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Autor: Allen, D.E.

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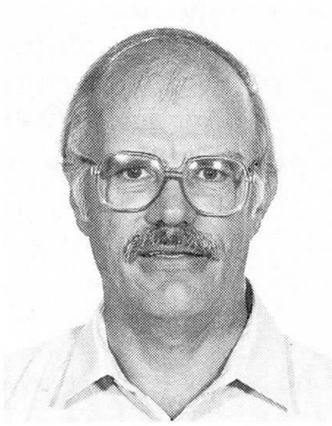
Safety Criteria for the Evaluation of Existing Structures

Critères de sécurité pour l'évaluation de structures existantes

Sicherheitskriterien für die Bewertung bestehender Tragwerke

D.E. ALLEN
Research Officer
National Research Council
Ottawa, ON, Canada



David E. Allen, born 1934, obtained a Ph.D. from University of Illinois in 1966 and has been a researcher with the National Research Council Canada ever since. He has authored about sixty papers in diverse subjects related to structural engineering, including safety criteria, human error, fire resistance and floor vibration. His current activities include guidelines for seismic evaluation and for durability.

SUMMARY

Limit states criteria which conform to a single conservative safety level are appropriate for the design of new structures because the savings in adopting different safety levels is marginal for any project. The cost and disruption in not meeting such a safety level, however, can become a major obstacle for an existing structure. For this reason different safety levels are being introduced in Canada for the evaluation of existing structures based on a life safety criterion. The recommended safety differentiation allows more flexibility in practice but requires more professional judgement. The paper describes the derivation of safety criteria for the evaluation of bridges and buildings in Canada.

RÉSUMÉ

Les dimensionnements aux états limites, qui correspondent à un niveau de sécurité unitaire et conservateur doivent être considérés comme adéquats pour le calcul de nouvelles structures, étant donné que les possibilités d'économie sont relativement minimes pour différents degrés de sécurité. Toutefois pour des structures existantes, les coûts et l'interruption d'utilisation en vue d'atteindre un tel degré de sécurité peuvent s'avérer prohibitifs. Raison pour laquelle différents degrés de sécurité, qui se basent sur un critère de sécurité de la durée de vie, ont été introduits au Canada en vue de pouvoir apprécier les structures existantes. Cette différenciation permet davantage de flexibilité dans la pratique, mais exige un supplément d'aptitude dans l'appréciation professionnelle.

ZUSAMMENFASSUNG

Bemessungen nach Grenzzuständen, die einem einheitlichen konservativen Sicherheitsniveau entsprechen, sind für neue Bauwerke durchaus angemessen, da die Einsparungsmöglichkeiten durch Annahme unterschiedlicher Niveaus gering sind. Für bestehende Tragwerke können jedoch der Aufwand und die Nutzungsunterbrechung, um solch ein Sicherheitsniveau zu erreichen, prohibitiv werden. Für die Bewertung bestehender Tragwerke wurden deshalb in Kanada unterschiedliche Sicherheitsniveaus eingeführt, die auf einem Konzept der Lebenssicherheit fussen. Diese Differenzierung gestattet mehr Flexibilität in der Praxis, erfordert aber zusätzlich professionelle Urteilskraft.

1. INTRODUCTION

There are increasing pressures to preserve and maintain existing structures such as buildings and bridges for as long as possible with a minimum of structural intervention. The pressures derive primarily from the cost of upgrading but include also user disruption, energy conservation and heritage value. These pressures, along with the fact that the structure exists, has performed satisfactorily and has been inspected for defects means that the criteria for evaluation of existing structures for continued use need not be as conservative as for the design of new structures. The following describes the basis for minimum safety levels for the evaluation of existing structures under development in Canada.

2. SAFETY CRITERION

The following safety concepts can be applied to determine appropriate safety levels for civil engineering structures:

1. Probability of failure (P_f) or reliability index (β). In Canada a reliability index of 3.5 is used for the design of bridges. For buildings it varies but is approximately the same. An exception is connectors such as bolts and welds for which, β is of order 5.

2. Life safety, or probability of death or injury for persons exposed to structural hazards. This considers, in addition to the probability of failure, the likelihood of death or injury if failure occurs, as well as other factors such as the activity and number of people at risk.

3. Optimum hazard reduction. This concept applies to an inventory of existing structures that contain structural hazards. The objective is to gradually reduce these hazards in accordance with benefit in reduced risk vs. cost. Such an approach is being carried out to reduce the seismic hazards posed by existing buildings in Los Angeles.

