RESPONSE SPECTRA FOR ELASTIC AND ELASTOPLASTIC SYSTEMS SUBJECTED TO EARTHQUAKES OF SHORT DURATION

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SYNOPSIS

The response of elastic and elastoplastic systems with large plastic deformations to earthquakes of short duration is considered. It is found that the principle of conservation of energy and the rule of approximately equal maximum displacements of elastic and elastoplastic systems are not applicable. Usually the maximum displacement of the elastoplastic system is smaller than that of the elastic system, even for systems with low yield level, but no rule can be stated for this. The possibility of repetition of earthquakes and plastic deformations is considered to be an important factor in establishing earthquake design criteria.

INTRODUCTION

Recent strong-motion earthquakes have shown that the intensity of ground motion can be very high, and the energy which the earthquake feeds into a structure is also very high. That energy in the structure has to be dissipated. The codes of earthquake-resistant design provide much smaller seismic forces than the actual forces of a strong-motion earthquake. Thus, the structures have to work in the plastic range. The energy is dissipated by internal friction, plastic deformations, and possibly by structural damage.

The problem is obviously nonlinear, but according to the codes, the structures are designed as if linear. Proposals have been made to use energy methods for design. The energy approach is appropriate, but for practical purposes the design method should be simple. The methods applied in present codes do have the advantage of simplicity, but their use raises the question of how to deduce the real behaviour during strong-motion earthquakes of a structure designed according to a code, as an elastic system, and to find out what is the safety of the structure against collapse or damage.

One way of representing the response of elastoplastic systems has been by the ductility coefficient, which is defined as the ratio of total displacement to the displacement at yielding. The ductility coefficient cannot always represent the state of a structural element. For example, the ultimate curvature of a reinforced concrete element does not much

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depend on the ductility coefficient as the axial load plays a very important role. For instability due to axial load or occurrence of nonstructural damage, it is important to know the maximum displacements.

The author thinks that a much simpler and better representation of response spectra of elastoplastic systems is obtained by means of the yield level (Figs. 1, 2, 3) rather than by the ductility coefficient. In this way the spectra are related better to design procedures provided by codes. This representation of spectra of elastoplastic systems is not new as it has been used by G. Berg and S. Thomaides (1).

The spectra of elastoplastic systems have been the subject of numerous investigations, and there have even been analyses of spectra of elastoplastic systems subjected to simple ground shocks (2). The conclusions about the relationship between displacements of elastic and elastoplastic systems found in Ref. 2 for simple ground motion are similar to those found for real earthquakes, however, the analysis of three real earthquakes of short duration, presented herein, leads to somewhat different conclusions.

RESPONSE SPECTRA

The system considered herein is a one degree of freedom system with equivalent viscous damping, elastic and elastoplastic, with force-displacement diagram as shown in the insert of Fig. 1. This is, of course, an idealization of a real structure. This type of force-displacement relationship was chosen because of its simplicity. The study was intended to exhibit the nature of the response of nonlinear, weak structures, to strong earthquakes of short duration (shock type). For this purpose, three earthquakes were analyzed: the Port Hueneme, 1957, NS component (3), the Parkfield, 27 June 1966, station No. 2 (4, 5), and the Matsushiro, 1966, station Hoshima A, No. 53(6) earthquake. All three earthquakes are characterized by relatively small magnitudes, high ground acceleration, and short duration of the intense motion.

The Port Hueneme, 1957, earthquake consisted of a single displacement pulse of about 1 sec. duration. The maximum ground acceleration was about 0.17g. An enlarged copy of the record in Ref. 3 was analyzed, and scaled to a maximum acceleration of 0.30g.

The Parkfield earthquake was essentially a single displacement pulse of about 1.5 secs. duration, and a maximum ground acceleration of 0.5g. The first four seconds of the accelerogram given in Ref. 4 was analyzed. The zero velocity correction was made by a straight line fit. This truncated the earthquake, however, for the purpose of comparing the responses of elastic and elastoplastic systems, which was the main purpose of the analysis, this would not introduce significant error. Actually, the difference between the spectrum of the elastic system presented in Fig. 2, and that in Ref. 5 is only a few percent, reaching to about 10% at long periods.

