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Retrofit Yield Spectra–a practical device in seismic rehabilitation

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Abstract. The Retrofit Yield Spectrum (RYS) is a new spectrum-based device that relates seismic demand of a retrofitted structure with the fundamental design parameters of the retrofit. This is obtained from superposition of Yield Point Spectra with design charts that summarize in pertinent spectrum-compatible coordinates the attributes of a number of alternative retrofit scenarios. Therefore, once the requirements for upgrading a given structure have been determined, the RYS enable direct insight of the sensitivity of the seismic response of the upgraded structure to the preliminary design decisions made while establishing the retrofit plan. By virtue of their spectrum-based origin, RYS are derived with reference to a single mode of structural vibration; a primary objective is to control the contribution of this mode in the retrofit design so as to produce a desirable distribution of damage at the ultimate limit state by removing soft storey formations and engaging the maximum number of structural members in deformation, in response to the input motion. Calculations are performed with reference to the yield-point, where secant stiffness is proportional to the flexural strength of reinforced concrete members. Derivation and use of the Retrofit Yield Spectra (RYS) refers to the seismic demand expressed either in terms of spectral acceleration, spectral displacement or interstory drift, at yield of the first storey. A reinforced concrete building that has been tested in full scale to a sequence of simulated earthquake excitations is used in the paper as a demonstration case study to examine the effectiveness of the proposed methodology.

Keywords: retrofit; spectra; seismic upgrading; yielding; ductility

1. Introduction

The retrofit strategy adopted for seismic upgrading of existing reinforced concrete (RC) buildings ideally is chosen as the optimum solution from a number of alternatives to achieve the required balance between performance, safety and economy. The process of selecting the most suitable retrofit approach may benefit from an assessment of the sensitivity of the ensuing retrofitted building to variations in a single design parameter of the alternatives under consideration.

To investigate the sensitivity of a given retrofit alternative for the purpose of providing insight as

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a guiding tool rather than on a case by case basis, a special type of inelastic spectra is derived in this paper. These spectra, referred to hereafter as Retrofit Yield Spectra, combine the characteristics of Yield Point Spectra (YPS) (Aschheim and Black 2000), with a chart representation of the dynamic properties of the structure (such as fundamental period and lateral stiffness) given in terms of the detailing parameters of a retrofit strategy. For example, such detailing parameters may be the longitudinal reinforcement ratio in the columns and the increase of cross-sectional area of vertical members in the case of jacketing of RC structures. By plotting the design charts in spectrum-compatible coordinates and superimposing them on the YPS, the RYS effectively compare deformation capacity and demand for various performance levels as a function of the design parameters of the retrofit.

To meet the performance objectives, retrofit often requires a radical modification of the response of the structure. This can be achieved through intervention methods that alter the global stiffness distribution in the structure (and consequently the strength distribution). In this context, the present paper focuses only on such measures, referred to hereon as global interventions. Other deficiencies in deformation capacity, such as those occurring in critical zones of beams and columns, can be mitigated through local measures, such as FRP jacketing, that do not significantly modify neither the secant-to-yield stiffness nor the yield strength of any individual RC member. Thus, although they may be a necessary attribute of the final retrofit scheme, they do not essentially modify the dynamic properties of the structural system (i.e. period and mode of lateral vibration); they will not therefore be considered in the context of the RYS.

The proposed methodology builds on the concepts of performance-based assessment. Therefore, demand is estimated for a given seismic hazard in terms of lateral drift of an equivalent single degree of freedom (SDOF) representation of the structure. Local demands such as member chord rotations (e.g. interstorey drift) are obtained from the structural drift using the fundamental mode of vibration as the basis of transformation between global displacement and local deformation indices. If it is determined through assessment that the global-local relationship leads to an unfavorable concentration of damage, then its optimum modification to achieve a more uniform distribution of interstorey drift by engaging more members in the structure becomes a guiding objective of the rehabilitation strategy. In the initial phase of retrofit planning, the engineer is confronted with many practical questions. For example, how much stiffness should be added for attainment of the retrofit objectives? which elements to strengthen? by how much? and what is the effect of increasing the component strength, stiffness or deformation capacity on the response of the structure? The above and other such issues are rarely quantified explicitly. The usual approach is to go through detailed analysis to assess individual scenarios one at a time. There is a pressing need for a systematic framework identifying a suitable retrofit strategy, with a rapid evaluation tool that enables immediate assessment of the global effects caused by intervention at the storey level.

The proposed method for the derivation of the Retrofit Yield Spectra (RYS) is presented in a step-by-step manner. The well-documented full scale 4-storey RC building test on the ICONS frame (Innovative seismic design CONcepts for new and existing Structures Project; Pinto *et al*. 2002) was utilized as a case study for the implementation of the proposed methodology. Reinforced Concrete (RC) jacketing was the global intervention method adopted here. Through a graphical representation, the RYS simplify substantially the retrofit design providing direct insight into the interrelation of demand expressed in terms of spectral displacement and acceleration at yield on the one hand, and the design parameters of the retrofit solutions on the other hand.

2. Conceptual framework of the proposed methodology

The contribution of a member to the overall stiffness of the structure is controlled by the member participation (through deformation) to the total structural drift. The above statement means that the most flexible members of the structure limit the magnitude of the effective stiffness which may be mobilized in systems that behave as springs in series, such as the consecutive floors of a multi-storey structure under lateral loads. To illustrate the latter point, consider the example of an old shear-frame swaying in the lateral direction, where rigid diaphragms (with beam flexural stiffness an order of magnitude higher than column stiffness) force the deformation to occur in the columns. If Ψ the fundamental mode of lateral vibration, then the associated *effective* or *generalized* stiffness of the structure is given by

$$K_{\Psi} = \sum_j 12 E_{c,j} I_{c,j} \cdot \Delta \Psi_j^2 / h_j^3 \tag{1}$$

where the summation is done over j columns, $\Delta\Psi$ is the difference in the mode shape coordinates within the column length, h_j, E_c is the elastic modulus of concrete and I_c the moment of inertia of columns. Therefore, in this structure, the beams which are very stiff do not contribute at all to the structural stiffness. Similarly, consider a wall structure, supported on rotationally-compliant soil with an equivalent rotational stiffness $K_s << K_{wall}$. The effective stiffness of the system in this case is reasonably approximated by K_s/H^2, where H is the total height of the structure, i.e., the stiffer component of the structure has no contribution to lateral stiffness, but rather, the magnitude of this variable is controlled by the most compliant elements (here, the soil).

2.1 Structure approximation through an equivalent single degree of freedom system

In the context of a generalized equivalent single degree of freedom approximation of the structure (Clough and Penzien 1993), an *effective* stiffness value K_{Ψ} for the entire structure may be calculated for any shape of lateral vibration, Ψ. The contribution of the j^{-th} member to the effective lateral stiffness K_{Ψ} is given by

$$\Delta K_{\Psi} = K_j \cdot \Delta \Psi_j^2 \tag{2}$$

where, K_j is the member resistance (stiffness) to relative lateral translation of its end nodes, and $\Delta\Psi_j$ is the relative displacement due to member deformation (i.e. it is associated with storage of strain

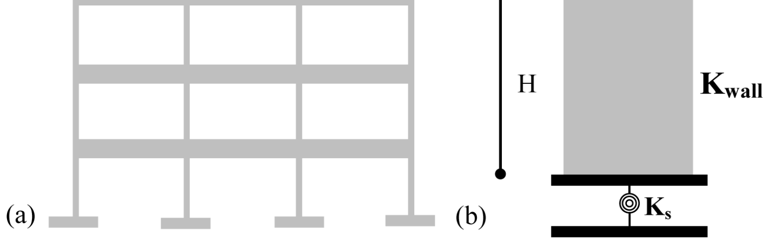

Fig. 1 (a) System with very stiff beams; (b) Wall structure supported on rotationally-compliant soil energy in the member) when the structural system displaces according to the shape Ψ. Eq. (2) quantifies the influence that a single member has on structural period, T_Ψ, through the dependence of the latter on effective stiffness ($T_\Psi = 2\pi\sqrt{(M_\Psi/K_\Psi)}$ where, $M_\Psi = \Sigma m_j \cdot \Psi_j^2$ and $K_\Psi = \Sigma K_j \cdot \Delta\Psi_j^2$). Furthermore, in light of the fact that displacement demand imposed by a given seismic hazard can also be expressed in terms of the period, it is possible to use Eq. (2) to readily inspect the changes in the seismic response of a retrofitted structure, imparted through redesign of the individual members. The latter process is depicted schematically in Fig. 2. For example, consider the displacement demand as defined by the EC8 (2004) displacement spectrum for a practicable range of structural periods ($T > T_c = 0.4$ sec)

$$0.4 \le T \le 2 \text{ sec:} \quad S_d(T) = a_g \cdot S \cdot \eta \cdot \frac{T}{4\pi^2} = a_g \cdot S \cdot \eta \cdot \frac{1}{2\pi} \cdot \left(\frac{M_\Psi}{K_\Psi}\right)^{0.5} \tag{3}$$

where α_g is the peak ground acceleration of the site, S is a soil factor (in the range of 1.0 for adequate soil conditions of either type A or B (EC8 2004)), and $\eta = 1$ for elastic response. Using Eq. (2) in the above in order to estimate the seismic response of a retrofitted structure it follows that

$$\sum_j K_j \cdot \Delta\Psi_j^2 \approx \left(\frac{\alpha_g}{2\pi \cdot S_d}\right)^2 \cdot 0.08W \Rightarrow \sum_j C_j = \zeta \cdot S_d^{-2}; \zeta = 0.002W \cdot \alpha_g^2 \tag{4}$$

In deriving Eq. (4), it was assumed that the mass excited by the 1st mode vibration is about 0.8 of the total mass of the system. The parameter $C_j = K_j \Delta\Psi_j^2$, represents the *j-th* member contribution to global stiffness. From Eq. (4) it is concluded that the global displacement demand, S_d, is inversely proportional to the strain energy stored through member deformation (which is implicit in the response shape, $\Delta\Psi_j$), while having a much milder dependence on individual member stiffness. The latter observation underscores the significance of retrofit measures that focus in optimizing the distribution of $\Delta\Psi$ rather than the actual magnitude of individual member stiffness K_j.

