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Seismic upgrading of existing structures

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ABSTRACT: The importance of proper seismic upgrading of existing hazardous structures to reduce seismic risk in urban areas is stressed, followed by a discussion of factors influencing the decision to upgrade and the selection of efficient strategies and techniques. Problems encountered in reliably assessing seismic activity, seismic hazards, and the seismic vulnerability of a given structure are briefly reviewed. Based on an energy balance equation, guidelines for the proper strategies and techniques are formulated.

1. INTRODUCTION

Most human injury and economic loss due to moderate and severe *Earthquake Ground Motions (EQGMs)* are caused by the failure of engineered structures, particularly buildings, which presumably have been designed and constructed to protect their users against expected natural hazards. Recent earthquakes (1988 Armenia, 1990 Iran and 1990 Philippines), in which large numbers of people have been killed and large economic losses have been suffered, confirm this dramatically. The 1989 Loma Prieta earthquake, in spite of the fact that it caused relatively few deaths (67), is considered one of the most costly natural disasters in U.S. history. The economic losses induced by these earthquakes clearly indicate that the level of *"acceptable damage"* should vary with the function and occupancy of the facility. For certain occupancies there is an urgent need to require damage control even under the major expected EQGMs (usually denoted in the literature as the *Maximum Credible EQGMs*).

Improving existing and developing better methods of designing, constructing and maintaining new structures, and particularly of upgrading existing seismically hazardous facilities, is one of the most effective ways to mitigate the destructive effects of EQGMs. This paper aims at the formulation of guidelines for the selection of efficient strategies and techniques for seismic upgrading of existing facilities. The problems encountered in attempts to evaluate seismic risk to an existing facility are discussed, as are the factors in the decision to upgrade a facility, the main concepts in the selection of the proper upgrading strategies and techniques, and the development of guidelines.

2. SEISMIC RISK ASSESSMENT AND CONTROL

Seismic risk to a facility is the probability that social or economic consequences of earthquakes will equal or exceed a specified value during a specified time period. It can be expressed briefly as follows [Dowrick 1987]:

$$\begin{pmatrix} \textit{Seismic} \\ \textit{risk} \end{pmatrix} = \begin{pmatrix} \textit{Seismic} \\ \textit{hazard} \end{pmatrix} (\textit{Vulnerability})\ (\textit{Value})$$

The evaluation and thus the control of seismic risk to a facility require evaluation of both the main seismic hazards to the facility, which depend on the seismic activity that can occur at the facility site and its surroundings, and the seismic vulnerability of the whole facility system (soil, foundation, superstructure, and nonstructural components and contents) expressed as a fraction of the value of this system.

2.1 *Assessment of seismic activity and hazards*

Seismic activity can be considered as the function describing the probability of occurrence of EQGMs of various intensities and their effects on the earth's surface at a given site, urban area or region during a given period of time. There are significant uncertainties in forecasting future seismic activity rates and strengths because relevant data are scarce and poor in quality. For reliable seismic activity assessment, it is important to gather as much information as is available regarding future earthquakes in terms of locations, magnitudes, frequencies of occurrence, the attenuations of the intensity of the waves and their energy with distance, and the intensities and durations of the strong EQGMs at the facility site and its surroundings.

Seismic hazard is any physical phenomenon associated with an earthquake which may produce adverse effects on human activities. For a given facility, there are many different types of seismic hazards. *The seismic hazards to which a facility may be exposed depend on (1) the seismic activity at the site and its surrounding area, and (2) on the interaction of the seismic effects originated by seismic activity (fault ruptures, landslides, ground failures, vibrations of the ground, floods, fires, etc.) with the whole facility system's vulnerability to them.*

A comprehensive approach to EQ risk reduction requires that all sources of seismic hazards to structures be identified. In the U.S. the assessments of seismic activity and hazards are presently based on zonation maps and information supplied in local building codes. The seismic effect emphasized in building code seismic regulations is the vibration of structures as a result of earthquake shaking. The author has questioned the reliability of these code maps and this information (1991b & c).

