EARTHQUAKE ENGINEERING RESEARCH

by

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Introduction

From the historical point of view it can be seen that research in earthquake engineering is of very recent origin, all of the significant research having been accomplished within the past twenty-five years. In fact, earthquake engineering itself is of recent origin. The first building code containing explicit earthquake design requirements that were enforced appears to have been that introduced at Messina, Italy following the destructive earthquake of 1908. This code was formulated without the benefit of earthquake engineering research and without the benefit of any very precise idea of what an earthquake really was. The code was of the $10\%_g$ type, which requires that the structure be designed to resist a static horizontal force equal to one-tenth the weight of the structure. Since the buildings in Messina were constructed of unreinforced masonry, the code aimed at increasing the earthquake resistance of this type of construction and, in fact, it did so. The fact that improvement in earthquake resistance could be achieved without really understanding the nature of the earthquake or the nature of building response during earthquakes is rather surprising.

When we examine the methods of designing and constructing buildings to resist earthquakes that are employed in the various countries in the seismic regions of the world, it becomes clear that earthquake protection is not basicly intended to protect individuals but, rather, it is employed to protect a functioning economy. This is shown by the adoption of earthquake-protective provisions by developing countries. A country that is undeveloped in the industrial sector will, in general, not have earthquake requirements in building codes and, in fact, the building codes themselves will be rather rudimentary. However, as the economy develops, and factories, dams, power plants, etc. are constructed, society feels that this investment should be protected against earthquakes.

The precise nature of the process by which a society decides to spend some of its resources on earthquake protection is not clear. Apparently, when the development of the economy reaches a certain point a feeling builds up that earthquake protection should be provided. It also appears that the more highly developed the economy, the greater is

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the effort that society is willing to devote to providing earthquake protection. We can see this not only in the various foreign countries, but also in the communities in my own country (U.S.A.). Coinciding with the great economic development in the United States during the past decade there has built up a much greater interest in protective measures against earthquakes; and, in general, those communities in seismic regions where there is not much industry.

To understand the development of earthquake protective measures it must be noted that the problem can be divided into two categories: first, those that we may call the "social" aspects of the earthquake problem, and secondly, those that we may call the "technical" aspects of the earthquake problem. The social aspects of the problem are those in which the decisions to be made involve considerations of the effects on the community as a whole; that is, the effects upon society. The technical aspects are those involving decisions that are made on the basis of physical laws, mathematics, experimentation, and design expediency without consideration of the effect on the community as a whole. The adoption of earthquake provisions in building codes is a social problem in that it represents implicitly a decision on the part of society to provide a certain measure of earthquake protection. The technical aspects of the problem involve such things as research and design. I want to distinguish between the social and the technical aspects because the point of view involved, the method of arriving at decisions, and the type of research required are quite different for the social aspects than for the technical aspects, and unless this difference is kept in mind, the true nature of the problem will not be apparent.

Socio-Seismic Problems

The social aspects of the earthquake problem are very important but they do not receive the attention they merit from engineers and scientists. Building codes that set standards of construction are one manifestation of the social problem. These determine the degree of protection or, conversely, the extent of damage that society is willing to risk. A rational analysis of this problem would require a determination of the cost of providing certain degrees of protection against earthquakes, the probability of experiencing destructive ground motions, and the amount of damage and the cost of repairs required to rehabilitate the damaged structures. A cost analysis based on these factors would enable some rational decisions to be made as to appropriate degrees of earthquake protection. I am referring here not only to buildings but also to bridges, dams, freeway structures, etc. It is not clear how the decisions are arrived at as to the amount of earthquake protection to be provided. All of the information required to make such decisions is certainly not available at present. We see also that in different countries quite different decisions are arrived at. I do not mean here purely formal decisions. These are frequently empty of substance in that the formal decision says one thing, but the standard practice is quite different. It appears that, at present, the making of these decisions is something like a game of pushball in which numerous individual contestants are each trying to push a large ball in different directions. The ball takes an erratic course, but on the average, over a considerable time, moves in the direction most favored by the majority. Because of this it is very difficult to evaluate the process.