The derivation above enables appreciation of the end result, as measured by the reduction in

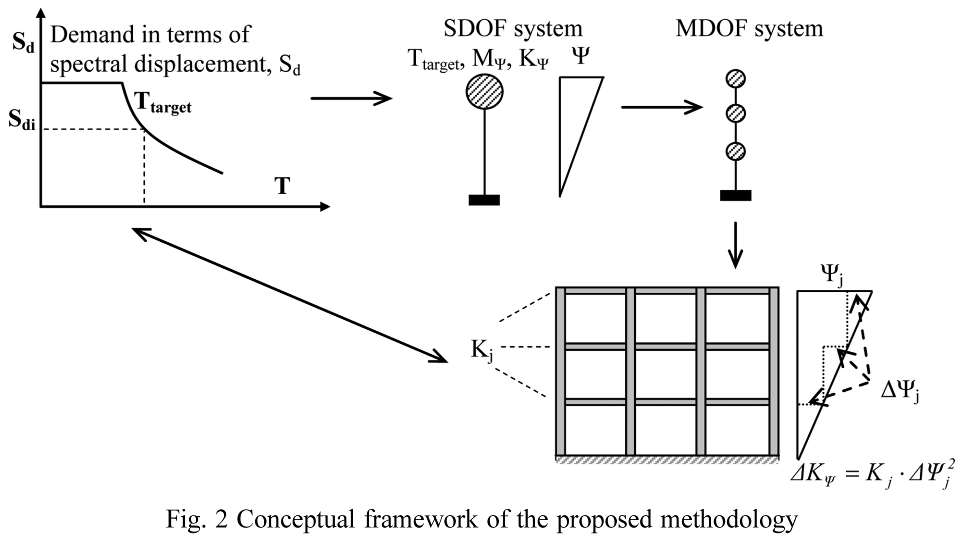

Fig. 2 Conceptual framework of the proposed methodology

demand, S_d, which is produced by any modification of the member properties, C_j. Clearly, from among the various physical parameters controlling the ESDOF's response, the greatest effect is displayed by the vibration shape, Ψ. The vibration shape is particularly sensitive to the stiffness ratios along the height of the building. Consequently, damage control is achieved by the correction of the distribution of interstorey drift in all the floors, which is directly related to the distribution of $\Delta\Psi$.

2.2 Distribution of stiffness along the height of the building

A methodology for distributing the additional stiffness along the height of the building in order to achieve a selected response shape has been developed by Thermou (2007) and Thermou *et al.* (2007). The outcome of the methodology is a vector of weighting factors, $\{w\}$, by which the required stiffness is distributed among the various storeys. To derive the vector of weighting factors, $\{w\}$, Rayleigh's method was used. The latter analysis converges to the fundamental mode shape that satisfies force equilibrium indirectly through energy conservation. The work-equivalent stiffness comprises contributions of the deformable elements in all floor levels; strain energy is associated with translational inter-storey drift for shear frame structures, and depends on tangential inter-storey drift in flexural wall-frame systems.

The proposed method for the estimation of the required distribution of stiffness may be applied to any targeted lateral displacement profile. The triangular response shape was used here for demonstration as it represents an ideal situation where all floors experience the same interstorey drift ratio, and therefore all members participate equally to the structural stiffness. For this scenario, the effective mass and stiffness, M_Ψ and K_Ψ are expressed as follows

$$M_\Psi = \frac{m}{n^2}\sum_i i^2 \tag{5a}$$

$$K_\Psi = (w_1K + w_2K + \ldots + w_nK)\frac{1}{n^2} = \frac{1}{n^2}K, \sum_i w_i = 1 \tag{5b}$$

where m is the typical storey mass (considered here the same for all typical storeys), n is the total number of storeys, i the storey number, and K is a reference stiffness value: floor stiffness K_i is obtained by multiplying K with the corresponding weighting factor w_i of floor i. The sum of the weighing factors, Σw_i, is equal to unity. The stiffness of the first floor, K_1, is related to the effective stiffness, K_Ψ through the following

$$K_1 = w_1K = w_1n^2K_\Psi \tag{6}$$

The weighting factor for *i-th* storey, w_i, for a target triangular vibration shape is defined by

$$w_i = \frac{\sum_i^n i}{\sum_I^n i^2} \tag{7}$$

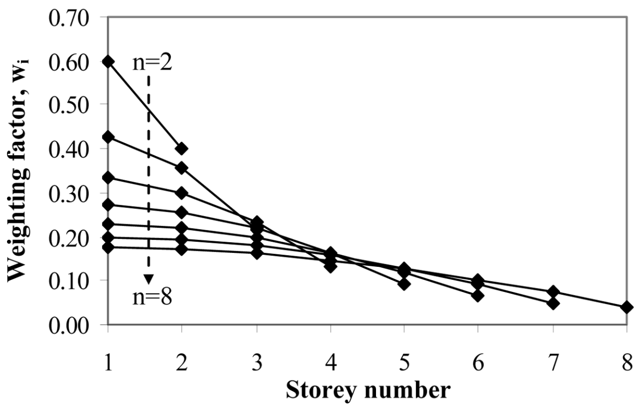

Fig. 3 Weighting factors for 2- to 8-storey buildings (n = 2 to n = 8)

whereas the corresponding values for different numbers of floors, n, are plotted in Fig. 3.

3. Derivation of Retrofit Yield Spectra

The procedure for establishing the Retrofit Yield Spectra for a given design hazard (earthquake with a site-specific Acceleration and Displacement Response Spectrum) is described below in steps. The basis for using this methodology is the implicit assumption that a structure has been deemed seismically deficient upon previous assessment; an important diagnostic indication as to the need for retrofit through global intervention is the estimated magnitude of the fundamental period of the existing structure, T_o, and the natural vibration shape, Ψ_o.

The period of the structure should not exceed by a substantial margin the nominal value recommended by the EC8 (2004): $T \approx \{0.075 \cdot H^{3/4}$, or, alternatively, $0.1n$ for n storey frames, $0.05n$ for n-storey wall-type structures$\}$. (Note that any calibrated expression for predicting the period of the structure can be utilized as guidance for the expected range of values of the fundamental natural frequency). The morphology of the natural vibration shape illustrates possible tendencies for drift localization, in points of drastic deviation of the modal interstorey drift, $\Delta\Psi_{o,j}/h_{st,j}$ from the average value of $1/H$. (Period and mode-shape assessment of the existing structure can be done relatively easily, using either ambient vibration tests (Ivanović *et al*. 2000, Dunand *et al*. 2004), or analytically, by conducting a few cycles of Rayleigh's method (Clough and Pienzien 1993).

3.1 Proposed methodology

A first step in the direction of establishing a retrofit strategy is to define an acceptable design region for the structural period by setting upper and lower acceptable limits for the target period of the retrofitted building, T_{target}. A lower limit, for example, may be taken to correspond to the empirically defined estimates of expected period values for frame, and for wall type buildings stated in the preceding.

Step 1: *Definition of the design region*: The Yield Point Spectrum (YPS) representation (Aschheim and Black 2000) is utilized for defining the acceptable design region, which is delimited between the lower and upper bounds selected for the target period, T_{target}, of the retrofitted building

($T_{target,min}$<T_{target}<$T_{target,max}$, where T_{target}<T_o and T_o the period of the existing building). (The YPS are isoductile total Acceleration – Yield Displacement Response Spectra (ADRS). These are obtained from the elastic spectrum of the design earthquake after scaling down its *x* and *y* coordinates through pertinent q-μ-T relationships. To obtain a point in the YPS for a given period value, T_o, the total acceleration and relative displacement coordinates of the elastic ADRS spectrum (corresponding to T_o) are simply divided by the behaviour factor, q_{target}, and the corresponding ductility demand, μ_{target}. The YPS curve that goes through the yield point of the ESDOF's pushover curve, simultaneously defines the ductility demand when the structure is subjected to the design earthquake.) For example, the case of a typical residential four-storey frame structure with an initial period T_o = 1.2 sec is illustrated in Fig. 4; T_o was obtained by applying Rayleigh-iteration using storey stiffness at yield $K_{y,st}$ in establishing the work equivalent stiffness of the representative SDOF. The shaded region between $T_{target,min}$ = 0.5 sec and $T_{target,max}$ = 1.0 sec in Fig. 4 (constant ductility YPS) was chosen to define an acceptable region of values for the fundamental period of this system; this region was used to guide seismic upgrading in this application.

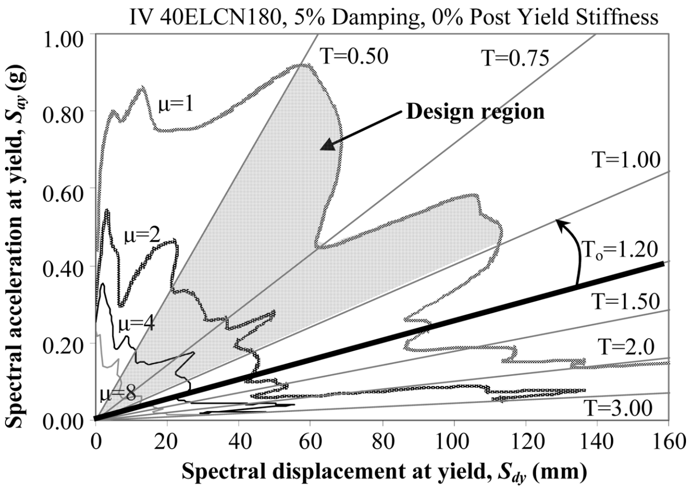

Fig. 4 Constant ductility Yield Point Spectra - Definition of design region - shaded region

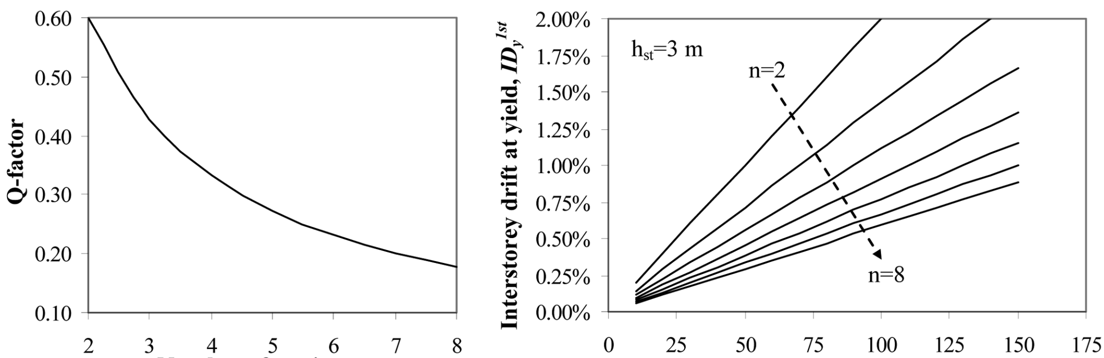

Fig. 5 (a) Relationship between Q-factor and number of stories, *n*; (b) Relationship between ID_y^{1st} and S_{dy} for h_{st} = 3 m, n = 2~8 according to Eq. (19) and Fig. 6(a)

Step 2: Selection of the target response shape, (Ψ_{target}): In selecting the target response shape, a driving consideration is the pursuit to obtain as nearly uniform as possible a distribution of drift demand. Between the shear type and the flexural type response bounds is the linear vibration shape, which is an ideal theoretical construct, whereby the same interstorey drift is achieved in all floors. For simplicity of demonstration, this target response shape, Ψ_{target}, is adopted in the remainder of this work to guide the calculation effort; in practice this may be considered too strict a design objective, as less expensive solutions can be attained if a moderated shear type response is tolerated instead. When considering structural vibration in the selected target mode shape ($\Psi_i = i{\cdot}h_{st}/H$), the generalized (effective) SDOF properties of the structure are related to the target period and from there to the required secant-to-yield stiffness of the first floor, K_1, as follows

$$T_{target} = 2\pi\sqrt{\frac{M_\Psi}{K_\Psi}} = 2\pi\sqrt{\frac{mw_1\sum_{i=1}^{n} i^2}{K_1}} \Rightarrow K_1 = \frac{4\pi^2}{(T_{target})^2}\left(m\cdot\sum_{i=1}^{n} i\right) \tag{8}$$

where K_1 is the stiffness of the first storey, w_1 the weighting factor value at the first storey, m the typical storey mass, i is the i^{th} storey and T_{target} is the target period.

