13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2758

PROBABILISTIC SEISMIC RISK AND DAMAGEABILITY ASSESSMENT

Hamid SADEGH AZAR[1], Konstantin MESKOURIS[2], Majid SADEGH AZAR[3]

SUMMARY

This paper presents a method developed for seismic risk and damageability/vulnerability assessment in three Levels (Level I-III) in the framework of Eurocode 8. The application of this method to a building enables the user to quantify the expected building damage for different seismic intensities. The procedure enables the engineer to evaluate failure probabilities as well as rough (Level I) and precise (Level III) vulnerability curves, relating different seismic intensities to damage states or values. It is also possible to determine the probabilities to exceed different damage values/states and quantify seismic risk.

The method can also be employed for "Performance Based Seismic Design" which enables the designer to link different building performance objectives with different hazard levels (earthquake design levels). At the end, a brief discussion on related economic and insurance aspects is presented.

INTRODUCTION

Vulnerability or "Damageability" is defined as the possible damage sustained by the building from a potential external influence, in this case a seismic event. The term "Damage" has, however, different connotations (e.g. structural damage, loss of life, different economic losses etc.). This paper discusses the different structural and economical definitions of damage and the developed damage assessment methods, considering also the different evaluation requirements given in corresponding codes and standards in Europe and in the United States.

According to Eurocode 8 [1], "Design provisions for earthquake resistance of structures – General rules – Strengthening and repair of buildings", a vulnerability assessment can be carried out at three different levels, depending on the scope and the accuracy required. The topmost level includes an in-depth probability study of the particular type of construction (e.g. as a Monte Carlo simulation in conjunction with detailed, dynamic, non-linear time history analyses), while the lowest level involves a brief and

[1]Hochtief Construction AG, IKS, Frankfurt, Germany, Email: hamid.sadegh-azar@hochtief.de
[2]Chair of Structural Statics and Dynamics, RWTH Aachen University, Aachen, Germany. Email: kmeskou@lbb.rwth-aachen.de
[3]University of Tehran, Tehran, Iran, Email: msadegha@chamran.ut.ac.ir

straightforward assessment that takes just a few minutes to complete. The choice of the appropriate level of assessment for investigating the vulnerability of a specific building is determined both by the desired reliability of the results and by the resources available. The three levels of assessment are:

- Level I, simple and quick (time requirement for assessment less than one hour per building), suitable for determining risk for a large number of buildings. Only general building data - such as the age and the type of building - is taken into account at this level.
- Level II, detailed and more time-consuming (time requirement for assessment in the order of half a day per building). At this level, a number of measurements of the building's properties (e.g. natural frequencies, building height, cross-sections of the shear walls, etc.) may also be required.
- Level III, significantly more precise, but very time-consuming (time requirement for assessment can run into several days or weeks for each building). At this level, a precise analysis of the load-bearing structure is carried out using all building data. All key geometric and mechanical building properties are determined and included in the model.

Essentially, Eurocode 8 leaves it up to the user to decide which level of assessment is to be chosen. ASTM (1999) [12] also defines several levels of investigation but, contrary to EC8, it associates different investigation levels to different sub-tasks of the building assessment procedure, thus defining the required extent of each sub-task more precisely than EC8 does.

Detailed instructions on how to carry out different vulnerability investigation levels are given neither in the EC 8 nor in the ASTM.

In this paper the "EQ-Fast" method for assessing the seismic vulnerability of existing and new buildings is presented. It is based on the Eurocode 8 [1] recommendations on vulnerability methods.

DEFINITIONS

In the following some of the most important terms used in vulnerability evaluation procedures are briefly described.

Seismic Hazard

The seismic hazard gives the relationship between seismic intensity and the corresponding probability of exceedance (or return period). There are plenty of parameters to quantify the seismic intensity. A summary of some of these parameters is given in the following:

- Damage-based Intensity Values: The Modified Mercalli Intensity (MMI) is often used in conventional models for loss estimation in order to represent the ground motion severity. It is based on a qualitative description of the local effects of the earthquake at a site. The European Macroseismic Scale EMS-98 proposed by Grünthal reflects the latest developments in this kind of seismic intensity scales. 12 Intensity classes are defined in the EMS-98. Other seismic intensity scales are the Medvedev-Sponheuer-Karnik Scale (MSK) and the Mercalli-Cancani-Seiberg Scale (MCS).
- Seismological Intensity Values: The earthquake magnitude (M) and the closest distance to the rupture zone (R) can also be employed to express the seismic intensity.
- Engineer-seismological parameters: Time-domain or frequency-domain parameters and characteristic values of accelerograms, like maximal peak ground acceleration (PGA), effective peak acceleration (EPA), spectral acceleration value (S_a), ARIAS-intensity and RMS-quantity, represent scientific quantifications of the seismic intensity, which can be used to investigate structures [2].The spectral acceleration value S_a (f_1, ξ) at the fundamental frequency f_1 and for the damping value ξ of the

undamaged structure is the most precise parameters to describe the intensity and damage potential of earthquakes. The investigations performed show that this parameter correlates well with seismic damage [3, 4]. Its value can be estimated accurately and conveniently in a probabilistic manner using attenuation functions, independently of the definition of seismic damage.

