected by modification of members' key design quantities. An example concerns the response curve of a floor comprising RC columns jacketed with RC jackets. To simplify calculations, all reinforcement is considered to act at the location of the added (jacket) reinforcement; existing longitudinal reinforcement (given by the ratio $\rho_c=A_c/(b_c h_c)$) may either be neglected, or an equivalent amount may be transferred to the centroid of the extreme layers of jacket reinforcement using the parallel-axis theorem (Figure 4). The equivalent longitudinal reinforcement ratio, ρ_e, is given by the following:

$$\rho_e = \rho_J + \rho_c \frac{(0.5h_c - d_c)^2}{AB(0.5h_J - d_J)^2} \tag{3.2}$$

where, $\rho_J(=A_J/(b_J h_J)$ is the longitudinal reinforcement ratio of the jacket (a fraction of the total area of the final member cross section), h_J, b_J are the height and the width of the jacketed cross section, h_c, b_c are the height and the width of the existing cross section, $A(=b_J/b_c)$ and $B(=d_J/d_c)$. In case that $d_J'=0.1h_J$, $d_c'=0.1h_c$, $d_J=0.9h_J$ and $d_c=0.9h_c$, then ρ_e is simplified further to: $\rho_e=\rho_J+\rho_c/AB^3$.

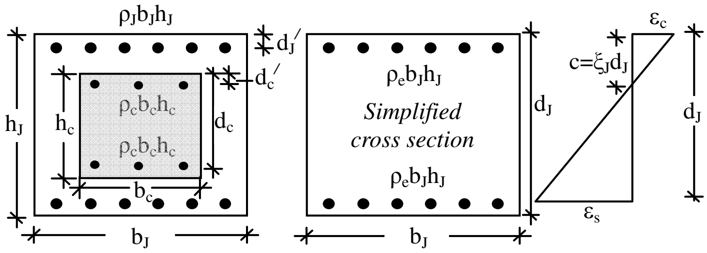

Figure 4 Simplified model (a) of the jacketed cross section, (b) for curvature distribution

Expressions that relate deformation and strength capacity at yield, δ_y, F_y, and ultimate, δ_u, F_u, to the characteristics of the jacketed cross section are presented in Thermou (2007).

Design charts may be constructed which relate the abscissa of the performance point ($S_{d,pp}^R$) to the key design characteristics. The key design characteristics which are used in obtaining the RDS in this example are, the mean area increase ratio of the retrofitted columns (resulting from application of the jacket), R_{AJ}, and, the mean value of the total equivalent longitudinal reinforcement ratio of the jacketed members, ρ_{tot}, estimated in the first floor. The parameters R_{AJ} and ρ_{tot} are defined by:

$$R_{AJ} = \sum_{n=1}^{n_m}((A_{J,n} - A_{c,n})/A_{c,n})/n_m = \sum_{n=1}^{n_m}((b_{J,n}h_{J,n} - b_{c,n}h_{c,n})/b_{c,n}h_{c,n})/n_m = \sum_{n=1}^{n_m}(A_n B_n - 1)/n_m \tag{3.3a}$$

$$\rho_{tot} = \sum_{n=1}^{n_m}\rho_{tot,n}/n_m \tag{3.3b}$$

where, the subscript n refers to the n-th storey member considered as participating in the lateral load resisting system, n_m the number of vertical components of the storey and $\rho_{tot,n}$ the total equivalent reinforcement ratio of the jacketed cross section (with reference to Figure 4, $\rho_{tot,n}=2\rho_{e,n}$).

4. RETROFIT DESIGN SPECTRA (RDS) FOR RETROFITTED RC BUILDINGS

The performance point of each retrofit scenario may be estimated directly as detailed in the preceding. The pushover curve of the retrofitted structure is expressed parametrically and the corresponding performance point is defined by the solution of equations similar to (2.7) depending on the adopted hysteretic model. Definition of the performance point corresponds to the intersection point of the capacity curve with the appropriately damped demand spectrum and represents the maximum structural displacement expected for the applied earthquake ground motion. Performance points corresponding to different retrofit scenarios may be utilized to construct the Retrofit Design Spectra (RDS). This new type of spectrum links the characteristics of the intervention method to the spectral ordinates of the performance point, thereby providing the engineer with the necessary data for rapid assessment of the retrofit solution before reaching a final decision.