Step 3: Distribution of stiffness heightwise: Having estimated the required first floor stiffness, K_1, the reference stiffness value K in Eq. (5) is evaluated from: $K = K_1/w_1$. By definition, the required stiffness in the i-th floor associated with the selected target shape is obtained from: $K_i = w_i{\cdot}K = K_1{\cdot}w_i/w_1$.

Where K_1 is the stiffness of the first storey, w_1 the weighting factor value at the first storey and w_i the weighting factor of the i-th floor.

Step 4: Relating lateral stiffness K_1 to the characteristics of the intervention method: A practical design approach is developed herein to relate the required effective stiffness, K_1, to the target drift values at yield. To enable the development of the design approach, the translational stiffness values of the members that participate in the global intervention scheme are expressed in terms of the design parameters of the retrofit. Only global interventions are usually needed in stiffness-deficient systems, i.e., systems that have a tendency for drift localization either in soft stories or in members located away from the center of stiffness in structures with plan eccentricities. Thus, the floor stiffness can be expressed in terms of the important design variables of the global retrofit schemes through parameterized expressions. Such expressions were derived for the most popular global interventions techniques, the RC jacketing technique and the addition of RC walls, in Paragraph 4.2 and in Appendix A1, respectively. The approach detailed by Eq. (5) could be applied with reference to the required stiffness of any floor in the structure, K_i; the first floor stiffness (K_1) has been used in the remainder of this presentation as a point of reference. (This is not to be interpreted that the retrofit methods are applied only in the first floor; rather, since they refer to global interventions, it is essential that the stiffness values in all floors should comply with the required stiffness distribution established in Step 3). To carry-out practical calculations in the following, an additional simplification is made, by estimating storey-stiffness from column contributions only. If RC jacketing is the global intervention method of choice, stiffness demand at the member level, K_y^J, may be calculated by assuming that the floor stiffness will be distributed according to the moment of inertia of the vertical members of the floor. The stiffness demand at member level is related to the characteristics of the jacket (h_J, b_J, ρ_e) through Eq. (11).

Step 5: Construction of design charts: By plotting the relationship between design variables and equivalent first storey stiffness or period, it is possible to immediately grasp the implications of variation in the design values on the dynamic properties. Different types of design charts may be constructed to facilitate the selection of the retrofit solution. Among the parameters used to describe the retrofit scenario are, the stiffness ratio $K_1/K_{o,1}$, and the target period, T_{target}, of the retrofitted building. In case that RC jacketing is the intervention method adopted in the retrofit scenario, parameters R_A^J Eq. 16(c) and ρ_{ave}^J Eq. 16(a) may be utilized for the construction of the alternative types of design charts.

Step 6: Construction of the Retrofit Yield Spectra (RYS) – The Retrofit Yield Spectra (RYS) are inelastic spectra of the design seismic hazard, on which the design charts of Step 5 have been superimposed, by exploiting the fact that structural period is a common coordinate in both groups of plots. Note that seismic demand may be expressed in terms of spectral acceleration, spectral displacement or interstory drift at yield of the first storey with the latter defined by the following expression

$$ID_y^{1st} = \Delta_y \cdot \Psi_1 / h_{st} = \frac{S_{d,y}}{h_{st}} \frac{\sum_1^n i}{\sum_1^n i^2} = \frac{S_{d,y}}{h_{st}} Q, \quad Q = \frac{\sum_1^n i}{\sum_1^n i^2} \tag{9}$$

where Δ_y is the roof displacement at yielding, Ψ_1 is the mode shape in the first storey, h_{st} is the storey height, $S_{d,y}$ is the spectral displacement at yielding and the value of factor Q corresponds to the triangular response shape used for the transformation of the spectral displacement at yielding to the drift at yield of the first storey, ID_y^{1st}.

The chart in Fig. 5(a) depicts the relationship between factor Q and the number of storeys, n. Given a storey height equal to h_{st} = 3 m, the relationship between the interstorey drift at the first storey, ID_y^{1st}, and the spectral displacement at yield for the triangular response shape for frame buildings from 2 up to 8 storeys is depicted in Fig. 5(b).

Based on the demand index selected to represent the seismic hazard as outlined above, three alternative types of Retrofit Yield Spectra are defined, where for each retrofit scenario there is a direct interrelationship between demand in terms of spectral ordinates and design parameters. After arriving at the appropriate retrofit solution, the next phase involves detailing of the upper floors (Thermou 2007, Thermou *et al.* 2007).

4. Implementation of the proposed methodology

The ICONS frame (Fig. 6(a)) was used as an example for the illustration of the Retrofit Yield Spectra method (RYS). It was a 4-storey, 3-bay frame representative of former construction practices prevailing in Southern Europe in the 1950's. The frame featured a number of local and global structural deficiencies. It was gravity-only designed without specific provisions for seismic detailing and inelastic dissipation mechanisms.

Storey height was 2.7 m. Two of the three bays were 5 m wide, whereas the third span was 2.5 m only (Fig. 6). Cross-sectional dimensions and detailing of the vertical members are outlined in Fig.

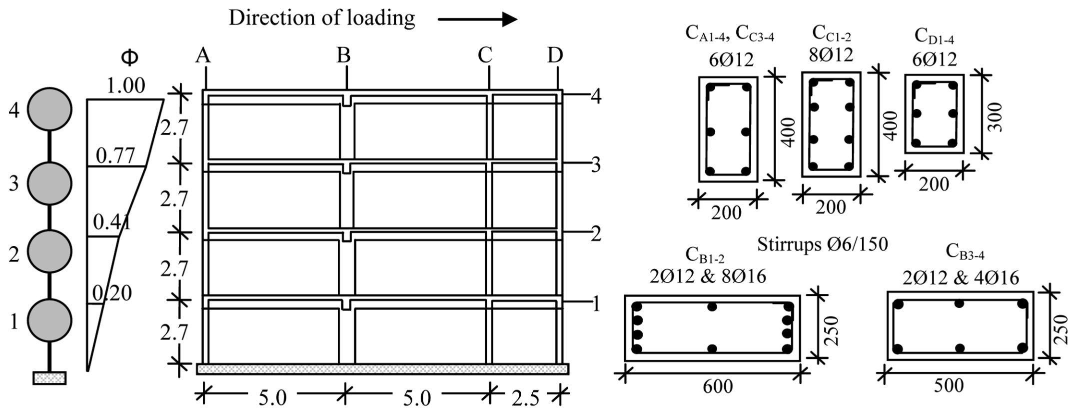

Fig. 6 Configuration and cross-sectional detailing of existing frame

6. All beams in the direction of loading were 250 mm wide by 500 mm deep, whereas transverse beams were 200 mm wide by 500 mm deep. The solid concrete slab thickness was 150 mm. Materials considered in the design phase were, a low strength concrete having a nominal compressive strength of f_{ck} = 16 MPa and smooth longitudinal reinforcing steel of class Fe B22k, with nominal yield strength of f_{syk} = 215 MPa. Test series were carried out for the determination of concrete compressive strength and steel mechanical characteristics. More information relative to reinforcement detailing and material properties was provided in Pinto *et al*. (2002). The fundamental natural period of the original frame was estimated by applying Rayleigh's method (using secant-to-yield floor stiffnesses; i.e. column equivalent E_cI_c values were obtained from the ratio of yield moment to yield curvature); the estimated value was, $T_o = 0.79$ sec ($m = 44.7$ ton, $K_{o,1} = 33346$ kN/m, $\Phi^T = [1.00,\ 0.77,\ 0.41,\ 0.20,\ 0.00]^T$, Fig. 6). The stiffness at yield of the first storey columns were estimated as $K_{o,A1} = 1368$ kN/m, $K_{o,B1} = 29149$ kN/m, $K_{o,C1} = 1790$ kN/m, $K_{o,D1} = 1039$ kN/m.

4.1 Retrofit strategy adopted

The retrofit strategy aimed at reduction of the period of the existing building by increasing its stiffness through application of RC jacketing to all but the stocky columns of the first and second floor, denoted as C_{B1} and C_{B2}, respectively in Fig. 7(a). The frame was intended to respond after retrofit in a linear fundamental mode shape. The design region was defined by a minimum and a maximum target period as follows: $T_{target}^{min} = 0.40$ sec, $T_{target}^{max} = 0.50$ sec. The minimum target period was set according with the prevalent practical design rule for frame structures $T_{target}^{min} = 0.1 \cdot n = 0.40$ sec, where $n = 4$ the number of floors. The upper limit, T_{target}^{max} was chosen to reflect the tolerance acceptable by the stakeholder from the desirable T_{target}^{min} value. The shaded area in Fig. 7(b) defines the design region (0.40 sec < T_{target} < 0.50 sec). Demand is expressed in terms of spectral acceleration ($S_{a,y}$) and spectral displacement ($S_{d,y}$) at global yielding of the retrofitted structure. The Yield Point Spectra of Fig. 7(b) were extracted based on the first type of the elastic design spectrum of Eurocode 8 (2004) for peak ground acceleration a_g = 0.36g, soil class A, S = 1.0, with corner point periods defining the various spectrum regions equal to T_B = 0.15 sec, T_C = 0.40 sec and T_D = 2.00 sec. The inelastic constant ductility spectra were constructed following the q-μ-T relationships provided by EC 8 (2004), i.e.: (i) $\mu = q$ for $T_i > T_C$ and (ii) $\mu = 1 + (q-1)T_C/T_i$ for $T_i \leq T_C$.