After a destructive earthquake it is not uncommon for the proposal to be made to relocate the damaged city and, in some cases, the city has been abandoned and a new city built. The most recent example of this is the town of Valdez in Alaska. After the earthquake of March, 1964 it was decided to abandon the old town and, at a distance of some five miles, to build a new town upon a site judged to be less hazardous. There are other examples of such relocation of cities in Central and South America. Proposals for relocating cities have been offered and cities have been relocated in the past in Europe and North Africa. The decision to relocate a city would be subject to rational analysis if all of the information were available.. To make such a decision requires a knowledge of the frequency of occurrence of earthquakes, the intensities of the ground motion, the degree of damage to be expected, and the cost of repairs. This must be balanced against the cost of rebuilding the city at a new location and the monetary value of the convenience of one site relative to the other. At present such information is not available, and this raises the question as to the validity of the decisions made in the past to move or not to move a city to a new location.

Another social problem that must be given consideration is the question of the utilization of land. It is known that certain types of soil are not suitable, because structures built on them will be subject to damage in the event of an earthquake. An example of this is the soil underlying much of the city of Niigata in Japan. The earthquake of June, 1964 produced a liquefaction of the soil over a large area of the city with the result that many buildings settled and tilted out of plumb. It has been estimated that the earthquake caused almost one billion dollars of damage, most of it attributed to the failure of the soil. The question then arises, should the government permit the construction of buildings on such soil? It is clear that the problem is different in Japan than it would be in the United States. In Japan, a mountainous country, most of the flat areas suitable for oceanfront cities are the alluvial fans of rivers coming out of mountain canyons. These alluvial plains, being of relatively recent deposition, are soft, with many undesirable properties so far as earthquakes are concerned. However, in Japan, the lack of suitable alternatives would make it very difficult to prohibit building on such sites, for the convenience of the location outweighs the hazards. The same problem exists, for example, in Alaska. This is also a mountainous country, and the only suitable locations for port cities are on alluvial outwash fans of recent deposit. Questions are currently arising in California as to whether building should be permitted in areas subject to earth slides which might be triggered by earthquakes, and whether building should be permitted on soft ground which may consolidate or lurch during an earthquake. Just how far government agencies should go in deciding which regions should not be built upon is an unresolved problem which is bound to become more important as the population increases and as cities increase in size.

Social problems of the foregoing type are certain to arise with greater frequency in the future. If these decisions are to be made on a rational basis it will be necessary to do research to develop the required facts and information.

Techo-Seismic Problems

At the Third World Conference on Earthquake Engineering held in New Zealand in 1965 there were presented 125 technical papers which can be taken to be representative of current thinking in the field and indicative of the research interests. Of these, three were directed to socio-seismic problems, and 122 were directed to techno-seismic problems. Of the technical papers, over 90% could be classified as basic research, and less than 10% as applied research.

By basic research I mean a study of the earthquake problem to develop general information and understanding of the nature of the ground motions, the behavior of buildings, etc. By applied research I mean study aimed at providing a solution for a specific design problem. The papers on applied research are particularly interesting to practicing engineers,whereas the papers on basic research are more interesting to university research workers. It is not possible in the time available to describe all of the interesting recent results of research, but I would like to mention a few items that seem to me to be of particular interest to practicing engineers. Since severe earthquake ground motion will force a structure to vibrate beyond the elastic limit and into the plastic range it is particularly important to understand the nature of plastic vibrations. It was shown in one of the papers of the Third World Conference that for a one-degree of freedom elasto-plastic system subjected to earthquake-type excitation the maximum displacement was approximately equal to the maximum displacement that an elastic system having from 4 to 5% of damping would experience. That is, two one-degree of freedom systems which, for small oscillations have zero damping and the same natural period, would under severe earthquake excitation experience maximum displacements that would be less for the elasto-plastic system than for the undamped elastic system. It would be approximately the same as the maximum displacement the elastic system would attain if it had about 4 to 5% of critical damping. This gives an idea of the approximate equivalent amount of damping introduced by deformations beyond the elastic limit. A study reported on in the Second World Conference dealt with two one-degree of freedom systems, having the same natural peiod and the same percentage of viscous damping, and excited by extremely severe earthquake ground motions so that one of them behaved in an elasto-plastic manner, whereas the other remained linearly elastic. It was found that for moderate amounts of viscous damping the maximum displacement of the two systems were approximately the same. This is somewhat cruder than the preceding relation but it is especially simple to handle.

