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INELASTIC BEHAVIOUR OF MULTISTORY BUILDING DURING ERTHQUAKE

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Abstract

Various problems associated with earthquake resistant design of multistorey buildings are discussed. Inelastic behaviour, as studied by various investigators is reviewed to provide an insight into the problem.

Introduction

Earthquake resistant design of multistory structures is a complex problem. Building codes specify seismic coefficients for estimating the lateral forces to be considered for design of structures in potential seismic zones. These provisions are mostly based on the experience gained during past earthquakes and are suited to yield economical designs. However, a linear dynamic analysis of structure would indicate that the structure would be subjected to lateral forces much higher than those provided in the codes. From this, one would be inclined to think that structures designed according to code provisions would fail during an actual shock. This is not true. Structures designed to resist relatively smaller lateral force have stood major shocks, without much damage, in the past. This is due to the fact the behaviour of structures is far from linear. The structure dissipates a good deal of energy imparted to it through its non-linear or inelastic behaviour. A multistorey building dissipates energy through some non-structural members and through shear walls. In modern high rise construction, the non-structural elements are being cut down to a minimum to reduce weight of the structure and therefore the frames alone will be required to dissipate all the energy through its own elastic and inelastic action. A study of the inelastic behaviour of such frames is therefore of vital interest. Introduction of inelasticity in structural systems presents a number of computational problems. However with the help of some numerical methods and with high speed digital computer it is possible to analyse nonlinear multistory frames. This paper reviews the workdone by various investigators in this direction to be able to understand this problem.

Earthquake Response of Multistory Structures

During earthquakes, behaviour of multistory structures is essentially a vibration problem in which forces in structural members are computed from the dynamic displacements, velocities and accelerations. However, for obtaining these response parameters it is necessary to convert the building into a mathematically solvable model. This is a very important point and must be carefully examined as different results would be obtained by choosing different models.

A multistory building has been represented by a multiple-degree of freedom system with the columns providing the spring and the relatively rigid floors the masses. The equations of motion for a shear type multistorey framed system can be written in matrix form as follows :

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$$[M]\{\ddot{Z}\} + [C]\{\dot{Z}\} + \{R(Z)\} = -[M]\{\ddot{Y}\} \quad (1)$$

in which M is the mass matrix, C is a damping matrix R(Z) is the restoring force characteristics of springs, Y is the ground displacement and Z is the relative displacement. Dots represent differentiation with respect to time.

Two parameters in the above eqn. (1) need special mention. One, the damping properties represented by C and the other restoring force represented by R(Z). Damping in structures is present due to more than one reason. Friction at the joints, internal friction in material and air damping contribute to this factor. However, all these could be expressed to-gether by an equivalent viscous damping. For convenience, almost all the investigators represent damping in this form and assume this as present between two adjacent floors. This is also referred to as interfloor damping.

Regarding the restoring force characteristics, various investigators have chosen a variety of mathematical models viz. bilinear, elasto-plastic and nonlinear to mention a few. A detailed description of these follows :

Types of Non-Linearities

Fig. 1 shows the various types of nonlinearities considered by various investigators. These can be broadly classified into two catagories-elastic nonlinearity and hysteretic type. These have been mostly adopted for the convenience in computations and are suitable for programming on a digital computer. Some experimental studies have shown that these mathematical models are not far from the actual behaviour observed in some materials of building construction.

Fig. 1(a) is a simple linear model in which the restoring force is directly related to the displacement Z through the stiffness matrix K. Mathematically,

$$\{R(Z)\} = [K]\{Z\} \quad (2)$$

Fig. 1(b) shows a hysteretic bilinear model in which the kink Y is the point where the structure starts yielding. Stiffness of such a member, beyond Y is reduced and the restoring force has to be defined in two parts as follows(1) :

$$R(Z) = (\mathrm{Sgn}\dot{Z})\,(K_1|Z_m| - F_n)\left(\frac{K_1-K_2}{K_1}\right) \text{ for regions of } K_1$$

$$R(Z) = (\mathrm{Sgn}\,\dot{Z})\,F_n\left(\frac{K_1-K_2}{K_1}\right) \text{ for regions of } K_2 \quad (3)$$

