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Simple analysis of RC frames with soft first story

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ABSTRACT: A method is proposed for inelastic seismic analysis of infilled plane RC frames with open first story. The whole frame above first story (superstructure) is assumed rigid. First, it is assumed that superstructure has one d.o.f., horizontal translation, and first story columns have constant axial forces N. For every column, its shear force-lateral deformation diagram V-δ is computed, as well as the total diagram ΣV-δ of first story. Then, all three d.o.f. of superstructure are considered and significant additional axial forces ΔN of first story columns are obtained, because of rotation of superstructure, which cause a slight reduction of strength and stiffness of first story, but a significant reduction of its ductility, usually equal to that of the most compressed column. Finally, the structure is analysed as a SDOF elastoplastic oscillator, with the initial diagram ΣV-δ, but with a reduced ductility.

1 INTRODUCTION

In a building, the first story (groundfloor) is the most suffering story, from vertical static loads and more from horizontal seismic inertia forces. So, it would be proper to strengthen first story more than the other above stories. However,in practice, often the opposite happens.

Often, in a building, all the stories are infilled, except of first story, which remains open (pilotis). A usual infill wall of bricks, in a story, increase, about two times, its lateral strength and, about four times, its lateral stiffness. So, an open first story is much more weak and flexible, to lateral loading, than the other above infilled stories. Also, the first story is usually made taller and is, for this additional reason, too, more flexible.

So, during an earthquake, the open first story exhibits much larger lateral deformations than the other above stories. If the earthquake is quite strong, plastic hinges are formed at the ends of first story columns, because of yield of tension reinforcement. If the columns do not possess sufficient ductility, concrete is fractured, in compression, in plastic hinges regions. And, if this happens to both ends of all first story columns,a collapse mechanism of building is formed.

For the above reasons, it worths paying particular attention to the seismic analysis of buildings with weak first story. This can be performed by general or special purpose computer programs (Kanaan 1974, Papadopoulos 1990), which, however, require a big amount of input data and do not offer complete transparency of computation, in the usual case, that the user of the program is not, at same time, the programmer.

Also, simplified methods can be alternatively used, for the analysis of the structure, which require only the use of a simple calculator. Although we live in the era of computer, such simplified methods maintain their usefulness, as they can give, in a fast manner, a first approximation of structure's behavior and offer transparency in every step of the computation.

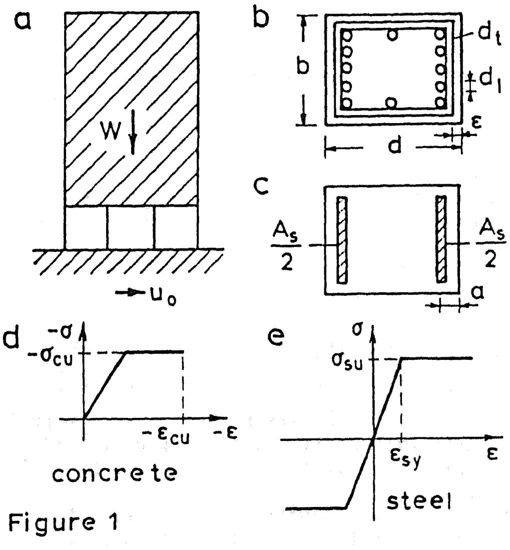

Figure 1

Such a simplified method, based on reasonable and generally accepted assumptions, will be proposed here, for the inelastic seismic analysis of plane frames of RC buildings with open first story (pilotis).

2 DESCRIPTION OF PROPOSED METHOD

A plane RC frame is considered, representative of a building with all stories infilled except of open first story(pilotis). The frame is subjected to horizontal seismic ground movement u_0. It is assumed that the whole building above first story (superstructure) is absolutely rigid (Fig.1a), whereas first story columns are fixed at