The foregoing two findings are very informative. They tell us, for example, that the spectrum curves calculated for elastic systems can also be used to derive information about the behavior of elasto-plastic systems. We may take the readings from the elastic displacement spectrum curve as the approximate maximum displacement that the system would receive if it were excited into the plastic range. The velocities and accelerations, however, would not be the same.

The large amplitude vibrations during earthquakes are of particular interest. If the ground motion is sufficiently mild, the structure will vibrate within the elastic range and the yield point will not be exceeded. If the ground motion is sufficiently severe, on the other hand, the structure may collapse. Between the range of elastic vibrations and the collapse vibrations there is a range where plastic vibrations occur and these are of special significance. Buildings designed according to current building codes will certainly vibrate into the plastic range when subjected to ground motion comparable to that which has been recorded in the past. This is clear, since the spectrum curves tell us that the structure would have to be designed for forces three or four times those specified by the building codes if the structure is to remain within the elastic limits under ground motion comparable to the El Centro Earthquake of 1940. For this reason, vigorous research should continue on the problem of the plastic vibrations. In view of the great theoretical difficulties in such nonlinear vibration problems it is of great importance to measure the nonlinear vibrations of actual structures when subjected to earthquakes, so that in all cities a number of typical and nontypical buildings should have recording accelerographs installed that will measure not only the motions of the base of the building, but also the motions of the upper parts of the building in the event of an earthquake. With the development of more precisely controllable force generators, recent building vibration tests show that during elastic vibrations the amount of damping in modern buildings is quite small, appreciably smaller, in fact, than had been supposed in the past. This means that such structures will reach yield-point displacements for relatively mild ground motions. This emphasizes the importance of plastic vibrations.

When a structure vibrates beyond the yield point it can be said to be in the process of failing, for if the vibrations continue for a sufficient time there will be a fatigue failure. Current building code requirements are such that plastic vibrations will result from strong ground motions and, hence, it is of particular importance to know for what amplitude and duration of plastic vibrations there will be failure. Such fatigue failure seems to me to be a very important consideration that requires additional research.

Applied Research

Applied research is aimed at finding solutions to specific design problems. Compared to some other field-, earthquake engineering suffers from the fact that there are no good model testing techniques, for model testing is a good way to solve design problems. Most specific design questions could be answered if we were able to construct and test a model that suitably represents the actual structure or part of a structure. At present, our knowledge of making models is not adequate for this task. We do not know how to make a model that has all of the pertinent properties of an actual building. This might be deduced from the fact that so many earthquake engineering studies are done by means of a digital computer. Studies using the digital computer can be same to be experimental studies of a type in which model structures are represented mathematically and their response to dynamic loads calculated. The models in this case have certain simple specified properties. These properties and the models themselves represent an actual structure in only an approximate fashion and, hence, the studies on a digital computer do not provide information on the failing characteristics of structures. The chief difficulty now seems to be that we do not know all of the significant properties of actual structures when loaded dynamically beyond the yield point. In this case, what one would like to do is make models properly scaled so that it would be known that the model is indeed representative of the actual structure, and that the observed behavior of the model can be extrapolated to the structure. Modelling techniques for earthquake engineering studies is a field that should be developed by intensive research.

At the Third World Conference on Earthquake Engineering there were some papers which described tests of actual structures and in some cases the tests were carried to the point of incipient failure. Such tests of actual structures provide extremely valuable information on failure characteristics and are the next best thing to having an earthquake for an exhibition of the strengths of structures. This is a very desirable type of applied research.