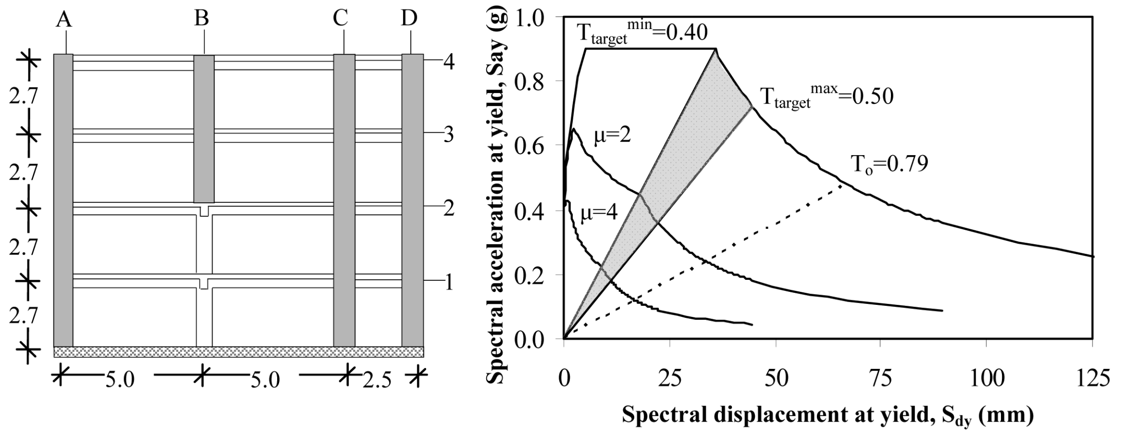

Fig. 7 (a) Retrofitted building, (b) Yield Point Spectra obtained from the 5% damped elastic spectrum of EC 8 (2004) using the *R*-μ-*T* relationship defined by EC8 (2004)

4.2 Proportioning of reinforced concrete jacketed columns for target upgrading

A simplified model of a typical jacketed cross section of a column member is depicted in Fig. 8. Dimensions of the initial section are b_c and h_c, whereas those of the section after jacketing are b_J, h_J. Compression zone depth c is expressed as a fraction of the depth of the jacketed section, $c = \xi_y^J \cdot d_J$. For calculations of yield moment and flexural stiffness, all reinforcement is considered to act at the location of the added (jacket) reinforcement. (Note that according to Steiner's theorem, existing tension longitudinal reinforcement (equal to compression reinforcement, Fig. 8), given by the area ratio ρ_c contributes to flexural stiffness of the jacketed section through the term $\rho_c b_c d_c(0.5h_c\text{-}d_c)^2$; thus, in order to maintain the same contribution in this calculation, the equivalent amount that is transferred to the location of jacket reinforcement is, $\rho_c b_c d_c(0.5h_c\text{-}d_c)^2/(0.5h_J\text{-}d_J)^2$). Furthermore, any other existing web longitudinal reinforcement is neglected as it is considered to have a small influence on post-jacketed flexural strength. Thus, the equivalent longitudinal tensile reinforcement ratio, ρ_e, of the jacketed cross section (total reinforcement area divided by the total area of the jacketed member) is given by

$$\rho_e = \rho_J + \rho_c \frac{(0.5h_c - d_c)^2}{(0.5h_J - d_J)^2} \cdot \frac{b_c h_c}{b_J h_J} \tag{10}$$

where $\rho_c(=A_c/b_c h_c)$ and $\rho_J(=A_J/b_J h_J)$ are the longitudinal tension reinforcement ratios of the existing cross section (equal to compression reinforcement) and the jacket, respectively, h_c and h_J are the heights of the existing and jacketed cross sections, respectively, b_c and b_J are the widths of the existing and jacketed cross sections, respectively, and d_c and d_J are the depths of the existing and jacketed cross sections, respectively.

The *j-th* member translational stiffness (secant to yield) is defined as

$$K_{y,j}^J = \frac{12E_c I_{y,j}^J}{h_{st}^3} = \frac{12M_{y,j}^J}{\varphi_{y,j}^J h_{st}^3} \tag{11}$$

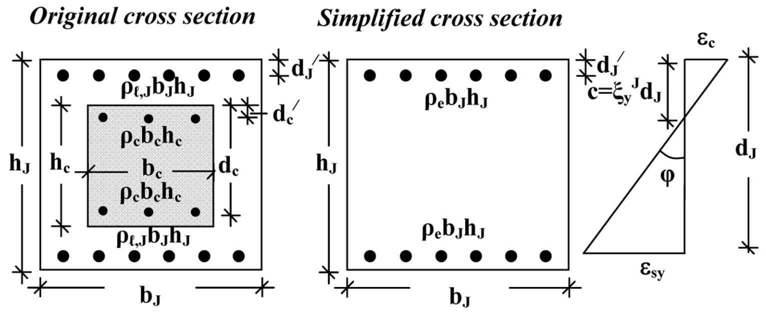

Fig. 8 Simplified model for RC jacketed members (existing web longitudinal reinforcement is neglected as it is considered to have a small influence on post-jacketed flexural strength)

The moment at yield, $M_{y,j}^J$, at the center of gravity of the simplified jacketed cross section is estimated equal to

$$M_{y,j}^J = \varphi_{y,j}^J b_J h_J^3 E_c[0.40\rho_e[\xi_y(-1-0.25n_c)+1.15n_c+0.10]+0.25\xi_y^2(1-0.66\xi_y)] \tag{12}$$

Hence, the *j-th* member translational stiffness is equal to

$$K_{y,j}^J = \frac{b_{J,j}h_{J,j}^3E_c}{h_{st}^3}\cdot\{4.8\rho_{e,j}[1.15\cdot\eta_c-\xi_{y,j}^J\cdot(1+0.25\eta_c)+0.1]+3(\xi_{y,j}^J)^2(1-0.66\xi_{y,j}^J)\} \tag{13}$$

where ρ_e is the equivalent longitudinal tensile reinforcement ratio, $\eta_c(=E_s/E_c)$ is the modular ratio of steel and concrete and $\xi_{y,j}^J$ is the normalized depth of compression zone of the RC jacketed member.

Depending on the magnitude of the axial load ratio, $v_j = N_j/b_Jh_Jf_c^/$, yielding may occur when either the tension steel reinforcement reaches yielding or the compressive concrete strain exceeds the limit of linear response in the compressive stress-strain envelope, estimated in the range of ($\varepsilon_c = 1.8\cdot f_c^/ /E_c$). From basic cross sectional equilibrium, the normalized depth of compression zone, $\xi_{y,j}^J$, associated with these two alternative definitions of phenomenological yielding is obtained from

(a) Upon yielding of tension steel

$$\xi_{y,j}^J = -\left[(2\eta_c-1)\rho_{e,j}+\frac{v_jf_c^/}{E_c\varepsilon_{sy}}\right]+\left\{\left[(2\eta_c-1)\rho_{e,j}+\frac{v_jf_c^/}{E_c\varepsilon_{sy}}\right]^2+2\left[(1.10\eta_c-0.10)\rho_{e,j}+\frac{v_jf_c^/}{E_c\varepsilon_{sy}}\right]\right\}^{0.5} \tag{14a}$$

where $f_c^/$ is the concrete compressive strength and ε_{sy} is the steel strain at yielding.

(b) At the onset of concrete strain nonlinearity, $\varepsilon_c = 1.8\cdot f_c^/ /E_c$

$$\xi_{y,j}^J = -[(2\eta_c-1)\rho_{e,j}+0.55v_j]+\{[(2\eta_c-1)\rho_{e,j}+0.55v_j]^2+2(1.10\eta_c-0.10)\rho_{e,j}\}^{0.5} \tag{14b}$$

The total floor stiffness $K_{y,st}^J$, that comprises n_c (number of) RC jacketed columns is equal to

$$K^J_{y,st} = \sum_{j=1}^{n_c} K^J_{y,j} \tag{15}$$

In the case of RC jacketing the key design characteristics used for construction of the design charts are, the mean value of the total equivalent longitudinal reinforcement ratio of the jacketed members, $\rho_{ave}{}^J$, the area index of jacketed columns, AI^J, which corresponds to the columns' area ratio in the first storey floor plan, and the mean value of area increase of the retrofitted columns normalized by the area of the existing columns, $R_A{}^J$, estimated in the first floor

$$\rho^J_{ave} = \sum_{j=1}^{n_c} 2\rho_{e,j}/n_c \tag{16a}$$

$$AI^J = \sum_{j=1}^{n_c} (b_{J,j}h_{J,j})/A_{fl} \tag{16b}$$

$$R^J_A = \sum_{j=1}^{n_c} ((A_{J,j}-A_{c,j})/A_{c,j})/n_c = \sum_{j=1}^{n_c} (A_jB_j - 1)/n_c \tag{16c}$$

where n_c is the number of RC jacketed columns, A_{fl} is the floor area, A_J, A_c are the cross sectional areas of the jacketed and the existing column, respectively, and parameters $A(=b_J/b_c)$, $B(=h_J/h_c)$ quantify the increase of width and height of the existing cross section.

4.3 Definition of the design parameters for the alternative retrofit solutions

The RC jacketing design parameters $R_A{}^J$ (mean value of area increase of the retrofitted columns normalized by the area of the existing columns estimated in the first floor), $\rho_{ave}{}^J$ (mean value of the total equivalent longitudinal reinforcement ratio of the jacketed members estimated in the first floor), and the ratio $K_1/K_{o,1}$ (ratio of the total stiffness of the first floor of the retrofitted building normalized to the stiffness of the first floor of the existing building) were used for the construction of three alternative types of design charts. Note that the design parameter AI^J (columns' ratio in the first storey floor plan) may be used as an alternative to $R_A{}^J$.

In this section alternative types of design charts are developed. To this end, various thicknesses for the RC jackets were examined. The values assigned to parameter $R_A{}^J$ which is defined based on Eq. 16(c) are listed in Table 1. Jacket width, b_J, given by the product of coefficient A and the width of the existing cross-section (core), b_c, was assigned a single value, whereas the jacket section height, h_J, was varied through values assigned to parameter B (which accounts for the increase of the height of the existing cross-section, h_c). For example, $R_A{}^J = 93\%$ corresponds to an increase of the cross-sectional height of the existing columns of the first floor by 75% ($B = 1.75$, $h_J = B \cdot h_c = 350$ mm, for columns: C_{A1}, C_{C1}, C_{D1}, according to the nomenclature of Fig. 7(a)) (Table 1). (Note that in the calculations for estimating $R_A{}^J$ as it appears in Table 1, the width of the jacketed cross section was kept constant (see column with A values in Table 1), whereas only the height of the jacketed cross section was varied through parameter B). Also listed is the columns' ratio in the first storey floor

Table 1 Definition of parameters R_A^J and AI^J for the alternative retrofit solutions

Column	Original dimensions		Parameters of RC jacketed columns					
	Width	Height	R_A^J =	69%	93%	117%	141%	165%
	b_c (mm)	h_c (mm)	AI^J =	1.14%	1.28%	1.42%	1.56%	1.70%
			A	B_1	B_2	B_3	B_4	B_5
C_{A1}	400	200	1.25	1.50	1.75	2.00	2.25	2.50
C_{B1}	250	600	1.00	1.00	1.00	1.00	1.00	1.00
C_{C1}	400	200	1.25	1.50	1.75	2.00	2.25	2.50
C_{D1}	300	200	1.33	1.50	1.75	2.00	2.25	2.50

Table 2 Interrelation of parameters R_A^J, AI^J, ρ_{ave}^J, $K_1/K_{o,1}$ and T_{target}

T_{target} (sec)	$K_1/K_{o,1}$	$R_{A\ ,1}^J$=93%	$R_{AJ,2}$=117%	$R_{AJ,3}$=141%
		$AI^J_{,1}$=1.28%	$AI^J_{,2}$=1.42%	$AI^J_{,3}$=1.56%
		$\rho_{ave,1}^J$ (%)	$\rho_{ave,2}^J$ (%)	$\rho_{ave,3}^J$ (%)
0.40	3.30	3.16	2.04	1.42
0.45	2.61	2.17	1.43	1.03
0.50	2.11	1.50	1.02	0.76

plan expressed through parameter AI^J (the floor area is estimated equal to $12.5 \times 4\ \text{m} = 50\ \text{m}^2$. ICONS frame is an internal frame at a 4 m transverse distance between parallel frames).

