Safety acceptance criteria for existing structures

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Abstract

Due to the social and economic need of utilizing existing structures, their safety evaluation is of major concern. In principle, criteria for safety acceptance of existing structures should be based on present guidelines, standards and methodologies. The mere fact that the structure fulfils the code of its time of construction cannot be decisive. Codes have changed over time due, for example, to technology development and experience gained with the performance of structures when struck by past events. This does not mean, however, that if a new code with more severe requirements than old ones comes into practice, old buildings should necessarily be deemed unsafe. A "discount" in the safety requirements for existing structures is simply unavoidable due to economical and legal constraints. The present contribution discusses current risk acceptability criteria for existing structures based on:

- experience gained from European practice
- review of current criteria for existing structures in seismic regions of US
- industrial experience gained from various projects
- recommendations given by the Joint Committee on Structural Safety (JCSS)
- cost benefit approach including implied costs to avert casualties

Suggestions for future recommendations for risk acceptance criteria of existing structures are also provided.

1. Introduction

Due to the social and economic need of utilizing existing structures, their damage assessment and safety evaluation are of major concern. In fact more than half of the budget spent for construction activities in developed countries such as Germany is related to retrofit of structures (Bayerische Ingenieurkammer Bau, 2004). Consequently the analysis of existing structures has received great attention in the technical literature. Risk acceptance and decision criteria, however, are not adequately developed in this field.

Criteria for safety acceptance of existing structures should be based on present guidelines and methodologies. Therefore the acceptability limits (or targets) should, implicitly or explicitly, account for probabilities of failure, potential losses, amount of investments necessary to improve safety, and possibly a combination of all these factors. Such targets have been developed for various industrial activities including new civil engineering structures (JCSS, 2007).

Present approaches to set acceptability limits for *new structures* include:

- Derivation from observed fatality rates and reported economic (insured and ground-up) losses.
- Calibration to present practice based on the postulate that the safety margin implied by present practice is acceptable and economically optimal. It is noted that in accordance with common non-technical terminology, safety is meant here as the property of a facility of exposing occupants to an acceptable risk of injury and death.
- By decision, based on the optimization of generalized benefits and cost including expected failure cost (e.g., structural, loss of function, environmental damage, and human losses).
- By a normative process or limits set by public legislation

Because limits set by building codes and regulations have roots in the criteria dictated by failure statistics, are calibrated to present practice, and contain elements of generalized cost-benefit analysis on behalf of the public, the normative approach is simply a derivation of the first three approaches.

However, acceptable limits for new structures are not necessarily the same as those for existing ones, because influencing factors such as

- Lifetime of the structure
- Degree of available technical knowledge (codes, methods, etc.)
- Relative effort (costs) to control safety
- Time constraints (for engineering and eventual repair)
- Consequences of potential failures
- Socio-economical and political preference

when the decision is made and thus the degree of available information on the above items may have changed over time. Therefore, a "discount" in the safety requirements for existing structures may be simply unavoidable due to economical and legal constraints.

The present contribution discusses current risk acceptability criteria for existing structures based on:

- experience gained from European practice and standards
- review of current criteria for existing structures in seismic regions in the USA
- industrial experience gained from various projects
- analysis of the recommendations given by the Joint Committee on Structural Safety
- cost benefit approach including implied costs to avert casualties

Suggestions for future recommendations related to safety acceptance criteria for existing structures are provided.

2. General Framework

To allow a reliability-based reassessment of existing structures acceptability limits regarding safety have to be explicitly set. Decisions regarding future actions to gauge the performance of a structure or to improve its safety, such as:

- Monitoring / control
- Application of load restrictions
- Change of use
- Repair
- Strengthening
- Replacement

can only be rationally made if the computed probability of failure associated to a certain performance or limit state criterion can be compared with the acceptability limits. Hence, safety limits must also be represented in a quantitative form such as the target p_F or, equivalently, the corresponding reliability index, β. The acceptability limits depend on structural characteristics (see, for example, Allen, 1993) and on economical criteria (JCSS, 2001) represented by:

- Marginal cost of reliability (relative cost to increase reliability or to decrease risk ΔCost/ΔRisk)
- Consequences of failure

The consequences of failure may include direct financial losses for damage repairs, for demolition and reconstruction, for casualties, and also for the so-called intangibles like loss of future opportunities, such as loss of public welfare and professional reputation. In general, targets may be different for different stakeholders (e.g., owners, tenants, developers, and public), given that each one has markedly different priorities and time horizons of interest in the structure. Finally, in a cost-benefit context, such acceptability limits are also influenced by the cost to improve safety.