Another type of applied research is the testing of full-scale structural members. This might be a test of a reinforced concrete beam-column under combined axial and bending loads with the tests being carried to failure. Needlessly to say, the loads here should simulate the dynamic loads that would be experienced if the member were a part of an actual building during an earthquake. The oscillatory tests of a steel frame that is representative of frames and their loadings in actual buildings would be extremely valuable if the tests could be carried out for oscillatory loadings far into the plastic range. Oscillatory tests of shear-wall panels made of different materials would also be of great value. Tests involving oscillatory loads on footings, simulating the loading that a footing in an actual building might have during an earthquake, would be most interesting. It would be very valuable to have precise information on the settlement and failing characteristics of different soils when they are subjected to oscillatory pressures of footings.

It can be seen that the foregoing remarks about applied research are all aimed at exhibiting the failure characteristics of structures or parts of structures. From the point of view of applied research the important thing is to be able to know how and under what conditions a structure or part of a structure will fail. This is really the essence of the design problem It is here that there is a lack of knowledge and that additional research is needed. It is to be understood, of course, that it is the failure characteristics under dynamic loading, such as would be sustained during a strong earthquake, that should beexplored. This is much more difficult than determining the failure characteristics under static loading and, in many cases, the dynamic failure characteristics may be quite difficult from the static failure characteristics.

Applied Research for Practicing Engineers

The central items in the practice of structural engineering are the building code, and the codes of standard practice. When we examine such codes we see that they are really more in the nature of a law or body of laws than they are in the nature of engineering. Just as a body of laws specifies what may or may not be done by individual citizens, so the code specifies certain things that must or must not be done by the engineers when designing buildings. These requirements are not necesarily derived from any rational body of knowledge. They are aimed directly at establishing a satisfactory result. In effect, the code says that if you do so and so, the result will be considered satisfactory. The means whereby the results are obtained are not necessarily germane to the process. For example, the code might aim at achieving a building which has satifactory strength properties, and so long as the resulting building doe have satisfactory properties, it is not really important whether the method of design was of one type or another, or even whether or not the method of design was based upon rational principles. If a designer were able to lay out the design of a building entirely by intuition without any analysis or calculations and yet achieve a satisfactory structure, he could not be criticised. In fact, in many cases, an experienced engineer will indeed make decisions based upon his intuition which, in turn, is based upon experience, to achieve satisfactory results without calculations. The point I am trying to make is that the engineering design process is really quite different from the engineering analysis process, and that, in general, the design makes use of the analysis only when it cannot get along without it. From the point of view of the practicing engineer, therefore, applied research should be aimed primarily at refining the building codes or the codes of standard practice, and, in fact, if we look at the practice of civil engineering fifty years or so ago, we see that indeed the emphasis was on the development of codes of standard practice, and research tended to be all of the strictly applied type. There was very little so-called basic research. The development of codes of practice by means of applied research and testing is a very slow process, and a relatively costly one. Because of this, during the rapid technological progress of the last few decades, this type of development could not move rapidly enough. In such a situation the tendency is for basic research to flourish and its results are utilized for rapid development of engineering practice. Engineering research in the space field is an extreme example of this. From the point of view of the practicing engineer, basic research is a cheap substitute for costly applied research.

In the practice of engineering based on building codes and codes of standard practice there is always the question as to the adequacy of the code. The real test of a code is whether the anticipated loads do or do not cause a failure. If a failure does result, then the code is modified to avoid this in the future. Now the difficulty here is that this procedure really requires a relatively frequent occurrence of the loads in order to check and to modify the code provisions. In the case of earthquakes, there may be a very large investment in construction made under existing code provisions before there is a test by an earthquake. This means that the engineer must continually ask himself if the provisions of the code are indeed adequate or if there are any instances where the code may be inadequate. It is true that engineers do ask these questions about the earthquake provisions of the building code and the danger to be avoided here is the habit of revising the earthquake provisions of the code without having a reliable factual basis for the modifications. A continual changing of earthquake provisions may provide a feeling of accomplishment which tends to obscure the fact that no solid progress is being made. It is very important for practicing engineers to promote as much applied research aimed at improving the building code as is possible, and I would like here to make some suggestions on various aspects of applied research to which practicing engineers might well contribute.