It was demonstrated earlier that the first floor stiffness K_1 could be related to the target values of the period through the linear target response shape (Eq. (8)). After defining the stiffness demand at the member level (required storey stiffness was distributed to the individual members according to their moment of inertia), $K_{y,j}^J$, Eq. (13) was subsequently used to quantify the required equivalent longitudinal reinforcement ratio, $\rho_{e,j}$, for specific dimensions of the RC jacketed member.

In the case of the ICONS frame, stiffness increase was attributed only to strengthening of columns C_{A1}, C_{C1}, C_{D1} (it is recalled that the strong columns of the first and second storey, C_{B1} and C_{B2}, respectively, were not strengthened in the schemes outlined in Table 1). The interrelation of the design parameters R_A^J, $\rho_{ave,J}$, $K_1/K_{o,1}$ for three values of target period, i.e., $T_{target} = 0.40$, 0.45 and 0.50 sec and the alternative combinations of R_A^J and ρ_{ave}^J, are presented in Table 2. A numerical example is the following: For $T_{target} = 0.40$ sec, utilizing Eq. (8) for a 4-storey frame, yields a required K_1 value of 110197 kN/m ($m = 44.7$ ton, $w_1 = 0.33$ see Fig. 3 or use Eq. (7), $\Sigma i^2 = 30$). Thus, $K_1/K_{o,1} = 110197/33346 = 3.30$. The stiffness at yield that corresponds to each column of the first storey apart from column C_{B1} is $K_{target} = (110197\text{-}29149)/3 = 27016$ kN/m (distributed evenly between columns C_{A1}, C_{C1} and C_{D1}). Eq. (13) was used in deriving the longitudinal reinforcement of the jacket. Average values Eq. (16) appear in Table 1; (in case of increasing the cross-sectional height of the existing columns of the first floor by 75%, i.e. $R_A^J = 93\%$, the value of ρ_{ave}^J which represents the average value of the total equivalent reinforcement according to the simplified model for RC jacketed cross sections according with Eq. (14a), Fig. 4(a), was estimated equal to 3.16%). Depending on the jacket thickness (definition of R_A^J) the longitudinal reinforcement of the jacket is estimated through Eq. (13) accordingly (see Table 1). A detailed derivation for $T_{target} = 0.40$ sec appears in the next paragraph.

4.3.1 Detailed numerical application to ICONS frame for T_{target} = 0.40 sec

It is required to design alternative retrofit scenarios for a target period $T_{target} = 0.40$ sec and a linear response shape, using RC jacketing as the selected intervention method.

- Finding the target stiffness of each storey:

For a four-storey structure and linear response shape, weighting factors are defined according to Eq. (7) as

$$w_1 = \frac{\sum_1^n i}{\sum_1^n i^2} = \frac{(1+2+3+4)}{(1^2+2^2+3^2+4^2)} = 0.333 \tag{17a}$$

$$w_2 = \frac{\sum_2^4 i}{\sum_1^4 i^2} = \frac{(2+3+4)}{(1^2+2^2+3^2+4^2)} = 0.300 \tag{17b}$$

$$w_3 = \frac{\sum_3^4 i}{\sum_1^4 i^2} = \frac{(3+4)}{(1^2+2^2+3^2+4^2)} = 0.233 \tag{17c}$$

$$w_4 = \frac{\sum_4^4 i}{\sum_1^4 i^2} = \frac{4}{(1^2+2^2+3^2+4^2)} = 0.133 \tag{17d}$$

For a target period $T_{target} = 0.40$ sec and storey mass, $m = 44.7$ ton, the required stiffness at the first storey is estimated from Eq. (8)

$$K_1 = \frac{4\pi^2}{(T_{target})^2}\left(m \cdot w_1 \cdot \sum_{i=1}^{n} i^2\right) = \frac{4\pi^2}{0.4^2}(44.7 \cdot 0.333 \cdot (1^2+2^2+3^2+4^2)) = 110197\,\text{kN/m} \tag{18}$$

Using Eq. (6) the reference stiffness value K is

$$K = \frac{K_1}{w_1} = \frac{110197}{0.333} = 330589.8\,\text{kN/m} \tag{19}$$

The stiffness of the 2nd, 3rd and 4th storey are determined from Eq. 5(b) as

$$K_2 = w_2 K = 0.300 \cdot 330589.8 = 99177\ \text{kN/m} \tag{20a}$$

$$K_3 = w_3 K = 0.233 \cdot 330589.8 = 77138 \text{ kN/m} \quad (20a)$$

$$K_4 = w_4 K = 0.133 \cdot 330589.8 = 44079 \text{ kN/m} \quad (20a)$$

The existing stiffness at the first storey is $K_{o,1} = 33346$ kN/m. Thus,

$$K_1/K_{o,1} = 110197/33346 = 3.30 \text{ (see Tables 2 and 4)} \quad (21)$$

- Alternative retrofit solutions – relating lateral stiffness to the characteristics of the intervention method:

With the first floor as a point of reference and assuming that storey-stiffness results only from column contributions (i.e., no infills), the required floor stiffness will be distributed according to the moment of inertia of the vertical members that are to be modified in the floor. According to the retrofit scenario for ICONS frame all the columns of the first storey will be strengthened apart from column C_{B1}, the stiffness level of which is considered disproportionately larger from that of the other members. The stiffness of the existing column C_{B1} is 29149 kN/m. Thus, assuming the same dimensions after the application of the jacket to columns C_{A1}, C_{C1} and C_{D1}, the target stiffness is determined equal to (110197-29149)/3 = 27016 kN/m.

The alternative retrofit solutions for this target value of stiffness are defined in Tables 2 (first row for $T_{target} = 0.40$ sec) and 4 (first row for $T_{target} = 0.40$ sec). As shown, parameters R_A^J or AI^J, which indirectly account for the dimensions of the jacketed members attain values that range as follows: for $R_A^J = 69\%\sim141\%$ and $AI^J = 1.14\%\sim1.56\%$. (It is recalled here that R_A^J corresponds to the mean value of area increase of the retrofitted columns normalized by the area of the existing columns, whereas AI^J gives the columns' ratio in the first storey floor plan). The case where $R_A^J = 117\%$ and $AI^J = 1.42\%$ is selected to be explained in detail herein. The chosen dimensions of the jacket are listed in Table 1. If the height of the existing cross section is doubled for all the columns in need of retrofitting, i.e. from 200 mm it is increased to $B_3 \cdot 200 = 2.00 \cdot 200 = 400$ mm (see Table 1), and the width is increased from 400 mm to 500 mm (A=1.25, Table 1) for columns C_{A1} and C_{C1} and from 300 mm to 400 mm (A = 1.33, Table 1) for column C_{D1}, then according to Eq. 16(c) the value of R_A^J is 117%. For these jacket dimensions and for an effective plan area for ICONS frame equal to 12.5 m × 4 m = 50 m^2, parameter AI^J is 1.42% based on Eq. 16(b).

Having selected the dimensions of the jacketed members ($R_A^J = 117\%$) and having already established the target (i.e., required) stiffness of each member (27016 kN/m), then the equivalent longitudinal reinforcement, $\rho_{tot,j}(=2\rho_{e,j})$, may be determined through Eq. (13). The normalized depth of the compression zone at yield, $\xi_{y,j}^J$, is given as a function of $\rho_{e,j}$, through Eq. (14). Results obtained after application of Eqs. (15) and (16) are presented in Table 3. The longitudinal reinforcement of column C_{B1} remains unaltered as depicted in Fig. 6 (2Ø12 & 8Ø16). Thus, the mean value of the total equivalent longitudinal reinforcement ratio of the jacketed members, ρ_{ave}^J, is

Table 3 Longitudinal reinforcement of the jacketed members, $\rho_{tot,j}(=2\rho_{e,j})$

Column	v_j (%)	$\xi_{y,j}^J$	$\rho_{tot,j}$ (%)
C_{A1}	9.0	0.317	1.9
C_{C1}	12.4	0.328	1.9
C_{D1}	7.0	0.334	2.7

calculated equal to 2.04%.

4.4 Retrofit design charts

The relationship between spectral demand and the design parameters derived above may be described in the form of three alternative types of design charts. These are referred to in the remainder as type I, type II and type III charts. Type I chart is used for the derivation of the RYS and is presented below, whereas the other two charts appear in the Appendix A2.

In this design chart, the same information is presented using R_A^J to control jacket retrofit design (Fig. 9). The target period, T_{target}, corresponds to the abscissa, whereas ρ_{ave}^J is the ordinate. The three curves correspond to different percentages of cross-sectional area increase, R_A^J. Consequently, for a target period value $T_{target} = 0.44$ sec, three alternative solutions for seismic upgrading are obtained (pairs of R_A^J, ρ_{ave}^J values given in the figure by the dashed lines).

4.5 Retrofit Yield Spectra (RYS) and alternative retrofit options

To derive the RYS, the Design Chart – Type I shown in Fig. 9 is superimposed on the acceleration and displacement response spectra, by exploiting the common abscissa of both groups of curves, which is the period, T. Three alternative options may be drawn depending on the definition of demand. Figs. 10(a), (b) and (c) depict RYS where the demand is expressed in terms of spectral acceleration at yielding ($S_{a,y}$), spectral displacement at yielding ($S_{d,y}$) and in terms of the drift at yielding of the first floor, ID_y^{1st}, (according with Eq. (9)), respectively. It is recalled that Eq. (9) has been derived for a linear distribution of lateral displacement (uniform interstorey drift) along the height of the building. Alternative expressions may be extracted for any target response shape.

