13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1519

SEISMIC VULNERABILITY OF R/C FRAMES WITH STRENGTH IRREGULARITY IN ELEVATION

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SUMMARY

A research study on the seismic behaviour of r/c frames with strength irregularities in elevation is presented; in particular, the results of non linear static analyses on r/c "regular" frames are compared to the ones obtained in the case of "irregular" frames. The irregularity is obtained assigning overstrengths either to the beams or to the columns of the "regular" frames (assumed as references). The static analyses are pushed to the "target displacement", evaluated by the N2 method, introduced by the last EC8 draft and by the new Italian code. The comparison is carried out in terms of interstorey drifts, maximum rotations at the element ends and relating the demand to the capacity in terms of plastic rotations. The results show that the frames characterised by the overstrength assigned to the beams have an irregular behaviour. Finally, an evaluation of the irregularity in elevation criteria proposed by some recent codes is carried out; the analysis allows to conclude that such criteria are not reliable.

INTRODUCTION

During the recent seismic events, the r/c buildings which were characterised by vertical irregularity showed a large vulnerability, with strong damage localised at some stories. Recent studies evidenced that among the mass, stiffness and strength vertical irregularities, the last ones are the worst in terms of negative influence on the non linear seismic response of frame structures (Valmundsson [1], Al-Ali [2], Magliulo [3-4]). At the same time it can be observed that current provisions of the most recent international codes provide criteria for the definition of the vertical irregularity which are often qualitative, generally discordant and surely questionable. This is, probably, due both to the complexity of the problem and to the current lack of studies on the topic.

Such topic is presented and discussed in this paper, which shows the results of non linear static analyses performed on plane r/c frames. In particular two frames are considered – one of them characterised by 5, the other by 9 storeys – which present uniform and, consequently, regular mass, stiffness and strength distribution. Both the frames are designed according to the Eurocode provisions, using a design spectrum for soil type B and a PGA equal to 0.4g. Furthermore, the design is made considering a low ductility class

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and using a behaviour factor (q) equal to 2.5. The material characteristic values used for the design are: concrete cylindrical strength equal to 20 MPa; steel yielding strength equal to 380 MPa.

The geometry of the regular frames is shown in Fig. 1. The designed beam and column sections purposely present the reinforcement exactly needed to satisfy the computed internal forces, in order to avoid the introduction of overstrength. Such frames are considered as regular because of the optimal mass, stiffness and strength vertical distribution.

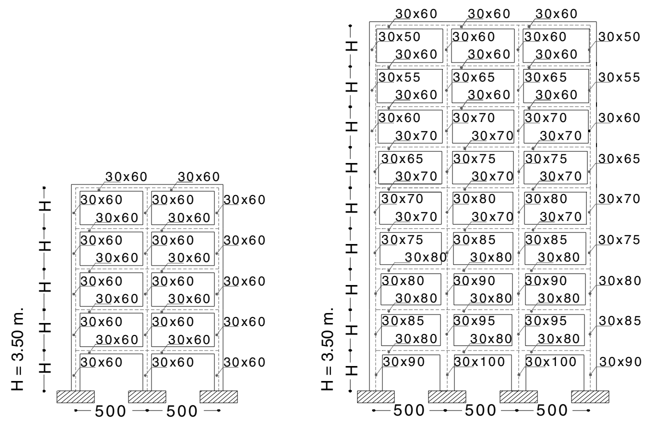

Fig. 1. Geometry of the reference frames.

Other frames are "generated" by the regular ones - considered as reference – by introducing overstrengths either in the beams (frames called "Sb") or in the columns (frames "Sc"). In the modified frames - denominated "theoretical cases" - the overstrengths are introduced modifying the moment-rotation relationship assigned to some elements multiplying by a coefficient larger than 1 the yielding bending moment. To this purpose three values of the increment coefficient are assumed: 1.2, 1.4 and 2.0 for the beams; 1.2, 1.4 and 3.0 for the columns.

In the everyday designs and applications, in order to simplify the calculations, the graphs and the execution, the reinforcement is often keep constant for some columns and beams at some storeys. This causes the presence of a random distribution of the overstrength, which can lead to an irregular behaviour. To take into account this possibility, other variants of the reference frames - called "practical cases" - are considered herein:

- ✓ the "Sc" cases which, for some floors, have a constant reinforcement in the columns on the same vertical line equal to the maximum among the design ones of such columns;
- ✓ the "Sb" variants which, for some floors, have the same reinforcement in the beams; such reinforcement is, for each side of each section, the maximum among the corresponding design reinforcement of the beams at the those floors;
- ✓ the "Sbc" cases, where overstrengths are assigned both to the beams and to the columns as in "Sb" and "Sc" respectively.

In all of the abovementioned variants at least the minimum reinforcement requested by the non seismic Italian code is considered: i.e. for beams $A_s/A_c = 0.15\%$, where A_s is the reinforcement area on the tension side of the section and A_c is the concrete cross section area; for columns $A_s/A_c = 0.3\%$, where A_s is the total reinforcement of the section. Furthermore, on the compression side of the beam sections a steel area A_s, equal to the 50% of the reinforcement placed on the tensile side, is considered, while for each column the reinforcement at the bottom section is equal to the reinforcement at the top one.
In the following all the "supposed irregular" frames (both "theoretical" and "practical" variants) will be

indicated with a label which illustrates where the introduced overstrength is localised: for example, the 5 storeys "theoretical" case with overstrengths in all the beams belonging to the storeys from the second to the fifth will have the label "Sb(2-5)"; for the "practical cases" the label "Sb(3-2)" means that the beams at the first 3 storeys have the same reinforcement which is, for each side of the end sections, the maximum among the corresponding design reinforcement of the same beams; also the beams at the 2 upper storeys have the same reinforcement computed as explained (see the example shows in Fig. 2).

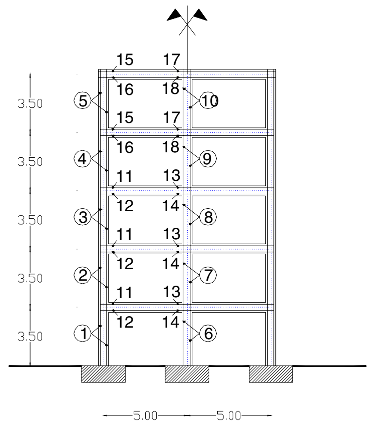

Fig. 2. "Practical" case Sb(3-2).

The comparison between each reference frame and the relative variants is performed on the basis of the non linear static analysis results, by evaluating: the interstorey drifts; the storey maximum rotations, for both the ends of each beam and each column; the ratios between the demand and the capacity in terms of plastic rotations. The available plastic rotations are estimated as according to the Italian code [5]:

$$\theta_{u,pl} = \left(\phi_u - \phi_y\right) \cdot L_{pl} \cdot \left(1 - \frac{0.5 \cdot L_{pl}}{L_V}\right) \tag{1}$$

where ϕ_u is the ultimate curvature, the ϕ_y the yielding curvature, L_{pl} (=0.08 L_v) the length of the plastic hinge without taking into account the slip of the longitudinal bars at the end section, L_v (=M/V with M bending moment, V shear) the shear span.

Finally, the results of the non linear analyses are also used in order to evaluate the reliability of the vertical regularity criteria proposed by some recent international codes (IBC [6], SEAOC [7], ATC40 [8], NEHRP [9], NBC [10]), by the Eurocode 8 [11] and by the already cited seismic Italian code [5].