2.2 *Seismic vulnerability assessment*

Seismic vulnerability is the amount of damage induced by a given degree of hazard, expressed as a fraction of value of the facility. Most methods for conducting seismic vulnerability assessments of existing structures are based on estimates of capacity/demand ratios using current seismic code-specified criteria. In general, this approach is not satisfactory because, even in present seismic regulations, the reliability of the procedures for evaluating seismic demands and capacities are highly questionable. Bertero (1988) and Miranda (1991) have conducted reviews of the available criteria for evaluating the vulnerability of existing structures.

The real problem in assessing the vulnerability of a given facility is in estimating its response to future critical EQGMs. Prediction of seismic response depends on an adequate knowledge of at least: (1) the seismic activity at the site; (2) the sources of seismic hazards, which depend on the seismic activity, local soil conditions, and the type, size, shape and detailing of the foundation, superstructure and nonstructural components of the facility and their mechanical characteristics under dynamic excitation; and (3) the desired level of safety and/or the acceptable level of damage. The difficulties involved in reliably assessing vulnerability were clearly in evidence in the studies assessing the vulnerability of the Cypress Viaduct, of which a large part collapsed during the 1989 Loma Prieta EQ [Miranda & Bertero (1991)]. In spite of the simplicity of the structure, the availability of "as built" drawings and the fact that tests of the structural materials were conducted, it was not possible to estimate the actual strength of the weakest frame, because in the real existing structure the anchorage length of some main bars were not as specified in the "as built" drawings.

2.3 *Concluding remarks*

In spite of progress in the above assessments, considerable uncertainties remain. The importance of reliable assessments of seismic hazards and activity and of the vulnerability of existing facilities cannot be overemphasized. If the expected intensity of EQGMs is greatly overestimated, the costs of new construction and rehabilitation of existing structures may be excessive. On the other hand, if the intensity of EQGMs is seriously underestimated, the result may be costly damage and loss of life such as that seen in the disasters of Tangshan, Mexico City, Armenia, Loma Prieta, and the Philippines.

Until the 1989 Loma Prieta EQ, not only were the assessments of seismic activity, hazards, vulnerability and, consequently, risk, based on the use of building code seismic regulations for *Earthquake-Resistant Design* (EQRD) of new buildings, but also the common philosophy for upgrading existing buildings was to bring them into compliance with such regulations. This approach usually results in inefficient rehabilitation of buildings, and in some cases, prohibitively uneconomical upgrading solutions. For example, many old concrete buildings are condemned because they have structural systems and/or reinforcement detailing which are not ductile enough to be acceptable under present seismic codes, in spite of the fact that they may possess sufficient overstrength over the code required yielding strength (C_y) to remain elastic under the effects of the maximum credible EQGM. The main difficulty in proving that they need not comply with the code is in the evaluation of the their actual dynamic characteristics, i.e., in assessment of their real seismic vulnerability.

In most cases, bringing the building up to compliance with building code seismic regulations does not guarantee good seismic performance, particularly when damage control is desired under the expected future major EQGMs. The basic philosophy of present building code seismic regulations is to protect the public in and about buildings from loss of life and serious injury during major earthquakes. These regulations are not intended to limit damage, maintain functions, or provide for easy repair. Recent EQs, particularly the 1989 Loma Prieta, clearly indicate that seismic codes ought to consider damage control: The level of "*acceptable damage*" should vary with the function (occupancy category) of the building. The need for code specifications which require damage control is urgent for certain occupancies. A comprehensive approach to the upgrading of existing buildings will require that the following three levels of critical upgrading EQGMs be considered: *Service Level; Functional or Operational Level; and Safety Level.* Guidelines for establishing these different levels of design EQGMs are suggested by Bertero (1991b & c) and Miranda (1991).