The seismic hazard produces a connection between the intensity of an earthquake quantified by these parameters and the probability of its appearance (return period). The curve, which gives the relation between the intensities of earthquakes at a location and the belonging exceeding probability, is called Site-Specific Hazard Curve. The curve can be approximated by the following Equation [5, 7]:

$$H(S_a) = k_0 \cdot S_a^{-k} \tag{1}$$

where $H(S_a)$ is the hazard or probability to exceed the spectral acceleration value S_a and k_0 and k are site specific constants. This curve has to be determined for each location for different structural eigenfrequencies [8, 9, and 10]. A typical site-specific hazard curve is given in Figure 1.

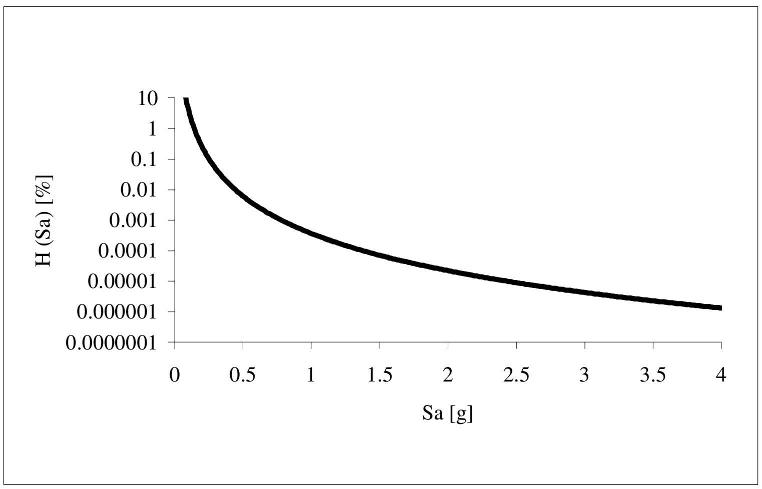

Figure 1: Site Specific Hazard Curve of Istanbul, Turkey (T =2.2 s)

The different ground motion parameters can be approximately related to each other by mostly empirical formulas. The Engineer-Seismological parameters can also be evaluated empirically as functions of probable earthquake Magnitudes (M), Distances (D) and other seismological parameters by using so-called “attenuation laws”.

Building Damage

The seismic damage can be divided into the following parts:

- Structural damage: This is the damage suffered by the load carrying structural components.
- Non-structural damage: This is the damage to non-structural elements (e.g. partitions, technical equipment, etc.)
- Inventory damage
- Business interruption

In this paper the main emphasis is on structural damage, however, the other damages types may also be integrated in the procedure. Two types of damage indicators are introduced: structural and economical. Structural and economical damage indicators can be linked together using relationships developed in the FEMA HAZUS 99 Project [13]. Additionally, a variety of other empirical expressions relating different damage indicators can be found in the literature.

Structural damage indicators

In earthquake engineering, various damage indicators are used to quantify the damage to buildings caused by seismic activity. In the following, representative indicators for dynamic and non-linear structure simulations are presented. The structural damage expressed in this way only includes the direct damage to the building. Inventory damage, losses caused by interruptions to operation and so on are initially not taken into account. Personal damage is currently not taken into account either. This may be determined, for example, in relation to the building's use and its useful area.

1. Local damage indicators

- Displacement ductility, μ: μ is defined as:

$$\mu = \frac{|u|_{max}}{u_y} \quad (2)$$

with the interstory drift u_{max} and the yield displacement u_y. u_y is ascertained as the point of intersection of the tangents of the elastic and the plastic range of the pushover-curve (force-displacement-curve). The interstory drift is defined as the maximal absolute reciprocate displacement of the floors divided by the story height. For steel constructions this value is in accordance with the ductility of the story [10].

- Interstory drift, ID: ID is the maximal relative displacement of two neighbouring floors:

$$ID = \frac{|u|_{max}}{h} \quad (3)$$

Herein h is the story height.

- Normalized hysteretic energy, NHE: NHE is equated to the cumulative hysteretic energy, absorbed in any cycles, scaled by the twofold yield strain energy:

$$NHE = \frac{\sum_{1}^{N} \left(\oint R_u \, du \right)}{R_y \cdot u_y} \quad (4)$$

with the force-displacement-relationship in every story R_u, the number of cycles N and the yielding force R_y. The value of this integral is conform to the area under the pushover-curve in every cycle.

- Park/Ang-indicator, DI: The most famous cumulative damage indicator is a linear combination of the scaled displacement as well as NHE and as a rule is dominated by the first term:

$$DI = \frac{|u|_{max}}{u_{ult}} + \beta \cdot \frac{HE}{R_y \cdot u_{ult}} \quad (5)$$

with the maximal monotone displacement capacity u_{ult} (value depends mainly on the kind of steel, the cross-section and its class, the kind of load and the construction of the nodal points), the weighting factor β and the cumulative absorbed hysteretic energy

$$HE = \sum_{1}^{N} \left(\oint R_u \, du \right) \quad (6)$$

2. Global damage indicators

- Ductility, μ: The global ductility is defined as the maximal displacement of the top level (relatively to the foundation) divided by the global yield displacement.
- Normalized hysteretic energy: The global normalized hysteretic energy I is defined as the cumulative hysteretic energy HE, absorbed in any story. I is scaled by the product of the global yield displacement and the corresponding global force, which is in accordance with the shear force at the foundation. These values can be calculated by using the pushover-curve.