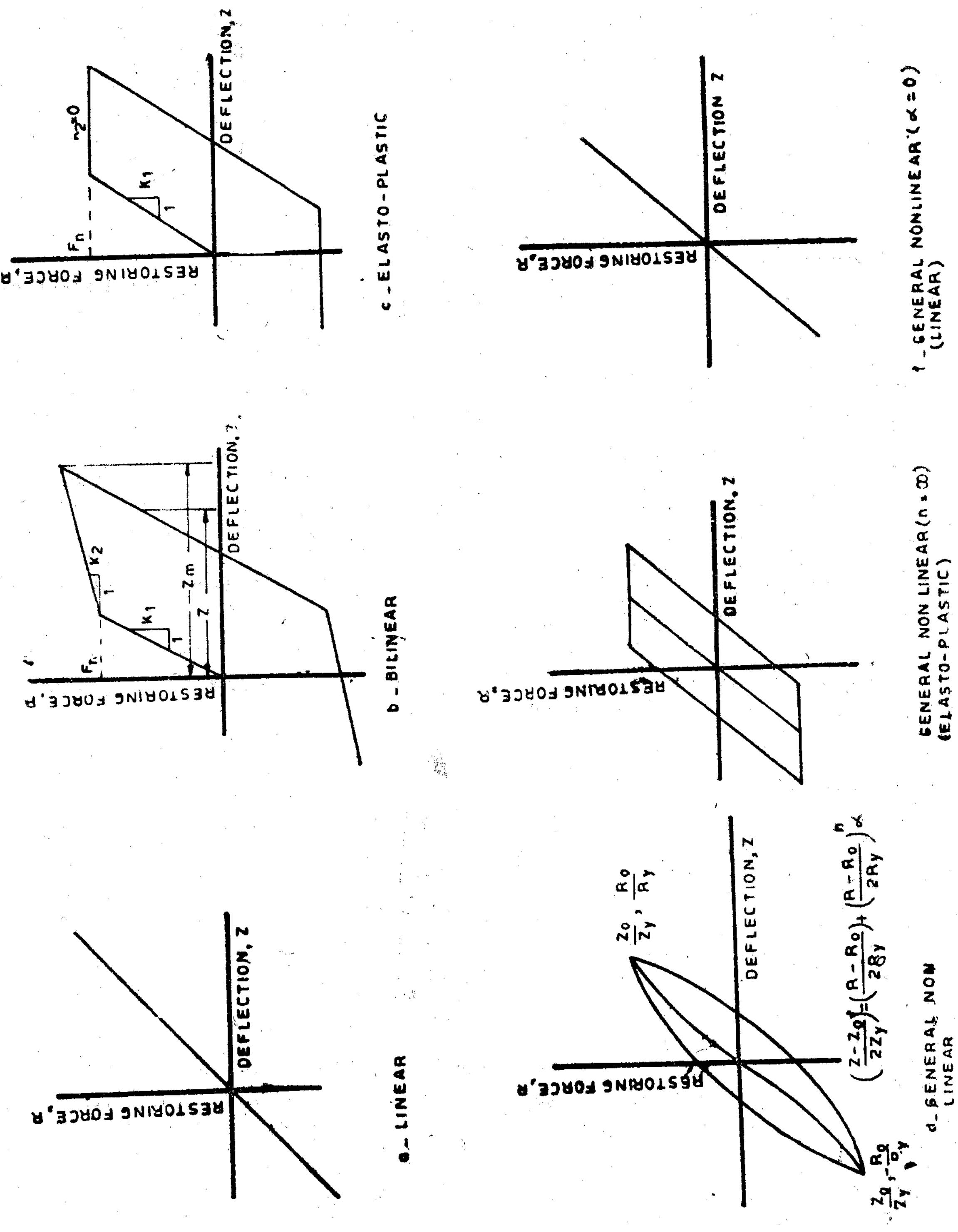
in which the various quantities are as indicated in Fig. 1 (b). The arrows marked on the figure indicate the position when loading is reversed. The elastic bilinear model retraces its skelton curve if loading is reversed.

Fig. 1(c) is a special case of bilinear model in which $K_2 = 0$.

Fig 1 (d) shows restoring force characteristics of a general nonlinear structure. This has been developed by Jennings (2) from the basic Ramberg-Osgood relationships (3). This type of nonlinearity covers a wide range of mathematical models varying from linear to elasto-plastic. The force-displacement relationship can be expressed as follows :

$$\left(\frac{Z-Z_0}{2Z_y}\right) = \left(\frac{R-R_0}{2R_y}\right) + a\left(\frac{R-R_0}{2R_y}\right)^n \quad (4)$$

in which Z_0 is the displacement corresponding to restoring force R_0 at the time of reversal



a_ LINEAR

b_ BILINEAR

c_ ELASTO-PLASTIC

d_ GENERAL NON LINEAR

e_ GENERAL NON LINEAR (n = ∞) (ELASTO-PLASTIC)

f_ GENERAL NONLINEAR (α = 0) (LINEAR)

Figure 1

and Z_y is the yield displacement corresponding to yield force R_y, α and n are parameters to define the order of non-linearity.