3. UPGRADING OF HAZARDOUS FACILITIES

The decision to upgrade a facility and the choice of the retrofitting strategy and techniques depend on many factors, including not only assessments of (1) The seismic activity; (2) the sources of seismic hazards; and (3) the main seismic hazards given the vulnerability of the facility's whole system; but also (4) the type, function and age of the facility; (5) the required levels of performance (serviceability, continuous operation, life safety) expected of the upgraded facility for different levels of EQGMs and seismic hazards that can occur during the expected service life of the structure; (6) architectural requirements; (7) the need to minimize disturbance to the occupants and operation of the facility during the upgrading; (8) selection of the best strategy for rehabilitating the whole facility system; (9) development of alternative rehabilitation schemes; (10) the availability of equipment and expertise for the field work; (11) cost vs. benefits of the upgrading work, and the socio-economic impact on the community; (12) assessment of the vulnerability of the alternative upgrading schemes to the identified sources of seismic hazard; and (13) selection of the most efficient solution.

3.1 *Selection of the proper upgrading strategy*

The selection of the most efficient upgrading strategy requires thorough study of the factors discussed above. There are many uncertainties involved in these studies. Although basic concepts and guidelines for seismic upgrading of structures have been formulated [Bertero & Whittaker (1989); Jirsa & Badoux (1990)], the upgrading of a given facility is a unique problem requiring a customized solution. For two identical buildings with different occupancies or functions and located on sites with different soil conditions, the upgrading strategies can be vastly different.

In selecting the upgrading strategy the designer should examine the two sides of the design equation:

$$\text{DEMANDS} \leq \text{SUPPLIES} \qquad (1)$$

This equation shows that the designer can seismically upgrade an existing facility by: (1) decreasing the seismic hazard demands; (2) improving the facility's supplied mechanical (dynamic) characteristics; or (3) a combination of (1) and (2). A promising methodology for rational selection of upgrading strategies for existing hazardous facilities as well as for EQRD of new structures is one based on an energy approach, specifically on the use of an energy balance equation. Although Uang & Bertero (1988) have shown that two different basic energy equations can be derived from the basic equation of a viscous damped *Single Degree of Freedom System* (SDOFS) subjected to an EQGM, they have also shown that the maximum values of the Energy Input (E_I) are very close in the period range of practical interest for buildings, which is 0.3 to 5.0 secs. Therefore, the two basic energy equations can be rewritten as

$$E_I = E_E + E_D \qquad 2(a)$$

$$E_I = \overbrace{E_K + E_s} + \overbrace{E_\xi + E_H} \qquad 2(b)$$

$$\begin{pmatrix}\textit{Input}\\ \textit{energy}\end{pmatrix}\begin{pmatrix}\textit{Kinetic}\\ \textit{energy}\end{pmatrix}\begin{pmatrix}\textit{Elastic}\\ \textit{strain}\\ \textit{energy}\end{pmatrix}\begin{pmatrix}\textit{Damping}\\ \textit{energy}\end{pmatrix}\begin{pmatrix}\textit{Hysteretic}\\ \textit{energy}\end{pmatrix}$$