- Park/Ang-indicator: This value is a weighted summation of the local Park/Ang-indicators of all stories. For each floor the weighting factor is in accordance with the hysteretic energy of the story in relation to the whole building's hysteretic energy [11].

Economic damage indicators

The majority of the above mentioned indicators are of limited use from the perspective of the decision-making, administrative, finance and insurance sector, since they take no or only minimal account of the monetary consequences of the damage. For this reason, seismic damage is also quantified using:

- Damage ratio, DR: This value is defined as (ASTM 1999, [12]):

$$DR = \frac{\text{Repair costs of a building}}{\text{Value of the undamaged building}} \tag{7}$$

- Mean Damage Ratio, MDR(I): This value is the expected value of the DR at earthquake intensity I.
- Probable Loss (PL): Damage in percentage of the building replacement cost corresponding to a certain exceedance probability for a given time period (ASTM 1999, [12]).
- Scenario Loss (SL): Damage in percentage of the building replacement cost caused by seismic events from specific fault zones or other defined ground motions (ASTM 1999, [12]).
- Probable Maximum Loss (PML): Upper limit of the seismic damage as percentage of the building replacement cost which can occur at a specific location due to all possible events (according to EERI). This value has a number of significantly different explicit and implicit definitions and the ASTM guideline [12] discourages the use of this damage indicator.

BASICS OF THE PROBABILISTIC DAMAGE

Investigations by ATC [20] have proofed that the distribution of the non-linear building response at a given earthquake scenario is similar to the lognormal distribution. Because this distribution is asymmetric, the best approximation of the building's response is the median θ of the damage values. An additional advantage of the median compared to the mean value is that the median is more "resistant" and stable against highly dispersed values which are common in nonlinear seismic analysis. For a lognormal distribution this value is identical to the geometric mean:

$$\theta = \exp\left[\frac{\sum_{i=1}^{n} \ln x_i}{n}\right] \tag{8}$$

with the values of the random sample x_i and its number n. The standard deviation of the data's natural logarithms acts as a measure of dispersion and is given by:

$$\delta = \left[\frac{\sum_{i=1}^{n} (\ln x_i - \ln \hat{x})^2}{n-1}\right]^{\frac{1}{2}} \tag{9}$$

RISK AND VULNERABILITY EVALUATION PROCEDURE

In conjunction with Gerling Globale Rückversicherungs AG and Gerling Consulting Gruppe GmbH, a method known as "EQ-Fast" was developed for the rapid assessment of the seismic vulnerability of residential buildings. It is based on the Eurocode 8 [1] recommendations on vulnerability methods, and its application to a specific building yields a quantitative assessment of its susceptibility to damage by future seismic events; the method also includes measurements of the building's and the adjoining soil's fundamental natural frequencies (only Level II&III). As stipulated in Eurocode 8, the evaluation can be carried out at three different evaluation levels (Level I-III) with different time and expenditure requirements, depending on the desired accuracy and reliability. The method was developed in the aftermath of the catastrophic earthquake in Turkey on August 17th, 1999, due to the demand from the finance and insurance sector for tools with which to assess future damage probabilities, enabling them to develop appropriate insurance services and products ([6], [18], and [21]). Since the "EQ-Fast" method yields estimates for the failure probability of seismically excited buildings, its results can be used in various ways for enhancing seismic protection and building safety.

Investigation Level I and II

The first step is always a visual building inspection. During this inspection, a number of parameters that are important in seismic behavior (such as construction type, the presence of irregularities, etc.) are recorded. If necessary, the building's dimensions and its fundamental natural frequency are also determined. If necessary, the fundamental natural frequency of the subsoil is also determined, or frequency ranges are determined within which a particular amplification of seismic excitation occurs through the adjoining soil layers. For this, the H/V process according to NAKAMURA is used.

The acquired data is entered into "EQ-Fast" from the laptop computer, and the program performs the analysis based on the developed methods. Entered data and the results are stored in a file and can be printed out as an assessment report, while the file can be integrated in a further step into a global database for statistical purposes. The procedure is described in detail in Sadegh-Azar [21].

It is known that the changes to the building's natural frequencies following an earthquake can provide an indicator of the extent of the damage to the building's structure. This effect has been investigated in many publications e.g. Fox [14] and Salawu [15], although the approaches used for this are not yet generally suitable for all buildings. The natural frequencies determined using this method can be used as a basis for a comparison with values measured at a later point in time (e.g. after an earthquake), and can be used to provide information about the damage sustained.

In Level I a fast and relatively inexpensive assessment of the building is carried out. It does not involve a structural analysis, but rather just a building inspection of between 30 and 60 minutes' duration where data is recorded and then evaluated at a later stage. During this tour of the building, a rapid process is used to investigate whether the structure may be able to withstand potential seismic forces, or whether there are grounds to doubt this. Particular attention is paid to detecting the presence of typical vulnerable construction types or weak points, which experience has shown can lead to extensive damage (e.g. "soft story"). During the inspection, the collected information is stored in the "EQ-Fast" expert system, which also carries out the assessment. Some of the building and site characteristics required at this level are listed in Table 1.