SEISMIC BEHAVIOUR OF THE PRESUMED IRREGULAR FRAMES

As already said, the seismic response of the previously described frames is evaluated by "push over" analyses pushed till a "target" displacement value, which is evaluated applying the N2 method [12]. The non linear analyses are performed by the computer program CANNY99, using for beams and columns an element with lumped plasticity at the ends, where a trilinear moment-rotation relationship is assigned. For each element this relationship is computed by the moment-curvature one, considering an anti-symmetrical bending moment diagram characterised by a zero value at the element middle point. Since the model does not take into account the axial force variation, the moment-curvature relationship for the columns is obtained for the axial force value given by the vertical loads considered in the seismic combination (vertical loads = G+0.3Q, with G dead loads, Q live loads). In order to avoid additional overstrength the effect of the concrete confinement is neglected.

“Theoretical Frames”: non linear analyses results

In the following the results of the non linear static analyses concerning the two considered regular frames, the 5 storey presumed irregular frames “Sb(2-5)”, “Sc(2-5)”, “Sb(1-2,4-5)” and “Sc(1-2,4-5)” and the 9 storey ones “Sb(2-9)”, “Sc(2-9)”, “Sb(1-4,6-9)” e “Sc(1-4,6-9)” are presented. As already said, for each irregular case three different values of the overstrength are considered.

In the Figs. 3 and 4, for the 5 and 9 storey frames respectively, the base shear (V_b) vs the adimensionalised top displacement (Δ/H) curves are presented. As already observed in other papers [4, 13], the “push over” curves concerning the frames with overstrength assigned to the columns (“Sc” cases) do not present significant variations with respect to those of the reference regular frames.

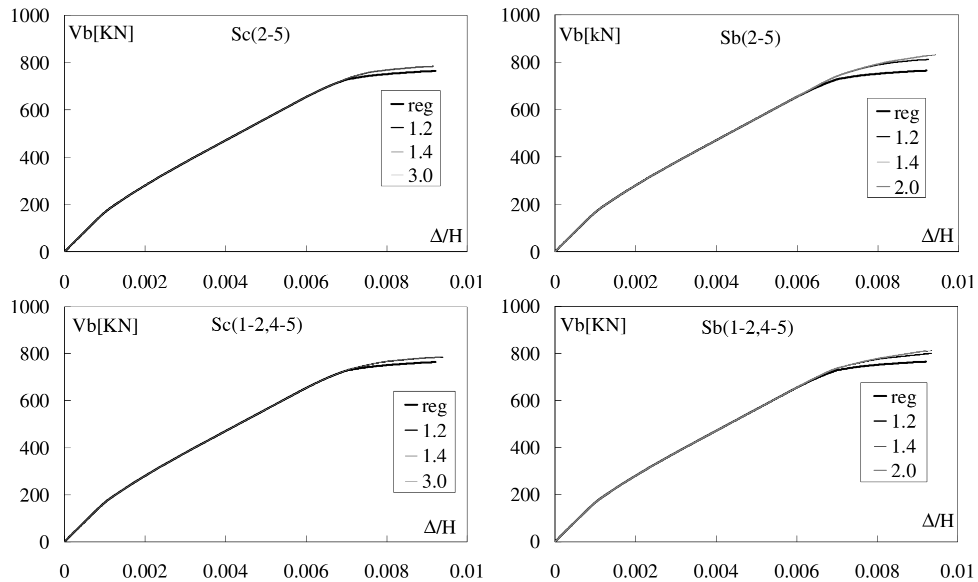

Fig. 3. 5 storey frames: “Push over” made till the “target displacement”

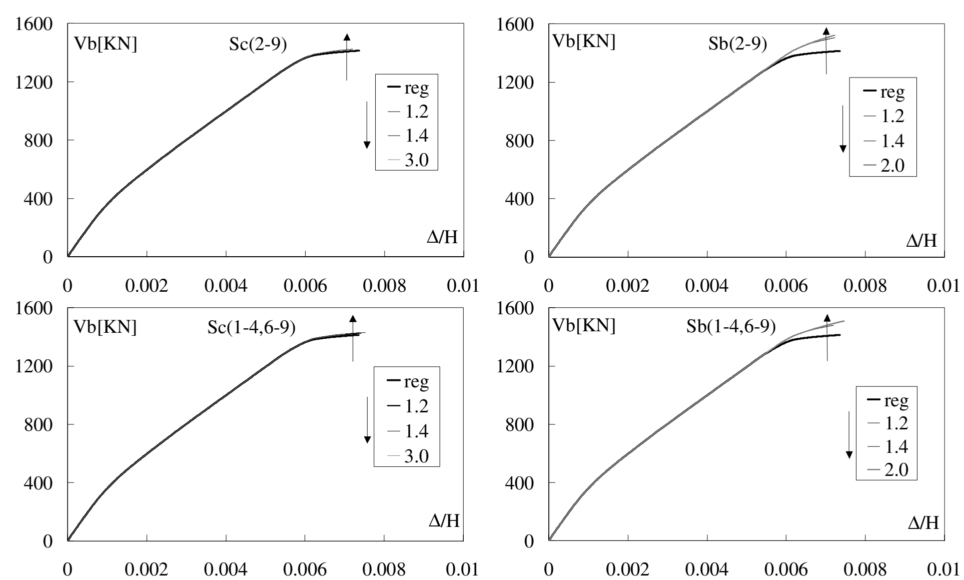

Fig. 4. 9 storey frames: “Push over” made till the “target displacement”

Indeed, the reference frames show an ideal “weak beam-strong column” behaviour which is not significantly modified by the introduction of the overstrength in the columns; on the contrary, the “Sb” cases present a global strength (the base shear) larger than those obtained for the regular structures and depending on the overstrength entity. Actually, as it will be better shown in the following, the overstrength in the beams causes a relevant modification of the structural behaviour, with more plastic hinges in the columns than in the beams. It has to be underlined that, having introduced the overstrengths simply by multiplying by a coefficient larger than 1 the yielding bending moments, before yielding, the supposed irregular frames do not present variations in the vertical stiffness distribution with respect to the reference frames; this is confirmed by the trend of the pushover curves shown in Figs. 3 and 4.

In the Figs. 5 and 6 at each floor the “interstorey drifts” concerning all the examined cases are presented.