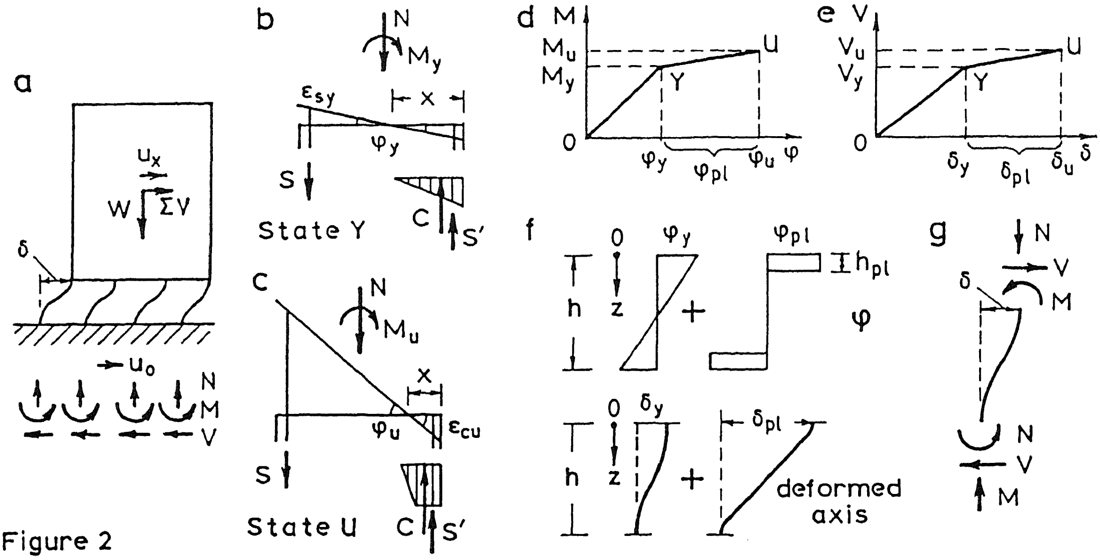

Figure 2

both ends, and have a constant rectangular section. By adding the loads of all stories, corresponding to the studied frame, we obtain the total weight W of superstructure, applied at its center of gravity.

For every first story column, the geometrical data of its section of concrete and steel are given (Fig.1b). Then, a simplified column section is considered, with only the longitudinal reinforcements of the left (let be tensioned) and right (let be compressed) side, whereas the intermediate ones are omitted (Fig.1c). Also the simplified uniaxial stress-strain σ-ε diagrams of structural materials, concrete and steel, are given (Fig.1d,e).

At a first stage, it is assumed that the columns have constant axial loads N, which result from the distribution of superstructure's weight W, proportionally to their axial stiffnesses $K_\alpha = v(E_c A_c + E_s A_s)/h$, where h is column's height, E_c, E_s initial elasticity moduli and A_c, A_s sections of concrete and steel, respectively. Coefficient v, where $0<v<1$, takes into account the damage of column (concrete cracking, reinforcement yield). At this stage, we can take $v=1.0$ or an other value, empirically estimated.

It is also assumed, at first stage, that the superstructure has only one degree of freedom, its horizontal parallel translation u_x; thus, the lateral deformation of first story columns is $\delta = u_x - u_0$ (Fig.2a).

For every first story column, based on its section data, the material σ-ε diagrams and the axial load N, we compute the diagram M-ϕ of bending moment versus curvature of its section (Fig.2d).

For this purpose, it is enough to compute two characteristic states of the section: 1)the state Y (FIg.2b), in which the tension reinforcement begins to yield and 2)the state U, in which concrete is fractured in compression (Fig.2c).

In state Y, it is usually required to try 3-4 values of the abscissa x of neutral axis, before a satisfactory approximation of its accurate value is attained. Whereas, in state U, as usually the resultant S of tension reinforcement is of equal magnitude and opposite sign of S' of compression reinforcement, the x can be found directly from the solution of only one equation, that of forces equilibrium perpendicularly to the section.

The diagram M-ϕ of column section is transformed to the diagram V-δ of shear force versus lateral deformation for the whole column (Fig.2e). For the transformation of ϕ to δ, we consider the distribution of ϕ, over the height of column, in elastic and plastic state (Fig.2f), the simple empirical formula $h_{pl} = 0.5d + 0.05h/2$ for the equivalent lengths of plastic hinges at the ends of column and we apply the integral $\delta = \int_0^h z\phi(z)dz$. Thus, we obtain $\delta_y = \phi_y h^2/6$ and $\delta_{pl} = \phi_{pl} h_{pl}(h - h_{pl})$.