Table 1: Some building and site characteristics for Level I

Building Data	Structural System	Site and Subsoil data
Year of construction	Building type	Seismic zone
Building use / importance	Torsion	Soil properties
Number of stories	Soft story	Soil liquefaction
Height of stories	Plan irregularity	Risk of landslide
Building inspector	Short columns	GPS data

To enable the geographical location of the building under investigation to be determined, its GPS coordinates (geographical latitude and longitude) are also stored. This data can be used to later simulate various regional earthquake scenarios.

EQ-Fast can be used for 15 different types of construction, including

- Rigid steel moment frames,
- Steel moment frames with bracing reinforced concrete walls,
- Reinforced concrete frames,
- Braced steel moment frames and
- Non-reinforced masonry constructions

The 15 types of construction supported by EQ-Fast cover the majority of cases that arise in practical situations.

In Level II, further measurements are taken on site in addition to the data gathered in Level I. The overall time spent on the Level II inspection, the measurements and the subsequent evaluation with "EQ-Fast" is around six hours. Measurements are taken in particular of data such as the building's fundamental natural frequency and, where necessary, also the fundamental natural frequency of the adjacent subsoil. Simplified calculations are also used to check whether the building is able to withstand seismic forces, and whether any visible weak points are present. These simplified mathematical investigations include, for instance, the following points:

- Calculation of the horizontal seismic forces in accordance with several national and European codes and a check of the construction's safety against overturning.
- Drift checks for frame load-bearing structures, based on the calculated seismic forces.
- Shear stress checks in reinforced concrete columns. The calculated shear stresses are then compared with conservatively estimated permissible values. The calculation is based on simplified formulas from FEMA 310 [16] and 178 [17].
- Shear stress checks in shear walls. The calculated stresses in shear walls are compared with permissible values. This calculation is also based on simplified formulas from FEMA 310 (1998) [16] and FEMA 178 [17].
- Check of the diagonal bracing elements.

As already mentioned, the fundamental natural frequency of the building is also measured, and compared with the natural frequency of the subsoil. If both values lie very close to each other, resonance effects should be anticipated that can cause extensive damage to the building. The procedure for measuring the building/soil frequency is described in detail in Meskouris et al. [18].

At the end, the Level I and II assessments produce the following results / information:

- Information on the structural weak points of the building
- The building's score, which quantifies the likelihood of failure (failure meaning $DR > 60\%$)
- Values of the building's mean damage (mean damage ratio, *MDR*) for various earthquake intensities

Using the entered data, the "EQ-Fast" program calculates a score for the building. This building score (*Sc*) is defined as the negative decadic logarithm for the probability of the building failure, failure corresponding to a DR value of 60% or more:

$$Sc = \text{-log (failure probability)}$$
with
$$Sc = \text{-log (probability of damage } DR \geq 60\%\text{)}.$$

The building score *Sc* can be thought of as an approximation of the building safety index ß for static loads. The statistical data contained in ATC 13 [19] and ATC 21 [20] provides the basis for calculating the building scores. These reports supply some of the few generally available, complete and systematically documented assessments of damage in earthquake regions.

From the building scores, the lognormal distribution function can be used in a further step to calculate the *MDR* values for various earthquake intensities. From these values, the building's damage curve can be derived. Figure 2 shows a damage curve of this kind. It was calculated for a 12-story steel moment frame building located in seismic zone "high" (EPA > 0.20 g) with a soil class C (according to EC 8). Figure 2 also shows the 10% and 90% fragility curves. The seismic load can alternatively be described using the MMI (Modified Mercalli Intensity), the EPA (Effective Peak Acceleration) or the PGA (Peak Ground Acceleration).

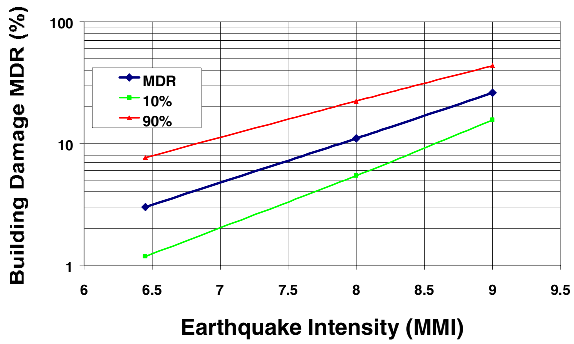

Figure 2. Damage curve and the corresponding 10% and 90% fragility curves for a 12-story steel moment frame building located in seismic zone "High" (EPA>0.20 g).

Investigation Level III

Level III is an in depth investigation of the building and uses probabilistic seismic hazard analysis (PSHA) on one hand and probabilistic nonlinear dynamic time-history simulations on the other hand to evaluate the annual damage curve of the building. This curve represents the most scientific and rigorous expression of the expected seismic damage. The seismic intensity is expressed in terms of spectral acceleration value at the first natural frequency of the building. This intensity value has a very good correlation with the resulting structural damage in the building, except for time histories featuring near source effects. An extensive study regarding the choice of an appropriate intensity parameter is given in Sadegh-Azar [21] and Elenas and Meskouris [22].

A probabilistic approach is utilized to analyze the building because of the high dispersion of building damage in the time history analysis. For instance, Figure 3 shows the damage values (quantified here by maximum interstory drift) for different time histories using the same earthquake Magnitude M and Distance from the building site r_{rup}.