Safety targets have been developed mainly for new structures in the last two decades. Much debate has been thereby going on whether to include human lives into cost benefit analyses and whether it is at all admissible to perform cost-benefit analysis when casualties may be involved in case of structural failures. This requires introducing a monetary equivalent to save human life and limb into the analysis. More recent studies on behalf of the public use so-called compound social indicators (Natwani *et al*., 1997; Rackwitz, 2002). Social indicators are statistics that reflect some aspect of the quality of life in a society or group of individual. More specifically, they aim to reflect broadly accepted goals that may carry labels such as national development, high expectancy of quality-adjusted life, the common good or the public interest. Any undertaking (e.g., a specific project, a program or regulation, or the adoption of a new therapy) that affects the public by changing health or risk and expenditure will have an expected impact on a compound social indicator. A positive net impact of an undertaking on the accepted social indicator will lend to support the undertaking.

For example, the Life Quality Index (LQI) (Natwani *et al*., 1997; Rackwitz, 2002) is intended as an indicator for quality-adjusted life expectancy. It is a function of the real gross national product (GNP) per person per year and of the life expectancy at birth. If applied to the fatality risk for structural failure in developed countries, it can be shown that in the 1990s money saving a human life has approximately a cost of US$ 100.000 per year or about US$ 4.000.000 per average life time. (JCSS, 2001). By using the LQI it is possible to include human losses when deriving optimal target reliability indices (Streicher and Rackwitz, 2006). In such an optimization the target probability of failure could be obtained to minimize the overall cost, which include cost of planning, cost of repair, cost of maintenance, and cost related to the consequences of failure (economic, ecological, human).

However, cost-benefit analysis and associated considerations cannot be the sole basis for decision due to social and political constraints on the decision process. In fact target reliability depends also on public concern and on mass media’s focus on ecological, economical and human loss issues.

Target values for the ultimate limit states related to failure of structural members of *new* structures have been presented by the JCSS (2001, 2007). The values correspond to individual structural elements and to one year reference period and reflect code calibration experience and the aforementioned cost-benefit considerations (Ellingwood, 2005). Acceptability criteria for existing structures are explored in the following sections.

3. Review of current standards and recommendations

The safety evaluation of existing structures is different depending on, for instance, the type of structure and the reason for evaluation. In regions of high seismicity, for example, guidelines and standards, such as ATC (1996), FEMA (1998), and ASCE (2001), provide concepts and tools for the seismic evaluation of existing buildings. The evaluation procedures are based on a rigorous approach to determine whether existing buildings subject to ground motions associated with specific mean return periods suffer consequences that are within the definition of pre-specified acceptable performance levels. The performance is measured in terms of monetary losses, fatalities, and downtime.

Safety aspects for existing structures are also provided in national and international standards and recommendations. The American Concrete Institute (ACI, 2003) guidelines and the recommendations by the Joint Committee on Structural Safety (JCSS, 2001) as well as the Swiss note SIA (1994) are typical examples. In addition, reliability based criteria for the assessment of existing structures have been presented in various publications (for example, see Ellingwood, 2005; Schueremans and Van Gemert, 2004).

As mentioned earlier, criteria for safety acceptance of existing structures should be based on present guidelines, standards and methodologies but allow for "discounts" in the level of safety. In fact, many organizations (e.g., FEMA and SEAOC) authorities set the precedent that the acceptable seismic performance objectives for existing buildings maybe somewhat lower than those for new ones. These allowances reflect a realistic recognition of the reduced cost-effectiveness of seismic retrofits versus new construction and implicitly account for legal considerations as well.