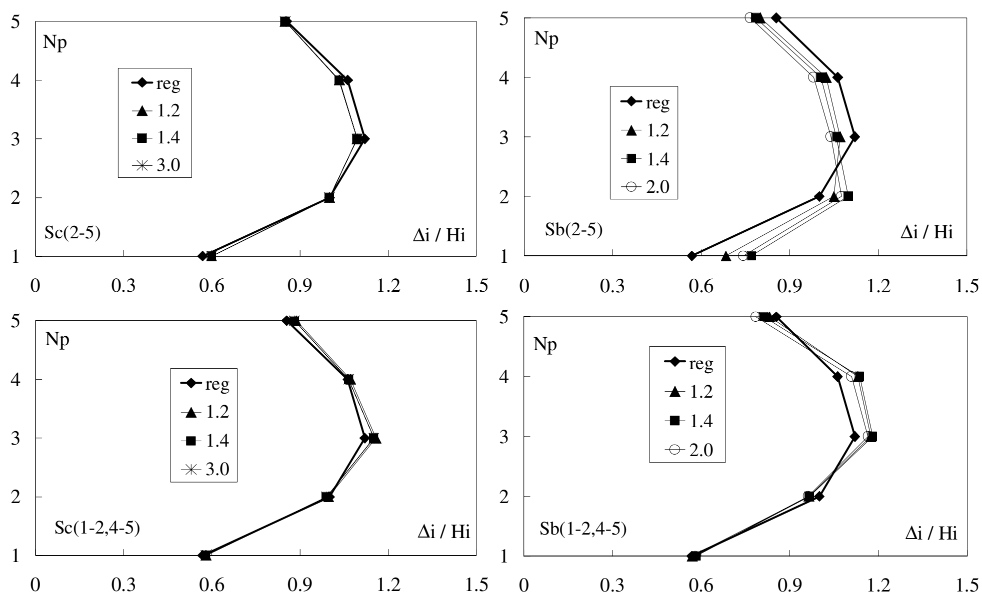

Fig. 5. 5 storey frames: adimensionalised interstorey drifts (Np is the number of the floor)

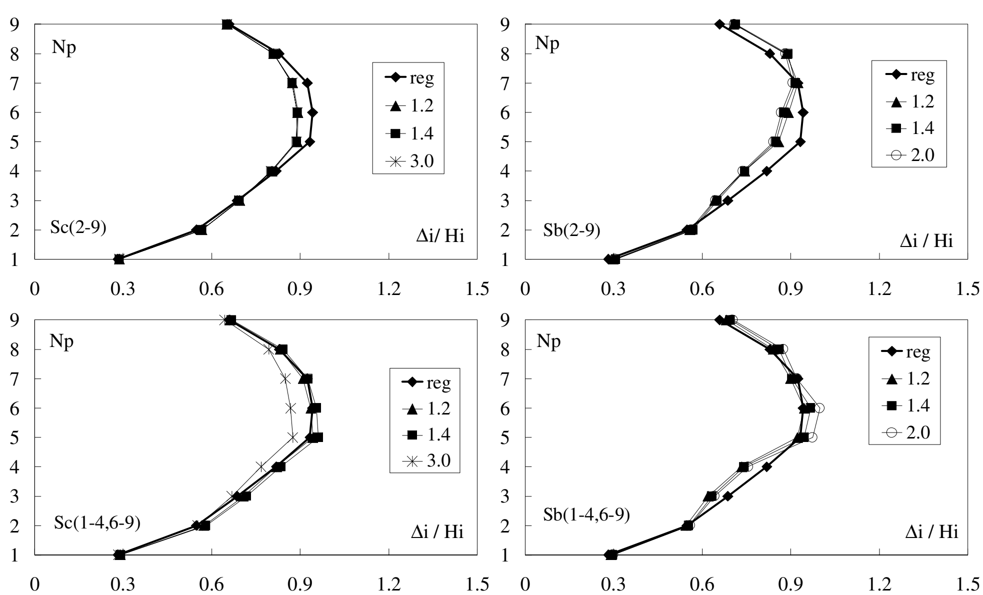

Fig. 6. 9 storey frames: adimensionalised interstorey drifts (Np is the number of the floor)

The response of the frames with overstrength is always compared to the one concerning the "regular" frame. It is observed that the presence of overstrengths does not significantly condition the interstorey drifts; larger increments of such drifts with respect to the reference cases are obtained for "Sb" frames.

The Figs. 7 and 8 show, for the beams and the columns ends, the ratios between the storey maximum rotations (Θ^{I}_{max}) of the "irregular" frames (i.e. at each storey the maximum rotation among all the ones obtained at the beam and column ends) and the storey maximum rotations (Θ^{R}_{max}) of the "regular" frame. Such ratios allow to evaluate the local variations of the demand in terms of rotations of the supposed irregular frames with respect to the reference frame.

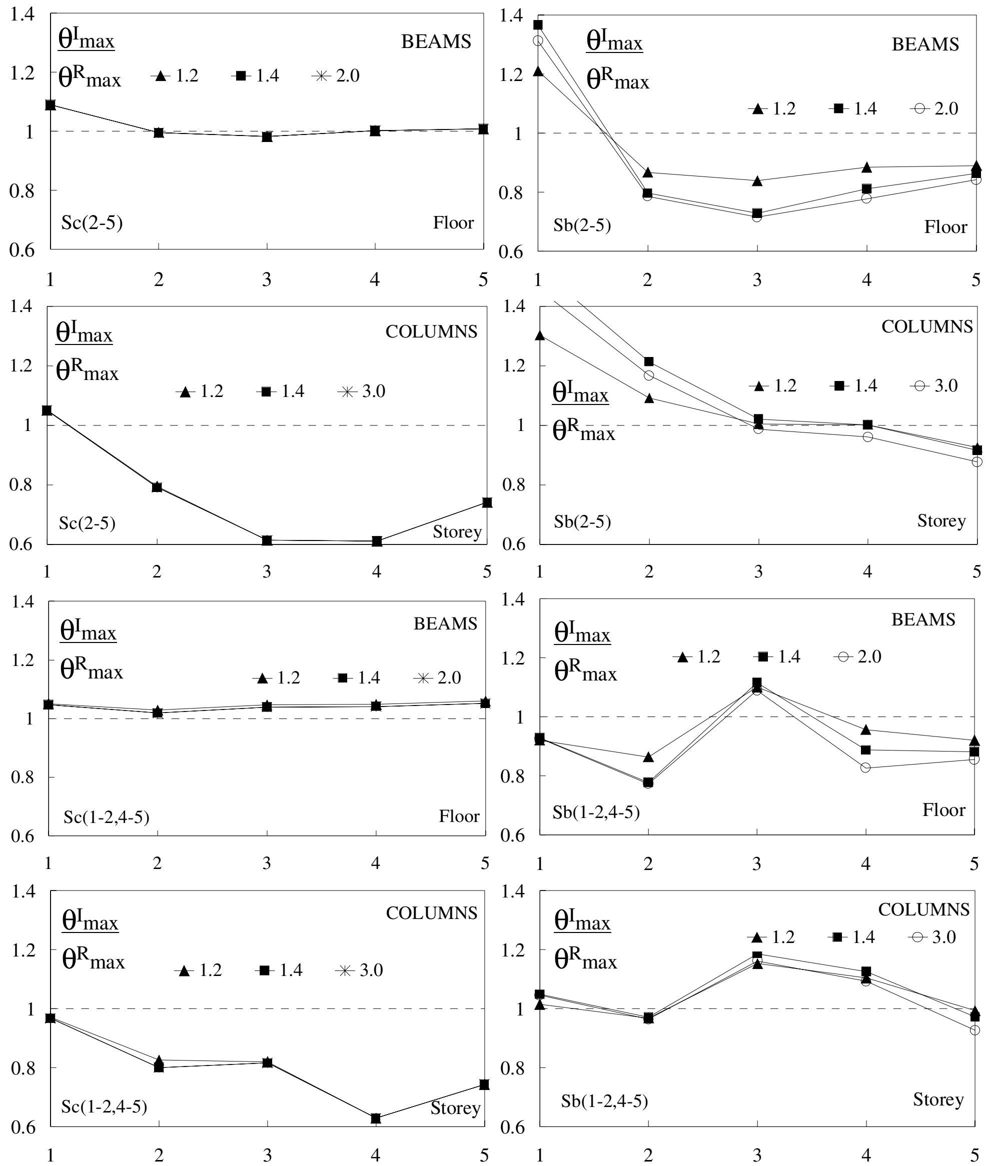

Fig. 7. Maximum rotations at the ends of beams and columns ratios for the 5 storey frames

It can be noted that in the case of "Sc" frames, in particular at those floors where the overstrength is introduced, even large reductions of the maximum rotations of the columns are evidenced; on the contrary, whatever the number of the storeys is and, above all, whatever the entity of the overstrength is, such presumed irregular frames do not show significant increments of the maximum rotations with respect to the reference frame. Consequently, such results show a satisfactory behaviour of the "Sc" frames, which do not present negative characteristics of the response. Instead, in the case of "Sb" frames, increments of the rotations with respect to the regular frames are observed. Such increments are more evident in the columns, but they are also not negligible for the beams at the floor without overstrength. This put in evidence a less regular behaviour of such variants with respect to the two reference frames.