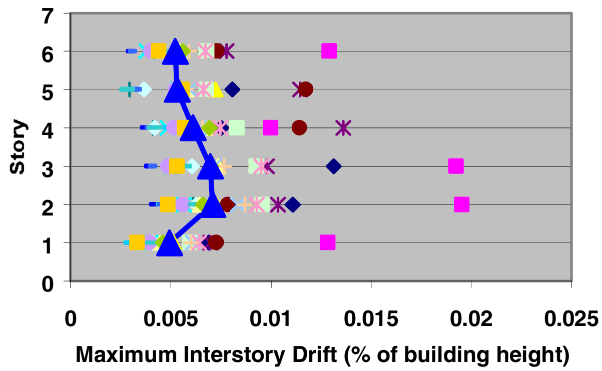

Figure 3: Damage dispersion in time history analysis. The continuous line corresponds to the Median damage values.

Also the latest investigations revealed that a separate analysis of the seismic hazard (relationship between intensity and return period) and the vulnerability evaluation (relationship between intensity and damage) leads to imprecise or inaccurate results. This issue should be taken into account especially if the damage dispersion is high for a specific seismic intensity.

In the proposed procedure for Level III the PSHA is incorporated in the vulnerability evaluation. The flowchart of the risk and vulnerability analysis procedure is shown in Figure 4.

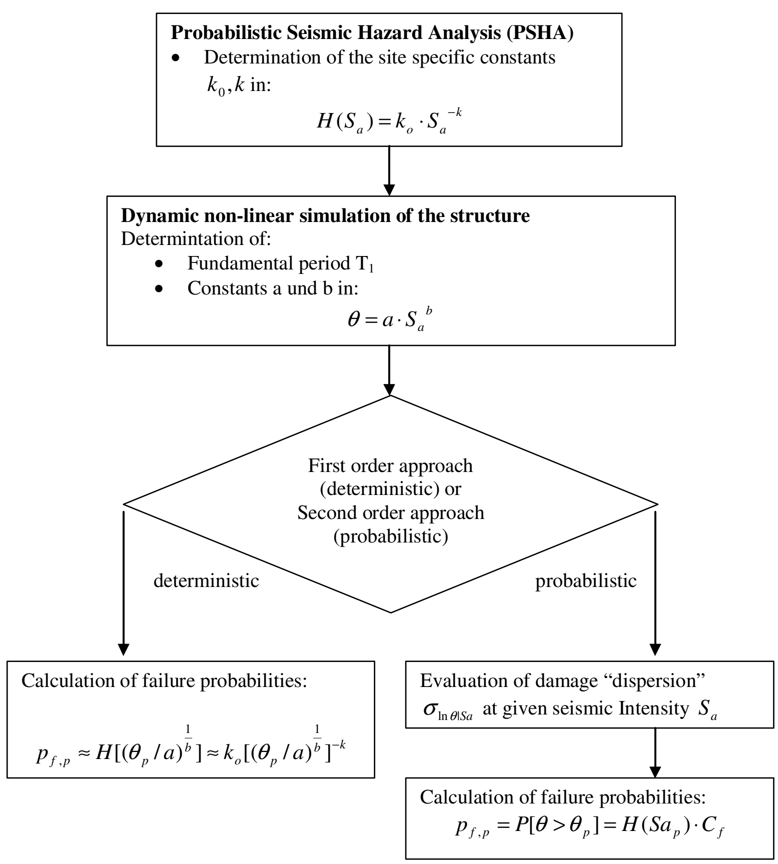

Figure 4: Level III risk and vulnerability evaluation

A preceding scaling of the required time histories to the spectral acceleration at the first natural frequency improves the efficiency of the procedure enormously. For a given confidence band the number of required time-history analysis will be reduced to about 1/4.

The correlation between the earthquake intensity quantified by S_a and the median θ of the damage values quantified by Interstory Drift can be approximated by [12, 22, 23, 24]:

$$\theta = a \cdot S_a^{\ b} \qquad (10)$$

with the constants a and b, which have to be calculated by regression analysis.

Figure 5 shows a level III structural damage curve for a steel moment frame designed according to EC 8 for Istanbul. S_a is the spectral acceleration at the first building natural frequency. Building Damage is quantified here by maximum global and interstory drift (Global drift being defined as the roof displacement divided by the building height).

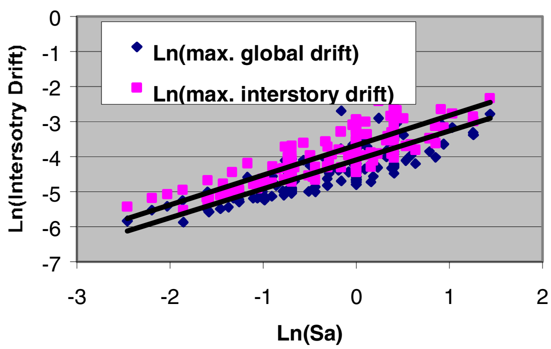

Figure 5: Structural damage curve for a steel moment frame designed according to Eurocode 8 (Istanbul)

The probability $p_{f,p}$ for θ to exceed a given value θ_p corresponding to the damage state p can be calculated by the following formula [7], [9]:

$$p_{f,p} = P[\theta > \theta_p] = H(Sa_p) \cdot C_f \qquad (11)$$

with

$$C_f = \exp[\frac{1}{2} k^2 (\sigma_{\ln \theta | Sa} / b)^2]. \qquad (12)$$

C_f serves to take into account the variation of the building's response due to a certain earthquake intensity.