Whereas, in order to transform M to V, we consider the equal bending moments M at two ends of column and write the equation of moments equilibrium of column, including P-δ effect (Fig.2g): $2M - N\delta - Vh = 0$.

Usually, in a column V-δ diagram, holds $V_y \approx V_u$.

By adding the diagrams V-δ of all first story columns, we obtain the total ΣV-δ diagram of first story(Fig.3). In the general case of non equal columns, the ΣV-δ results multilinear,but it can be approximated by a bilinear curve. The ultimate lateral deformation δ_u of

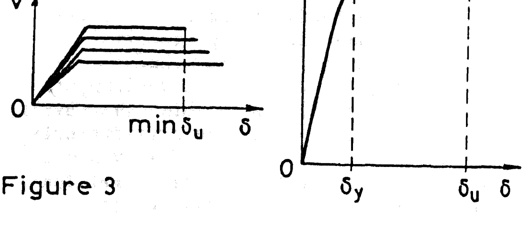

Figure 3

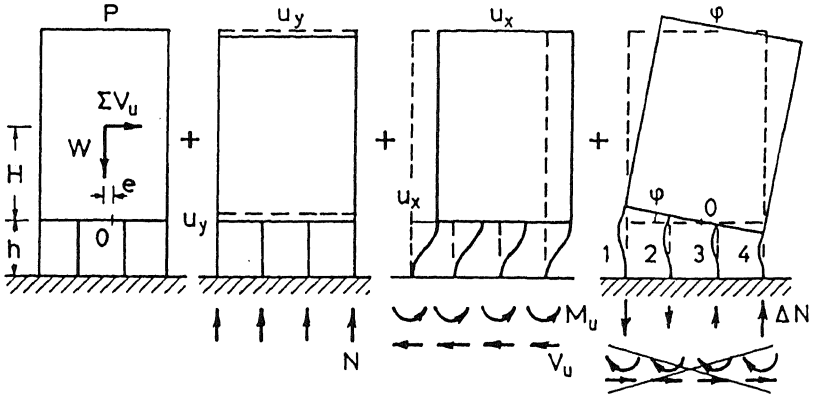

Figure 4

first story is obviously equal to the minimum δ_u of all first story columns.

The shear strength force of first story ΣV_u, found above, is, now, imposed, as external horizontal load, at the center of gravity of superstructure, so that to represent the maximum possible horizontal seismic inertia force of superstructure. For this horizontal load ΣV_u and, at same time, for the weight W of superstructure, the static analysis of the structure will be performed, under the assumption, now, that the rigid superstructure has all three plane degrees of freedom, so that to take into account the, usually significant, additional axial forces ΔN of first story columns, because of superstructure's rotation. In Fig.4 is shown, on one hand, the state P of external loading of structure and, on the other hand, the states of three degrees of freedom of superstructure (parallel translations along x,y and rotation ϕ about an, arbitrarily choosen, point O, at the base of superstructure), as well as the deformations and the reactions M, V, N, they cause to first story columns.

Before proceeding to static analysis, some simplifications will be made. Numerical examples show that, in the studied problem, the following hold:

-The internal reactions M, V, at first story columns, because of rotations ϕ of their heads, due to the rotation ϕ of superstructure, are negligible and can be omitted.

-The reductions of axial stiffnesses K_α of first story columns, different from one column to another, due to the damage of columns, have a little influence on computation results. So we can give, from the beginning, values to the coefficients v of columns, pre-estimating approximately the damage, they will sustain.

Further simplification of computation is achieved by taking the reference point O, of superstructure's base, at the "center of gravity" of axial stiffnesses K_α of first story columns, that is, the point where $\Sigma x K_\alpha = 0$, where x is the abscissa of a column axis, with respect to O.

After the above simplifications, the static analysis of studied structure can be performed by the following simple algorithm:

1.The weight W of superstructure is distributed to the axial forces N of first story columns, proportionally to their axial stiffnesses K_α.

2.The horizontal load ΣV_u of superstructure is distributed to the shear forces V of first story columns. Obviously, for every column, results $V = V_u$.

3.From moments equilibrium of every first story column, the equal bending moments at its two ends are obtained, $M_u = V_u h/2$.