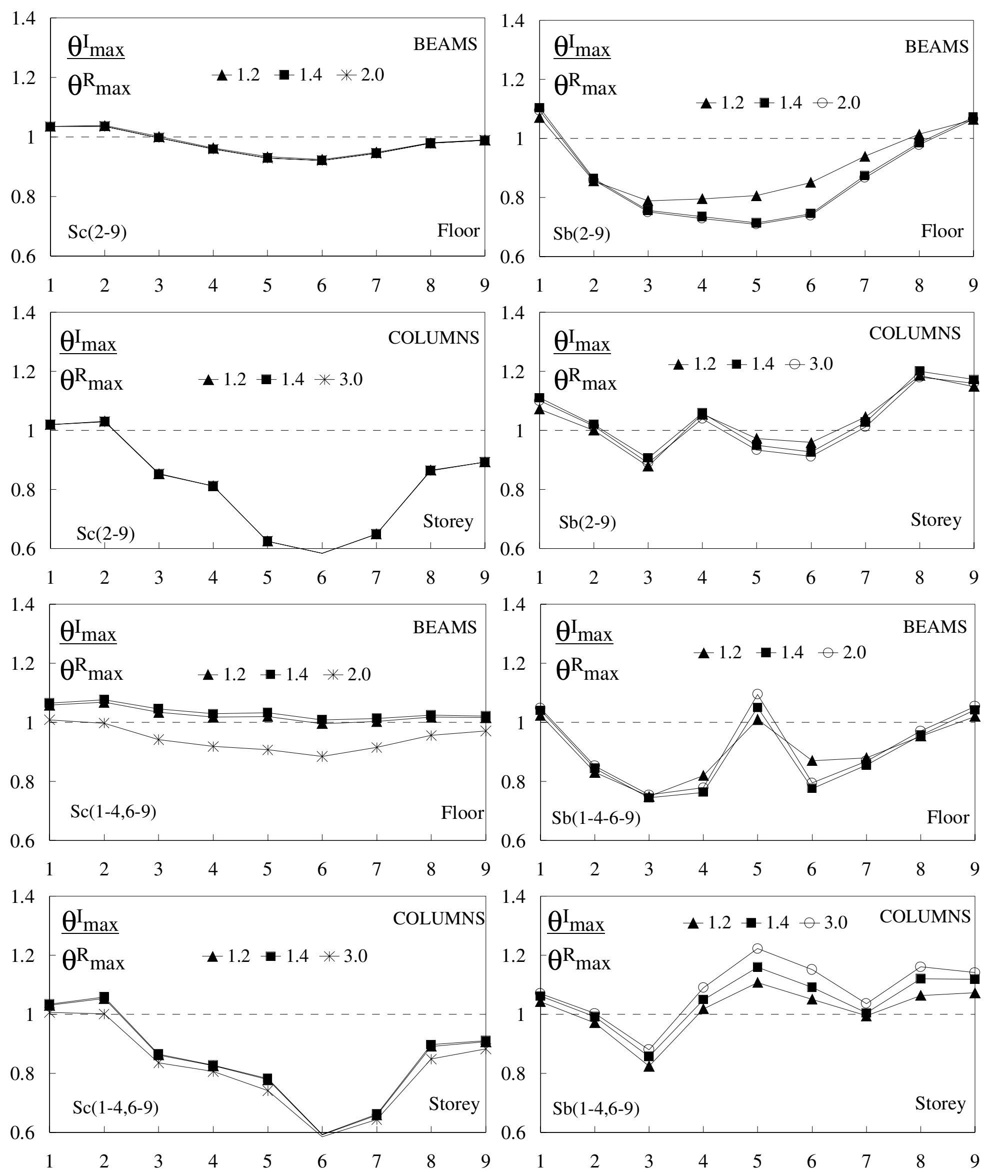

Fig. 8. Maximum rotations at the ends of beams and columns ratios for the 9 storey frames

In order to study more in detail the behaviour of the examined frames, the maximum values of the demanded plastic rotations are evaluated for all the beams and columns ends, having pushed the non linear static analysis of each frame at the "target" point. Subsequently the demanded rotations are compared to the available ones, these ones estimated according to the "Ordinanza n.3274" [5], that is by the Equation (1). It is to be underlined that, having introduced the overstrength by modifying the moment-rotation relationship, the available plastic rotations of the "Sb" and "Sc" frames are considered to be equal to those evaluated for the relative regular frames. It is considered, indeed, that this approach is conservative, because in the real cases overstrengths with entity equal to the ones considered in this paper are generally due to an increment of the geometrical percentages of the longitudinal reinforcement and reductions of the available plastic rotations are often associated to this increment.

In the Figs. 9 to 12, for the 5 storey frames, and 13 to 16, for the 9 storey frames, the ratios between the demanded and the available plastic rotations are shown for all the examined cases.

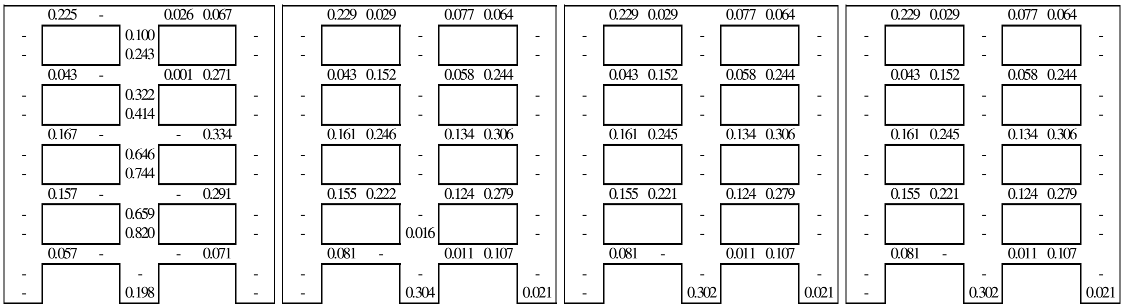

Fig. 9. Demand – capacity ratio in terms of plastic rotations – 5 storey frames: Regular (the first on the left) vs Sc(2-5) [from the left to the right cases 1.2, 1.4 and 3.0 respectively]