Consider a retrofit scenario described by the parameter values: R_A^J = 117% and $\rho_{ave}^J = 2\%$ (this retrofit solution corresponds to doubling the section height of the existing columns of the first floor C_{A1}, C_{C1}, C_{D1} by the addition of RC jackets with $h_J = 400$ mm (7th column in Table 1)). The target period of the retrofitted building is equal to $T_{target} \approx 0.40$ sec and is defined graphically by the

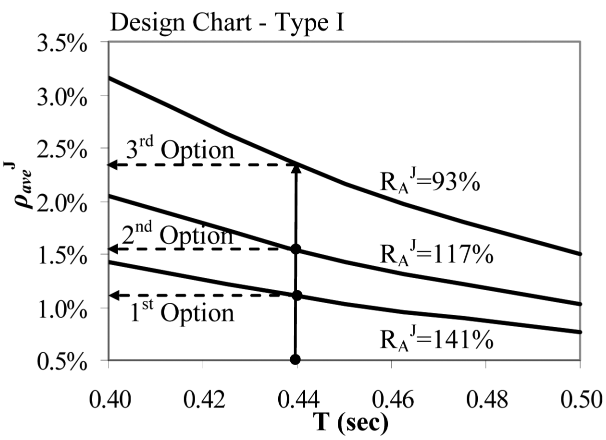

Fig. 9 Design Chart Type I: Plot of parameter ρ_{ave}^J (Eq. 16(a)) over T_{target} for various values of R_A^J (Eq. 16(c)) (T_{target} is related to the stiffness of the first storey, K_1, through Eq. (8) and K_1 is related to parameters ρ_{ave}^J R_A^J through Eqs. (11) and (13))

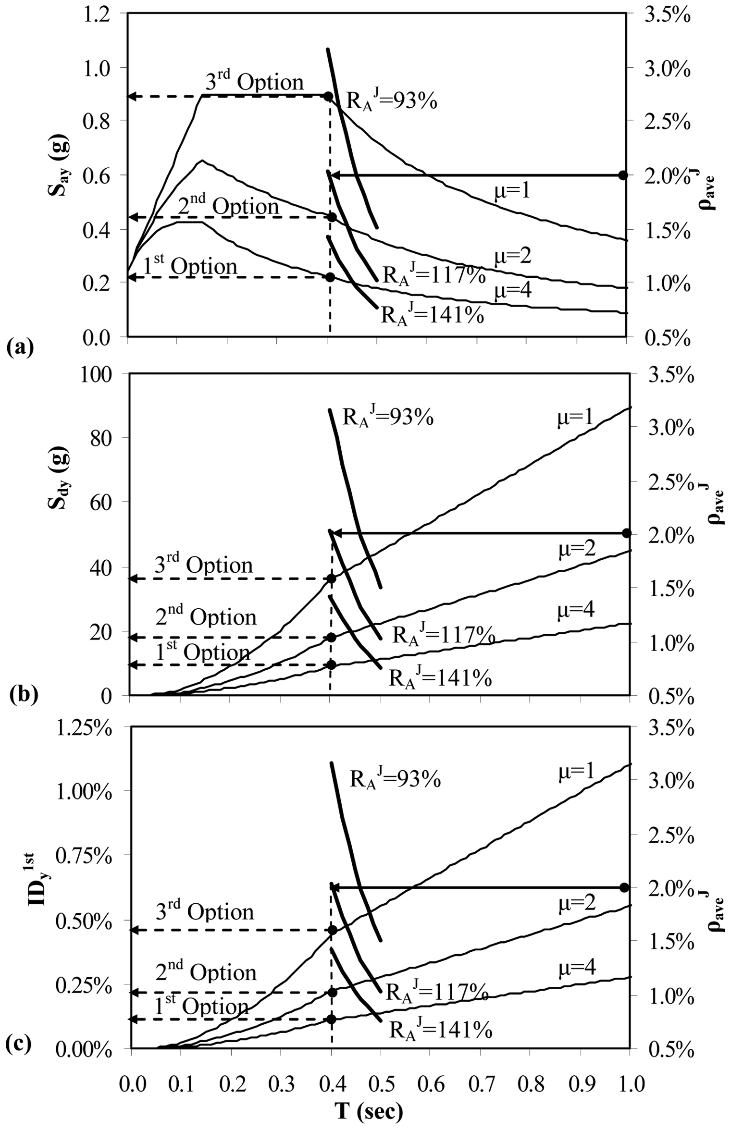

Fig. 10 Retrofit Yield Spectra – use in practical retrofit design. Primary axes: plot of S_{ay}, S_{dy} or ID_y^{1st} (Eq. 9) over period, T. Secondary axes: plot of parameter ρ_{ave}^J over T for various values of parameter R_A^J (T_{target} is related to the stiffness of the first storey, K_1, through Eq. (8) and K_1 is related to parameters $\rho_{ave,}^J$ R_A^J through Eqs. (11) and (13))

vertical dashed line that passes through the intersection point of the solid arrow line with the curve which corresponds to $R_A^J = 117\%$ (Fig. 10(a)). Curves associated with different values of R_A^J were derived based on the assumption that the target periods take values in the range 0.40 sec $<T_{target}<$0.50 sec (Fig. 7(b)). Three alternative scenarios, which depend on the target ductility level, are defined for the target period value, $T_{target} = 0.40$ sec. Here, a displacement ductility level $\mu = 2$ is considered achievable for retrofitted reinforced concrete frame buildings. The demand in terms of spectral acceleration and displacement at yielding is $S_{a,y}$=0.45g (Fig. 10(a)) and $S_{d,y}$=17.9 mm (Fig.

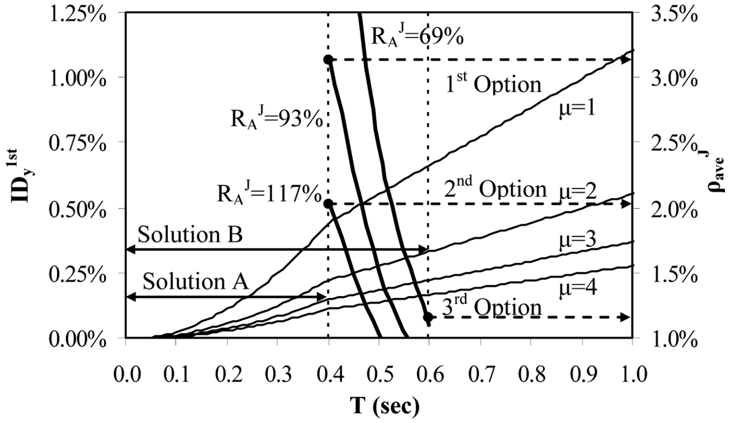

Fig. 11 Retrofit Yield Spectra – emphasis on ID_y^{1st}

Table 4: Relation of parameters R_A^J, ρ_{ave}^J, $K_1/K_{o,1}$ and T_{target}

T_{target} (sec)	$K_1/K_{o,1}$	$R_{A,1}^J$=69%	$R_{A,2}^J$=93%	$R_{A,3}^J$=117%
		$AI_{,1}^J$=1.14 %	$AI_{,2}^J$=1.28%	$AI_{,3}^J$=1.42%
		$\rho_{ave,1}^J$ (%)	$\rho_{ave,2}^J$ (%)	$\rho_{ave,3}^J$ (%)
0.40	3.30	5.36	3.16	2.04
0.50	2.11	2.47	1.50	1.02
0.60	1.47	1.10	0.72	0.54

10(b)), respectively. The latter corresponds to an interstorey drift value in the first floor, of $ID_y^{1st} = 0.22\%$ (Fig. 10(c)). Hence, for a retrofit scenario where, the cross-sectional height of the existing columns is doubled with the addition of the jacket ($R_A^J = 117\%$, Table 1), the mean value of the total equivalent longitudinal reinforcement ratio of the jacketed members in the first floor is $\rho_{ave}^J = 2\%$ and the target displacement ductility level $\mu = 2$, then the retrofitted building is expected to yield at an interstorey drift level $ID_y^{1st} = 0.22\%$ (linear response shape), and will satisfy a strength level at yielding given by: $V_y = (L^2/M_\Psi)S_{a,y} = 657$ kN (for a linear shape $L = 111.6$ ton and $M_\Psi = 83.7$ ton).

The retrofit scenario may be defined in terms of drift at yield of the first storey, ID_y^{1st}, for a target displacement ductility level and a target response shape. In the application presented in Fig. 11, the curves which correspond to various values of parameter R_A^J were constructed so as to correspond to a range of period values 0.40 sec $<T_{target}<$0.60 sec (the upper limit was increased from 0.50 sec to 0.60 sec to allow for greater tolerance in the solution). The relation between parameters R_A^J, ρ_{ave}^J, $K_1/K_{o,1}$ for target period values $T_{target} = 0.40$, 0.50 and 0.60 sec is outlined in Table 4. The procedure followed for deriving the values that appear in Table 4 is the same with that followed in Table 2.

Two alternative retrofit solutions may be studied based on the ductility level and the upper and lower limit for the target period. As depicted in Fig. 11, in case of solution A the target period is set equal to $T_{target} = 0.4$ sec and the ductility level equal to $\mu = 3$. The demand in terms of interstorey drift at yield at the first storey is $ID_y^{1st} = 0.15\%$. Two alternative design options result. The first one (1st Option) corresponds to $R_A^J = 93\%$ (jacket thickness 75 mm) and $\rho_{ave}^J = 3.2\%$, whereas the second (2nd Option) corresponds to $R_A^J = 117\%$ (column sectional height is doubled after the jacket application) and ρ_{ave}^{J} = 2%. Solution B is guided by the upper limit in target period, T_{target} = 0.6 sec, and ductility level equal to μ = 2. Demand is set to ID_y^{1st} = 0.33%, which may be satisfied by the 3rd option, which is considered the most economical one, since the jacket thickness is only 50 mm (R_A^J = 69%) and the equivalent longitudinal reinforcement of the jacketed cross section is ρ_{ave}^{J} = 1.1%.

If demand is required in terms of spectral coordinates, then Eq. (9) may be utilized for determining the spectral displacement at yield, $S_{d,y}$ (Option #1 & #2 $S_{d,y}$=12.0 mm, Option #3 $S_{d,y}$ = 27 mm). The strength level at yielding that should be satisfied by the three retrofit options is: $V_y = (L^2/M_\Psi)S_{a,y}$ = 434 kN, $S_{a,y}$ = 0.30g receives the same value for Solution A (T_{target} = 0.4 sec and μ = 3) and Solution B (T_{target} = 0.6 and μ = 2) (for a linear shape and with the assumption that mass in the retrofitted structure remains unaltered L = 111.6 ton and M_Ψ = 83.7 ton).

5. Conclusions

An efficient tool for assessing alternative retrofit solutions at the preliminary stage in rehabilitation of seismically-deficient reinforced concrete structures was developed in this paper. The Retrofit Yield Spectra (RYS) are obtained from superposition of inelastic design spectra curves that describe alternative retrofit scenarios. Three alternative types of RYS were defined depending on whether demand was expressed in terms of spectral acceleration, spectral displacement or interstory drift at yield of the first storey. Alternative design charts were developed as well, in order to facilitate the design procedure of the retrofit solution. A key element of the proposed method was that the target interstorey drift could be achieved with a weighted distribution of added stiffness along the height of the building.

