Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 11 (1980)

Artikel: Structural design for serviceability

Autor: Turkstra, Carl J. / Reid, Stuart G.

DOI: https://doi.org/10.5169/seals-11407

X

Structural Design for Serviceability

Dimensionnement des structures pour le domaine d'utilisation

Tragwerksbemessung im Hinblick auf Gebrauchstüchtigkeit

CARL J. TURKSTRA
Professor
McGill University
Montreal, Quebec, Canada

STUART G. REID
Research Assistant
McGill University
Montreal, Quebec, Canada

SUMMARY
In this paper design for serviceability is considered from a fundamental point of view. The differences between design for safety or ultimate limit states and design for service conditions are emphasized. A methodology for the evaluation of alternative design constraints is presented together with a preliminary numerical application.

RESUME
Dans cet exposé, l'utilité des constructions est calculée d'un point de vue fondamental. On insiste sur les différences entre les calculs visant à la sécurité ou aux limites de rupture et les calculs visant aux conditions d'utilisation. Une méthodologie permettant d'évaluer d'autres limites est proposée, accompagnée d'une application numérique préliminaire.

ZUSAMMENFASSUNG
In diesem Beitrag wird die Bemessung im Hinblick auf die Gebrauchstüchtigkeit von Tragwerken von einem grundsätzlichen Standpunkt aus betrachtet. Die Unterschiede zwischen der Bemessung gegen Tragwerkversagen und der Bemessung auf Gebrauchstüchtigkeit werden dargestellt. Eine Methodik für die Bewertung weiterer Randbedingungen für die Bemessung wird — zusammen mit einem praktischen Zahlenbeispiel — vorgestellt.

1. INTRODUCTION

The essential criteria for structural engineering were stated succinctly in the nineteenth century by Henry Wotton - "*In Architecture as in all other Operative Arts, the end must direct the operation. The end is to build well. Well building has three conditions - Commodity, Firmness, and Delight.*" Basic problems associated with assuring "firmness", or safety against structural failures are the major concern of the theme paper for the session on Safety Concepts. The purpose of this contribution is to examine closely related problems associated with "commodity" or assuring that structures can perform their intended functions.

Within the context of at least North American practice, it seems evident that inadequate building performance rather than structural collapse is the major source of professional liability at the present time. Current practices which limit professional supervision and inhibit development of adequate control in the building process must be critically evaluated and substantially revised in the future.

The role of a structural engineer relative to serviceability is very similar to his role relative to safety. As mentioned in the theme paper, there are two general strategies in current practice: (1) formal design constraints, and (2) checking and supervision procedures. However, design for serviceability is fundamentally different from design for safety in several important respects.

2. TYPES OF SERVICEABILITY CONTROLS

A design approach to the control of serviceability conditions normally involves a set of simple rules limiting, for example, deflections, drift, slab or beam depths as a function of span, crack formation or crack width. Coupled with these is a family of general rules of practice such as minimum reinforcement for shrinkage and crack control, or the maximum number of storeys of brick facing without supporting steel angles.

Throughout design and construction, serviceability control can be exercised by means of performance specifications, performance recommendations and a system of supervision. Inadequate controls during design permit design oversights, inadequate analysis, and the use of inappropriate design serviceability constraints. Design oversights and inadequate analysis can lead to isolated cases of very serious unserviceability, while inappropriate design serviceability levels can lead to the development of systematic serviceability problems.

Control during construction normally involves checks on material properties coupled with on-site inspection to ensure compliance with specified design requirements. Failure of control during the construction phase can lead to economically disastrous serviceability failures, in the extreme resulting in total abandonment of a building.

3. MAJOR SERVICEABILITY PROBLEMS

Although service failures are undoubtedly of major importance, research on the subject is relatively limited. A survey of the literature relative to deflection problems has been made by Galambos et al [1]. In the realm of concrete buildings, significant results have been provided by, for example, Mayer and Rusch [2] and the error survey of the American Concrete Institute [3].

In an effort to clarify the nature of serviceability problems and identify critical areas for detailed study, a survey of structural engineers was undertaken [4]. For each of steel, concrete, timber and masonry structures, a comprehensive list of building elements was given with subsidiary lists of potential limit states, their manifestations and their likely causes. Correspondents were asked to rank all states and their causes in terms of relative importance.

While individual responses within the 17 replies received varied a good deal, a consensus was quite clear. The most significant current concerns are:
- transverse deflections of concrete slabs and beams, steel and timber beams, and masonry walls
- durability of all types of construction
- axial deflections of concrete columns
- sway deflections of concrete and steel structures
- transverse vibrations of concrete slabs and steel beams
- sway vibration of steel frames
- cracking of concrete slabs

Material variation with time, creep deflection, ponding, material incompatabilities, and dynamic actions were identified as primary causal factors.