The record of the Matsushiro earthquake analyzed herein was the strongest in the sequence of many shocks in the Matsushiro area, having maximum ground acceleration of about 0.42g. The record was taken from Ref. 6, and only the significant part of the record, 2.5 secs duration, was analyzed.

The computation of the response spectra was carried out by digital computer IBM 1130. The program was written by assuming linear variation of the acceleration in a time interval of 0.01 sec. The results of the analysis are presented on Figs. 1, 2 and 3. In the figures Qy represents the yield force level. Damping is 5% of critical, based on the initial slope of the force-displacement curves.

ANALYSIS OF THE RESULTS

Figure 1 shows the results of computations of response spectra of elastic system (Qy = ∞) and elastoplastic systems of the Port Hueneme 1957 earthquake (scaled-up intensity). The results are somewhat unusual. In the past it has been suggested that for shock-type ground motion, as this earthquake is, the principle of conservation of energy should be applied, i.e., the energy stored in a completely elastic system should be equal to the energy stored and dissipated in the elastoplastic system. However, the results presented on Fig. 1 show that this is not true, and that there is no simple relationship.

The weakest system, that is, the one with the lowest yield level, has the lowest response over most of the spectrum. At short periods, up to about the period at which the maximum acceleration response occurs, the response of the elastic system is lowest. The highest response is associated with the highest yield level, so that the weaker the structure, the smaller the maximum relative displacements, which is an unexpected result. The maximum response of elastic systems occurs at a period approximately equal to the length of the significant part of the record. At long periods, all spectra approach the maximum ground displacement.

The Port Hueneme earthquake was a small shock, so there is a question whether the results for this earthquake would also be found for stronger earthquakes of short duration. The Parkfield earthquake is the strongest acceleration ever recorded and the results shown in Fig. 2 are similar for the Port Hueneme earthquake (Fig. 1). Over most of the spectrum the system with the lowest yield level has the lowest response. The system with the highest yield level has the largest response, except at the portion about the period of 1 sec., where the system with yield level of 8%g is highest, so that a decrease of yield level does not always mean a decrease in response. At short periods, up to about the period at which maximum response acceleration occurs, the spectrum of the elastic system is lowest, however, the response spectra of elastoplastic systems of yield level Qy = 4%g and Qy = 8%g are not much higher. The maximum response displacement is at period of about 2 secs which is approximately equal to the significant part of the record. At long periods all spectra approach the maximum ground displacement.

The Matsushiro earthquake was a small magnitude shock with rather high ground acceleration of 0.42g. The relations between the spectra of elastic and elastoplastic systems of this earthquake are similar to those of the earthquakes discussed previously, however, the spectra of the elastoplastic system are not much higher than the spectrum of the elastic system. The first two earthquakes, the Port Hueneme and the Parkfield, are of shock type, but the Matsushiro earthquake is not of shock type. Thus, the results presented herein are not due to the type of earthquake. Most probably they are due to the short duration of each of the earthquakes.

Results similar to these have been presented in Ref. 1, but there was found that, if the yield level is higher than about 6%g, the maximum displacement of elastoplastic systems is not higher than the same of elastic systems, and that the yield level is about 1/3 to 1/5 of the maximum ground acceleration. But in the analyses of earthquakes of short duration presented herein, the maximum response displacements of elastoplastic systems are smaller than the same of elastic system, even for systems of low yield level of about 1/12 of the maximum ground acceleration. That is the principal difference between spectra of earthquakes of "long duration" like El Centro, 1940 and Taft, 1952 analyzed in (1), and the spectra of earthquakes of short duration analyzed herein.