The conceptual framework of the proposed methodology relies on performance based design concepts, where demand, expressed in terms of lateral interstorey drift guides dimensioning and detailing of the retrofit. Design is performed with reference to the point of yielding and emphasis is placed on the secant to yield stiffness for proportioning the retrofit solution. The method is applicable to buildings without eccentricities that may be dependably considered to respond in a single mode. The system ductility demand targeted for through the choice of the design YPS should not be excessive (i.e., up to 3, at most) due to the fact that the nonlinear behavior of the retrofit is often limited by the existing reinforcement anchorages (unless the anchorages are upgraded). Higher mode effects are not taken into account in defining the retrofit strategy, but should be quantified at the stage of verification of the retrofit design (i.e., after the preliminary retrofit design has been arrived at). Local interventions should also accompany the global measures, in order to preclude connection failure and to ensure post-yield deformation capacity in the horizontal diaphragms, beams and column elements that are not modified through jacketing in the global retrofit scheme.

A four-storey building frame tested at full scale was used as a model problem, for which seismic retrofitting schemes were designed using the proposed methodology. The model structure represents older construction practices, where no seismic design requirements or detailing had been considered. Illustration of the calculation procedures used reinforced concrete jacketing as the means for global intervention. Using the Retrofit Yield Spectra (RYS) enabled a speedy process for proportioning of the required details. Furthermore, it provided immediate visual assessment of the effect of the retrofit design parameters on the response of the building. Development of the RYS tool is amenable to various possibilities for selection of the post-retrofit target response shape, for the type of global intervention used in the retrofit, and for the level of target ductility demand to be sustained by the retrofitted structure in the event of an earthquake.

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Notation

A_{fl} : floor area,
AI^J : area index of jacketed columns,
AI^w : area index of RC walls,
b_c; b_J : width of the existing and jacketed cross section, respectively,
C_j : parameter that represents the *j-th* member contribution to global stiffness,
E_c; E_s : elastic modulus of concrete and steel,
$f_c^{/}$: concrete compressive strength,
f_{ck} : nominal compressive strength of concrete,
f_{sy} : yield strength of steel,
f_{syk} : nominal yield strength of steel,
H : total height of the structure,
h_c; h_J : height of the existing and jacketed cross section, respectively,
h_f : section height of the boundary element of the RC wall,
h_j : column length,
h_{st} : storey height,
h_w : section height of the RC wall,
i : storey number,
I_c : moment of inertia of column,
ID_y^{1st} : drift at yield of the first storey,
K : reference stiffness value,
K_1 : stiffness of the first storey,
K_i : stiffness of the *i-th* floor,
K_j : member stiffness to relative lateral translation of its end nodes,
$K_{o,1}$: stiffness of the first storey of the existing building,
K_s : equivalent rotational stiffness of a rotationally compliant soil,
K_y^J : flexural stiffness of the RC jacketed column,
$K_y^{w,fl}$: flexural stiffness of the RC wall,
K_Ψ : effective (or generalized) stiffness,
L ($=\Sigma m_j \cdot \Psi_j$) : earthquake excitation factor,
m : typical storey mass,
M_Ψ : effective (or generalized) mass,
n : number of storeys,
n_c, n_w : number of RC jacketed columns and RC walls, respectively,
q : behaviour factor,
R_A^J : mean value of area increase of the retrofitted columns normalized by the area of the existing columns,
S : soil parameter,
$S_{a,y}$; $S_{d,y}$: spectral acceleration and displacement at yielding,
S_a; S_d : spectral acceleration and displacement, respectively,
T : period,

T_c : period value corresponding to the end of the constant acceleration range,
T_o : period of the existing building,
T_{target} : target period,
t_w : section width of the RC wall,
V_y : strength level at yielding,
W : total weight of the structure,
w_i : weighting factor of *i-th* floor.

Greek symbols
α_g : peak ground acceleration (pga),
Δ_y : roof displacement at yielding,
$\Delta\psi$: difference in the mode shape coordinates within the column length,
η : spectral correction factor [EC8, Part 1, 2004],
$\eta_c(=E_s/E_c)$: modular ratio of steel and concrete,
μ : displacement ductility,
μ_{target} : target ductility demand,
ν : applied axial load ratio,
$\xi_{y,j}^{J}$: normalized depth of compression zone of the RC jacketed member,
$\xi_{y,j}^{w}$: normalized depth of compression zone of the RC wall,
ρ_{ave}^{J} : total equivalent longitudinal reinforcement ratio of the jacketed members,
ρ_{ave}^{w} : mean value of the total vertical reinforcement ratio of n_w RC walls,
$\rho_c(=A_c/b_ch_c)$: longitudinal tension reinforcement ratio of the existing cross section (equal to compression reinforcement),
ρ_e : equivalent longitudinal tensile reinforcement ratio,
$\rho_{fl,i}$; $\rho_{w,i}$: end and web wall reinforcement,
$\rho_J(=A_J/b_Jh_J)$: longitudinal tension reinforcement ratio of the jacket (equal to compression reinforcement),
ρ_w : web longitudinal reinforcement ratio,
Ψ : shape of lateral vibration,
Ψ_1 : target mode shape coordinate at the first storey.

Appendix

A1. Reinforced concrete walls

Addition of new reinforced concrete walls is one of the most common methods used for strengthening of existing structures. This method is efficient in controlling global lateral drift, thus reducing damage in frame members. During the design process, attention should be paid to the distribution of the walls in plan and elevation (to achieve a regular building configuration), transfer of inertial forces to the walls through floor diaphragms, struts and collectors, integration and connection of the wall into the existing frame buildings and transfer of loads to the foundations. Added walls are typically designed and detailed as in new structures. For this reason they are provided with boundary elements at the base (in the plastic hinge zone), well-confined and detailed for flexural ductility. They are also capacity-designed in shear throughout their height and over-designed in flexure above the plastic hinge region (with respect to the flexural strength in the plastic hinge zone), in order to ensure that inelasticity or pre-emptive failure will not take place elsewhere in the wall before plastic hinging at the base and that the new wall will remain elastic above the plastic hinge zone.

A design consideration related to the addition of RC walls is the extent of the intervention (whether the wall will extend along the height of the building or up to a certain height). In case that the RC wall is placed in the first storey of pilotis frames (e.g. frames that present stiffness discontinuity in the first floor), then it is assumed that the wall is fixed in the upper and lower diaphragm. If the wall extends to the entire height of the building, then it may be assumed that it behaves as a cantilever.

The stiffness of a RC wall extending to the building's height ($n \cdot h_{st}$ where n the number of storeys and h_{st} the typical storey height) is given by the following expression (Fig. A1)

$$K^{w}_{y,i} = \frac{1}{\dfrac{1}{K^{w,fl}_{y,i}} + \dfrac{2.5(n \cdot h_{st})}{E_c t_{w,i} h_{w,i}}} \tag{A1}$$

where the first fraction in the denominator represents the work-equivalent contribution of flexural deformations and the second that of shear deformations. With regards to the first component in (A1), the following expression is extracted for the flexural stiffness of the RC wall, $K_{y,i}{}^{w,fl}$

$$K^{w,fl}_{y,i} = \frac{3E_c I^{w}_{y,j}}{(n \cdot h_{st})^3} = \frac{3M^{w}_{y,j}}{\varphi^{w}_{y,j}(n \cdot h_{st})^3} \tag{A2}$$

The moment at yield, $M_{y,j}{}^{w}$, at the center of gravity of the simplified jacketed cross section is estimated equal to

$$M^{w}_{y,i} = \varphi^{w}_{y,j} t_{w,j} h^{3}_{w,j} E_c (k_I + k_{II}) \tag{A2}$$

$$k^{I} = 0.4(\eta_c - 1)\rho_{fl,i}\left(1 - \frac{h_{f,i}}{h_{w,i}}\right)\left(\xi^{w}_{y,i} - 0.625\frac{h_{f,i}}{h_{w,i}}\right) + 0.24\,\eta_c \rho_{fl,i}(1 - \xi^{w}_{y,j}) + 0.32(\xi^{w}_{y,j})^2(0.5 - 0.27\,\xi^{w}_{y,i}) \tag{A3a}$$

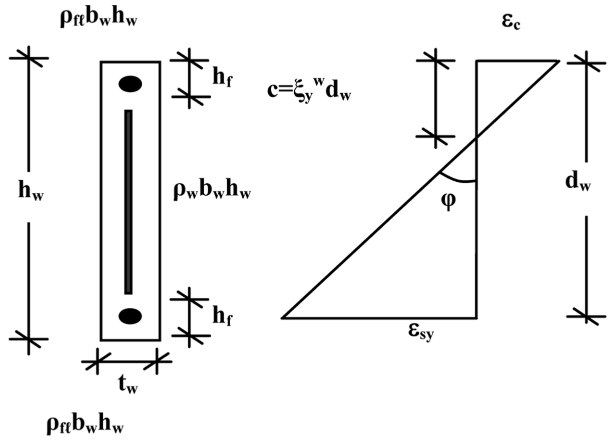

Fig. A1 RC walls

$$k^{II} = 0.67\rho_{w,i}\begin{bmatrix} (\eta_c - 1)\left(0.8\xi^w_{y,j} - \dfrac{h_{f,i}}{h_{w,i}}\right)^2\left(0.5 - 0.27\xi^w_{y,j} - 0.67\dfrac{h_{f,i}}{h_{w,i}}\right) \\ + \eta_c\left(1 - \dfrac{h_{f,i}}{h_{w,i}} - 0.8\xi^w_{y,j}\right)^2\left(0.17 + 0.22\xi^w_{y,j} - 0.67\dfrac{h_{f,i}}{h_{w,i}}\right) \end{bmatrix} \tag{A3b}$$

Hence, the the flexural stiffness of the *j-th* RC wall is

$$K^{w,fl}_{y,i} = \frac{3t_{w,i}h^3_{w,i}E_c}{(n \cdot h_{st})^3}(k^I + k^{II}) \tag{A4}$$

where t_w and h_w are the section width and height of the RC wall, respectively, h_f is the section height of the boundary element of the RC wall, $\xi_{y,j}{}^w$ is the normalized depth of compression zone of the RC wall and $\rho_{fl,I}$, $\rho_{w,I}$ are the end and web wall reinforcement.