4.The sum of all moments of forces acting on the superstructuree, with respect to reference point O, at its base, is put equal to zero: $\Sigma M_0 = \Sigma V_u H - Ve + \Sigma M_u - \phi \Sigma x^2 K_\alpha = 0$. From this equation, the rotation ϕ of superstructure results. Now, the additional axial force of a first story column is $\Delta N = \phi x K_\alpha$ and its total axial force N+ΔN.

Numerical examples show that the additional axial forces ΔN of first story columns, because of rotation of superstructure, are significant, particularly in tall buildings. Under the unfavorable (with the side of safety) simplifying assumption that the ΔN's are brought, from the beginning, with their whole value, we compute the new diagrams V-δ of first story columns, for their new axial forces N+ΔN(Fig.5a). And, it is observed that, for a great compressive ΔN, the lateral strength of a column is significantly increased, its lateral stiffness is slightly increased, whereas its ductility, more specifically its ultimate deformation, is significantly reduced. While, for a great tensile ΔN, of course, the opposite phenomena are observed.

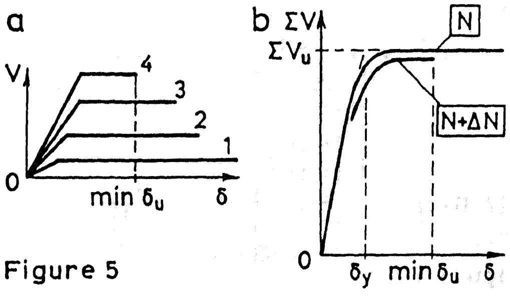

Figure 5

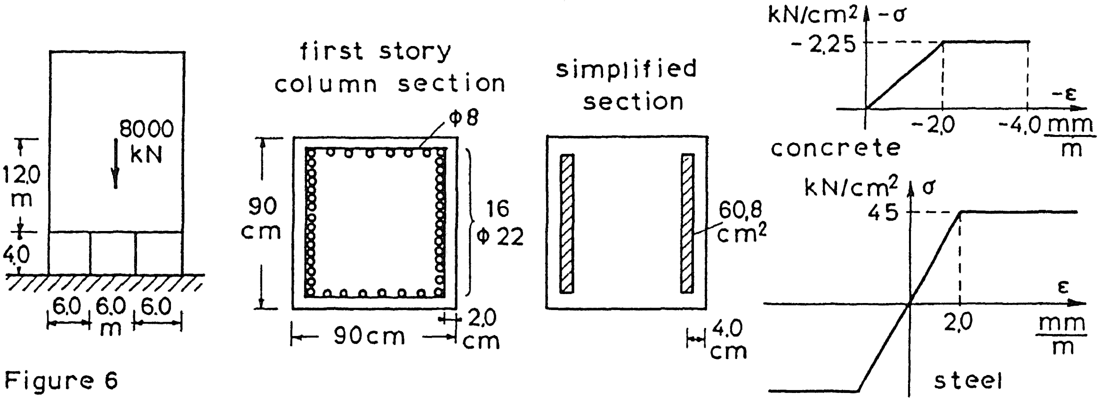

Figure 6

In the new total diagram ΣV-δ of first story(Fig.5b), the strength ΣV_u is slightly reduced, because the variations of strengths V_u of individual columns almost eliminate each other, between columns with ΔN of opposite signs. The mean stiffness of diagram ΣV-δ (after its bilinear approximation) is also slightly reduced. Whereas the ductility of first story is significantly reduced, because its new ultimate deformation is equal to the new, reduced because of the ΔN's, minimum δ_u of the columns, which usually corresponds to the most compressed column.

According to the above, the studied structure can be viewed as a SDOF oscillator with the horizontal parallel translation of superstructure as its only one degree of freedom. And with a bilinear diagram of first story columns, in which the strength ΣV_u and the stiffness $\Sigma K = \Sigma V_u/\delta_y$ have the values initially found, by taking into account only the static N of columns, whereas the ductility is reduced, because of the additional axial forces ΔN. It is assumed that this diagram ΣV-δ is the envelope of an elastoplastic law ΣV-δ.