The nonlinear structure therefore requires some more parameters to define it. The most important being the yield deflection or yield force. This is commonly referred to as the yield level'. In other words, yield level of a structure is defined as the lateral force which causes initial yielding in the structure.

Fig. 1(e) and Fig. 1(f) indicate the values of r and n which reduces the general non-linear system into elasto-plastic and linear system.

Methods of Solution

Whatever be the restoring force characteristics, the problem is to solve eqn. 1. For linear systems, the solutions are relatively simple and response cound be computed using the concept of response spectrum(4) and mode superposition principle(5,6). However, for all other cases, no direct form of solution is available and invariably one has to employ numerical methods. Popular amongst these are the Euler's method, the Runge-Kutta third and fourth order methods, linear acceleration method and the corrector-predictor method. These have been dealt with in standard books (7,8,9,10) on numerical techniques and are not included here.

The corrector-predictor method is useful if the time increment used in the solution is uniform. Sometimes the input, earthquake data, may not permit use of this method as the time ordinates are unequally spaced. Studies (11,2) have shown that a maximum time increment of $T_p/40$ is necessary, otherwise results would be quite different and absurd. Kobayashi(12) felt that a time increment equal to 0·01 sec may be adequate for computation of structural response.

Electrical analogs have also been used to compute response(13), These are very handy and one can control a large number of parameters by means of switches on a panel. These are becoming obsolete now witn the advent of digital computers.

With the availability of highspeed digital computers now, numerical techniques are finding increased application in analysis. All the methods mentioned earlier are very suitable for programming on a digital computer and are extensively used by various investigators.

Response of Inelastic Systems - A Review of Results Obtained by Various Investigators

This subject has been the centre of interest for the last several years and continues to be so because of the complexity of this problem and the large number of variables that are associated with it. In what follows, a brief review will be made of the results obtained by various investigators so far.

Inelastic response of multiple degree of freedom systems was first studied by Berg(12) followed by a large number of investigators notably Clough(15,16,17) Penzien(18,19), Heidebrecht(20) and Tanabashi(21). These studies presented a broad perspective of the various problems associated with computation of response in post elastic range.

The studies carried out by the various investigators can be grouped into two catagories. On group studies determination of response of multistory buildings with arbitrary theoretical stiffness distribution and yield levels in various storeys. As such these provide some guidelines for predicting behaviour of buildings. The contributions in this group are due to Berg(14), Clough et al(17), Penzien(19), Bycroft(22), Berg and Thomaides(23), Hisada et al (24), Ibanez(25), Berg and Dedeppo(26), Saul et al(27), Veletsos(28), Poceski(29), and Giberson(30)

These investigators have used one or more earthquakes for the purpose of computing response. These earthquakes are generally El Centro May 18, 1940, Taft July 21, 1952 and the artificial shocks developed at the California Institute of Technology(31).

The second group studies response of certain special buildings that are either already existing or are specially chosen for the purpose of the study. Investigators in this group include Clough(17), Giberson(30), Berg(32), Kuroiwa(33), Walpole and Shepherd(34), and Spencer(35).

The studies mentioned above cover steel, reinforced concrete and prestressed concrete buildings represented by various models mentioned in earlier paragraphs.

Discussion of Results

Response of structures has been examined from different angles by various people. However, they all seem to agree that introduction of inelasticity in a structure results in reduction of structural response. It is due to this that structures designed to resist very little lateral force are able to withstand moderate shock with little or no damage. Whereas most of the investigators report that, generally, inelastic deformations are less compared to those of an associated linear system, Clough, et al(17) report that it is the other way round. However, they observe that these deformation vary widely through the structure itself. Hisada, et al(24) have reported that inelastic deformations are about the same as that of an associated linear system. Veletsos(28) observes that the relationship between maximum inelastic deformations and deformations of associated linear systems is the same as that for a single degree of freedom system with the same period and subjected to same excitation. He shows that displacements in inelastic systems are not equal to linear systems and gives the ranges of periods where displacements are lower, equal and higher than linear systems.