Figure 4 shows displacement response versus time of a system with a natural period of T = 0.64 secs. and damping 10% of critical based on the initial slope of the force-displacement curve, of the Port Hueneme earthquake. It is evident that the response of elastoplastic systems consists of only one large amplitude cycle, followed by small cycles. The response is similar to the response of a long period system. In the first half cycle the response of the elastoplastic system is higher than the response of the elastic system, and in the second half cycle the resulting maximum displacement of elastoplastic system is smaller than the maximum displacement of elastic system. When the yield level is high, the increase of the maximum displacement in the first half cycle is small, and the stored energy is high, and consequently the resulting maximum displacement in the second half cycle is high. In that way the maximum displacement of elastoplastic system could be higher than for an elastic system. Such is the case with the spectrum of elastoplastic systems of Q_y = 10%g (Fig. 1). It means, contrary to what was found before, that at periods longer than a certain period, the response of elastic systems is not higher than the response of elastoplastic systems, and at short periods the response of elastic systems is not lower than the response of elastoplastic systems. Neither does the principle of conservation of energy hold completely.

The relations of responses of elastic and elastoplastic systems, and characteristics of the response spectra of elastoplastic systems in function of the yield level, depend on the relation of acceleration pulses, which, in turn, depend on the position of inflection point of ground displacement pulse. Acceleration pulses of equal intensity in opposite directions, as are the shocks analyzed in Ref. 2, are only one particular case of possible ground motion.

From Fig. 4 it is evident that if the duration of strong motion had been longer, the response of systems of low yield level would have larger maximum displacements. Therefore, it is of interest to examine the response to the Parkfield earthquake. Although the Parkfield earthquake is a stronger and longer duration earthquake than the Port Hueneme, the relations of the response spectra of elastic and elastoplastic systems (Figs. 2 and 5) are similar to those of the Port Hueneme earthquake. The low yield level systems behave as long period systems. The response of yielding systems practically ends with the significant part of the ground motion. The response of yielding systems practically consists of one large displacement cycle (Fig. 5). In the first half cycle the accumulated strain energy in the elastoplastic systems is lower than the same in elastic systems. Consequently, the contribution of that energy to the maximum displacement in the second half cycle is lower, and the maximum displacement of elastoplastic system is lower than the maximum displacement of elastic system.

Theoretically speaking, a system with zero yield level would have a maximum displacement equal to the maximum ground displacement. For the shock-type ground motion, the first two analyzed earthquakes, the maximum spectral response displacement of the elastic system is greater than the maximum ground displacement, and the response displacements of yielding systems, even of very low yield level, would be lower than the response of the elastic system for longer periods. It would be of interest to compare the maximum ground acceleration and velocity, the degree of damage to structures, and the response of elastoplastic systems. The analyzed earthquakes had relatively high maximum ground velocity, but did little damage. This was particularly striking in the case of the Parkfield earthquake. The fact that real structures are nonlinear would lead one to believe that they would have much smaller response than linear structures and this might account for the small amount of damage.

One measure of the intensity of an earthquake defined by G. Housner, is the area under the response spectrum. For earthquakes of short duration, this is smaller than the intensity of long duration earthquakes of the same maximum ground acceleration, because the response spectra of earthquakes of short duration are lower at long periods than for long duration earthquakes. However, the intensity, by Housner's definition, would be an overestimation of the real damage potential for ductile structures.

A good example of a strong-motion earthquake of short duration was the Skopje, 1963 earthquake. Analyses of damaged structures indicate very high relative velocity response, about 90 cms. per sec. Most of the destroyed or badly damaged structures were of brick masonry type. The reinforced concrete structures suffered little damage. Thus, on the basis of the behaviour of ductile structures, the earthquake could be classified as one of low intensity.

It seems the maximum ground velocity is not always a good indication of the intensity of an earthquake. The duration of strong ground motion is one of the most important factors in the damaging effect of an earthquake.

DESIGN IMPLICATIONS

A common philosophy in designing earthquake-resistant structures is, the structures should withstand moderate intensity earthquakes which might occur several times in their lifetime without or with little damage, and during strong-motion earthquakes the structures must not collapse.

Consider a reinforced concrete structure. That structure reinforced with a small percent of reinforcement will have a lower yield level than the same structure reinforced with a high percent of reinforcement. But the ultimate curvatures and rotations of the structural elements of both structures will be not much different. In fact, an element with small reinforcement, in bending, may have a higher rotational capacity than the element with a high percent of reinforcement. The chief difference in behaviour would be that the element of low yield level (small reinforcement) will get plastic deformations earlier than an element of high yield level (high reinforcement).

