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Optimal target reliabilities for aseismic design of R/C buildings

Ang, A. H-S., de Leon, D.
University of California, Irvine, U.S.A.

ABSTRACT: The approach proposed by Ang and de Leon (1995) is applied to obtain the optimal target reliabilities (or acceptable risks) for damage control and collapse prevention of reinforced concrete buildings against earthquake hazard. These optimal reliabilities are then used to develop corresponding criteria for design, which may be expressed in conventional terms such as base coefficients for existing codes (e.g. the UBC, 1994). The implementation is illustrated for a class of reinforced concrete buildings in Mexico City.

1 INTRODUCTION

The determination of the optimal target reliabilities for damage control and life safety of structures against seismic hazard has been proposed by Ang and de Leon (1995). The approach is based on minimizing the expected life-cycle cost function.

The basic approach is applied to the development of criteria for design of reinforced concrete buildings, with particular reference to a class of buildings in Mexico City. In this regard, the seismic design code procedure of Mexico City is used in the development of the initial cost functions, whereas structural damage and associated cost data from the 1985 Mexico City earthquake form the bases for developing credible damage cost functions.

Optimal target reliabilities (or acceptable risks) for specified levels of tolerable structural damage are obtained for the specific class of R/C buildings. Similar target reliability for life safety (i.e. collapse prevention) is also obtained. Seismic base coefficients corresponding to the respective optimal target relatibilities are developed, which can be used to update existing seismic design codes.

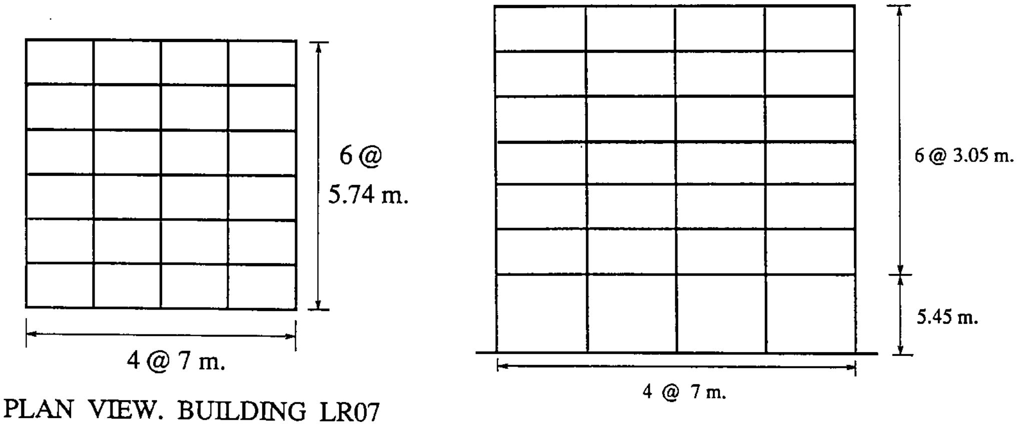
2 SUMMARY OF APPROACH

The basic approach proposed for the determination of target reliabilities for design is based on minimizing the expected life-cycle cost functions. As such, it involves the proper integration of technical and economic factors that influence the determination of the required reliabilities. Specifically, these include the seismicity (or seismic hazard) of the site of a structure; the degree of structural damage expected from a given intensity of earthquake ground motion; and the competing cost functions (i.e. the initial cost versus the potential damage cost).

Because the parameters and factors in the decision problem contain significant degree of uncertainties, the minimization would require probability-based trade-off consideration and analysis. The seismic capacity of a structure, as well as the damage that may be incurred from a given earthquake, are highly variable and uncertain. Moreover, the ground motion intensity and occurrence time of a future earthquake are unpredictable. For these reasons, it is not possible to formulate the life-cycle cost function directly for all possible future earthquakes. A multi-step process has been proposed (Ang and de Leon, 1995) as a practically more feasible approach.

By assuming a given intensity of an earthquake (or ensemble of earthquakes) at the site of a structure, the expected life-cycle cost can be formulated as a function of the probability of damage (or collapse), consisting of the initial cost of the structure and the expected damage cost from future earthquakes. For the initial cost function, a particular structure can be designed for different levels of seismic safety (or performance) following the procedure of an existing code (e.g. the UBC, 1993) but applying different base coefficients. The initial cost of each of the designs may then be related to the corresponding calculated reliability (or damage probability) under the given earthquake intensity; thus, establishing the initial cost function. For the various designs, the respective damage costs (including repair cost and other potential losses) may also be estimated and related to the corresponding calculated reliabilities; thus, establishing the damage cost as a function of the reliability (or damage probability) under the given earthquake intensity.