The resulting curve expressing the relationship between the different damage values (e.g. represented by Interstory Drift) and their annual probability of exceedance is called the annual damage curve. The damage curve is shown in Figure 6 for the investigated building in Istanbul (Seismic design according to Eurocode 8). This curve is the most precise and accurate quantification of seismic damage.

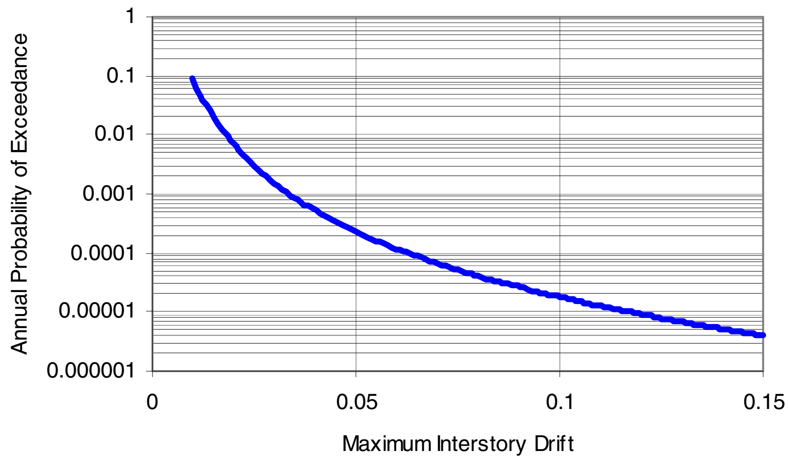

Figure 6: Annual damage curve for the investigated building in Istanbul

The damage results of a Level III analysis are, of course, structural damage values, which in turn can be related to the corresponding monetary damage values (e.g. DR, MDR). References on this matter can be found in FEMA 273 [23] and FEMA HAZUS [13].

PERFORMANCE BASED SEISMIC DESIGN

The method described in the previous section (Level III) can also be employed for "Performance Based Seismic Design" which enables the client/owner/designer to link different building performance objectives/levels with different hazard levels (earthquake design levels). The complete procedure is described in Sadegh-Azar [21]. Typical hazard and performance level are given in Fig. 7. For instance, the owner of a high-tech chip producing facility may demand a higher performance level than those prescribed by the code, to protect his investment in the case of a very rare, but possible earthquake. The Structural Performance Levels are defined in recently developed guidelines (e.g. FEMA 273 [23], SEAOC's Vision 2000 [24], FEMA 283 [25]).

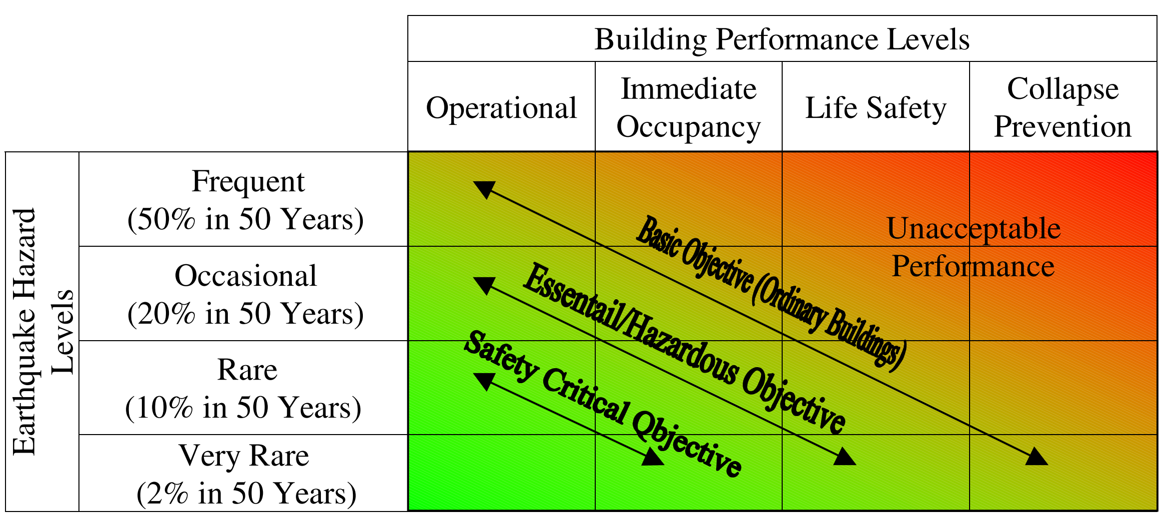

Figure 7: "Performance Based Design" - Typical hazard and performance levels

The drift limits given in the FEMA 273 guidelines can be used to determine the corresponding performance level from the Level III damage results. For instance, Table 2 shows corresponding drift limits for steel moment frame structures.

Table 2: FEMA 273 drift limits for different structural performance levels in steel moment frames

	Structural Performance Level		
	Immediate Occupancy	Life Safety	Collapse Prevention
Maximum Interstory Drift	0.7 %	2.5 %	5 %

The procedure described in Level III enables the designer not only to allocate different performance levels to hazard levels; it yields also the annual failure (or exceedance) probabilities of a building. Using this measure, different buildings in different seismic zones can be compared from a global point of view. It can also be used to determine and compare the safety inherent in seismic codes.