The current practice in defining target criteria for existing structures is reviewed here

- Recent developments in performance based design
- European experience in limit state design including the JCSS recommendations and other proposed approaches

3.1. Performance based design

Performance-based design is a relatively recent framework that articulates the performance intent and the design standards through performance objectives that couple the desired performance level to be achieved for a given level of hazard. The effort of introducing these concepts into practical guidelines arose from the realization that the two major earthquakes that occurred in California in the last 20 years, the 1989 M6.9 Loma Prieta earthquake and the 1994 M 6.7 Northridge earthquake, created disproportionately large and unacceptable economic consequences. The loss of human lives in those two events, however, was relatively minor when compared to similar earthquakes such as the 1995 event that struck Kobe in Japan. Hence, it was felt that the then-current design was providing an acceptable level of safety towards collapse but was not adequate for less threatening but very costly limit states.

Therefore, for example, the Structural Engineers Association of California SEAOC's Vision 2000 (SEAOC, 1999) and the National Earthquake Hazard Reduction Program (NEHRP Guidelines, see ATC, 1996) have attempted to provide more quantitative definitions of building performance levels as shown in Table 1.

Table 1: Performance Levels (SEAOC, 1999)

Performance Level NEHRP (ATC, 1996)	**Performance Level Vision 2000**	**Short Description**
Operational	Fully Functional	No significant damage to structural and non-structural components
Immediate Occupancy	Operational	No significant damage to structure; non-structural components are secure and most could function if utilities available
Life Safety	Life Safe	Significant damage to structural elements; non-structural elements are secured but may not function
Collapse Prevention	Near Collapse	Substantial structural and non-structural damage; limit margin against collapse

The SEAOC (1999) defines four seismic hazard levels as given in Table 2. The maximum considered earthquake ground motion has the same definition as in the NEHRP seismic provisions for new and existing buildings. The combination of the seismic hazard level associated to the mean return period of the ground motion level at the structure's site and of the performance level represents a specific design performance objective.

Table 2: Seismic hazard levels (SEAOC, 1999). The values in the third and fourth columns refer to the exceedance of the ground motion at the structure's site.

EQ -Level	**Event**	**Annual Exceedance Probability**	**Mean Return Period (years)**
I	Frequent	4%	25
II	Occasional	1.4%	72
III	Rare	0.125% - 0.4%	250 - 800
IV	Max Considered	0.04% - 0.125%	800 - 2500

Using the total probability theorem, the performance objective for non-collapse in the event of maximum credible earthquake ground shaking can be restated as being less than a 2% chance in 50 years of earthquake-induced structural collapse (Hamburger *et al*., 2003). Note that the approach represented in Tables 1 and 2 originally did not explicitly include the effects of capacity uncertainty in the structure's reliability requirements. Additional refinements were subsequently added to the performance matrix (see, for example, Wen, 2000; Hamburger et. al., 2003) related to the confidence level that a structure subject to a certain ground motion level would reach the specified performance criteria. For example:

With respect to the collapse performance criterion a confidence of 90% was required (see, for example. FEMA 350, 2000 and also Hamburger *et al*., 2003), that is 90% confidence that a structure will remain stable in earthquake ground motions having a mean probability of exceedance of 2% in 50 years. The collapse event is of major importance for existing structures, since it can be generally assumed that an existing structure in very active seismic regions has experienced serviceability or operational level loads and the structure should not be checked for these lower load levels.

Again the marginal cost to increase the safety of an existing structure is usually higher compared to an existing one (JCSS, 2001; Ellingwood, 2005) and also the desired remaining lifetime is shorter than the original design lifetime; consequently in order to account for a requirement reduction in case of existing structures it is recommended:

a) to implement lower values for the mean return period in case of the maximum credible earthquake and/or
b) to allow for a lower confidence level that the structure will satisfy the specified performance criterion.

A differentiation related to the first item above has been recommended, for example, in the Department of Energy Standard (DOE, 2002). More specifically, it was allowed to perform the reassessment using hazard exceedance probability equal twice the value specified for new design. This would have the effect of slightly reducing the seismic, wind and flood loads by about 10% to 20% (DOE, 2002).

A similar approach is adopted for the re-evaluation of existing platforms according to API (2000). Compared to the design of new platforms the lateral environmental load may be reduced to 85% of the 100-year condition for high-consequence existing platforms, and to 50% for low consequence existing platforms.

Explicit recognition and consideration of randomness is implemented in the confidence level that the performance objective can be met (Hamburger *et al*., 2003). The acceptance of a lower reliability level for an existing structure can be in addition implemented in the confidence level as stated above in b) by accepting a lower confidence level (75% or 50%) for the collapse prevention performance. In fact FEMA 352 (2000) consider a confidence level in the range between 50% to 90% (50% is considered to be low and 90% to be high).