Effect of Fundamental Period on Inelastic Response

The inelastic deformation spectra obtained(19,23,24,25) shows that fundamental period of structure is an important parameter in determining response. Like the displacement spectra of linear systems, inelastic response in all storeys increases generally with the increase in fundamental period.

Larger displacements as would be expected in structures of relatively larger fundamental periods could prove disasterous. Ibanez(25) has stressed this point and has suggested that functional failure may occur due to displacement rather than overstressing.

Effect of Yield Level

Yield level is the parameter that defines the magnitude of lateral force which causes the structure to start behaving inelastically. (This parameter is therefore a property of the structure). This is commonly expressed in terms of fraction of acceleration due to gravity and assumed to act at floor level.

Berg and Thomaides(23), Penzien(19), Poceski(29), Wen and Janssen(36) and others conclude that for earthquake type excitation, response gets reduced with decrease in yield level. Also, maximum response is associated with highest yield level. However, Penzien(19) observes that there is a certain optimum yield level below which elasto-plastic response increases. He suggests this level as 0.10 g for tall flexible structures with long periods and 0.20 g for stiff structures with short period. These values were suggested only for El Centro shock of May 18, 1940 and should not be taken as universal. Berg and Thomaides(23) are are of the opinion that this level is 0.06 g. They also observe that decrease in yield level is accompanied by decrease in total input energy at all levels of damping.

Effect of Stiffness Distribution

This aspect has received relatively less attention so far. Bycroft(22), Hisada et al(24) and Veletsos(28) have studied the effect of stiffness distribution on the inelastic response of structures. The ratio of top storey stiffness to bottom storey stiffness (K_T/K_B) has been kept varying linearly from 0 1 to 0.5 for a twenty storey building(24). It was found that in structures with linear stiffness reduction towards higher storeys, maximum storey displacements increase remarkably in upper storeys but decrease in lower storeys. On the basis of that study, reasonable equitable distribution of ductility in various storeys can be expected if K_T/K_B is equal to 0.20.

Bycroft(22) assumed a linear variation of stiffness (K_n) and strength (G_n) with height **h** as follows

$$K_n \propto (1 + \rho \, . \, Z_n/h)$$
$$G_n \propto (1 + \rho \, . \, Z_n/h) \qquad (5)$$

in which Z_n = position of point midway between (n—1)th and nth floors measured from top of structure. $\rho = 0$ corresponded to a uniform building. Studies indicated that ρ is vital in deciding about response in inelastic systems but not so in elastic systems. He and Veletsos(28) felt that optimization of ρ is a difficult task. If this were possible, economic designs of multistory frames would be worked out distributing the plasticity over the height of the structure.

Effect of Ground Motion

The results presented by various investigators would be comparable only if everyone choses the same accelerogram for computations. As long as this is not there, the results will have only limited qualitative usefulness. Studies carried out by Gibreson(30) recently, have indicated that response characteristics are determined by properties of structures rather than the earthquakes. These conclusions have been drawn by him after a detailed study of a twenty storeyed structure subjected to seven different earthquake motions. However, most people present results for particular shocks only and warn against making any generalized conclusions for earthquakes in general.

Other Effects

While attempts are being made to understand the structural response in inelastic range, some studies on secondary effects have also been reported.

Goel(37) has studied the effect of axial deformations on the inelastic response of frames subjected to earthquakes. It is found that response is affected to the tune of 10 to 20% by considering this aspect.

Nigam(38) has shown that inelastic response depends on the interaction between forces and displacements at a section during the process of yielding. He concludes that significant changes in response could be expected due to this interaction and presents a series of curves to show this effect. Use of these curves for inelastic design has also been explaind by him.

Kobori et al(39) have considered the effect of ground compliance on elasto-plastic structures and conclude that response is greatly affected to this.

Odaka et al(40) analysed some actual multistoreyed structures having steel frames with reinforced concrete walls for the Kanto earthquake considering bilinear characteristics and could explain the damage caused to these during this shock. However, he observed that distribution of ductility is quite different in different types of buildings.

Conclusions

The foregoing analysis of the problem of inelastic response shows that this field is attracting attention of a number of investigators. It is interesting to see that the same problem has been attempted by many people employing various numerical methods. The results obtained by them are sometimes not consistant and are even contradictory to findings of some others. Housner(41) points out that this difficult field is associated with complicated problems and it is difficult to grasp the general significance of computations. The problem needs examination from the point of view of design of structures. In an elastic analysis, the base shear and distribution of shear is suggested based on consideration of various parameters. On the other hand, in a nonlinear case, it would be useful to proportion the members such that same ductility is obtained in all the storeys. This sort of optimization would be rather difficult to achieve, but it would be quite useful to have a relationship between the intensity of ground motion and the maximum ductility in a structure.