ECONOMIC AND INSURANCE ASPECTS

Global Aspects

Earthquakes claim many human lives in the residential and commercial regions of our world, and destroy countless items of value. The increase in globalization, with the international networking of markets, infrastructural dependencies and value concentrations in conurbations are all creating systems that are sensitive to earthquakes. The relatively long periods between the recurrences of these natural disasters often conceal the fact that the next earthquake will definitely come. It can be expected that the extent of the damage caused by future earthquakes will grow significantly, and building owners, original insurance and reinsurance companies will have to bear rising damage costs. Here, existing buildings are the largest source of risk.

Over the next decades, at least, the predominant portion of the earthquake risk faced by people in Europe and the States and indeed, in most nations with advanced earthquake resistive construction practices relates to the existing stock of buildings, rather than those that are yet to be constructed. Given an average building life of at least 50 years, it can be seen that the existing stock of buildings includes many vulnerable structures with long remaining lives.

Among them, it is not just the major buildings (skyscrapers, wide-spanned bridges, etc.) that are of interest due to their high value or even the importance of their use (e.g. public buildings, hospitals), but also the large number of small or privately owned buildings which could sustain damage.

To assess the seismic behavior of buildings of all levels of complexity, highly-developed computer-based solutions are available such as the finite elements method, or the finite difference method. These frequently have the disadvantage, however, that the time required for the modeling process and the associated costs are so high that they preclude more or less comprehensive application, which is what would be required in small or privately owned buildings.

If we are to significantly reduce our earthquake risk and vulnerability, we must find the means to analyse and improve the seismic performance of our existing stock of buildings in an economical justifiable framework. The first challenge is to identify highly vulnerable buildings. This can be accomplished economically using the vulnerability evaluation procedure described before. The results can also provide the data required to coordinate and optimize the planning activities of local authorities, disaster prevention bodies or the insurance industry.

During the development of the vulnerability evaluation procedure, particular attention have been paid to the parameters that need to be recorded - they must have a high significance in terms of seismic vulnerability, and their acquisition needs to be simple, fast and therefore inexpensive.

After evaluating the vulnerability of a building, the next issue is, if the costs of retrofit or seismic upgrading are justifiable. Owners will be motivated to upgrade their structures if the present value of the upgrade cost is less than the present value of the probable benefit.

Typical cost-benefit or economical feasibility studies can be made using the vulnerability results, especially the annual failure or damage probabilities. An economic model for cost-benefit analysis is given in the next section.

Also in the insurance industry, there is an increasing trend towards natural disaster risk management, which initiated the development of the presented procedure.

Technical Economic and Insurance Aspects

The first issue in this part is the determination of the expected annual loss (= technical insurance premium). Using this value the upgrade benefits can also be evaluated in a subsequent calculation.

By folding the Hazard Curve *h(I)* (which establishes the relationship between the annual exceeding probability and the earthquake intensity *I*) with the damage curve (which reproduces the relationship between the earthquake's intensity *I* and the damage to the load-bearing structure), the probable annual damage or technical insurance premium can be calculated. The probable annual damage R_i (in % of the building's value) is proportional to the annual insurance premium and is calculated as:

$$R_i = E[MDR_i] = \int h(I).MDR_i(I).dl \qquad (13)$$

or

$$R_i \approx \sum_I \frac{MDR_i(I)}{T(I)} \qquad (14)$$

where

$T(I)$ = Return period of a earthquake with intensity I

$MDR_i(I)$ = Mean damage ratio for intensity I.

In practice, the left hand term of the given equations is governed by only one earthquake intensity with a specific return period. Based on this formula, there are a variety of proposals regarding the calculation of the gross insurance premium. For instance the following formula is given by Tiedmann (Oliveira et al. [27]):

$$R_i = \max_I\left(\frac{MDR_i \cdot f \cdot v \cdot P \cdot 100}{SI \cdot T(I)}\right) \qquad (15)$$

where

f = Factor covering overheads, profits, etc.,

v = Factor covering uncertainities

P = Period of exposure to hazard (or reference time interval)

SI = Percantage of sum insured

As stated before an important issue is the economic advantage for seismic rehabilitation or upgrade. A simple economic model for analyzing seismic upgrade is to compare the present value of expected upgrade benefit and upgrade cost. If the costs are less than the expected benefit, then upgrading/retrofit is economically feasible. The following formulations apply to the model:

Expected Annual Loss (before upgrading/rehabilitation) = R_i^E = R_i[before upgrading]· (Building Value)

Residual Annual Loss (after upgrading/rehabilitation) = R_i^R = R_i[after upgrading]· (Building Value)

$$\text{Present Value of Expected/Residual Annual Loss in year i} = \frac{R_i^E}{(1+e)^{i-1}}$$

$$\text{Present Value of Residual Annual Loss in year i} = \frac{R_i^R}{(1+e)^{i-1}}$$

The expected upgrade benefit for a building during its lifetime ("n" years) can be determined from:

$$\text{Expected Upgrade Benefit} = \sum_{i=1}^{n}\left[\frac{R_i^E - R_i^R}{(1+e)^{i-1}}\right] \qquad (16)$$

Typical building lifetimes "n" are 50-80 years.