where *E_E is the stored elastic energy and E_D the dissipated energy*. A comparison of this equation with the design equation (1) makes it clear that E_I represents the demands, and the summation of $E_E + E_D$ represents the supplies. From analysis of Eqs. 2a and 2b it is clear that a good estimate of the E_I for the critical EQGM is the first step in selecting an efficient upgrading strategy. Next, the designer has to analyze whether it is possible to meet this demand just by keeping the behavior of the structure in the elastic range, or whether it is convenient to try to dissipate E_I as much as possible, i.e., to increase E_D. As shown in Eq. 2b, there are three ways to increase E_D: one is to increase the linear viscous damping (E_ξ); another is to increase the hysteretic energy (E_H); and the third is to increase both E_ξ and E_H. It is common practice at present to try to increase E_H through inelastic (plastic) behavior alone, which implies damage of the structural members. It has recently been recognized that it is possible to increase E_D significantly with energy dissipation devices such as viscous dampers (visco-elastic shear, or oil) and hysteretic dampers (friction, yielding metals and lead) [Bertero & Whittaker (1989) and Kelly & Aiken (1991)]. Although hysteretic energy dissipation devices by themselves do improve behavior efficiently at safety level, where some level of damage is tolerable, viscous dampers have the great advantage that they can be used to control the behavior of the upgraded structure under both safety and service levels. If technically and/or economically it is not possible to balance the required E_I through either E_E alone or $E_E + E_D$, the designer has the option of attempting to decrease the E_I to the structure with base isolation techniques. Combining base isolation techniques with energy dissipation devices is a very promising strategy both for upgrading existing hazardous structures and for EQRD of new structures. This energy approach requires the reliable selection, for each of the limit states that need to be considered (service, function, and/or safety), the critical design EQGM that controls the design, i.e., which has the largest damage potential for the structure. Most of the parameters used to establish design EQs are unreliable for assessing the damage potential of EQGMs. A promising parameter for this assessment is E_I. However, as discussed by Bertero (1991a & b) and Bertero & Uang (1991), E_I alone does not give a clear picture of the E_D that has to be supplied to balance the E_I for any specified acceptable damage, and the additional information given by E_ξ, E_H, μ_a (*cumulative ductility ratio*) and NYR (*Number of Yielding Reversals*) spectra is needed.

3.2 *Guidelines for selecting efficient upgrading strategy*

From analysis of design Eqs. (1) and (2), it is obvious that, generally, three main strategies can be considered for upgrading a seismically hazardous facility: (1) decreasing the earthquake demands [E_I in Eq. (2)]; (2) improving the facility's supplied mechanical (dynamic) characteristics [E_E and/or E_D in Eq. (2)]; and (3) both (1) and (2). It should be noted that strategies (1) and (2) are not independent, because the demands of seismic excitations depend on the mechanical characteristics supplied to the whole facility system. The following main guidelines should help with the selection of efficient upgrading strategies. In applying these guidelines it should be kept in mind that damage is more a consequence of deformation than of strength, and thus that in order to control damage it is desirable to limit the deformations, particularly the tangential interstory drift.

1. *Decreasing the demands*. If the effects of the expected critical EQGMs at the site at the different limit states are reliably defined by their response spectra [E_I, *C_y (yielding strength) and S_d (displacement)*, as illustrated in Fig. 1], the demands on the structure depend on the relation between the period of the structure, T, and the predominant period of the EQGM, T_{GM}. The largest response, and thus the largest demands on E_I and C_y, usually occur when $T/T_{GM} \doteq 1$. Thus, one main strategy for decreasing demands is:

1a. *Shifting the T of the whole facility system.* How? By increasing or decreasing T depending on the ratio of T/T_{GM}. If $T \leq T_{GM}$ and the structure is on soft soil, the solution is usually to decrease T, because, as can be seen from Figs. 1(b), 1(d), 1(f) and 1(h), this decreases the demands. If the structure is on firm soil, with a T close to T_{GM}, and its C_y is very small, then the solution is to increase T with base isolation, because, as can be seen from Figs. 1(a), 1(c), 1(e) and 1(g), except for C_y