The initial cost and expected damage cost functions may be combined to obtain the expected life-cycle cost function under the given earthquake intensity. By varying the intensity, a series of expected life-cycle cost functions, therefore, is generated. For each of the expected life-cycle cost functions, there is a reliability for which the life-cycle cost is minimal; this is the conditional optimal reliability under the given earthquake intensity. For various possible intensities of future earthquakes at the site, a series of conditional optimal reliabilities is obtained. Weighing these conditional optimal reliabilities by the respective probabilities of the earthquake intensities should yield the expected optimal reliability for damage control or life safety.



PLAN VIEW. BUILDING LR07

Direction of analysis →

ELEVATION FOR BUILDING LR07

Fig. 1. Plan and elevation of 7-story building

3 APPLICATION TO REINFORCED CONCRETE BUILDINGS

The general approach described above is illustrated for a class of reinforced concrete buildings in Mexico City. For this purpose, a 7-story R/C building (representing buildings with 5 to 10 stories) is considered. The plan and elevation of the building are shown in Fig. 1, which is a regular R/C frame structure.

3.1 Analysis of damage and cost data

A large number of structures, including many reinforced concrete buildings were damaged to different degree of severity during the 1985 Mexico City earthquake. Several of the damaged buildings, for which the original structural design information is available, were modeled and analyzed to obtain the respective calculated median global damage indices (Park and Ang, 1985) and the corresponding probabilities of damage exceedance under the earthquake of 1985. The calculated damage indices were calibrated with the observed damages, and based on the subsequent disposition of each of the buildings (some were repaired whereas others were demolished), the limiting reparable damage was determined to be at a median damage index of 0.5 (de Leon and Ang, 1994).

For five of the buildings, the actual repair costs were reported in Guerrero (1990). These repair cost data can be plotted against the calculated median global damage indices of the respective buildings, as shown in Fig. 2, from which the following linear regression equation is obtained for relating the repair cost with the level of structural damage,

$$\frac{C_r}{C_0} = 1.64 D_m \qquad (1)$$

where, C_0 = the replacement cost of the original building.

The economic loss that may be caused by a structural damage (such as business interruption, loss of revenue, etc.) will depend on the usage of the structure and the severity of damage. This loss may be assumed to be a quadratic function of the median global damage index, up to a maximum loss at the limit of reparable damage, namely at $D_m = 0.5$. In the case of a residential apartment building, the maximum economic loss may be estimated as the loss of rentals during the period of repair or reconstruction. For this case, the maximum loss for Mexico City may be estimated with the following assumptions:

(i) the maximum period of repair is two years;
(ii) the average monthly rental is $20.00 per square meter of floor area.

Thus, the maximum possible loss for reparable damage to apartment buildings is,

$$C_{max} = 20 \times 12 \times 2A = 480A \qquad (2)$$

Therefore, for a median global damage of D_m, the economic loss would be,

$$C_e = 480A\left(\frac{D_m}{0.5}\right)^2 \qquad (3)$$

Analyses of the injury and casualty data from the 1985 earthquake provide information for estimating the corresponding losses. The cost of injury in Mexico City may be estimated based on the following assumptions:

(i) the cost of each disabling injury is \$117,000; whereas for each non-disabling injury the cost is \$1,667.

(ii) the average number of injuries per unit area of collapsed buildings is 0.0168 per square meter of floor area; this is estimated from data reported in UNAM (1985) and TMG (1986).

(iii) 2/3 of all injuries are non-disabling, and 1/3 are disabling.

With these assumptions, the maximum cost of injury associated with the collapse of structures (at D_m=1.0) is

$$C_{in_{max}} = 0.0168\left(\frac{1}{3} x\, 117{,}000 + \frac{2}{3} x\, 1667\right) A = 672A \tag{4}$$

whereas, for intermediate median damage, a quadratic injury cost function may be assumed; thus, for a given D_m the cost of injury is

$$C_{in} = 672A\,(D_m^2) \tag{5}$$

where A = the floor area of building.

The cost associated with the loss of human lives is controversial. However, in order to complete the life-cycle cost the potential loss of life caused by the damage or collapse of a structure must be included and translated into economic terms. There have been alternative suggestions for this purpose. For example, Rosenblueth (1976) proposed that the average cost of a human life be estimated as the economic loss to the gross national product over the remaining life of the individual. For Mexico City, the following data is available:

(i) the average per capita annual income is \$4,680 (Europa, 1993);

(ii) the average casualty per unit area of the collapsed buildings during the 1985 earthquake is 0.0122 per square meter of floor area (UNAM, 1985; TMG, 1986).