It is hoped that future work on this problem will examine the above points and will clarify the doubts that have been raised due to inconsistencies in various reported investigations.

Acknowledgements

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Abstract

PRE-CAMBRIAN STRATIGRAPHY AND GEOCHRONOLOGY OF PENINSULAR INDIA By S.N. Sarkar, Professor and Head of the Dept. of Applied Geology, Indian School of Mines, Dhanbad, Dhanbad Publishers, India December, 1968

On the basis of systematic stratigraphic tectonic and metamorphic studies in certain critical Pre-Cambrian regions in Peninsular India and Ceylon, reinterpretation of all relevant data from the other areas, and more than 500 radiometric age data (by K-Ar, Sr-Rb and Pb isotopic and isochron methods) available upto date, the author has suggested a revised correlation and classification of the Pre-Cambrians of this subcontinent and has established a generalised succession of the dated orogenic cycles and phases. Some of the important conclusions are :—

(a) The Older Metamorphic Group of Singhbhum represents the oldest orogenic belt (c. 3200 Myr) recognisable in India, and there are evidence of the presence of Basement Complex older than 3000 Myr in Rajasthan, Mysore and Madras.

(b) The Dhawar, Iron Ore, Charnockite-Khondalite (Eastern Ghats I), B.G. Complex and Bundelkhand cycles accompanied by widespread granitic activity, closed between 2500 and 2700 Myr and are broadly correlatable. These represent the relics of continental nucleii older than c. 2500 Myr. Within the younger belts the relics of the older basement are often present.

(c) Singhbhum orogenic cycle in Singhbhum-Gangpur region (closing at c. 850 Myr), is correlatable with metamorphism and granitic activity in Gaya (955 Myr), Gurpa (930 Myr), Ranchi-Muri (890-970 Myr), Dhanbad (893-1086 Myr) and Sausar (864-996 Myr) regions and all belong to the Satpura cycle, which again may be provisionally correlated with the Aravalli cycle closing at c. 950 Myr.

(d) The deposition of Singhbhum, Gangpur and Dhanjori groups took place between c. 1700 and c. 2000 Myr, of Kolhans at c. 1600 Myr and of Aravallis at c. 2000 Myr (?)

(e) In the Cuddapah basin (type area) deposition commenced at c. 1500 Myr and Cuddapahs are correlatable with the Kaladgis. The sedimentation of the Lower Vindhyans (type area) commenced at c. 1100 Myr and the Upper Vindhyans at c. 920 Myr. Vindhyans may be broadly correlated with Kurnools, Bhimas and Badamis.

(f) Delhi cycle closed ot c. 750 Myr and Malani and Khetri phases are still younger (c. 600 Myr). Prominent metamorphic and/or granitic activity affected part of S. India at c. 2000, 700-800 Myr, Eatern Ghats belt at c 1600 Myr, Madhya Pradesh at c. 2100, c. 1450-1750, c. 1300 c. 900 Myr.

(g) A pronounced orogenic-metamorphic cycle with granitic activity (c. 450-600 Myr is recognisable in different parts of India e. g. Rajasthan, Monghyr, Assam, Eastern Ghats, Travancore and Ceylon (Indian Ocean cycle).

(h) The orogenic metamorphic cycles closing at about 3200, 2600, 2000, 1600, 900 and 600 Myr in India are broadly correlatable with the corresponding orogenic events recognised in other continental shield areas of the world. The Indian Pre-Cambrians may be provisionally grouped as follows :—

Pre-Cambrian V	(600-900 Myr) :	Chattisgarh basin, Up. Vindhyan, Khairagarh, Malani, Monghyr (?)
Pre-Cambrian IV	(900-1600 Myr) :	Cuddapah, Lo. Vindhyan, Satpura, Aravalli and Delhi.
Pre-Cambrian III	(1600-2500 Myr) .	Satpura and Aravalli (in part), Amgaon, Eastern Ghats (II).
Pre-Cambrian II	(2500-3000 Myr) :	Iron ore, Dharwar, B.G. Complex, Bundelkhand, Eastern Ghats I).
Pre-Cambrian I	(3000-3500 Myr) :	Older Metamorphics (Bihar, Orissa), Basement Complex (S. India, Rajasthan).