4. Damage control. There may be life safety, economic and other reasons not only to prevent collapse but to control structural damage as well. For hospitals, for example, damage control becomes a life safety issue in the event of a disaster such as an earthquake or hurricane.

Each concept has its applications depending on the project under consideration. It is, however, possible to identify minimum safety levels for 'ordinary' structures based on life safety. These minimum safety levels must be adjusted upwards for evaluation of special structures such as hospitals, key bridges or communication towers, depending on the consequences of failure or damage. Also, based on life cycle considerations, it often becomes economical to follow current design criteria if structural upgrading is required.

The following life safety criterion is used to determine minimum safety levels for structural evaluation [1]:

$$P_f = \frac{TAK}{W\sqrt{n}} \tag{1}$$

where

P_f = target probability of failure based on life safety (this is a notional probability for setting technical criteria, not an actuarial one)

K = calibration factor based on experience with existing criteria

A = human activity factor which reflects what risk is acceptable in relation to other non-structural hazards associated with the activity (taken as 1 for buildings, 3 for bridges, 10 for certain work-related activities [1])

W = warning factor corresponding to the likelihood that, given failure or recognition of approaching failure, a person at risk will be killed or seriously injured (W=1.0 for impact with no warning)

$\sqrt{n}$ = importance factor based on the number of people likely to be at risk if failure occurs, essentially an aversion factor based on public reaction to high fatality hazards

T = assumed reference period

3. CALIBRATION TO DESIGN CRITERIA

It is well known that life-threatening structural collapses are relatively rare, furthermore most are due to human error or accidents not addressed by current design criteria. Therefore current design criteria, if correctly applied, provide a safe upper bound to the life safety criterion, Equation (1). This assumption can be used by considering the ratio of the target probability of failure for evaluation to the target probability of failure for design where, from Equation (1):

$$\frac{P_{fe}}{P_{fd}} = \frac{A_e}{A_d} \cdot \frac{W_d}{W_e} \cdot \frac{\sqrt{n_d}}{\sqrt{n_e}} \tag{2}$$

where the subscripts d and e refer to design and evaluation respectively.

Because of the logarithmic relationship between P_f and β, the ratio P_{fe}/P_{fd} can be approximated by an adjustment in target reliability index, i.e.

$$\Delta = \beta_d - \beta_e \tag{3}$$

where β_d and β_e are the target reliability indices corresponding to the target failure probabilities P_{fe} and P_{fd} determined from the standard normal distribution curve. For example, $\Delta = 0.5$ corresponds to P_{fe}/P_{fd} of approximately 1/5 for β_d in the range 2.5 to 3.5.

4. EVALUATION FACTORS FOR DETERMINING SAFETY LEVELS

If the ratios W_d/W_e, $\sqrt{n_d}/\sqrt{n_e}$ and A_e/A_d can be determined for evaluation as compared to design then the target reliability index β_e can be determined from Eqn. (3) and safety factors determined by current reliability techniques. The factor W, however, is not easy to assess in practice. Factors that can be assessed by the structural evaluator which affect W include the following:

- component behaviour: If a component fails gradually then failure is likely to be noticed before collapse takes place allowing time to avoid life-threatening consequences.

- system behaviour: If a component fails without collapse because of alternate paths of support (redundancy) then the risk to life is considerably reduced.

- inspection: Inspection affects the warning factor W by providing clues of approaching or potential failure in time to avoid life-threatening consequences.

These factors, along with risk category which is related to $\sqrt{n}$ and A, are listed in Table 1 along with a comment as to whether or not they are taken into account in current Canadian structural design codes for bridges and buildings.

Table 1 Structural Evaluation Factors Affecting Risk to Life

Evaluation Factor	Parameter in Eqn (2)	Factor Taken into Account by: Bridge Code[2]	Building Code[3]
Component Behaviour	W	no	yes
System Behaviour	W	no	no*
Inspection	W	no	no
Risk Category	$\sqrt{n}$ and A	no	no**

* partly, for earthquake only
** only on the basis of building use and occupancy

5. APPLICATION TO BRIDGE EVALUATION

Minimum safety levels for bridge evaluation under traffic load have been developed based on the above approach [4] and incorporated in the Canadian bridge code [2]. The safety levels are expressed in terms of a target reliability index given in Table 2, adjusted as a function of the four evaluation factors in Table 1. The reliability index adjustment, Δ, is made up of contributions from each of the four evaluation factors. The maximum contribution for each factor is based partly on a consideration of the values of the life safety factors in Eqn (2) and partly on existing criteria used in other codes. A maximum Δ of 0.5 for component or system behaviour, for example, corresponds to an assumed likelihood of death/injury if failure occurs of approximately 1 in 5, or 1 in 25 for both together. A Δ of 0.5 is applied for supervised passage of an overloaded vehicle, because all other traffic is kept off the bridge, which reduces the factor $\sqrt{n_e}$ in Equation (2), and only the driver is at risk, which increases the factor A_e in Equation (2).