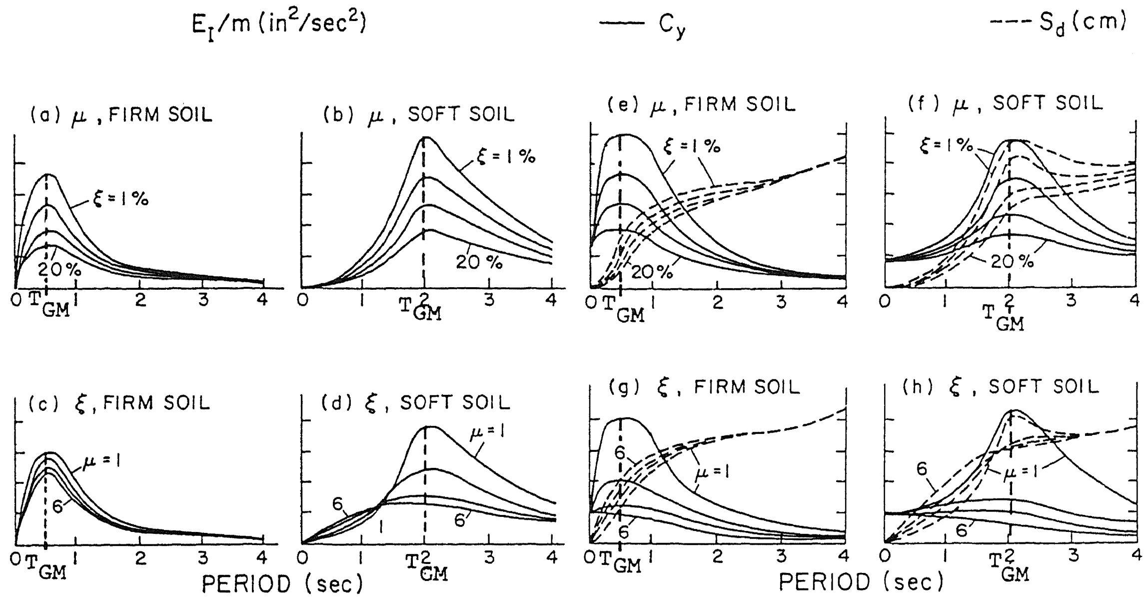

Figure 1. Qualitative illustration of the following response spectra E_I (energy input), C_y (yielding strength coefficient), and S_d (displacement) corresponding to firm and soft soil earthquake ground motions and the variation of these spectra when for: (1) a given ductility ratio, μ, the damping ratio, ξ, varies from 1 to 20%; and (2) a given ξ the μ varies from 1 to 6.

in the case of large μ, this decreases the C_y and E_I demands. However, Figs. 1(e) and 1(g) show that the increase in T can lead to a considerable increase in lateral displacement (S_d) demands - but this increase is concentrated in the base isolation elements, which are specially designed for such large displacements. In general, if base isolation cannot be used, T should be decreased by increasing the supplied stiffness and/or decreasing the mass, because both lead to smaller deformations and therefore to better control of damage. In practical applications of this strategy, the extent to which the T of the original structure has to be shifted depends on the reliability with which T and T_{GM} can be predicted.

1b. Another strategy for decreasing the demands is to *increase the damping ratio ξ [Figs. 1(a), 1(b), 1(e) and 1(f)], and/or to lower the C_y by increasing μ [Figs. 1(c), 1(d), 1(g) and 1(h)].* In the case of soft soils and where $T < T_{GM}$, the increase in μ could lead to larger values of input energy [Fig. 1(d)]. Comparison of Figs. 1(e) and 1(f) with Figs. 1(g) and 1(h) shows that when it is necessary to control deformations (S_d) at either service or safety level, and where $T < T_{GM}$, it is better to increase ξ than to increase μ, because at service level no inelastic deformations are acceptable, and at safety level an increase in μ results in an increase in S_d.

2. *Improving the dynamic characteristics supplied to the existing structure.* The demands depend not only on the dynamic characteristics of the EQGM, but also on the interaction of these characteristics with the dynamic characteristics supplied to the structure. Some guidelines for improving the supplied dynamic characteristics follow. The legitimacy of these guidelines is supported by the plots of Fig. 1.

2(a) *Decrease the reactive mass.* Why? Because it can result in a reduction of EQ inertia forces, and so will reduce the EQ's demand (this is particularly true in the case of $T \leq T_g$). How? By removing unnecessary weight, reducing the weights of walls, partitions, and so on -- in the case of a multistory building, removing one or more of the upper stories.

2(b) *Minimize the distance between the centers of mass, stiffness and resistance.* Why? To reduce torsional effects. How? By modifying the dispositions of reactive mass, stiffness and resistance of the structural elements.

