A NEW PROCEDURE FOR ASEISMIC DESIGN OF MULTI-STOREYED SHEAR TYPE BUILDING BASED UPON DEFORMATION CHECKING

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SUMMARY

In this paper, principles of the deformation checking method are suggested for aseismic design of multi-storeyed buildings. Formulae for evaluation of maximum story drifts of multi-storeyed shear type structures due to nonlinear seismic responses are presented and the allowable deformability indices of story drifts are given. These findings make the application of the deformation checking method quite simple in the aseismic design of such structures.

INTRODUCTION

The well known theory of elastic response spectrum has been the basis for the determination of the so called earthquake loadings in the aseismic design code in many countries. In China,a coefficient C, called the structural influence factor, has been adopted in order to reduce the elastic seismic loads as the structure enters the elasto-plastic stage during strong earthquakes. Strength cheching method with a certain factor of safety is used for the aseismic design of such structures under the reduced seismic loads. In due course, a number of conspicuous contradictions have been exposed and it has been found that such strength checking method is especially inappropriate for the aseismic design of multi-storeyed buildings.

According to the current code method, the reduced seismic loads have very often been mistaken by many designers as the actual externally imposed loads absolutely independent of the yield strengths of different parts of the structure in much the same character as the externally imposed wind loads. Consequently, the load effects of reduced seismic loads which can occur only in the case of structures entering elasto-plastic range are evaluated by the ordinary elastic method of analysis and superimposed to the load effects due to other live and dead loads as if the structure were totally working in the elastic stage. Clearly, the is erroneous. Furthermore, the strength checking method defined in the current code of aseismic design can in no way offer a resonable way for the evaluation of the elasto-plastic story drifts that may occur when it comes into the elasto-plastic stage under the attack of strong earthquake ground motions.

In this paper, part of the research work of a new aseismic design method for multi-storeyed buildings based upon deformation checking is presented.

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Based on the statistical analysis of large number of time-history seismic response computation results, a simplified and practicable method for evaluating the maximum story drift of shear type buildings during strong earthquakes and the place where it occurs is established. By collected test results concerning the ultimate deformabilities of RC structures as much as possible both at home and abroad, some tentative values of allowable story drifts for multi-storeyed buildings keeping them within an acceptable damage condition under the expected intensity of earthquake attack are suggested.

BASIC STEPS OF DESIGN

The aseismic design based upon the deformation checking method can be summarized in the following steps:

a) Determine the "design intensity of earthquake", which has the maximum frequency of occurrence on the localtion of the structure, and "maximum expected earthquake", which is taken from the acceptable seismic risk level.

b) According to the fully elastic analysis and strength checking method, the design for the members of structures under equivalent elastic seismic loads may be carried out for "design intensity of earthquake".

c) Compute the yield strengths of storys for the structure by means of ultimate analysis theory, and then determine the "strength ratio coefficient" ξ as

$$\xi(i) = Fy\ (i)\ /\ Qe\ (i) \tag{1}$$

in which $Fy(i)$ is the yield shear strength of the i^{th} - story,
$Qe(i)$ is the maximum elastic seismic story shear of i^{th} story under the "maximum expected earthquake" when the structure is treated as fully elastic.

d) Evalute the maximum story drift and corresponding place of the structure by the method proposed below.

e) Check the seismic safety, such that the maximum story drift should not exceed the allowable range of deformability of the structure.

SIMPLIFIED APPROACH TO DEFORMATIONS OF SHEAR TYPE STRUCTURES

The inelastic deformations of multi-storeyed structures can be obtain by the expensive and time consuming method of time-history analysis. Simplification should be made in order to provide the structural engineers with more practical methods of aseismic designs.

Main Rules of Inelastic Deformations

By investigating a large number of existing framed structures and other shear type buildings in seismic zones and having done thousands of numerical examples of elasto-plastic response analysis for such buildings with different number of stories and varying parameters such as masses, rigidities, yield strengths, etc., it has been found that the main features characterizing the performances of elasto-plastic deformation of shear type structures are as:

a) The ratios between the nonlinear seismic deformation and corresponding elastic one of such structures are maily connected with the yield strengths at various stories of the structures and bear slight relation to their masses and stiffnesses. Fig.2 shows an example of a 5-story framed structure. This means that, in general, the distribution of the deformations and shear forces at various stories are not parallel to that of them obtained by using the elastic seismic analysis and treating the structure as fully elastic no matter how strong be the earthquake ground motion.