3 NUMERICAL EXAMPLE

A plane RC frame is studied, of a building with all stories infilled, except of open first story(pilotis), with equal columns at first story, subjected to horizontal seismic ground movement. The superstructure is assumed absolutely rigid. In Fig.6, the necessary numerical input data are given.

Solution:

Static load per column, $N = W/4 = 8000\text{kN}/4 = 2000\text{kN}$.
Computation of state Y of column section, in which tension reinforcement begins to yield (Fig.7a): After the consideration of three trial values for the abscissa x of neutral axis, we result in the value x=37cm. So, it is obtained $\phi_y = 4.08\text{mrad/m}$, $\sigma_c = 1.70\text{kN/cm}^2$, $C = 2831\text{kN}$, $S' = 1843\text{kN}$ and $M_y = 2802\text{kNm}$.

Computation of state U of the section, in which concrete is fractured in compression (Fig.7b): Thanks to the equality $S = S'$, the x can be directly obtained from only one equilibrium equation, that of forces perpendicularly on the section:
$\Sigma F = 2000 - 0.75x90*2.25 = 0 \rightarrow x = 13.0\text{cm}$.
Thus, $\phi_u = 30.3\text{mrad/m}$ and $M_u = 3044\text{kNm}$.

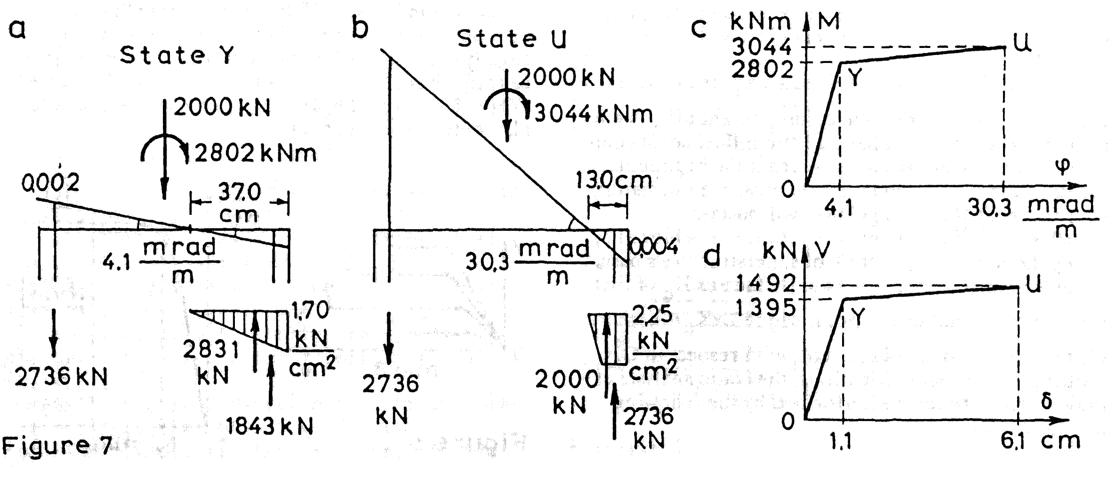

Figure 7

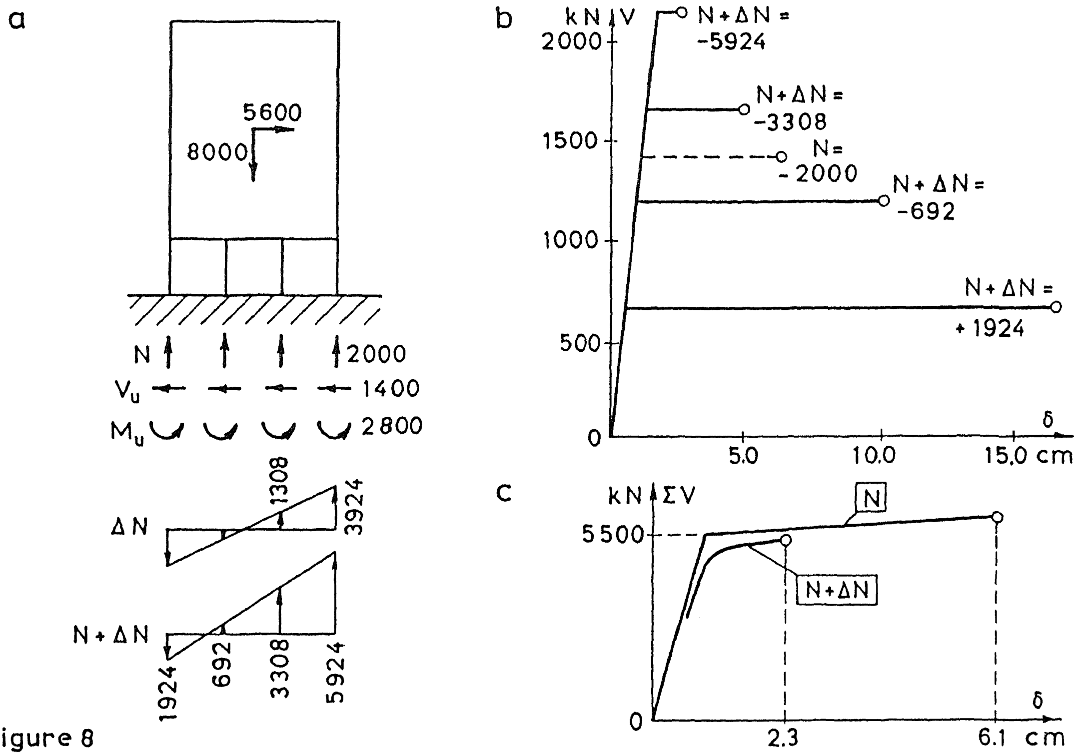

Figure 8

With the values φ, M of two computed states Y,U, the diagram M-φ of column section is drawn (Fig.7c), which is, then, transformed to the diagram V-δ of whole column (Fig.7d), with the help of previously given formulae. Now, the total shear strength of first story is: $\Sigma V_u \approx 4x1400 = 5600kN$.