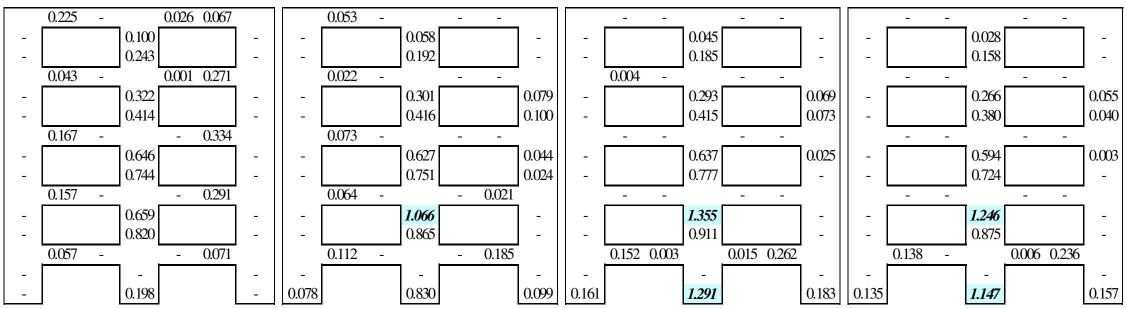

Fig. 10. Demand – capacity ratio in terms of plastic rotations – 5 storey frames: Regular vs Sb(2-5) [from the left to the right cases 1.2, 1.4 and 2.0 respectively]

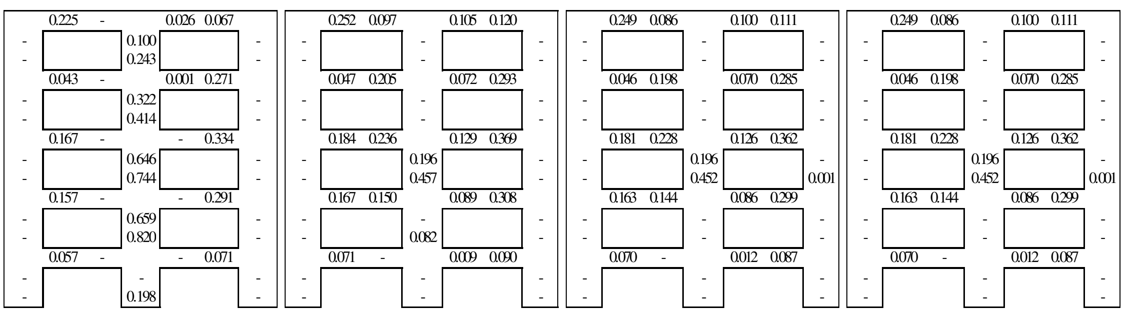

Fig. 11. Demand – capacity ratio in terms of plastic rotations – 5 storey frames: Regular vs Sc(1-2, 4-5) [from the left to the right cases 1.2, 1.4 and 3.0 respectively]

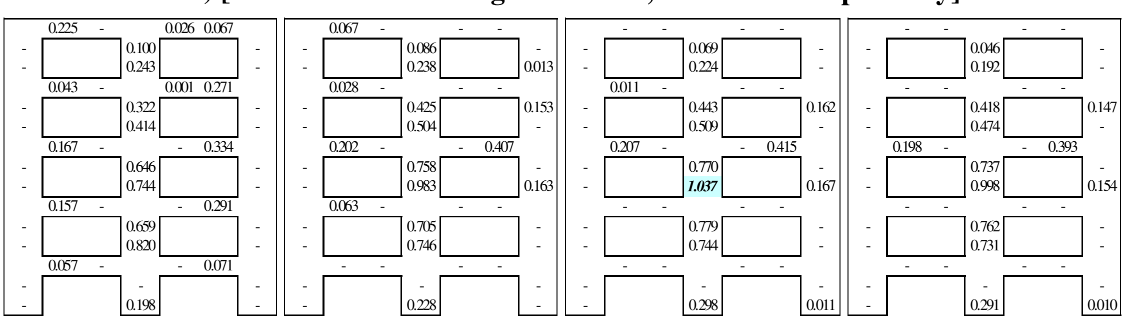

Fig. 12. Demand – capacity ratio in terms of plastic rotations – 5 storey frames: Regular vs Sb(1-2, 4-5) [from the left to the right cases 1.2, 1.4 and 2.0 respectively]

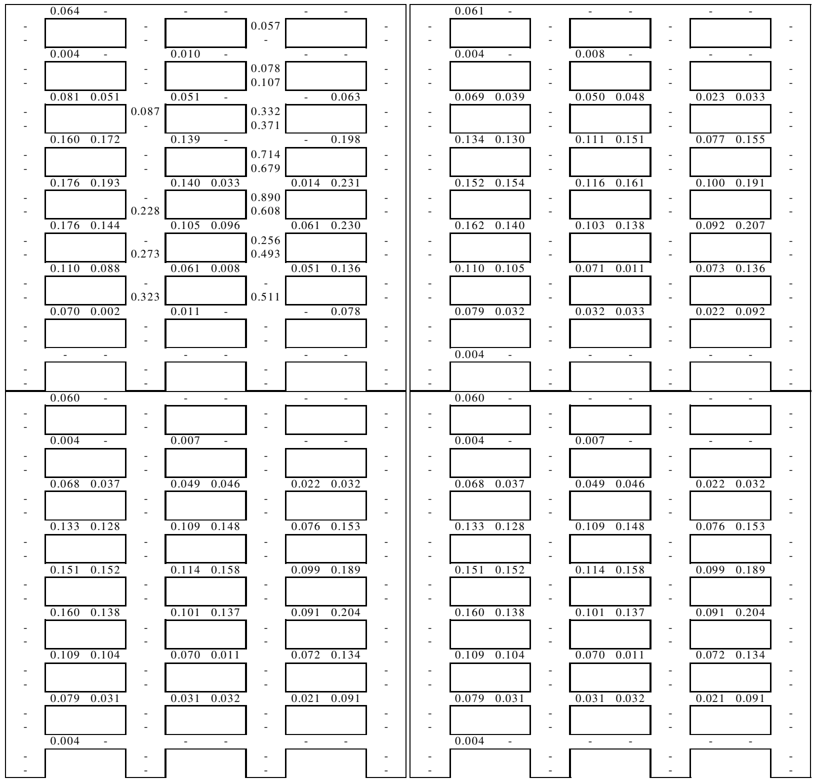

Fig. 13. Demand – capacity ratio in terms of plastic rotations – 9 storey frames: Regular vs Sc(2-9) [cases 1.2 (up-right), 1.4 (down-left) and 3.0 (down-right) respectively]