b) In most cases, the structure is a non-uniform one and the strength ratio coefficient $\xi(i)$, which has been defined by equation (1), varies at different stories. The smaller value of ξ that a story possesses, the weaker it is against earthquake ground motions. In a story where $\xi(i)$ is obviously smaller than that of any other story, very large story drift would result at that story during strong earthquakes, while the other stories usually bear smaller story drifts than the corresponding ones if the structure were treated as fully elastic in the analysis. This phenomenon, called as the "Plastic Deformation Concentration" at the weak story, should be carefully studied in the aseismic design of the structure. Fig.3 shows some examples of this phenomenon.

c) The maximum top displacement $\Delta_p(N)$ of the nonlinear seismic response of a multi-storeyed shear type structure bears a relation to the maximum top displacement $\Delta_e(N)$ of the elastic seismic response of the same structure expressed by

$$\Delta_p(N) = \eta \Delta_e(N) \tag{2}$$

in which η is a non-dimensional coefficient, which depends on the vibration period of the structure, the strength ratios of stories and type of soil foundation conditions, but bears hardly any relationship to the total story height of the structure. For the cases of structures from 3 to 15 stories high and ξ varying from 1/6 to 1/2, it can be approximated by

$$\eta = \begin{cases} a(T_0 - T)/\xi + 0.75 & \text{for } T \leq T_0 \\ 0.75 & \text{for } T > T_0 \end{cases} \tag{3}$$

where T is the fundamental vibration period of the structure in sec.,
T_0 is equal to o.5 sec. for stiff soil foundation or equal to 0.7 sec. for soft soil foundation,
a is equal to 0.6 for stiff soil foundation and equal to 0.75 for soft soil foundation,
N is the total number of stories,
and ξ is the average strength ratio of all stories expressed by

$$\xi = (1/N)\Sigma_1^N F_y(j)/Q_e(j) = \Sigma_1^N \xi(j)/N \tag{4}$$

Fig.4 shows the statistical histogram of η in the cases of $T \geq 0.8$ sec., $N = 3 \sim 15$ and $\xi = 1/2 \sim 1/6$.

d) The maximum top displacement by the nonlinear seismic response analysis may be taken approximately as 0.9 times the sum of the maximum story drifts as given by the formula

$$\Delta_p(N) = 0.9\Sigma_1^N \Delta_p^S(j) \tag{5}$$

in which $\Delta_p^S(j)$ is the maximum story drift of j^{th} - story due to the non-linear seismic response with consideration of the elasto-plastic properties of the structure. Fig.5 shows the statiatical histogram of the ratio between $\Delta_p(N)$ and $\sum_1^N \Delta_p^S(j)$, in which λ is such a ratio.

Practicable Formulae of Deformation Computation

Based upon above rules, the practicable formulae of evaluating the maximum nonlinear story drift can be derived as follows:

The maximum top displacement $\Delta_e(N)$ and story drifts $\Delta_e^S(j)$ of the elastic seismic response of the structure can be easily calculated by elastic stiffness and no-reducing seismic shears. For example, using the mode analysis method, we can write as

$$\Delta_e^S(j) = \sqrt{\sum_1^n [\Delta_{ek}^S(j)]^2}, \qquad \Delta_{ek}^S(j) = Q_{ek}(j)/K_j \tag{6a}$$

$$\Delta_e(N) = \sqrt{\sum_1^n [\Delta_{ek}(N)]^2}, \qquad \Delta_{ek}(N) = \gamma_k\, g(T_k/2\pi)^2 \alpha_k \tag{6b}$$

in which K_j is the elastic stiffness of the j^{th} - storey,

α_k, γ_k and T_k are seismic influence factor, participation coefficient and period of k^{th}-vibration mode of the structure, respectively.

Assume that the i^{th}-story is the weakest of all and has yielded under the action of earthquake, then we should have

$$Q_p(i) = F_y(i) = \xi(i)\, Q_e(i) \tag{7}$$

This leads to a decrease of story shears for all the stories expect the i^{th}-story. According to the equilibrium of shears, we can suggest

$$\begin{aligned} \text{for } j<i \quad & Q_p(j) = Q_e(j) - [Q_e(i) - Q_p(i)] = \\ & = Q_e(j) - [1-\xi(i)]\, Q_e(i) \\ \text{for } j>i \quad & Q_p(j) = \xi(i)\, Q_e(j) \end{aligned} \tag{8}$$

Except the i^{th}- story where the plastic deformation concentration occurs, we can assume that the following approximation holds

$$\Delta_p^S(j) = Q_p(j)/K_j \qquad (j = 1.\ 2,\ 3,\ \ldots\ i-1, i+1, \ldots N) \tag{9}$$

Substituting the relations (2), (8) and (9) into formula (5), the maximum story drift of the weakest story i^{th} can be given by

$$\Delta_p^S(i) = 1.11\ \Delta_p(N) - \sum_{j\neq i,1}^{N} \Delta_p^S(j) = \tag{10}$$

$$= 1.11\,\eta\,\Delta_e(N) - \xi(i)\sum_{i+1}^{N}\Delta_e^S(j) - \sum_1^{i-1}\Delta_e^S(j) + [1-\xi(i)]\,K_i \sum_1^{i-1}\frac{1}{K_j}$$

in which $\Delta_e^S(j)$ and $\Delta_e(N)$ are expressed by formulae (6).