Following the considerations defined as a) and b) above, the acceptable failure probability of an existing structure compared to a new one becomes 2 to 10 times higher, depending upon the requirement relaxation, which has to be specified.

3.2. Limit state design

The performance based design is mainly associated to natural and accidental hazards, such as earthquake, wind, fire. State-of-the-art design is based on the concept of limit states. A limit state design defines a physical state of the structure that can be related to important consequences, such as loss of serviceability, unsafe occupancy, or structural collapse. A limit state design aims to assure that the constructed facility will have sufficient strength and ductility capacity to satisfy the demands associated with each limit-event with an acceptable failure probability, $p_{F,}$ or equivalently, the associated reliability index, β. The proposed targets, $p_{F,}$ or β values, depend on whether failure is global or local failure, whether it may happen with or without warning, and on the severity of the potential consequences of failure (e.g., via a safety class differentiation).

The limit state approach is usually related to structural components rather than the entire structure, which is instead the direct focus of the performance based approach. Background information on reliability-based limit-states design can be found in JCSS (2007). Explicit target reliability levels for new structures and structural components are provided in this document. Guidance for the definition of target reliability of existing structures is also given in ISO (2003).

Cost-benefit considerations can be used to define risk acceptance criteria and consequently target failure probabilities for structural components. For existing structures there is a willingness to accept lower probabilities compared to new ones also due to the fact that costs of achieving a higher reliability level are usually high compared to structures under design. For this reason the target level for existing structures usually should be lower. Some examples are shown next.

The JCSS (2001) has proposed target reliability values for new structures related to one year reference period and to ultimate limit states. For existing structures it is commented in the document that these values are lower since the cost of achieving a higher reliability level are usually higher compared to structures under design. The reduction can be assessed from Table 3 by implementing the values associated to the higher category of relative cost of safety. Lifetime acceptable failure probabilities can be approximately obtained by multiplying the annual failure probability values by the desired residual lifetime T and by a factor *c*, where *c* accounts for the dependence of different failure events within one year. In many cases the annual failure events are independent and consequently $c \cong 1$ (de Winter and Vrouwenvelder, 1989).

Table 3. Target annual reliability index for ultimate limit states(JCSS, 2001)

Relative Cost of Safety Measure	Minor consequences	Moderate consequences	Large consequences
Large	β=3.1	β=3.3	β=3.7
Normal	β=3.7	β=4.2	β=4.4
Small	β=4.2	β=4.4	β=4.7

The classification in Table 3 for both the relative effort to achieve reliability and the expected failure consequences agrees well with calculations provided in various studies (JCSS, 2001).

A comparison between the criteria of a performance-based design approach for earthquake ground motion and the aforementioned limit state criteria can be approximately done by defining the mean return period for verification purposes in the reassessment phase based on first-order reliability considerations using the following equation:

$$T \approx 1 / \Phi(\alpha\beta) \tag{1}$$

where

- T is the mean return period for design/redesign purposes
- $\Phi(\,)$ is standard normal integral
- α is the sensitivity factor of earthquake hazard (for the definition see, for example, Madsen et *al*., 1986)
- β is the target reliability index (see Table 3)

If for example the marginal cost of reliability is small target reliability index $\beta = 4.2$ and a sensitivity factor of $\alpha = -0.8$ are applied, sice earthquake load has a significant importance on the failure probability, , the associated mean return period for redesign is approximately 2,500 years. In other cases with larger marginal costs of reliability lower values for the mean return period are obtained.

Other procedures can be found in the literature. Minimum safety levels for the evaluation of existing bridges have been for example developed (Allen, 1993) and incorporated in the Canadian bridge code (CSA, 1990). The proposed target reliability index β is given as:

$$\beta = 3.5 - (\Delta_C + \Delta_S + \Delta_I + \Delta_R) \geq 2.0 \tag{2}$$

Where

Δ_C: adjustment factor for component behavior (0.0 for failure with without warning, 0.25 for failure with little or no warning but retention of post failure capacity, 0.5 for gradual failure with warning)

Δ_S: adjustment factor for system behavior (0.0 if element failure leads to total collapse, 0.25 if element failure probably does not lead to total collapse, 0.5 if element failure leads to local failure only)

Δ_I: adjustment factor for inspection level (-0.25 if component is not inspectable, 0.0 if component is regularly inspected, 0.25 if critical component is inspected by evaluator)

Δ_R: adjustment factor for risk category (0.0 for all traffic categories except supervised overload, 0.5 for supervised overload)

For normal buildings the adjustment factor for inspection level has been replaced by an adjustment factor for past performance. We note here, however, that such a condition (past performance, level of inspection) should affect the actual reliability of the structure and not the target one.