The proposed methodology is applied for illustration purposes to a three-storey three-bay frame representative of old-type construction. The storey height is 3 m and the bay length 4 m. All vertical members have a 250 mm square cross-section with four 14 mm (4Ø14, ρ_c=1.0%)) diameter longitudinal bars placed uniformly on the cross sectional perimeter. Transverse reinforcement comprises smooth steel, rectangular shaped 8 mm diameter stirrups, with stirrup spacing 250 mm. The materials used for the existing frame followed the requirements for seismic applications according to DIN1045 (1972) and DIN 488 (1975). The nominal yield strength of transverse reinforcement is 220 MPa (S220), which corresponds to StI. The longitudinal bars have nominal yield strength of 500 MPa that corresponds to steel quality StIV. The nominal compressive strength of concrete is $f_c^{/}$=20 MPa, which corresponds to Bn250 (nominal cubic strength of 250 kg/cm^2). All beams in the direction of applied lateral loading are 250 mm wide and 500 mm deep, whereas the solid concrete slab thickness is 150 mm.

The retrofit strategy adopted requires strengthening of the frame by the addition of RC jackets to all the vertical members. This option leads to an improved distribution of damage amongst members of the same floor, through increased participation of all the floor members in the lateral load resisting system. The thickness of the jacket is selected to be 50 mm (R_{AJ}=96%), whereas the total equivalent longitudinal reinforcement ratio of the jacketed members varies between ρ_{tot}=0.8%~1.8% ($\rho_{J*}=(A_c+A_J)/(b_Jh_J)$=1.0%~2.0%). The concrete selected for the jackets has a compressive strength of $f_c^{/}$=20 MPa, whereas longitudinal reinforcing and transverse steel with nominal yield strength of 500 MPa is used. Eurocode 2 (2003) is used for the design of the jacketed members.

The alternative retrofit scenarios are defined for the various percentages of the longitudinal reinforcement of the jacket for two levels of seismicity. The levels of demand adopted for soil profile type S_B have seismic coefficients $C_A=C_B$=0.3g for the medium and $C_A=C_B$=0.4g for the high seismicity level (ATC 40, Chapter 4, 1996). Following the proposed methodology, the results of the parametric study are presented in Table 4.1.

Table 4.1 Results of the parametric study

	$C_A=C_B$=0.3g			$C_A=C_B$= 0.4g		
ρ_{tot} (%)	0.8	1.3	1.8	0.8	1.3	1.8
ρ_{J*} (%)	1.0	1.5	2.0	1.0	1.5	2.0
μ_{pp}	1.98	1.52	1.13	2.67	2.11	1.70
β_{eq} (%)	8.7	6.2	5.1	13.6	9.6	7.0
T_{pp} (sec)	0.96	0.70	0.54	1.11	0.82	0.66

The Acceleration Displacement Response Spectra (ADRS), which correspond to the retrofit solutions of Table 4.1, are presented in Figures 5a and 5b for the medium ($C_A=C_V$=0.3g) and high ($C_A=C_V$=0.4g) levels of seismicity, respectively. The performance points of the alternative retrofit solutions examined lie on the gray (Figure 5a) and black curves (Figure 5b) for the medium and high levels of seismicity, respectively. If these curves are isolated as in Figure 5c, the Retrofit Design Spectra (RDS) are constructed. Hence, the RDS utilize the ADRS format and are constructed from the performance points, which correspond to alternative retrofit solutions, estimated from the closed-form expressions similar to Eqns. 2.7 (depending on the hysteretic model adopted). Supplementary design charts, which relate the characteristics of the intervention method (for the case of RC jacketing: R_{AJ} ρ_{tot} or ρ_{J*}) to the abscissae of the performance point, facilitate the design procedure (Figure 5d).