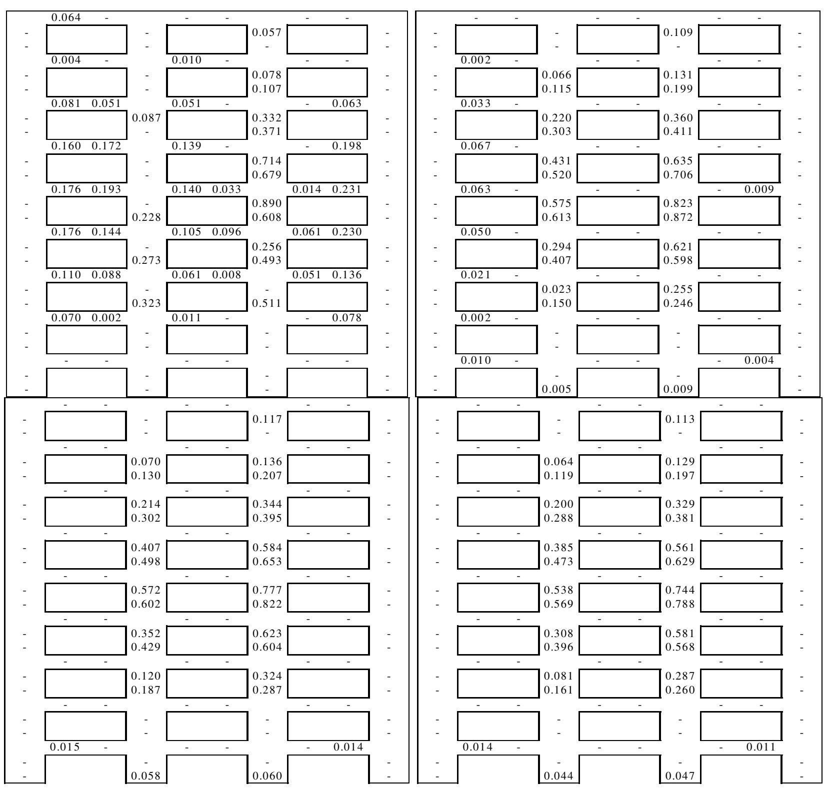

Fig. 14. Demand – capacity ratio in terms of plastic rotations – 9 storey frames: Regular vs Sb(2-9) [cases 1.2 (up-right), 1.4 (down-left) and 2.0 (down-right) respectively]

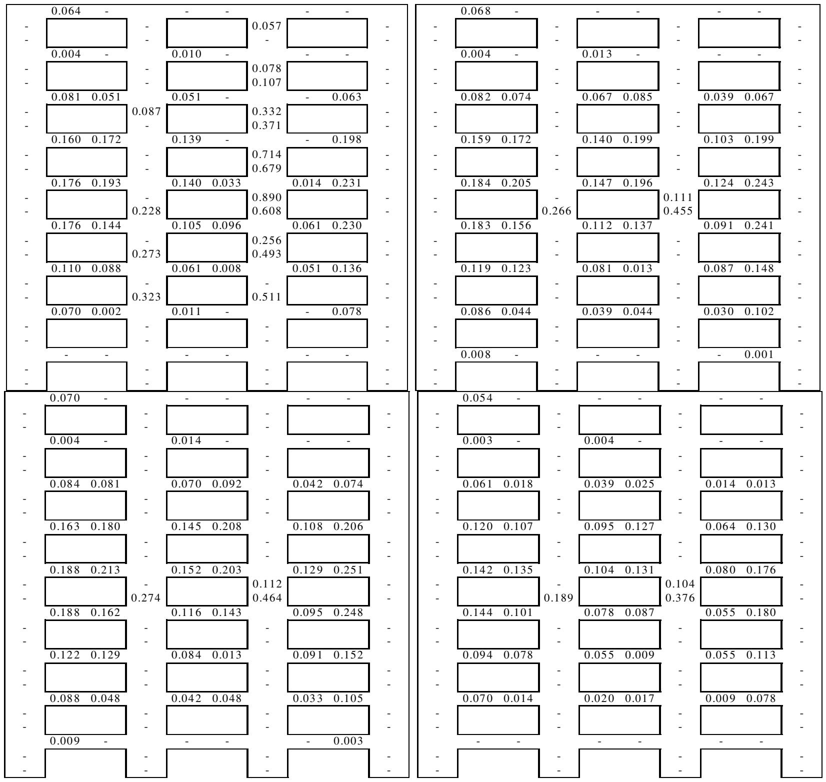

Fig. 15. Demand – capacity ratio in terms of plastic rotations – 9 storey frames: Regular vs Sc(1-4,6-9) [cases 1.2 (up-right), 1.4 (down-left)and 3.0 (down-right) respectively]

Fig. 16. Demand – capacity ratio in terms of plastic rotations – 9 storey frames: Regular vs Sb(1-4,6-9) [cases 1.2 (up-right), 1.4 (down-left) and 2.0 (down-right) respectively]

The value of this ratio is only reported when the member end is yielded, i.e. when a plastic hinge is formed; a value of the ratio larger than the unity means that the demand is larger than the capacity and, consequently, that a local collapse of the structure is reached: such cases are evidenced in bold. Finally, it is to be noted that in the examined cases the available rotations are evaluated neglecting the effect of the concrete confinement due to the steel stirrups, effect that produces an increment of the rotational ductility of the plastic hinges.

The analysis of the Figs. 9-16 provides another element of comparison between the behaviour of the cases "Sc" and "Sb" and the one of the regular reference frames. Regarding this, observing the figures it can be noted that the most critical situations are observed in the case of frames with overstrength assigned to the beams; in some of these the available plastic rotations are lower than the demanded ones; the larger ratios are for the column sections. On the contrary, when the overstrength is assigned to the columns the non linear response is, frequently, even better than the one of the two regular reference frames; in this case the largest values of the computed ratio are obtained for the beams. Consequently it is confirmed that an irregular behaviour is individuated only for the case of the "Sb" frames.

"Practical Frames": Non linear analyses results

In the following results of non linear static analyses performed for the frames called "practical cases" are reported. For sake of brevity, only the results concerning the frames obtained as variants of the 5 storey regular frame are presented herein, and in particular: the frames "Sb(3-2)" and "Sb(5)", which - due to the already cited particular distribution of the reinforcement - present larger overstrength in the beams than in the columns; the frames "Sc(3-2)" and "Sc(5)", which - on the contrary - have larger overstrength in the columns; the frames "Sbc(3-2)" and "Sbc(5)", which present overstrength both in the beams and in the columns. On the base of the results seen for the "theoretical cases", an irregular behaviour is expected above all for the two "Sb" cases.

The increments of the beams and columns yielding bending moments (which represent the introduced overstrength) with respect to the ones of regular reference frames caused, as already said, by modifying the distribution of the longitudinal reinforcement, are not uniform and, for some sections, even much larger than the ones considered in the analysis of the "theoretical cases".

In Figs. from 17 to 20 the results of the analyses are presented, in the same order of the previous paragraph. In the figures the label "min" indicates the frame obtained by the regular reference one only introducing, when necessary, the minimum reinforcement provided by the Italian code and already cited.

By the analysis of the figures, in particular it can be noted that:

- the push over curves (Fig. 17), always carried out till the target displacement, present a similar shape to the ones obtained for the "theoretical" variants. However, due to the fact that in the "practical" cases the overstrengths are introduced modifying the reinforcements, the post-cracking stiffness inevitably changes; any way, such stiffness variations are not very relevant and consequently it is considered that their effects are negligible with respect to the ones due to the strength variations. Finally, also for the "practical" case larger increments of the base shear can be noted for "Sb" frames;
- the comparison made in terms of interstorey drifts (Fig. 18) shows increments with respect to the regular case more sensitive than for the "theoretical cases", in particular for "Sb" and "Sbc" cases, above all at the lowest floors;
- the ratios between the maximum rotations confirm this result (Fig. 19): the "Sc" frames do not show a very different behaviour with respect to the regular case, while when the beam strength distribution is altered ("Sb" and "Sbc" cases) a relevant increment of the maximum rotation with respect to the one evaluated for the regular case happens; even in this case the larger increments are localised in the columns at the lowest storey;

- finally, in Fig 20 the comparison between demand and capacity in terms of plastic rotations is shown for all the 8 presented cases; the analysis of this figure confirms the result of the study. The frames "Sc" present a very satisfying behaviour: in this case, indeed, low increments of the examined ratio, and always for the beams, can be observed; consequently, an ideal behaviour is exalted (weak beam – strong column) and the demanded rotations are much lower than the available ones. For the other examined cases it does not happen the same: a general increment of the values of the ratio for the less ductile elements, i.e. the columns, can be observed, which indicates a certainly more unfavourable behaviour with respect to the reference frame; furthermore, even though in few sections localised at the lowest floors, the demanded rotations are larger than the available ones with the consequent collapse of the relative plastic hinges.