On these bases, and assuming an average remaining productive life of an individual is 30 years, the cost associated with the loss of human lives (following Rosenbueth, 1976) caused by a structural collapse is,

$$C_{f_{max}} = 0.0112A\ x\ 4680\ x\ 30 = 1572A \tag{6}$$

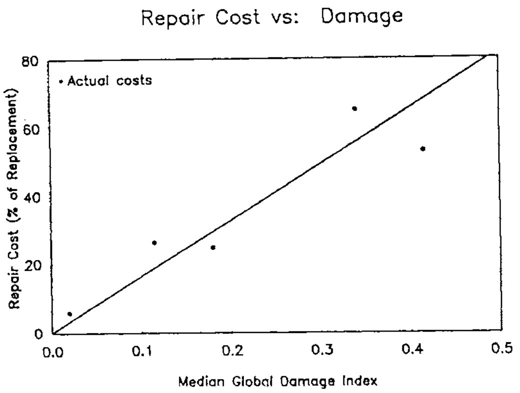


Fig. 2. Repair cost vs. median damage index

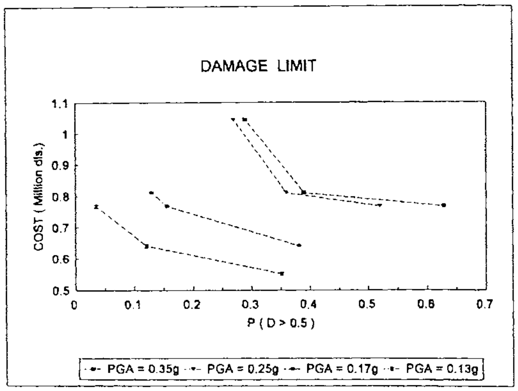


Fig. 3. Initial cost functions for damage control

In the case of less severe damage, assume that the loss of life varies as the 4th power of the damage; thus, the cost of human casualty caused by a median damage D_m would be,

$$C_f = 1572A(D_m^4) \tag{7}$$

3.2 Development of cost functions

Initial Cost -- To develop the required initial cost function for the 7-story R/C building, the structure is designed following the procedure of the 1987 Mexico City Seismic Code (DDF, 1987). The same building is designed repeatedly using the 14 different base coefficients shown in Table 1 with R_w=4. Based on the resulting designs for the building, the initial cost for each of the designs may be estimated; this will include the cost of material, design, and construction. In the present example, the cost of construction is assumed to be the same as that of the material.

Each of the designed buidlings is then subjected to an earthquake excitation (with the same spectral shape as the 1985 Mexico City earthquake) of given intensity; e.g. in terms of the peak ground acceleration. Under the given intensity, the probabilities of damage exceedance of the different designs are assessed, which can be related to the respective initial costs; thus, yielding the initial cost function for the particular intensity. By varying the earthquake intensity, a family of initial cost functions is generated, as shown in Fig. 3.

Table 1: Base coefficients used in design of 7-story building

0.10	0.15	0.20	0.25	0.30	0.35	0.40
0.45	0.50	0.55	0.60	0.65	0.70	0.75

Potential Damage Cost -- One component of the damage cost is the cost of repair; this cost is obviously dependent on the degree of damage and, therefore, will depend also on the earthquake intensity. For each of the designed buildings, the median global damage index can be obtained in the process of calculating the damage probability. Then from Fig. 2 or Eq. 1, the repair cost associated with the median damage can be obtained, and thus the repair cost as a function of the reliability is developed for the given intensity.

Under a given intensity of an earthquake in Mexico City, the expected damage cost for each of the building designs can be determined and related to the corresponding damage probability, thus obtaining the damage cost function for the building (Ang and de Leon, 1995). By varying the intensity, a family of damage cost functions, therefore, are generated as shown in Fig. 4. Each of the damage cost functions in Fig. 4 is in terms of the present worth which are based on the occurence rates for specified intensity given in Esteva and Ruiz (1989).

For life safety, the corresponding damage cost functions would be different from those for damage control. In particular, the cost would be a function of the probability of collapse instead of the probability of damage, and the cost of injury and loss of life would be more severe. Using the same process for generating Fig. 4, the family of damage cost functions for life safety can be developed resulting in the results summarized in Fig 5.

All the above damage cost items are in terms of 1985 dollars. The corresponding costs associated with future earthquake damages must be transformed into present worth as suggested in Ang and de Leon (1995). A discount rate of 4% is assumed for Mexico City.