From the point of view of applied research the occurrence of earthquakes is a proof test of existing structures. It will be important for engineers to profit as much as possible from this proof test. To this purpose engineers should make careful study of earthquake damage from the point of view of establishing whether the code provisions or the standard practice of applying code provisions are adequate. This is not a simple matter to determine. A casual inspection of the damage will not reveal much about the adequacy of the code. It is true, of course, that in the case of gross inadequacy the results are quite obvious. For example, if the anchorage of reinforcing bars is not adequate, the resulting rupture of buildings will make it very clear. However, except for such gross inadequacies, it requires a rather careful analysis and checking to determine anything about the adequacy of the code provisions, particularly in view of the fact that deficiencies in construction practices tend to obscure the influence of the design. There have been very few cases in the past where earthquake damage was analyzed carefully.

Another aspect of applied research to which practicing engineers might well contribute is that of performance tests during construction. On some projects it may be possible to actually carry out tests during construction, either on the prototype structure itself, or small-scale structures or structural members may be tested. Such tests, when properly conceived and executed, can provide very useful information and it appears that this is a case where the practicing engineers might be in a good position to contribute to the advance of knowledge.

Another aspect of applied research is the testing of actual buildings. It is not uncommon for buildings that are yet in good condition to be condemned for freeway clearance or urban renewal projects. These buildings are often available for destructive testing and, hence, they are an excellent source of information on failure strengths. Such tests would, of course, require special funding. It would appear that in any city, the practicing engineers, and engineers working for government agencies would be the logical persons to promote funding for such tests and to lay out the actual test programs. Many such opportunities have been lost, and others will be lost in the future, unless the engineers undertake some cooperative effort to finance the tests and to see that they are carried out.

Another possibility for applied research on earthquake engineering is to have the research done by various industrial agencies. For example, the Portland Cement Association laboratories could well perform tests on the ultimate resistance of reinforced concrete members under dynamic loads; and the steel companies could well sponsor research on the dynamic behavior of steel frames. It would seem that if practicing engineers could lay out specific test programs and endorse them, they might well influence the agencies to undertake the tests. If the practicing engineers are willing to think seriously about the earthquake problem, there are indeed many cases where they could promote or actually do applied research.

Application of Basic Research

Basic research looks at the earthquake problem from the point of view of trying to understand and explain the nature of the earthquake ground motion, the dynamic behavior of structures subjected to earthquake ground motion, the behavior of soils under dynamic stresses, etc. To be of use to the practicing engineer the results of the basic research must somehow be interpreted with reference to the building code and the codes of standard practice. It is a common complaint of the practicing engineer who attends technical meetings that papers presented by university research workers are not immediately applicable to the problems of the practicing engineer. Now, that is bound to be the case since research workers at universities are looking at the problem from an entirely different point of view than the design engineers. In fact, the points of view are so different that it is doubtful that many university research workers could really interpret the results of the basic research in terms of code requirements. Because of this, there is need for a middle man between the university research worker and the practicing engineer who can perform this function. Unfortunately, the way things have been developing during the past few decades, the gap between the university worker and the practicing engineer is getting larger and, at present, there is no middle man to perform the interpretation on the results of the research. It is just at present that the gap between the practicing engineer and the university research worker is particularly large. This comes about partly because the more senior practicing engineers who are influential in dictating code requirements, received their education at a time when earthquakes and structural dynamics were not taught in the universities. On the other hand, the active researchers of the universities are younger men who received their education at a time when structural dynamics, digital computers, mathematical analysis, etc., were stressed. As a result communications between the two groups is difficult. It would seem that the only way to bridge the gap is either to develop a middle man who can communicate between the engineers and university research workers, or the engineers themselves must develop sufficient familiarity with modern research techniques to be able to understand the results.