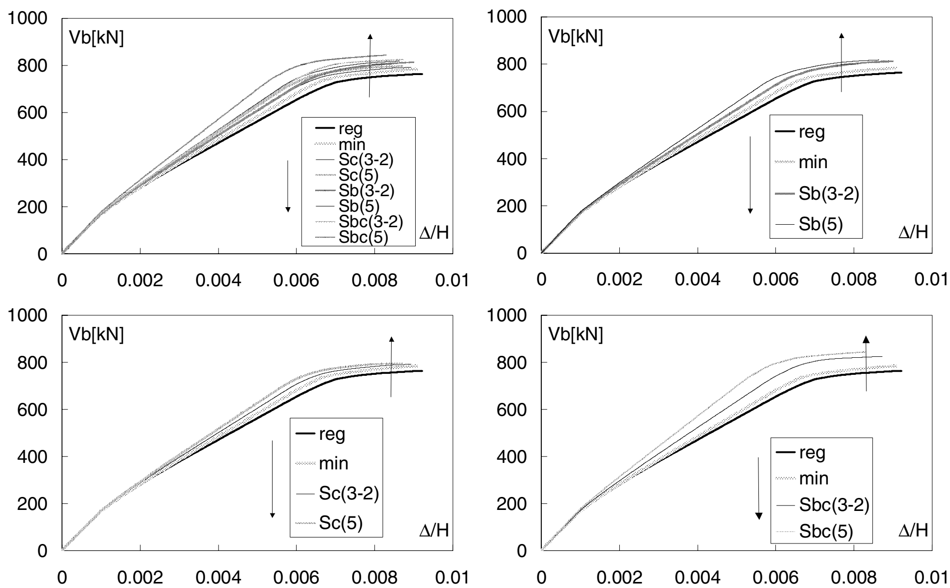

Fig. 17. "Push over" made till the "target displacement"

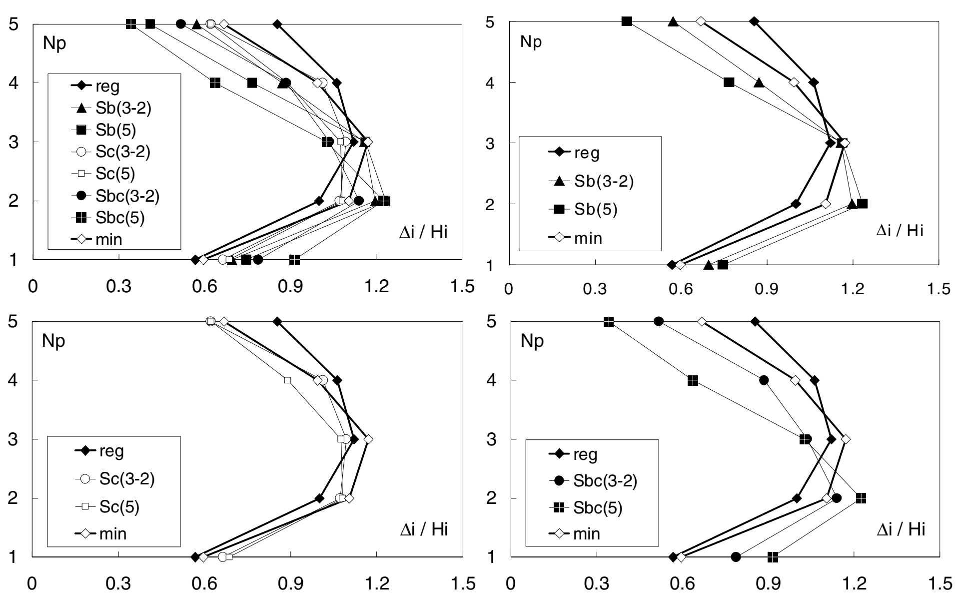

Fig. 18. Adimensionalised interstorey drifts

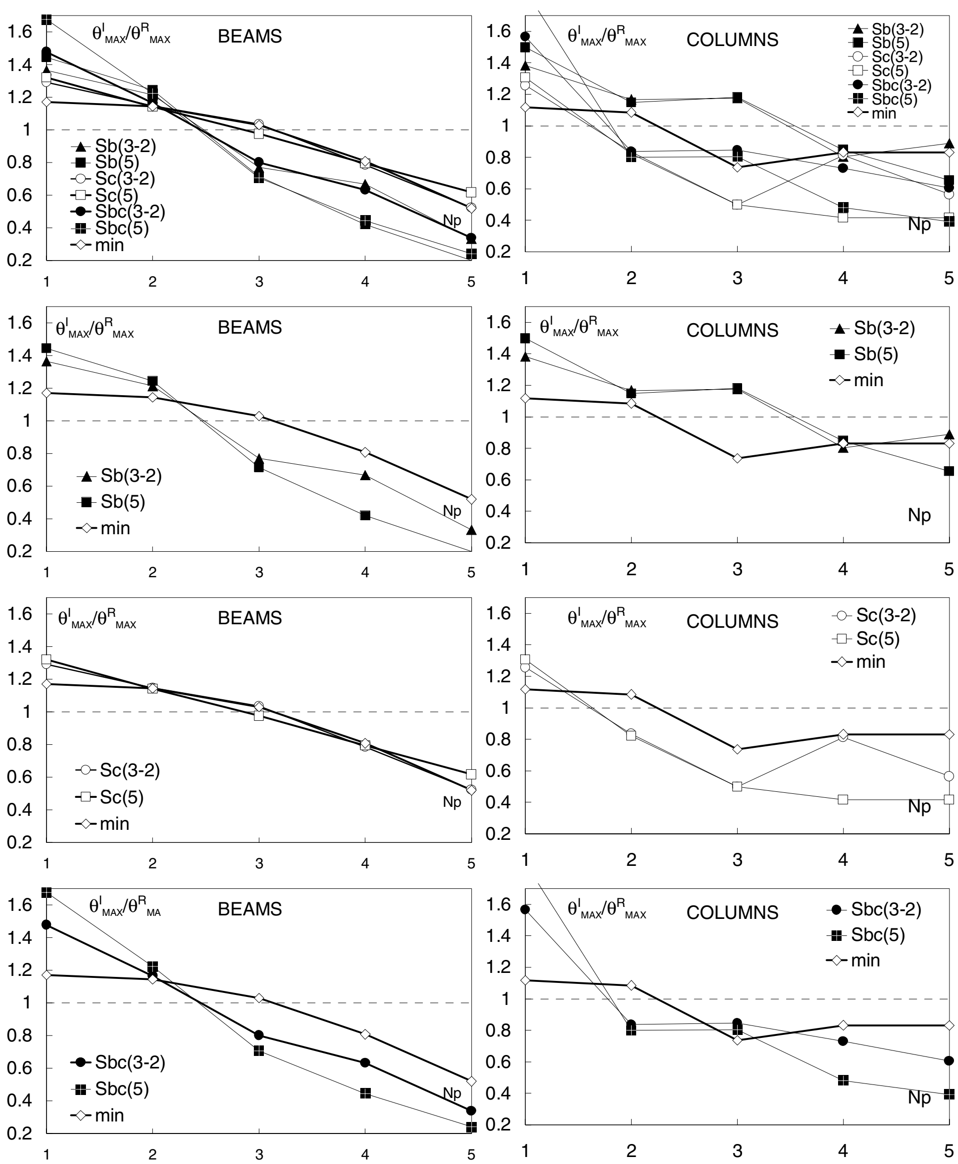

Fig. 19. Maximum rotations at the ends of beams and columns ratios

COMPARISON TO THE CODE CRITERIA

In the following, the regularity condition of the examined frames is evaluated using the vertical strength regularity criteria proposed by some international seismic codes (Italian, IBC, EC8, SEAOC, NEHRP, NBC). In this way, the comparison between what is assumed by the considered codes and the actual structural response of the examined cases will allow to give a first judgment on the reliability of the criteria provided by the codes. However, for sake of brevity, such a comparison is shown only for the "theoretical cases".