The results presented in this paper show that the response displacements do not depend strongly on the value of yield level. In fact, systems with lower yield level have lower response displacements than the systems with higher yield level. If only safety of the structures against collapse is taken in account, then it seems reasonable to design structures for rather low seismic forces. However, in this case, there is a problem of accumulation of plastic deformations in one direction due to a sequence of small intensity earthquakes which might cause damage and necessitate costly repairs. In order to solve this problem it is most important to know the expected frequency of occurrence of earthquakes of various intensities during the life of the structure. The structure should be designed to resist, in the elastic range or with small plastic deformations, those earthquakes for which there is a reasonable probability of occurrence during the life of the structure.

It seems that the frequency of occurrence of earthquakes (not the maximum intensity of a single earthquake), is the most important factor in economical earthquake-resistant design. In countries with frequent earthquakes, not of the highest intensity, the design seismic forces should be highest, and, in the countries where earthquakes seldom occur, regardless of their maximum possible intensity, the design seismic forces might well be small. For example, in Skopje, Yugoslavia, strong earthquakes occur very seldom (approximately each 500 years). It seems that an earthquake of 6 degrees on the MMCS scale is as intense as could be expected frequently. Thus, structures should be designed to withstand this intensity without damage or with small plastic deformations.

In view of this, it seems that the maximum design seismic forces, for ductile structures, at short periods should not be higher than 10%g, as it is in SEAOC code, but at long periods the forces should be much smaller than the SEAOC code provides.

It should be noted that there are some limitations on the applicability of the results obtained. Results for only three earthquakes should not be generalized. Also the results were obtained for elastoplastic systems whereas real structures are not elastoplastic, the *force-displacement relationship during vibrations may change very much*, especially in the case of reinforced concrete structures. However, the changes in force-displacement relationships during earthquakes of short duration are not so effective as they are during earthquakes of long duration, because there are not many chcles of vibration. Also, there is a question as to the applicability of results obtained for one degree of freedom systems to systems of many degrees of freedom.

CONCLUSIONS

The response spectra of elastoplastic systems usually are lower than the response spectrum of an elastic system, even for systems of quite low yield level. Usually the spectrum of lowest yield level system has the lowest values, but not invariably. These characteristics of the spectra are due to the short duration of the strong ground motion.

A most important factor which should be taken into account in establishing design seismic forces is the frequency of occurrence of earthquakes during the life of the structure. Also, the duration of strong ground motion is an important factor in the damage potential of the earthquake.

REFERENCES

1. G. V. Berg and S. S. Thomaides, "Energy Consumption by Structures in Strong-Motion Earthquakes," Proceedings of the Second World Conference on Earthquake Engineering, Vol. II, Tokyo, 1960.

2. A. S. Veletsos, N. M. Newmark and C. V. Chelapati, "Deformation Spectra for Elastic an Elastoplastic Systems Subjected to Ground Shock and Earthquake Motions," Proceedings of the Third World Conference on Earthquake Engineering, Vol. II, New Zealand, 1965.

3. G. W. Housner and D. E. Hudson, "The Port Hueneme Earthquake of March 18, 1957," Bulletin of the Seismological Society of America, Vol. 48, April, 1958.

4. S. T. Harding and W A. Rinehart, "The Parkfield, California, Earthquake of June 27, 1966," U. S. Government Printing Office.

5. G. W. Housner and M. D. Trifunac, "Analysis of Accelerograms – Parkfield Earthquake," Bulletin of the Seismological Society of America, Vol. 57, December, 1967.

6. Strong-Motion Records in Matsushiro Swarm Area, Earthquake Research Institute, The University of Tokyo, Tokyo, Japan, February, 1967.