The practicing engineer sometimes asks why it is that the university research worker does not pay more attention to the problems of design engineers rather than devoting his attention to basic research. There are several reasons for this. First,the particular problem of design that the practicing engineer faces almost always leads to a large-scale testing program which tends to be rather costly, and, although the precise nature of what is to be tested and the questions to be answered may be clear to the practicing engineers, it is usually not clear to the university research worker. Testing full-scale elements of structures or actual structures themselves is not well suited to university-type research. Laboratory facilities for this sort of work are usually not available, full-time laboratory tech nicians for carrying on the work are not available, and in general such a job is much more difficult for the university research worker to organize and carry through than is some smaller project on basic research. Paper and pencil is available at every university, access to digital computers is to be had at all universities and basic research lends itself better to a part-time effort, which is all that the usual university research worker is able to devote to the problem. Third, in order for the university research worker to carry out any sizeable project some funding is necessary. Laboratory costs must be covered, pay for graduate research assistants must be found, partial salary for the researcher must be found, and overhead costs of the university must be met. The university does not have money to subsidize the research work of its staff members and, at present, the great majority of all university research in the United States comes from government agencies such as the National Science Foundation, Department of Defense, NASA, Office of Naval Research, etc. It is a fact of life that these agencies tend to subsidize only small research projects at universities and favor basic research rather than applied research. It is no wonder, then, that the university research worker concerns himself primarily with basic research.

Another factor that influences the nature of earthquake engineering research is the present course of scientific research. In the past decade or so there has been a large expansion of scientific research, and large sums of money have gone into scientific research projects. That is to say that much manpower has been channeled into scientific research, for money is just a measure of manpower. For example, the U.S. Coast and Geodetic Survey has certain projects in seismology and earthquake engineering. One of the scientific projects is a world-wide network of seismographic stations. At a cost of some seven million dollars, approximately 100 seismographic stations were set up in the United States and the rest of the world. An operating budget of $800,000 per year is required to collect and process the seismograms produced by this system. Now if we compare this with the strong-motion work of the Survey which involves the installation and maintenance of strong-motion accelerometers that provide data for engineering, we find that the Survey's initial cost and the yearly operating budget for the network of strong-motion seismometers is somewhat less than one-tenth of the cost of the world-wide network. There are approximately 1,200 seismographic stations in the world as compared to approximately 300 strong-motion accelerometer installations, this despite the fact that a typical seismographic station costs three or four times as much as an accelerometer installation. This is indicative of the fact that research funds are much more easily obtainable for scientific research projects than for engineering research projects. As a consequence, the engineering research worker finds that the more close his proposed research is to pure scientific research, the easier it is to get funds. On the other hand, the more nearly his proposed research looks like applied engineering research, the more difficult it is to get funds. Now certainly, from the point of view of society, the important thing involved in the earthquake problem is to provide adequate protection to the public at reasonable cost, and one would expect that research aimed at this would receive more funds than pure seismological research. Since this is not the case, there appears to be an improper balance between scientific and engineering research in the earthquake field. My reason for mentioning this is to stress the fact that almost all factors in this problem tend to draw attention and effort away from applied research in earthquake engineering, and unless some steps are taken to change this, applied research will continue to move along on a small scale compared to the more scientific types of research. This situation is rather ironic in that it appears to result in the United States from the fact that the quality of engineering has in the past been rather high. Because of this, the public takes good engineering for granted. It is assumed that engineering will automatically be good without research being necessary. It seems to me that what is called for here is a determined effort by practicing engineers to strengthen applied research in earthquake engineering and, in fact, in other parts of civil engineering also. This, I think, cannot be done by individual efforts of engineers, but must be done through their professional organizations. What is required is an enlightened and continuing effort by engineering organizations to lay out desired applied research projects and to make strong efforts to see that they are funded.