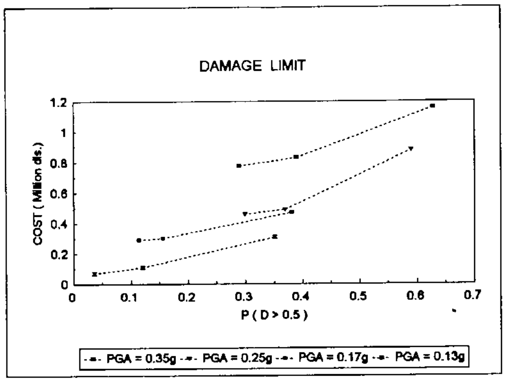


Fig. 4. Damage cost functions for damage control

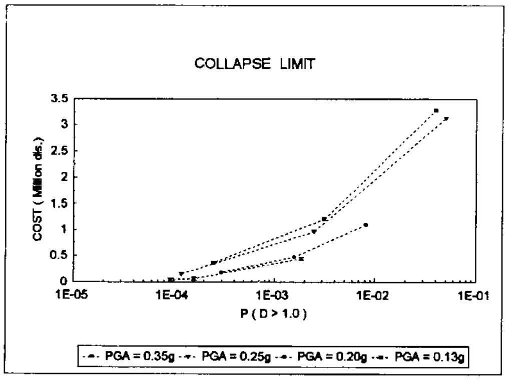


Fig. 5. Damage cost functions for life safety

3.3 Determination of optimal target reliabilities

Damage Control -- Combining the results of Figs. 3 and 4 for each intensity yields the expected life-cycle cost functions for the design of the apartment building to control damage as shown in Fig. 6. Observe that for each earthquake intensity, there is an optimal risk corresponding to the minimum life-cycle cost. Integrating all the conditional optimal risks with the 50-year seismic hazard curve for Mexico City (see Ang and de Leon, 1995), the expected optimal risk for damage control is obtained as

$$E(p_F) = 0.105 \qquad (8)$$

Life Safety -- For life safety (i.e. to prevent collapse) in the design of the building, the expected life-cycle cost functions for all the earthquake intensities of interest can be developed by combining the corresponding initial cost functions (similar to Fig. 3) with the damage costs of Fig. 5, yielding the results of Fig. 7. Again, for each intensity, there is an optimal collapse probability corresponding to the minimum life-cycle cost. Convolving these conditional optimal risks with the 50-year seismic hazard curve for Mexico City, the expected optimal risk for life safety becomes,

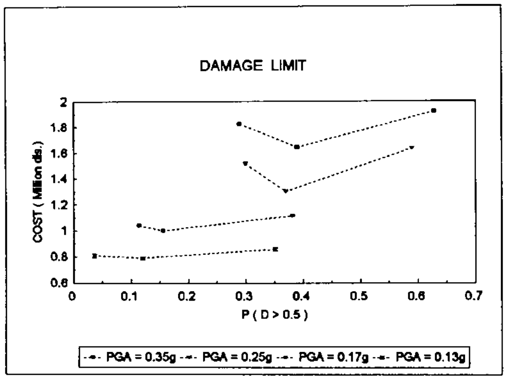


Fig. 6. Expected life-cycle costs for damage control

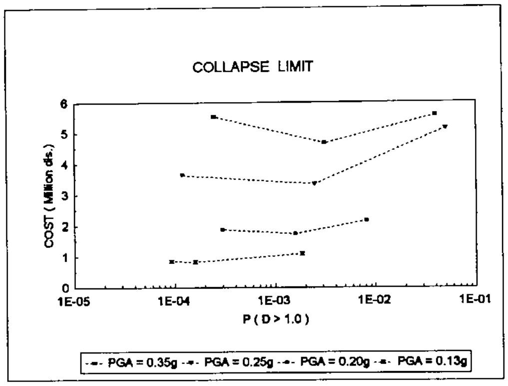


Fig. 7. Expected life-cycle costs for life safety

$$E(p_F) = 1.6 x 10^{-3} \tag{9}$$

Criteria for Design -- The optimal target reliabilities (or acceptable risks) determined above can be translated into criteria for the earthquake resistant design of R/C buildings in Mexico City. For example, in the UBC code format optimal base coefficients corresponding to the target reliabilities obtained above would be those shown in Table 2 for the respective limit states (defined by the tolerable damage).

Table 2: Summary of Results

Limit State, d	Optimal Acceptable Risk	Base Coefficient
0.5	0.105	0.30
1.0	$1.6x10^{-3}$	0.45

4 SUMMARY AND CONCLUSIONS

Optimal target reliabilities, or acceptable risks (damage probabilities), have been developed for a class of R/C buildings in Mexico City, from which the corresponding criteria for damage control and collapse prevention may be developed. For Mexico City, specific seismic base coefficients were obtained as suggestions for updating the current seismic design code.

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