Table 2 Reliability Index, β_e, for Bridge Evaluation

$$\beta_e = 3.5 - [\Delta_C + \Delta_S + \Delta_I + \Delta_R] \geq 2.0$$

where β_e is based on a one-year time interval for all traffic categories except for supervised overload, where β_e is based on a single passage.

Adjustment for Component Behavior	Δ_C
Sudden loss of capacity with little or no warning	0.0
Sudden failure with little or no warning but retention of post failure capacity	0.25
Gradual failure with probable warning	0.5
Adjustment for System Behaviour	Δ_S
Element failure leads to total collapse	0.0
Element failure probably does not lead to total collapse	0.25
Element failure leads to local failure only	0.5
Adjustment for Inspection Level	Δ_I
Component not inspectable	-0.25
Component regularly inspected	0.0
Critical component inspected by evaluator	0.25
Adjustment for Risk Category	Δ_R
All traffic categories except supervised overload	0.0
Supervised overload	0.5

The total range of β_e in Table 2 is from 1.75 to 3.75, where the upper limit, 3.75, corresponds to a safety equivalent to that assumed for design [2]. The lower limit, which occurs only for supervised overload, represents an economic risk to the bridge authority (theoretically 1/25 times the loss if failure occurs); a lower limit of β_e=2.00 was therefore imposed. Most traffic networks have considerable flexibility if a bridge failure takes place but in some cases the effect of a bridge failure on the local economy can be severe. In such cases the lower limit for β_e should be increased.

The target reliability index in Table 2 was used to develop load and resistance factors for the evaluation of bridges in the Canadian bridge code [5].

6. APPLICATION TO BUILDING EVALUATION

The same basic approach has recently been applied to buildings [6]. Although the basis is the same as for bridges, the method was altered. The reason for this is that the confidence in reliability methods is much greater for bridges under traffic load than for a wide variety of buildings under a wide variety of loads, including earthquake. Instead of recommending reduced target safety indices for building evaluation it is more practical to recommend reduced load factors. These were determined by use of the following log normal relationship [6]

$$\alpha_e = \alpha_d \exp\left[-\Delta\sqrt{(1+V_R^2)(1+V_S^2)}\right] \qquad [4]$$

where α_d is the design load factor and α_e is the evaluation load factor, Δ the target safety index adjustment. V_r and V_s are the coefficients of variation representing the uncertainties of resistance and load respectively. Based on assumptions for V_r and V_s given in Table 3, Figures 1-3 show the relationship between load factor and the target reliability index adjustment Δ. Based on Figures 1-3, Table 4 contains recommended load factors for building evaluation.

Table 3 Uncertainty Assumptions for Estimating Load Factors for Buildings

	Uncertainty
Load	V_S
Dead	0.1
Variable*	0.3
Earthquake	1.1
Resistance	V_R
Steel	0.1-0.15
Concrete	0.15-0.2
Masonry	0.2-0.3
Wood	0.3

* Occupancy, snow and wind loads

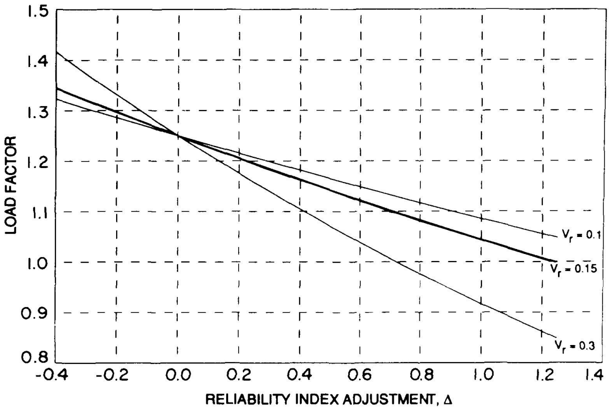


Fig. 1 Dead load factor (V_S=0.1)