The normalized depth of compression zone, $\xi_{y,j}{}^w$, upon yielding of tension steel is derived from basic cross sectional equilibrium

$$\xi^w_{y,i} = \frac{-b + (b^2 - 4\alpha\gamma)}{2\alpha} \tag{A5a}$$

where

$$\alpha = 0.4 - 0.54\rho_w \tag{A5b}$$

$$b = (2\eta_c - 1)\rho_f + \frac{vf_c^{/}}{E_c\varepsilon_{sy}} + 1.33\rho_w\left[\frac{h_f}{h_w}(1 - 2\eta_c) + \eta_c\right] \tag{A5c}$$

$$\gamma = \rho_f\left[0.625(\eta_c - 1)\frac{h_f}{h_w} + \eta_c\right] + \frac{vf_c^{/}}{E_c\varepsilon_{sy}} + 0.83\rho_w\left[\frac{h_f}{h_w}\left(-2\eta_c + \frac{h_f}{h_w}\right) + \eta_c\right] \tag{A5d}$$

The total stiffness of a storey that comprises n_w (number of) walls in the direction of seismic action is equal to

$$K_{y,st}^{w,fl} = \sum_{i=1}^{n_w} K_{y,i}^{w,fl} \tag{A6}$$

Another scenario could require the addition of the RC wall only in the first storey due to stiffness discontinuity (e.g. pilotis frames). In this case the RC wall is considered fixed in the upper and lower diaphragm and thus Eq. A4 would be multiplied by 4 to account for the increased restraint whereas n should be taken equal to 1.

Two meaningful and representative indices of the key design characteristics of RC walls may be derived and utilized for the construction of design charts. Hence, the mean value of the total vertical reinforcement ratio of n_w RC walls, ρ_{ave}^w, and the area index of walls, AI^w, which corresponds to walls' ratio in the floor plan, estimated in the first storey are defined by

$$\rho_{ave}^w = \sum_{i=1}^{n_w} (2\rho_{fl,i} + \rho_{w,i})/n_w \tag{A7a}$$

$$AI^w = \sum_{i=1}^{n_w} (t_{w,i} h_{w,i})/A_{fl} \tag{A7b}$$

With reference to the procedure detailed in the preceding, design charts may be constructed similar to those applicable for the RC jacketing technique (see Figs. 9, A2, A3). The period, T, or the stiffness of the first storey, K_1, (both terms related according to Eq. (8) in case of the triangular response profile) may be plotted against the mean value of the total vertical reinforcement ratio, ρ_{ave}^w, for various cases of area indices of walls, AI^w. Parameters ρ_{ave}^w and AI^w are related through Eqs. (A1) - (A5) to the stiffness of the first storey.

A2. Alternative design charts

Design Chart of Type II: Fig. A2 plots a Design Chart of Type II and the three alternative modes of its use, which depend on the objective of the retrofit scenario. This type of chart relates parameters, R_A^J, ρ_{ave}^J, $K_1/K_{o,1}$ with the period of the building, T, with the aid of a secondary axis representation (Fig. A2). The grey curve relates ratio $K_1/K_{o,1}$ with the period T of the building, whereas the group of black curves, which correspond to different values of parameter R_A^J (93%, 117%, 141%), relate ratio $K_1/K_{o,1}$ with the total equivalent longitudinal reinforcement ratio of the jacketed members, ρ_{ave}^J (0.76%~3.16%). The horizontal dashed line serves as a cut-off limit for ratios of longitudinal reinforcement lower than 1%.

As an example of the use of this design chart, consider the following scenario: if it is aimed through retrofit to increase the first floor stiffness by 2.5 fold over its initial value, ($K_1 = 2.5K_{o,1}$), then the following three alternative retrofit options are available, quantified by pairs of values for the relevant design parameters, R_A^J and ρ_{ave}^J, as illustrated in Fig. A2(a) (solid black arrow lines). These are, (1) $R_A^J = 141\%$, $\rho_{ave}^J \approx 1.0\%$, (2) $R_A^J = 117\%$, $\rho_{ave}^J = 1.3\%$ and (3) $R_A^J = 93\%$, $\rho_{ave}^J = 2.0\%$. The target period for all these alternatives is, $T_{target} = 0.46$ sec, which lies between the lower and upper bounds selected for this variable (0.40 sec $< T_{target} <$ 0.50 sec). For instance, if option #2 is adopted, the section height of the existing columns need be doubled through the application of RC

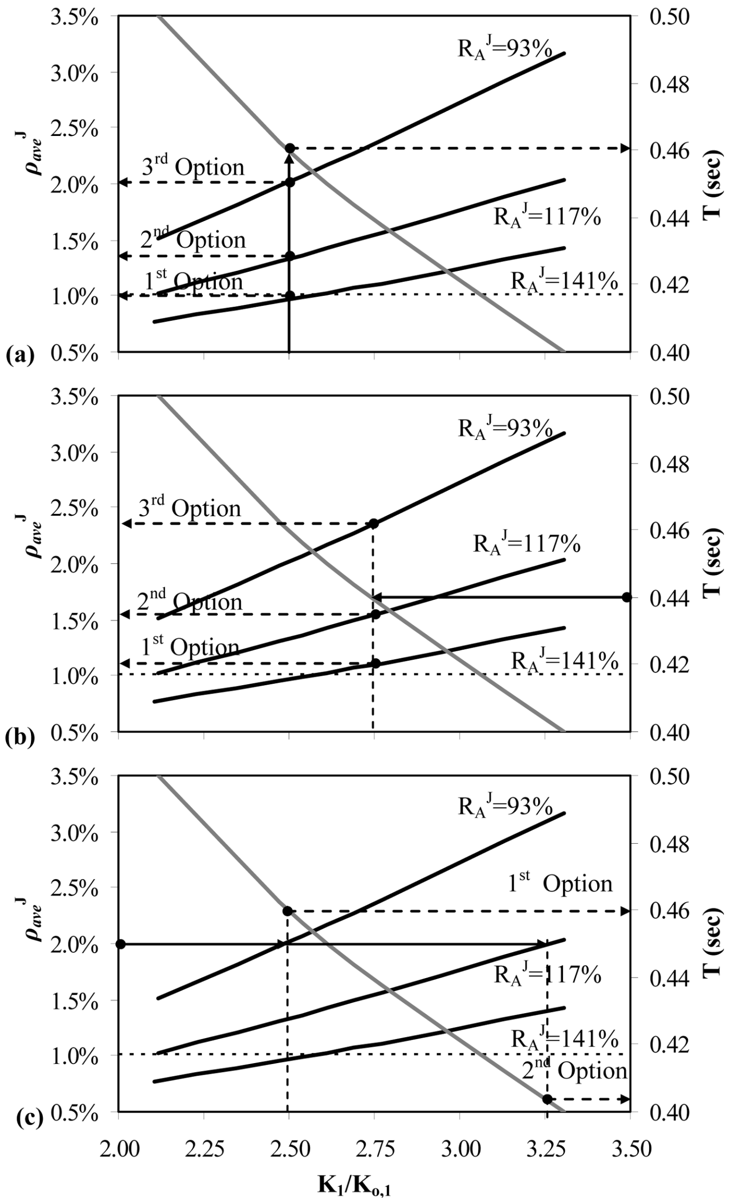

Fig. A2 Design Chart – Type II: (a), (b), (c) Three alternative ways of use. Primary axes: plot of parameter ρ_{ave}^{J} (Eq. 16(a)) over stiffness ratio of the retrofitted over the existing building $K_1/K_{o,1}$ (K_1 is a function of the dimensions of the jacket defined by parameter R_A^J and the jacket tension longitudinal reinforcement ρ_e, Eq. (13)). Secondary axis: plot of period T over stiffness ratio of the retrofitted over the existing building $K_1/K_{o,1}$ (period is related to the first storey stiffness of the retrofitted building through Eq. (9))

jacketing (R_A^J = 117%, Table 1) reinforced by 1.3% longitudinal reinforcement (Table 2), in order to increase the stiffness of the first floor by 2.5-fold thereby decreasing the period to T_{target} = 0.46 sec.

An alternative use of the design chart could begin with specification of the exact value of the target period: For example, by assuming T_{target} = 0.44 sec, the stiffness demand of the first floor is

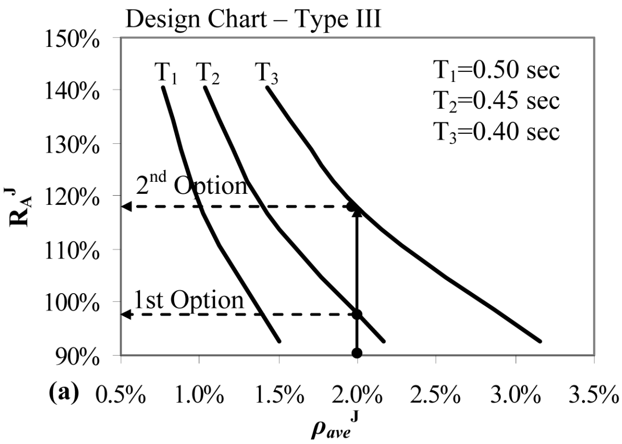

Fig. A3 Design Charts Type III: Plot of parameter ρ_{ave}^J (Eq. 16(a)) over parameter R_A^J (Eq. 16(c)) for various target periods, T_{target}

solved from Eq. (8) as, $K_1 = 2.75K_{o,1}$ (graphically this is the intersection point of the solid black arrow line and the grey curve). The required stiffness increase can be achieved by the following alternative options for the characteristics of the RC jackets (solid black arrow lines): (1) $R_A^J = 141\%$, $\rho_{ave}^J = 1.1\%$, (2) $R_A^J = 117\%$, $\rho_{ave}^J = 1.6\%$ and (3) $R_A^J = 93\%$, $\rho_{ave}^J = 2.4\%$.

The Design Charts can also be used with the amount of jacket reinforcement being the controlling variable as illustrated in the example of Fig. A2(c). Given $\rho_{ave}^J = 2.0\%$ (solid arrow lines) two alternative retrofit scenarios are defined (dashed arrow lines): The first one corresponds to an increase by 1.75 times of the section height of the existing columns C_{A1}, C_{C1} and C_{D1} through jacketing ($h_J = 350$ mm, $R_A^J = 93\%$, Table 1), which corresponds to a 2.5 times increase of stiffness of the first floor and a commensurate decrease of the target period to $T_{target} = 0.46$ sec. The second retrofit scenario, for $\rho_{ave}^J = 2.0\%$ corresponds to a 100% increase of the cross-sectional height of the existing columns C_{A1}, C_{C1} and C_{D1} ($h_J = 400$ mm, $R_A^J = 117\%$, Table (1) and a 3.26 increase of the first floor stiffness for $T_{target} \approx 0.40$ sec.

Design Chart of Type III: In this case (Fig. A3), each curve represents a target period value T_{target}, which corresponds to a combination for the parameters R_A^J and ρ_{ave}^J. By setting the longitudinal reinforcement ratio, ρ_{ave}^J equal to 2%, then, depending on the target period of the retrofit solution, two alternative solutions for the jacketing option result, as follows: (1) $T_2 = 0.45$ sec, $R_A^J = 98\%$ and (2) $T_3 = 0.40$ sec, $R_A^J = 118\%$.