Human losses and injuries can also be considered in the economic model. In this case the value of avoided deaths and reduced injuries should also be considered in equation (16). However, fixing the economic value of human life is a difficult and sometimes controversial issue. Reference can be found in Keech [26].

Keech's consensus value of $ 1,740,000 is suggested by many authorities and may be used in the cost-benefit analysis. Also major injuries may be valued at $ 10,000 and minor injuries $ 1000.

The economical feasibility depends on a large number of site/building/occupancy parameters and a building and country specific case study has to be conducted for reliable results. Generally, upgrading buildings is economically feasible for buildings in regions of high seismicity, poorly constructed buildings or heavily populated buildings like schools, government offices and so on (if the human losses are also taken into account).

REFERENCES

1. Eurocode 8, Part 1.4: "Design Provisions for Earthquake Resistance of Structures – General Rules – Strengthening and Repair of Buildings", 1998
2. Meskouris, K., "Structural Dynamics - Models, Methods, Examples", Ernst&Sohn/Wiley, Berlin, 2000
3. Elenas, A.; Meskouris, K.: "Correlation Study between Seismic Acceleration Parameters and Damage Indices of Structures", Engineering Structures 23 (6), pp. 698-704, 2001
4. Schmitt, T.: „Zusammenhang zwischen seismischen Parametern und der Bauwerksschädigung im Erdbebenfall", Diplomarbeit am Lehrstuhl für Baustatik und Baudynamik der RWTH Aachen, 2000
5. Bazzuro, P.: "Probabilistic Seismic Demand Analysis", Ph.D. Thesis, Dept. of Civil Engineering, Stanford University, Stanford, CA, 1998

6. Meskouris, K., Sadegh-Azar, H., “Seismic Vulnerability of Buildings in View of EC 8 and New US Standards”, Structural Dynamics, EURODYN 2002, Grundmann & Schueller (eds.) Munich, 2002
7. Cornell, C.A.: “Calculating Building Seismic Performance Reliability: A Basis for Multi-Level Design Norms”, Eleventh World Conference on Earthquake Engineering, Paper No. 2122, 1996
8. Gupta, A.: “Seismic Demands for Performance Evaluation of Steel Moment Resisting Frame Structures”, Dissertation, Stanford University, 1998
9. Sadegh-Azar, H., Meskouris, K., Kalker, I.: „Earthquake Risk Assessment in the Framework of Eurocode 8”, International Conference – Earthquake Loss Estimation and Risk Reduction, Bucharest, 2002
10. Shome, N.: “Probabilistic Seismic Demand Analysis of Nonlinear Structures”, Dissertation, Stanford University, Stanford, CA , 1999
11. Park, Y.J.; Ang, A.H.S.; Wen, Y.K.: “Seismic Damage Analysis for Reinforced Concrete Buildings”, Journal of Structural Devision, ASCE, Vol. 111, No. 4, pp. 740-757, 1985
12. ASTM E 2026-99: “Standard Guide for the Estimation of Building Damageability in Earthquakes” (1999)
13. Federal Emergency Management Agency, “HAZUS 99-Technical Manual”, FEMA, Washington, D.C., 1999
14. Fox, C. H. J., “The location of defects in structures: a comparison of the use of natural frequency and mode shape data”, Proceedings of the 10th International Modal Analysis Conference, San Diego, California, 522-528, 1992
15. Salawu, O. S., “Detection of structural damage through changes in frequency: a review”, Engineering Structures, Vol. 19, No. 9: 718-723, 1997
16. Federal Emergency Management Agency FEMA 310, “Handbook for the Seismic Evaluation of Buildings – A Prestandard”, 1998
17. Federal Emergency Management Agency FEMA 178, “NEHRP Handbook for the Seismic Evaluation of Existing Buildings”, 1992
18. Meskouris, K., Sadegh-Azar, H., Berezowsky, M., Dümling, H., Frenzel, R., “Schnellbewertung der Erdbebengefährdung von Gebäuden“, Bauingenieur, Band 76, 2001
19. Applied Technology Council, ATC 13, “Earthquake Damage Evaluation Data for California”, 1985
20. Applied Technology Council, ATC 21, “Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook”, 1988
21. Sadegh-Azar, H., „Schnellbewertung der Erdbebengefährdung von Gebäuden“, Dissertation am Lehrstuhl für Baustatik und Baudynamik der RWTH Aachen, 2002
22. Elenas, A., Meskouris, K., “Correlation study between seismic acceleration parameters and damage indices of structures”, Engineering Structures 23(6), pp 698-704, 2001
23. Federal Emergency Management Agency FEMA 273, “NEHRP Guidelines for the Seismic Rehabilitation of Buildings”, 1997
24. Structural Engineers Association of California SEAOC. “Vision 2000: A Framework for Performance Based Engineering”, 1994
25. Federal Emergency Management Agency FEMA 283, “Performance Based Seismic Design of Buildings”, 1996
26. Keech et al., “Economic Values of Federal Aviation Administration Investment and Regulatory Programs”, Office of Aviation Policy and Plans, Federal Aviation Administration, Dept. of Transportation, Waschington, D.C., 175pp., 1989
27. Oliveira, C. S., Campos-Costa, A. and Sousa, M. L. “Basis for Earthquake Insurance Policies”, Eleventh World Conference on Earthquake Engineering, Acapulco, Mexico, Published by Elsevier Science Ltd, Oxford, U.K., 1996