While the results of this survey are limited several conclusions may be drawn. Firstly, time dependent phenomena are of much greater significance than generally assumed in practice. Furthermore, more sophisticated analysis of behaviour and material interactions may be required in future designs. Except perhaps for problems of durability, however, it does not seem that major new sources of uncertainty are involved.

4. DESIGN FOR SERVICEABILITY

Although design for serviceability involves relatively well known physical phenomena, major philosophical problems arise. On a very fundamental level, it is not obvious that design codes should define serviceability constraints with the degree of authority normally used for safety constraints. While there is a consensus that building owners must not be permitted to subject the population to undue risks of injury or death, there is much less moral justification for imposing uniform building quality standards. If an owner wishes to reduce initial investments at the cost of inferior building performance and shorter expected useful life, the right of a state or professional body to prevent such a compromise is not evident. In the extreme it can be argued that the general legal regulation of construction should be limited to questions of public safety.

A second fundamental problem of design for serviceability is the absence of limit states. In structural safety analysis there exists an algebraic relationship between variables which, at least conceptually, uniquely separates the space of building response into safe and unsafe regions. Safety analysis is thus a binary problem in which response can be evaluated as an either-or situation.

In design for serviceability there is no clear boundary between acceptable and unacceptable behaviour. Instead, there are degrees of undesireability related to a spectrum of possible building responses.

Formulation of serviceability design in terms of specific boundaries thus involves an artificial set of criteria imposed on the true situation.

4.1 Serviceability Measures

Unfortunately,the measurement of serviceability involves value judgments which can only be expressed on a subjective scale of relative loss or benefit. Such a "utility" scale can be mapped onto a monetary scale to allow an objective economic assessment of situations involving subjective evaluations.

Assessment of the utility of a structure may require several behaviour parameters. Some parameters such as maximum crack widths and inelastic deformations involve "absorbing" failure states caused by the occurrence of a single maximal event during the service life of a structure. More commonly, serviceability involves the parameters of "recurrent" failure states such as vibration and elastic deflection. For some recurrent conditions, such as non-structural storm damage, the mean rate of occurrence of an event may be relevant, while for others, such as human response to vibrations, the stationary probabilities of events may be important. In every case, the definition of efficient serviceability parameters requires careful consideration.

Given the definition of efficient behaviour parameters, the degree of structural serviceability or alternatively of nonserviceability or "aversion", can be expressed as a function of these parameters. Such functions may take many forms, but the following general characteristics are evident.

- The function has finite bounds of complete serviceability and complete unserviceability.
- Realistic functions are continuously differentiable; i.e., there are no "limit states" at which discontinuities occur.
- The function is monotonic.

As mentioned previously, serviceability is not a binary function (e.g., satisfactory/unsatisfactory) with a discrete "limit state" such as is generally assumed. It is thus impossible to calculate probabilities of serviceability "failures" and a generalized measure of structural utility is required.

4.2 Generalized Utility Measures

A generalized measure of structural utility is total expected utility, $E(U)$, defined as

$$E(U) = \int_{-\infty}^{\infty} u(x) \; f_X(x) \; dx = \int_{-\infty}^{\infty} v_X(x) \; dx$$

where x is some serviceability parameter (a function of time)
$u(x)$ is utility as a function of x
$f_X(x)$ is the probability density function of x
and $v_X(x)$ is the density function of expected utility

Note that the classical reliability, R, is a measure associated with a binary (0 ,1) utility function, discontinuous at a failure point or limit state, x_L, so that

$$E[U] = \int_{\infty}^{\infty} u(x) \; f_X(x)dx = \int_{-\infty}^{x_L} f_X(x)dx = R$$

The usefulness of expected utility lies in its applicability to non-binary utility functions. In general, one must define utility in terms of a suitable state variable, determine the probability distribution function of the selected state variable with reference to appropriate load and structural response models and relevant design constraints, and finally integrate the derived density function of expected utility to obtain total expected utility as a basis for decision.

4.3 An Example of Expected Utility Evaluation

As an example of the application of utility concepts, consider a serviceability condition associated with the maximum elastic mid-span live-load deflection of a simply supported office floor beam during one office tenancy. The simplified live-load model of McGuire and Cornell [5] can be adopted and load response can be assumed given by the elastic response of a simply supported beam providing a simple support for a one-way floor system.