Schueremans and Van Gemert (2004) proposed the following target failure probability, which is suitable as it accounts for social criterion that can be reinterpreted to encapsulate the importance of historical buildings or the preservation value.

$$p_f = \frac{S \cdot T \cdot A \cdot C_F}{N \cdot W} 10^{-4} \tag{3}$$

Where

T: residual service life
N: number of lives put to danger
S: Social criterion Factor (Preservation value)
A: activity factor
C_F: economical factor (consequences of failure)
W: Warning factor

Equation (3) includes social criteria in a simplified form. The warning factor corresponds to the likelihood that, given failure or recognition of approaching failure, a person at risk will be killed. The economical factor reflects cost-benefit considerations. The proposed equations (2) and (3) have a similar background and dot not account directly for a lower acceptable failure probability of an existing structure compared to a new one due to higher marginal cost to increase the safety of an existing structure. Further information regarding the applicability of Eq. (2) and (3) can be found in the respective literature source.

4. Industrial Experience

Some experience of the authors in industry case studies is reflected in this paragraph. The experience is related to:

- Requalification of several offshore structures in the North Sea, Adriatic Sea and West Africa
- Assessment of various buildings in Germany
- Evaluation of damages in existing bridges in Central Europe
- Safety assessment of existing tunnels subjected to fire risk
- Seismic retrofit analysis of structures in seismically active regions

From the experience reflections the following conclusions can be drawn:

- In general lower safety levels are accepted for existing structures in cases where costs of safety are high; in cases in which such lower values cannot be reached directly other additional measures such as load restrictions (on live loads) are applied. For example several older office buildings in Germany (60 – 80 years old) have been strengthened to meet relaxed minimum safety requirements compared to those for new structures, and in addition have been subjected to live load restrictions in order to satisfy the lowered acceptability limits. Similarly, many offshore platforms in the Gulf of Mexico have been requalified at the end of their designed lifetime by reducing the equipment on the topside and by lowering the consequence exposure category.

- Basically only in the case of a complete upgrade of an existing structure, the target safety level is kept the same as that for new structures. Typical examples are the design of a new steel support system for older and degraded concrete structures and the design of steel bracing system to support lateral forces in existing unreinforced masonry buildings.

- The desired residual lifetime has a significant influence on the decisions and in many cases regular inspections intervals (every 2 to 5 years) are proposed to check the safety of the structure. This is a typical case for deteriorating steel offshore platforms due to corrosion and fatigue.

- Trade-offs and expert judgements are particularly important in order to evaluate different repair options. For example consider an existing offshore jacket platform with a reduced strength and a replacement cost of \$180 million. If the loss in strength is due to damaged braces costing $15 million to replace, the repair could be justified based on cost-safety analyses. If the resistance reduction is due to general deterioration costing $60 million to strengthen the structure in order to achieve the acceptable safety level, then the decision is different.

5. Concluding remarks

Risk acceptance criteria for existing structures have been reviewed in this contribution. The following conclusions can be drawn from the presented analyses:

- Risk acceptance criteria for existing structures have been defined in terms of annual probability of failure or target reliability index in various sources.
- In case of reassessment and possible strengthening of existing structures there seems to be an agreement that, in many cases, it is appropriate to consider lowering the safety standards compared to new structures.
- The selected acceptance criteria depend on parameters such as costs of safety, consequences of failure and desired residual lifetime.
- An increase represented by a multiplicative factor of up to 10 for the acceptable probability of failure of an existing structure compared to a new structure is recommended herein, especially in cases in which the marginal costs of safety are very high; a factor of the order of 2 to 5 can be adopted in the other cases; the proposed factors are compatible to current tendencies in guidelines, standards and recommendations.
- Further work is needed in order to harmonise optimal and absolute risk acceptability criteria for existing structures at an international level.

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