If the plastic deformation concentration occurs at the level of the ground floor, then $i=1$, and formula (10) can be simplified as

$$\Delta_p^S(1) = 1.11\,\eta\,\Delta_e(N) - \xi(1)\sum_2^N \Delta_e^S(j) \qquad (11)$$

For all other stories $(j \neq i)$, the story drift $\Delta_p^S(j)$ will generally be somewhat less than the corresponding $\Delta_e^S(j)$ and so it can be taken approximately equal to the latter

$$\Delta_p^S(j) \doteq \Delta_e^S(j) \qquad (12)$$

Experience shows that by so doing, it is generally on the safer side.

Although rather rare in ordinary engineering realization, there are, however, structures in which the distribution of yield strengths along the height approaches to be proportional to that of the maximum elastic shears (in other words, $\xi(i)$ = const.). The story drifts due to nonlinear seismic responses may, in this case, still be non-uniform but the non-uniformity is not so pronounced, and the maximum story drift of such structures can be approximated by the formula:

$$\Delta_p^S(i) = [1 + 0.17(1 - \sqrt{\xi})(N-1)]D_p \qquad (13)$$

where D_p is elasto-plastic sesimic deformation of SDOF system and can be written as:

$$D_p = \{a(\tfrac{1}{\xi} - 1)(T_0 - T) + \tfrac{1}{2}(\xi + \tfrac{1}{\xi})[\xi + (1-\xi)\sqrt{\xi}]\}D_e \qquad (14)$$

in which

$$a = \begin{cases} 0 & T \geqslant T_0 \\ 1.91 & T < T_0 \quad \text{for stiff soil foundation} \\ 1.14 & T < T_0 \quad \text{for soft soil foundation} \end{cases}$$

D_e is elastic seismic displacement response of SDOF system.

THE DEFORMATION CHECKING METHOD

Deformation checking method used for seismic design of structures can be briefly summarized as follows:

Values of Allowable Deformation

It is necessary to specify the allowable deformation of various kinds of structures for different cases in order to keep them within an acceptable damage condition under strong earthquake motions. Various deformation requirements can be set at the following levels:

to work in the elastic state with no cracking allowed,

to accept the damage of non-structural members that no yielding stage of structural members is allowed,

to avoid only the collapse so that the structural deformation should not exceed the ultimate deformability of the structure, etc..

According to collected test results and the investigation of earthquake damages, the degree of damage of a structure can be evaluated, in general, by the story drifts or the drift angles, and some tentative values of the allowable drift angle are listed in Table 1, in which degree 1 of damage is the case of no-cracking or slight damage of non-structural members, degree 2 means moderate damage, degree 3 indicates severe damage, and degree 4 shows that the structure might be collapsed.

Values of Allowable Drift Angle Table I

Type of Structures	Degree of damage 1	2	3	4
Single-story factories	1/150 – 1/200	1/80 – 1/120	1/50 – 1/60	1/30
Framed constrction	1/300 – 1/400	1/200 – 1/250	1/100	1/50
Brick influlling Frames	1/400	1/250	1/150	1/80
Frame-wall structures	1/500	1/300	1/200	1/120

When special details are given to increase the structural ductility, the above values can be exceeded.

Safety Check for Structures

When certain degree of the damage for the structure under the expected intensity of earthquake action is obtained form Table I, then

$$\Delta_p^S(i) < \Delta_a^S(i)$$

or

$$R_p^S(i) < R_a^S(i) \qquad (15)$$

in which the drift angle $R_p^S(i)$ is equal to $\Delta_p^S(i)/h_i$, and h_i is the height of the i^{th}- story.

Some times, the top displacement of a structure is limited due to functional requirements, we should also have

$$\Delta_p(N) < \Delta_a(N) \qquad (16)$$

where $\Delta_a(N)$ is the allowable top displacement of the structure subjected to the expected intensity earthquake.

EXAMPLE

A 8-storyed framed structure situated on soft soil foundation is subjected to earthquake ground motion of intensity VIII. The fundamental vibration period of the structure is $T=1.05$ sec.. Other known data are given in Table II. It is required to check the plastic deformation at the weakest story.