In order to use the aforesaid code criteria it is often necessary to evaluate the storey strength. But, this parameter is difficult to define; it seems that the provided criteria of the aforesaid international codes are calibrated on the base of studies performed on shear type frames, for which it is appropriate to define the storey strength. Anyway, in order to apply the aforesaid criteria to the herein analysed cases, in the following as storey strength the storey shear at the formation of the storey mechanism is assumed.

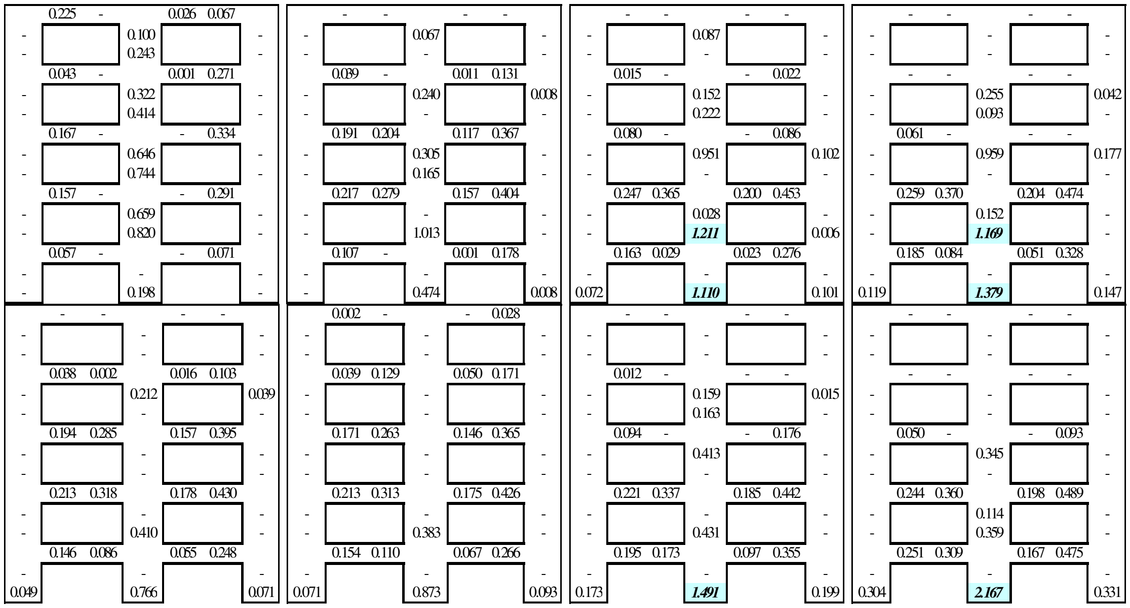

Fig. 20. Demand – capacity ratio in terms of plastic rotations – 5 storey frames: Regular (up-left), Min (up-left/centre), Sb(3-2) (up-right/centre), Sb(5) (up-left), Sc(3-2) (down-left), Sc(5) (down-left/centre), Sbc(3-2) (down-right/centre), Sbc (5) (down-right)

On the base of this assumption, in Tab. 1, for each case, the result of the strength regularity evaluation of the considered frames according to the quoted codes is presented. The analysis of the table revels that all the frames which present overstrength in the beams ("Sb" cases) would be regular, for all the examined codes. Actually, this is a consequence of the aforesaid difficulty in defining the storey strength: indeed, if the storey strength only depends by the column yielding moments, it cannot vary introducing overstrength in the beams. Consequently, in the application of the code criteria, the "Sb" frames are completely equal to the reference regular frames and, then, regular. On the contrary, many frames of the "Sc" type are irregular according to the examined codes; this is evidently in contrast with the results of the performed analyses. Consequently, it can be concluded that the criteria of the current codes are not reliable.

Tab. 1. Irregularity judgement given by the codes

CODES	Sc(2-5)			Sc(1-2)(4-5)			Sb(2-5)			Sb(1-2)(4-5)		
	1.2	1.4	3.0	1.2	1.4	3.0	1.2	1.4	2.0	1.2	1.4	2.0
EC8	*NO*	*NO*	**YES**	*NO*	*NO*	**YES**	*NO*	*NO*	*NO*	*NO*	*NO*	*NO*
Italian code	*NO*	**YES**	**YES**	*NO*	**YES**	**YES**	*NO*	*NO*	*NO*	*NO*	*NO*	*NO*
NBC	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	*NO*	*NO*	*NO*	*NO*	*NO*	*NO*
IBC SEAOC ATC 40 NEHRP	*NO*	**YES**	**YES**	*NO*	**YES**	**YES**	*NO*	*NO*	*NO*	*NO*	*NO*	*NO*
CODES	Sc(2-9)			Sc(1-4)(6-9)			Sb(2-9)			Sb(1-2)(4-5)		
	1.2	1.4	3.0	1.2	1.4	3.0	1.2	1.4	2.0	1.2	1.4	2.0
EC8	*NO*	*NO*	**YES**	*NO*	*NO*	**YES**	*NO*	*NO*	*NO*	*NO*	*NO*	*NO*
Italian code	*NO*	**YES**	**YES**	*NO*	**YES**	**YES**	*NO*	*NO*	*NO*	*NO*	*NO*	*NO*
NBC	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	*NO*	*NO*	*NO*	*NO*	*NO*	*NO*
IBC SEAOC ATC 40 NEHRP	*NO*	*NO*	**YES**	*NO*	*NO*	**YES**	*NO*	*NO*	*NO*	*NO*	*NO*	*NO*

CONCLUSIONS

Non linear static analyses are performed on r/c plane regular frames and on frames generated by them assigning overstrength to beams and columns. The latter ones present a strength vertical distribution which let presume an irregular behaviour. Nevertheless, the results show that an actual irregular behaviour is observed only when the overstrength is assigned to the beams; indeed, in this cases, relevant increments of the maximum demanded rotations of the columns with respect to the ones obtained for the "regular" reference frames are obtained. On the contrary, when the overstrength is introduced in the columns such increments are not observed and the response can be considered regular.

The criteria provided by many international codes for the vertical strength irregularity are also evaluated: the comparison between the estimation performed according such criteria and the seismic response numerically computed, demonstrates that the provisions currently introduced by codes here considered are inadequate.

According to the writers opinion, the evaluation of the vertical strength regularity is probably not necessary for the structures designed by using at the beam-column nodes the "hierarchy of resistance" criterion. Vice versa for structures not covered by the aforesaid hierarchy criterion, could be opportune to limit the bending overstrength of the beam end sections.

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