2(c) *For flexible buildings on deep soft soil deposits, reduce the fundamental period.* Why? To avoid resonance problems with long period ground motions. How? By reducing the building's mass or increasing its stiffness or both. The stiffness can be increased efficiently with steel bracing and/or shear walls.

2(d) *For buildings lacking ductility, tie all of the lateral load resisting elements together to maximize the building's yielding and maximum strengths, or increase the damping, or both.* Why? It is difficult to improve the ductility of structural members, but relatively easy to increase a building's strength, reducing its required ductility. How? By a variety of means, e.g., using prestressed rods to tie the roof and floor slabs to the gravity load supporting elements and/or as bracing elements to enhance the building's lateral stiffness and strength. In the case of an isolated building, buttresses and outriggers can be used, as can dampers.

2(e) *For stiff structures lacking the necessary strength and ductility and subject to earthquake shaking with high frequency content, increase the building's fundamental period or increase its damping, or both.* Why? To reduce EQ demand by avoiding engineering resonance and decreasing the dynamic amplification factor. How? By some combination of eliminating infills, isolating nonstructural elements from the structure, adding dampers, using base isolation systems and using energy dissipation devices.

2(f) *For flexible buildings lacking ductility and located on soft soils and where interstory displacements are the major concern, increase the building's stiffness, strength, and damping.* Why? An increase in stiffness will decrease T, which, together with an increase in strength, will reduce deformations and ductility requirements; the increase in damping will reduce the required strength and the deformations. How? Through the use of braces in the form of prestressed rods, concentric braces and/or eccentric braces; or through the use of shear walls and energy dissipation devices. If the T of the building cannot be shifted very much, i.e., the stiffness and/or the reactive mass cannot be changed significantly, the supplied dynamic characteristics can be improved by a change (usually increase) of the: strength (C_y); μ; ξ, or a combination of these. Jirsa and Badoux (1990) formulate redesign strategies based on strength-ductility relationship.

2(g) *In selecting the retrofitting strategy, careful consideration should be given to the entire soil-foundation-superstructure-nonstructural component system, and not just to the superstructure.* Evaluation of the adequacy of the foundation is an essential step in the selection of the most appropriate strategy.

3.3 *Selection of appropriate technique and final design*

After the selection of the proper strategy, schemes by which it can be implemented must be developed and analyzed. The final implementation scheme must consider not only the technical aspects and the total cost of the upgrading, but must also minimize disturbance to the function of the building during upgrading. The latter consideration necessitates upgrading strategies which either (1) involve construction activity only on the external faces of the building or (2) require only minimal reconstruction work inside the building. Generally, the final upgrading strategy is a compromise among the optimal technical strategy, the strategy that demands the smallest construction costs, and the strategy with minimum disturbance to the building's occupants.

The ideal approach for obtaining an efficient upgrading program is, after selecting an efficient upgrading strategy and technique, to conduct the design and estimate the cost for the existing facility according to three alternatives regarding desired future performance: (1) the upgraded structure will realize all of the objectives of the presently accepted philosophy of EQRD for new buildings with a minimum possible extra cost in initial construction and the slightest possible sacrifice of the architectural features which would be required if the building could be designed for just gravity loads; (2) under the maximum credible EQGM, the upgraded building will not only be safe but operational as well; and (3) the structure will not suffer any damage even under safety EQGMs. The advantages and costs of each of these different designs should be explained to the client, and he or she should decide what is affordable.

The final design of the upgrading scheme must include both detailed analyses of the building's performance under all significant levels of EQGM, and complete details and procedures of the field work, because some techniques may be unfamiliar to construction workers.

3.4 *Application of the concepts, strategies and guidelines to the upgrading of existing buildings*

The author and his research associates have conducted a series of detailed studies on the seismic upgrading of existing structures [Gu (1987), Bertero & Whittaker (1989) and Miranda (1991)]. Because of space limitations, only the *main observations* made in the application of the above concepts and guidelines are presented below. The details of the existing buildings and of the upgrading strategies and techniques investigated in these studies, as well as the main observations made in other projects in which the author acted as a consultant, will be illustrated and discussed in the oral presentation of this paper at the 10WCEE.