Known Data for Computation Table II

No, of story	1	2	3	4	5	6	7	8
K_j (t/cm)	61.3	59.8	57.3	39.9	24.6	16.7	14.9	19.8
$\Delta_e^S(j)$ (cm)	2.02	2.08	2.10	2.86	4.27	5.51	4.62	1.09
$\xi(j)$	0.31	0.27	0.22	0.18	0.15	0.10	0.20	0.62

and $\Delta_e(N) = \Delta_e(8) = 22.12$ (cm)

From the above Table, the weakest is at the 6^{th}-story with minimum strength ratio $\xi(6) = 0.10$. Using formula (10), we can obtain

$$\Delta_p^S(6) = 18.41 - 0.57 - 13.33 + 9.62 = 14.13 \quad \text{(cm)}$$

the storey height of 6^{th}-story is 3.9 meter, we can obtain

$$R_p^S(6) = 14.13 / 390 \doteq 1/28 > R_a^S = 1/50$$

Thus it is quite possible that this structure will collpase.

CONCLUSION

In this paper, the necessity and possibility of formulating a deformation checking method for aseismic design of structures has been discussed and a simplified approach to evaluation of nonlinear seismic story drifts of multi-storeyed shear type structures is presented. It should also be pointed out that the practical method for the calculation of inelastic deformation of other type structures should be investigated and the ability of the structure to stand against the earthquakes lies in its deformability under seismic actions. It is, therefore, of great importance to find measures of how to prevent structures from occurence of plastic deformation concentrations, of how to realize reasonable structural layouts and of how to develope good ductility in reinforced concrete members such as good allocation of reinforcements and the use of confined stirrups. All there measures should aim at raising the deformability of structures against earthquakes.

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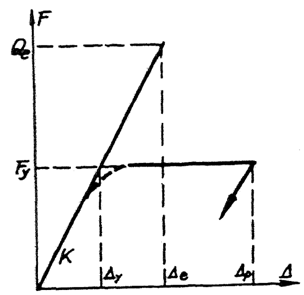
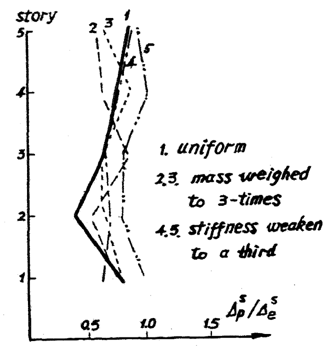
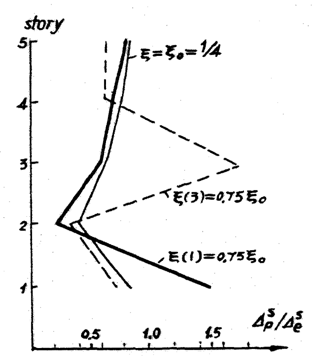


Fig.1



(a) changing the distribution of masses or stiffnesses



(b) changing the distribution of yield strength

Fig.2

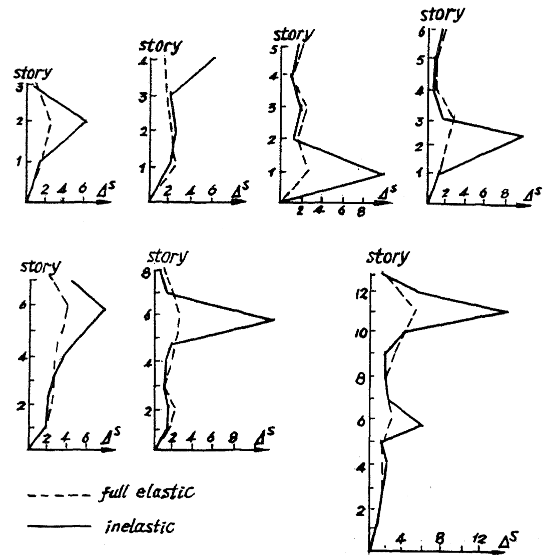


Fig.3 *story drift responses*

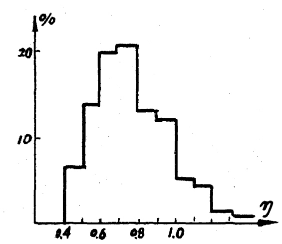


Fig.4

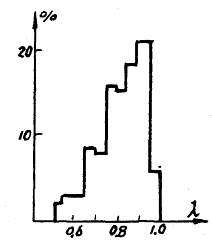


Fig.5

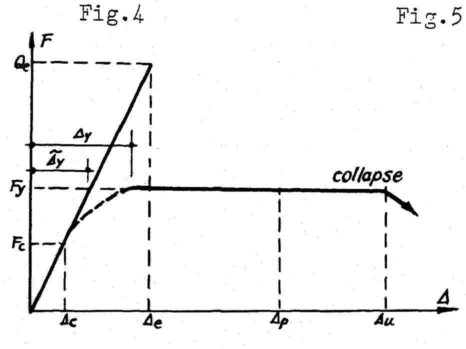


Fig.6