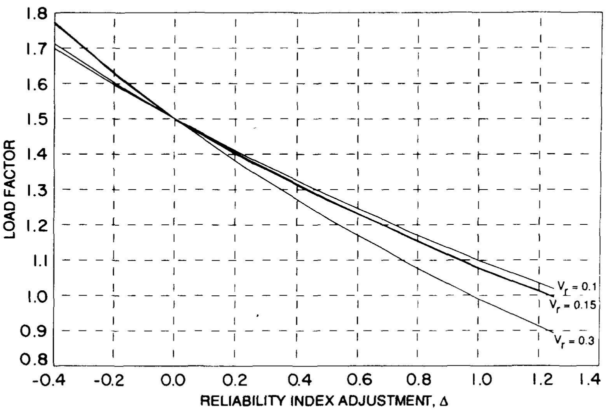


Fig. 2 Variable Load Factor (V_S=0.3)

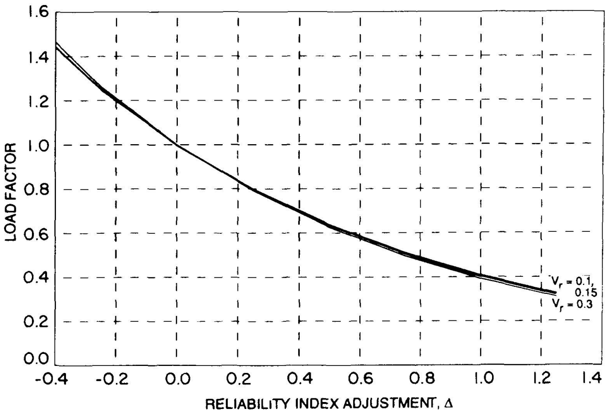


Fig. 3 Earthquake load factor (V_S=1.1)

Table 4 Load Factors for Building Evaluation

Adjustment to Design Safety Level $\Delta = (\Delta_s + \Delta_R + \Delta_P)$†	Load Factor for:		
	Dead Load*	Variable Loads	Earthquake
0	1.25 (0.85)	1.50	1.00
0.25	1.20 (0.88)	1.40	0.80
0.5	1.15 (0.91)	1.30	0.63
0.75	1.11 (0.93)	1.20	0.50
1.0 or more	1.08 (0.95)	1.10	0.40

† Adjustment for System Behaviour — Δ_S
- -failure leads to collapse, likely to impact occupants — 0.0
- -failure is unlikely to lead to collapse, or unlikely to impact occupants — 0.25
- -failure is local only, very unlikely to impact occupants — 0.5

† Adjustment for Risk Category — Δ_R
- -high building importance or high occupancy exposed to failure — 0.0
- -normal occupancy exposed to failure — 0.25
- -low occupancy exposed to failure — 0.5

† Adjustment for Past Performance — Δ_P
- -no record of satisfactory past performance — 0.0
- -satisfactory past performance** or dead load measured*** — 0.25

* The value in the brackets applies when dead load resists failure

** Apply only to dead and variable load factors, age 50 years or more, no significant deterioration.

*** Apply to dead load factor only.

Two evaluation factors in Table 1 were not included in Table 4, namely 'component behaviour' because it is already taken into account in current design criteria, and 'inspection' because building structures are not inspected on a regular basis and therefore warning is not reliable. The risk category for occupancy in Table 4 (high, normal, low) can be estimated on the basis of floor area exposed to potential collapse if the failure occurs, occupant density and duration of occupancy (hours per week).

A new evaluation factor 'past performance' is included, however not because it affects the life safety criterion Equation (1), but because it reduces the uncertainty in estimating loads and resistance compared to design. Dead load parameters, for example, may be measured, and the corresponding reduction on uncertainty (V_S from 0.1 to 0.05) corresponds to a Δ of 0.25 [6]. More significant, however, is satisfactory past performance over many years under dead and variable loads such as wind and snow.

Successful past performance, however, is difficult to quantify in terms of reduced safety coefficients. Table 4 contains a conservative adjustment, Δ=0.25, the same as for measured dead load [5].

Besides the load factor adjustments contained in Table 4, there will also be adjustments in the resistance factors for components such as bolts and welds.

7. REFERENCES

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[3] National Building Code of Canada 1990, Part 4, Structural Design, National Research Council Canada, Ottawa, Ontario

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