Static analysis of structure follows, with loads W(weight) and ΣV_u(horizontal inertia force) at the center of gravity of superstructure. It is assumed that the columns have equal axial stiffnesses. The simple algorithm, previously described, is performed and the results, shown in Fig.8a, are obtained. Then, the new V-δ diagrams of columns are computed, for their total axial forces N+ΔN, which are presented all together in Fig.8b.

The variations of V_u's of columns oblige us to correct the previously found V_u, $M_u = V_u h/2$ of the columns, but without any other influence on the computation. Also, the consideration of different axial stiffnesses K_α of columns, through different values of coefficient ν, would not significantly alter the results.

By adding the new V-δ diagrams of columns, we obtain the new total ΣV-δ diagram of first story, shown in Fig.8c, in comparison with the initial diagram ΣV-δ, which did not take into account the additional axial forces ΔN of columns. Indeed, it is observed, that the strength ΣV_u and stiffness ΣK have been slightly reduced, while the ductility, more specifically the ultimate deformation δ_u, has been significantly reduced.

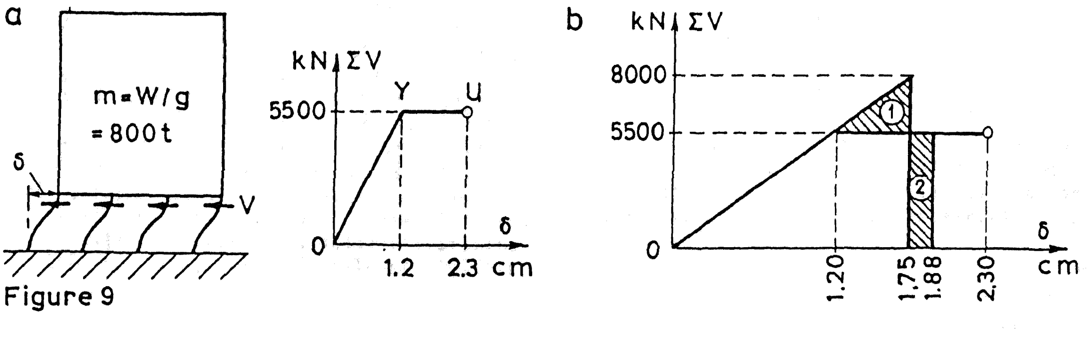

Figure 9

Now, the studied structure is simulated by a SDOF oscillator, with the horizontal parallel translation u_x of superstructure, as its only one degree of freedom (Fig.9a), with an elastoplastic ΣV-δ law, of total shear force versus lateral deformation of first story columns, which has, as envelope, the previously computed diagram ΣV-δ, approximated by a bilinear curve.