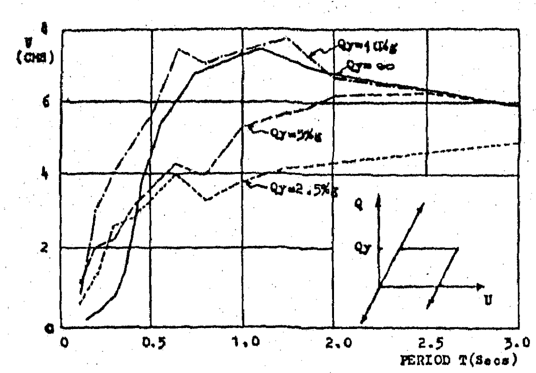

FIG.1 DISPLACEMENT RESPONSE, THE PORT HUENEME 1957 EARTHQUAKE (*MODIF. INTENSITY*), *NS COMPONENT DAMPING 5% OF CRITICAL.*

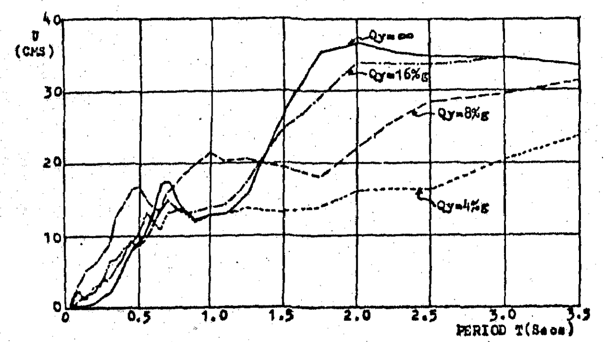

FIG.2 DISPLACEMENT RESPONSE, THE PARKFIELD 1966 EARTHQUAKE STATION No.2, DAMPING 5% OF CRITICAL.

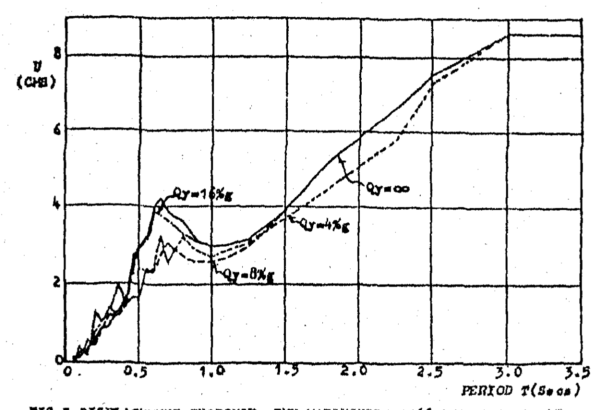

FIG.3 DISPLACEMENT RESPONSE, THE MATSUSHIRO 1966 EARTHQUAKE, STATION HOSHIMA A; DAMPING 5% OF CRITICAL.

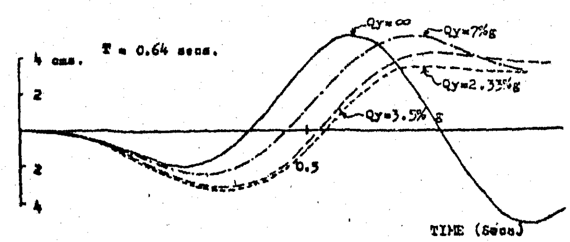

FIG.4 DISPLACEMENT RESPONSE, THE PORT HUENEME 1957 EARTHQUAKE (MODIF. INTENSITY), NS COMPONENT; DAMPING 10% OF CRITICAL.

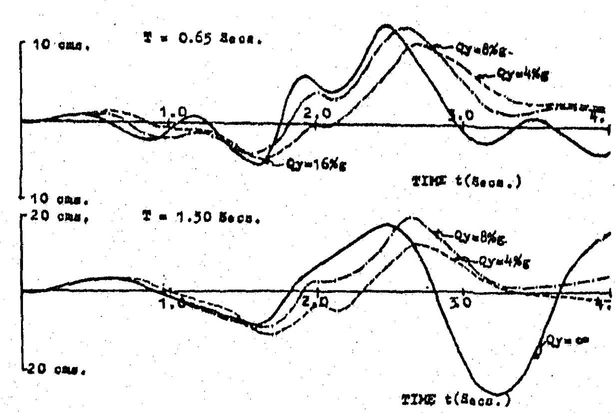

FIG.5 DISPLACEMENT RESPONSE, THE PARKFIELD 1966 EARTHQUAKE, STATION No.2; DAMPING 5% OF CRITICAL