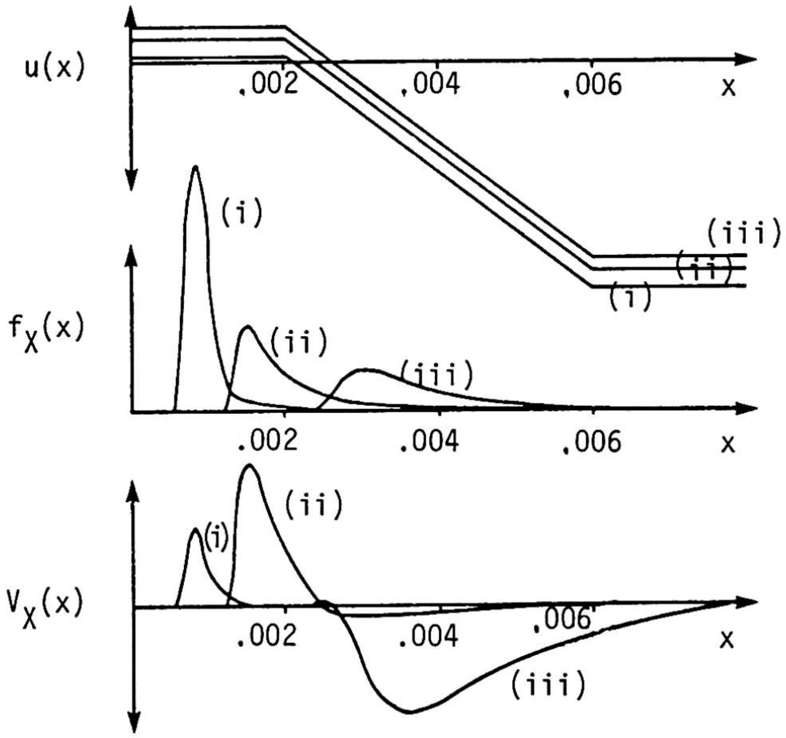
Conventional design in this case involves two basic criteria:

- a design load with a specified probability, q, of exceedance during an occupancy, and,
- a maximum permissible calculated midspan deflection to span ratio, Δ/L, under the design load.

By means of deterministic influence coefficients for midspan deflections, and appropriate statistics for the distributions of random sustained and extraordinary live loads, the probability distribution function of maximum midspan deflection during one occupancy can be derived.

To proceed further, a number of assumptions concerning the relative values of benefits derived from the use of a structure, construction costs, and penalties associated with serviceability characteristics must be made. For purposes of demonstration, the cost penalty associated with response was assumed to be zero for deflection to span ratios δ/ℓ up to 0.002 (full serviceability) and then to decrease linearly up to a complete loss of the investment in construction plus demolition costs for δ/ℓ of 0.006 or greater.

Figure 1 illustrates the elements of an evaluation of expected utilities associated with various design deflection ratios, Δ/L, for a design load of 2.4 kPa over a tributary area of 18.6 m^2, which corresponds to a design load fractile of .95.



(i) q = .05, Δ/L = 1/720, E[U] = .16

(ii) q = .05, Δ/L = 1/360, E[U] = .59

(iii) q = .05, Δ/L = 1/180, E[U] = -2.3

Fig. 1. Expected Utility Evaluation of Alternative Design Criteria

5. CONCLUSIONS

This brief overview of design for serviceability suggests a number of general conclusions. Firstly, serviceability design involves relatively well known physical phenomena. However, serviceability does not involve a set of discrete limit states which uniquely define acceptable and unacceptable behaviour. As a corollary to this observation, conventional safety index, or β, analysis is not valid.

One feasible approach to establishment of design constraints is based on concepts of utility. A measure of the degree of aversion or undesireability of behaviour over the whole range of structural response is required together with a realistic set of load and structural response models. By means of probabilistic analysis the total expected utility associated with alternative design proposals can be estimated and an optimal approach adopted. It should be noted that any analysis involving economic considerations adds another level of uncertainty to those already existing in conventional structural design.

Adequate mechanisms of control during design and construction are of great importance. Many errors in construction details lead to serious service problems which do not involve public safety. Implicitly or explicitly an owner tends to receive what he pays for - cost compromises in, for example, materials or site supervision will lead to inferior structural performance.

REFERENCES

1. GALAMBOS, T.V., GOULD, P.L., RAVINDRA, M.R., SURYOUTOMO, H., and CRIST, R.A., "Structural Deflections - A Literature and State-of-the-Art Survey", Building Science Series No. 47, National Bureau of Standards, Washington, D.C., October 1973.

2. MAYER, H., and RUSCH, H., "Building Damage Caused by Deflection of Reinforced Concrete Building Components", NRC Technical Translation 1412, Ottawa, 1970 [translated from Deutscher Ausschuss fur Stahlbeton Heft 193, Berlin, 1967].

3. FRACZEK, J., "ACI Survey of Concrete Structure Errors", Concrete International, American Concrete Institute, Vol. 1, No. 12, December, 1979.

4. TURKSTRA, C.J., and REID, S.G., "Serviceability Limit States - Basic Criteria for Design", Report ST 79-5, Dept. of Civil Engrg., McGill University, Montreal, April 1979.

5. MCGUIRE, R.K., and CORNELL, C.A., "Live Load Effects in Office Buildings", Journal of the Structural Division, ASCE, Vol. 100, No. ST 7, Proc. Paper 10660, July, 1974, pp. 1351-1366.