The function of the Retrofit Design Spectra (Figure 5c) and of the supplementary design chart (Figure 5d) is explained through the following example. For a percentage of longitudinal reinforcement of the jacketed cross section ρ_{J*}=1.5% the abscissa of the performance point is defined in terms of spectral displacement equal to $S_{d,pp}^{R}$=49.2 mm (red arrows) and $S_{d,pp}^{R}$=68.5 mm (blue arrows) for the medium ($C_A=C_V$=0.3g) and high

(C_A=C_V=0.4g) levels of seismicity, respectively. Demand expressed in terms of maximum roof displacement corresponds to 0.67% and 0.93% of the total height of the building for the medium (C_A=C_V=0.3g) and high (C_A=C_V=0.4g) levels of seismicity, respectively.

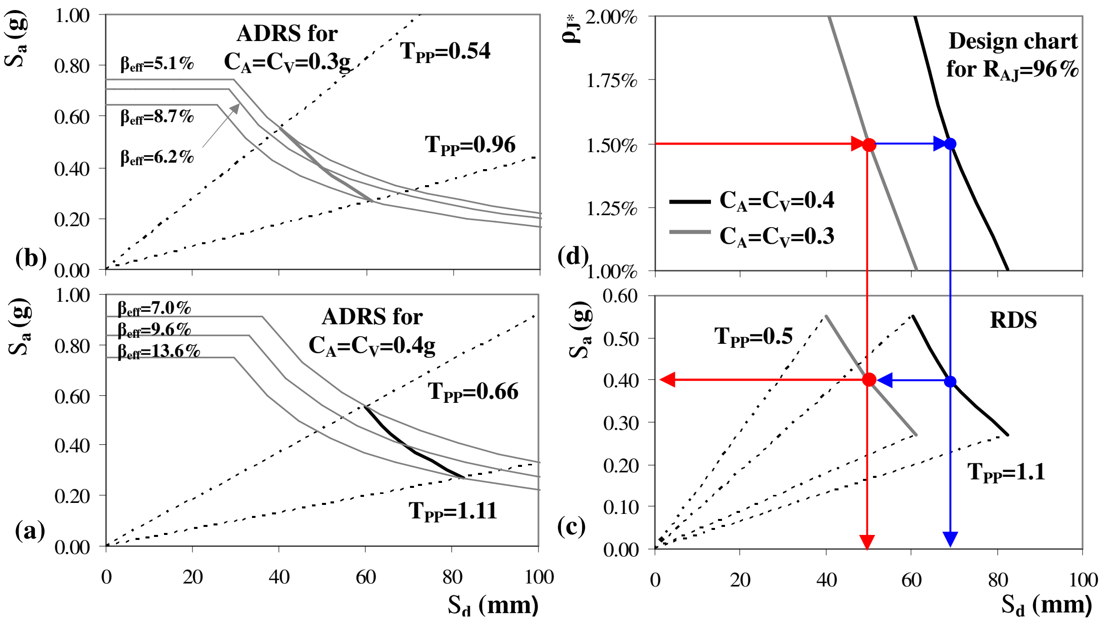

Figure 5 (a) Retrofit Design Spectra; (b) Design chart; (c) ADRS for C_A=C_B=0.4g; (d) ADRS for C_A=C_B=0.3g

5. CONCLUSIONS

Towards providing a framework for retrofitting RC structures, a method for deriving the new Retrofit Design Spectra (RDS), which relies on the Capacity Spectrum Method, described in ATC 40 (1996), as later modified in ATC 55/FEMA 440 (2005), was presented. The capacity curve of the retrofitted structure is expressed parametrically in terms of the intervention method characteristics of stiffness, strength and ductility. Closed-form expressions were derived, which enable estimation of the performance point as a function of the response characteristics of the retrofitted structure. The Retrofit Design Spectra (RDS) are constructed from the performance points which correspond to different retrofit scenarios. The RDS utilize the composite acceleration-spectral displacement format and supplementary design charts that facilitate rapid assessment of the implications of each possible scenario, which may combine different global interventions. In this paper, RC jacketing was selected as a case study in order to illustrate a practical implementation of the proposed approach.

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