(1) For very flexible, insufficiently strong, low rise reinforced concrete buildings located on very soft soil, an efficient strategy is to decrease their fundamental periods by increasing stiffness or reducing reactive mass, or both. Usually the increase in lateral stiffness should be accompanied by an increase in the elastic (yielding) strength. Two efficient techniques for increasing stiffness and strength are bracing, usually steel, and RC shear walls. In the design of the bracing or shear walls, the following two approaches should be compared. One approach is to try to keep the response of the upgraded building in its elastic range (i.e., and *elastic solution*): the other is based on an *energy dissipating solution*, i.e., an attempt to dissipate part of the input energy through the use of energy dissipation devices.
(2) Of all the schemes considered, it was found that the elastic solution based on the use of high strength post-tensioned steel cables seems to be the most economical. From the standpoint, of extra safety, the use of steel bracing members incorporating energy dissipating devices appears to be the most promising.

4. CONCLUSIONS FROM SUMMARIZED STUDIES

1. Proper upgrading requires (1) reliable evaluation of the seismic activity at the facility site and its surroundings; (2) identification, by evaluation of both the seismic activity and the built environment around the facility, of the sources of seismic hazards to the facility; and (3) reliable assessment of the vulnerability of the whole facility system (soil-foundation-superstructure and nonstructural components) to the identified sources of seismic hazards, expressed as a fraction of its value.
2. Present seismic codes do not properly identify seismic activity and sources of seismic hazards at a facility site. Their methodology and procedures for evaluating the dynamic characteristics and particularly

the deformation capacity of the facility's whole system and of the response of this system to the expected critical EQGMs are inadequate.

3. There are many uncertainties in conducting vulnerability assessments of an existing whole facility system, even when "as built" drawings exist.
4. The importance of reliable assessment of the seismic risk to an existing facility cannot be overemphasized: If it is greatly overestimated, rehabilitation costs may be prohibitive; underestimation can result in costly damage and loss of life.
5. The commonly used criterion for upgrading seismically hazardous existing facilities is compliance with the building code seismic regulations for EQRD of new buildings. This usually results in inefficient rehabilitation of such buildings, and in some cases in prohibitively uneconomical upgrading solutions.
6. Although basic concepts and general guidelines for upgrading of structures have been formulated, the proper upgrading of a given facility is a unique problem requiring a customized solution.
7. The use of an energy approach, and particularly the use of an energy balance equation, offers a promising basis for rational seismic upgrading of existing hazardous structures.
8. Understanding and simultaneous examination of the basic design equation and the energy balance equation can guide the designer to selection of the most efficient strategy and technique for upgrading a seismically hazardous structure.
9. In developing and selecting an efficient upgrading strategy, it should be kept in mind that damage is more a consequence of deformation than of strength.
10. The first and most difficult problem in upgrading an existing facility is the reliable establishment of the redesign EQGM for each of the limit states that can control the redesign according to the main purpose of the upgrading program, which depends on the performance expected at the service, functional and safety levels. A promising approach for establishing these is the computation, plotting, and analysis of the E_I , E_ξ , E_H , C_y and S_d response spectra for each of the above levels of expected EQGMs.
11. In selecting the most appropriate retrofitting strategy and technique for improving the supplied dynamic characteristics, careful consideration should be given to the entire soil-foundation-superstructure-and-nonstructural component system rather than just to the superstructure. Stiffening and strengthening the structure may lead to changes which are significant not only in the demands on the existing foundation but also in the soil-structure effects.
12. In the selection of the upgrading technique, the designer should consider not only the design that is the most technically efficient and least expensive in construction costs, but also the one with the minimum disturbance to the function (operation) of the building during the upgrading. Generally, the optimum upgrading strategy and technique are compromises among the ideal technical strategy, the strategy least demanding in construction costs and the one that causes minimum disturbance to building occupants.

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