The lateral stiffness of first story is $\Sigma K = 5500kN/0.012m = 459000kN/m$. The eigenperiod T of the oscillator is determined: $\omega^2 = (459000kN/m)/800t = 513 \rightarrow \omega = 23.9rad/sec \rightarrow T = 2\pi/\omega = 0.263sec$. A viscous damping $\xi = 0.05$ is chosen, corresponding to a story without infill walls, like the open first story. These values of ξ, T are introduced in the elastic response spectra of El Centro, California earthquake of 18/5/1940, component N-S, and the maximum horizontal absolute acceleration, $max\gamma \approx 1.0g$, is taken as result, which would be developed in the corresponding (with the same m, ΣK, ξ) linear elastic oscillator. So, the maximum inertia force, of this elastic oscillator, would be $m.max\gamma = 8000kN$ and its maximum deformation $\delta_{el} = 8000kN/(459000kN/m) = 1.75cm$. It is observed that $m.max\gamma = 8000kN > 5500kN = \Sigma V_u$; thus, the real structure enters the inelastic state. Because of $T = 0.263sec < 0.5sec$, the required δ_u will result from δ_{el}, according to A.Veletsos, N.Newmark (1960) findings, from the equality of deformation energies, between the real inelastic oscillator and the corresponding elastic one, which is represented by the equality of areas 1,2 in the diagram of Fig.9b.

So, the required $\delta_u = 1.88cm$ is obtained, for the studied El Centro earthquake, which is smaller than the available $\delta_u = 2.30cm$ of the structure, previously computed. This means that the structure, subjected to El Centro earthquake, exhibits plastic deformations (rotations of plastic hinges at ends of first story columns, because of yield of tension longitudinal reinforcement), but without fracture (of compressed concrete at plastic hinge regions), thus without formation of a collapse mechanism of the building.

4 COMPARISON WITH A MORE ACCURATE METHOD

Results of the proposed here simplified method have been compared with corresponding ones of a more accurate method of seismic analysis of plane RC frames of buildings with open first story (Papadopoulos 1990), for which a relevant computer program is available and which has been checked by comparison with experimental data (Schulz 1986). This more accurate method also assumes an absolutely rigid superstructure, with three degrees of freedom u_x, u_y, ϕ, whereas the structural elements of first story are simulated by trusses, with bars obeying inelastic uniaxial σ-ε laws of concrete or steel. And a sufficiently good approximation was observed, between the results of two methods.

5 CONCLUSIONS

The proposed method, for the inelastic seismic analysis of plane RC frames, of buildings with open first story, is based on reasonable, generally acceptable, assumptions and its results sufficiently approximate the corresponding ones of a more accurate relevant method. The proposed method is simple, requires only the use of a simple calculator, and gives, in a rather fast manner, a quite good first approximation of structure's behavior. In the usual case of equal columns of first story, one hour of computation is required, whereas, in case of non equal columns, about two-three hours are required. Also, the proposed method offers transparency in every step of the computation, which does not happen with methods using a computer program.

For the above reasons, the proposed method can prove a useful tool for the structural analyst.

Many examples, performed by the proposed method, showed that the significant additional axial forces ΔN of first story columns, because of overturning moments, to the base of building, of superstructure's inertia forces, slightly reduce the total lateral strength and stiffness of first story, but significantly reduce its ductility, which is usually equal to that of the most compressed column of first story.

Parametric studies, performed with the help of proposed method, verified the effectiveness of various measures for aseismic strengthening of open first story: Sections increase, increase of columns number, improvement of confinement or concrete quality improvement, increase the lateral strength and stiffness, as well as the ductility of columns. The increase of longitudinal reinforcement implies increase of lateral strength and stiffness of columns. The reduction of loads or, better, the reduction of stories number, increase the ductility of columns.

By the same parametric studies, the known general criterion for increased column ductility was verified, which is the low value of ratio $(N+\Delta N)/N_u$. Moreover, it resulted, that it is good to keep the ratio N/N_u less than 0.1.

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