Papers

Volume 6: 2001-2003

Thoft-Christensen, Palle

Publication date:
2007

Document Version
Publisher's PDF, also known as Version of record

CHAPTER 109

HUMAN ERRORS AND BRIDGE MANAGEMENT SYSTEMS [1]

P. Thoft-Christensen* & A.S. Nowak**
*University of Aalborg, Aalborg, Denmark
**University of Michigan, Ann Arbor, MI, USA

SUMMARY

Human errors are divided in two groups. The first group contains human errors, which affect the reliability directly. The second group contains human errors, which will not directly affect the reliability of the structure. The methodology used to estimate so-called reliability distributions on basis of reliability profiles for bridges without human errors are extended to include bridges with human errors. The first rehabilitation distributions for bridges without and with human errors are combined into a joint first rehabilitation distribution. The methodology presented is illustrated for reinforced concrete bridges.

1. INTRODUCTION

Human error is defined as a departure from acceptable practice (Nowak and Arafah [1]; Nowak and Carr [2]; Nowak [3]; Nowak and Collins [4]). The traditional reliability analysis deals with natural variation in loads and resistance. However, the statistical models of load and resistance do not include errors even though they are an inevitable part of all human activities. They add a considerable degree of uncertainty to the design and construction. However, it is difficult to provide a formal definition of a human error.

The major types of uncertainties are natural hazards and man-made hazards. Natural hazards are due to wind, earthquake, temperature differentials, and snow load or ice accretion. Also included are natural variations of structural material properties

[1] Proceedings IABSE Conference on “Safety, Risk, and Reliability – Trends in Engineering”, Malta, 2001, 867-872.

(strength, modulus of elasticity, dimensions) and loads (weight of people, furniture, or trucks on bridges) (Nowak [5]). Man-made hazards can be subdivided into two groups: from within the building process and from outside the building process. The latter includes uncertainties due to fires, gas explosions, collisions and similar causes. The former contains uncertainties due to acceptable practice and uncertainties due to human errors, or departures from acceptable practice.

Surveys of structural failures of buildings and bridges indicate that human error is the major cause. Moreover, error in design or construction may increase the damaging effect of other hazards. Therefore, the control of human error in structures can be an increasingly effective strategy to reduce probability of failure. From sporadic efforts in the late 1970's, the breadth and the importance of the human error problem as a major issue in structural safety became recognized around 1980 (Nowak [6]). Since then, other studies of the problem have been underway in North America, Europe, Australia and Japan.

2. HUMAN ERRORS IN BRIDGE ENGINEERING

The team at the University of Michigan performed the survey of human errors. It covered various types of structures, including bridges. It was observed that most of errors are not bridge-specific but more general and they affect equally various types of structures. Error may affect all stages of the project, from planning to demolition. Typical errors observed in bridge structures include:

- Incorrect assumptions about boundary conditions (support conditions)
- Use of inadequate quality of concrete
- Use of inadequate steel type (weathering steel in an aggressive environment)
- Illegal overloads with regard to weight and height
- Inadequate maintenance (inspection intervals and intensity, repainting intervals, preventive repairs)
- Abuse of salt as a deicing agent

Errors often occur due to ignorance, and they can be considered as errors of concept or errors of execution. Sometime they are a result of conscientious decision as errors of intension. There can be different frequencies of occurrence and reasons for errors. Inspections, checking, improvement of the working environment, or use of special design and construction techniques can reduce frequency of errors. Motivation has been identified as the most important factor affecting human performance in the building process (Schneider [7]). Other factors affecting performance are knowledge, experience and physiological conditions. Eliminating or reducing the opportunity can reduce error frequency. Foolproof approach is based on use of design and/or construction procedures, which are easy to understand and follow.

Consequences of errors can be controlled through identification of the consequential errors using the sensitivity analysis (Nowak and Carr [2]). The objective of the sensitivity analysis is to relate error magnitude and structural reliability. Human error may affect parameters or modes of structural behavior. For each considered parameter, a reliability analysis can be performed to determine the reliability corresponding to various realizations of error.

3. RELIABILITY PROFILES FOR CONCRETE BRIDGES

Reliability profiles for reinforced concrete bridges were investigated by (Thoft-Christensen et al. [8]), see also (Thoft-Christensen & Jensen [9]). Corrosion initiation period refers to the time during which the passivation of steel is destroyed and the reinforcement starts to corrode actively. Fick's law of diffusion may represent the rate of chloride penetration into concrete, as a function of depth from the concrete surface and of the time, as follows:

$$\frac{dC(x,t)}{dt} = D_c \frac{d^2C(x,t)}{dx^2} \tag{1}$$

where $C(x,t)$ is the chloride ion concentration, as % by weight of cement, at a distance of x cm from the concrete surface after t seconds of exposure to the chloride source. D_c is the chloride diffusion coefficient expressed in cm^2/sec. The solution of the differential equation (1) is

$$C(x,t) = C_0 \left\{ 1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_c \cdot t}} \right) \right\} \tag{2}$$

where C_0 is the equilibrium chloride concentration on the concrete surface, as % of the weight of cement, x is the distance from the concrete surface in cm, t is the time in sec, erf is the error function, and $C(x,t)$ is the chloride concentration at any position x at the time t.

In a real structure, if C_{cr} is assumed to be the chloride corrosion threshold and d is the thickness of concrete cover, then the corrosion initiation period, T_I, can be calculated. The time T_I to initiation of reinforcement corrosion is

$$T_I = \frac{d^2}{4D_c}(erf^{-1}(\frac{C_{cr} - C_0}{C_i - C_0}))^{-2} \tag{3}$$

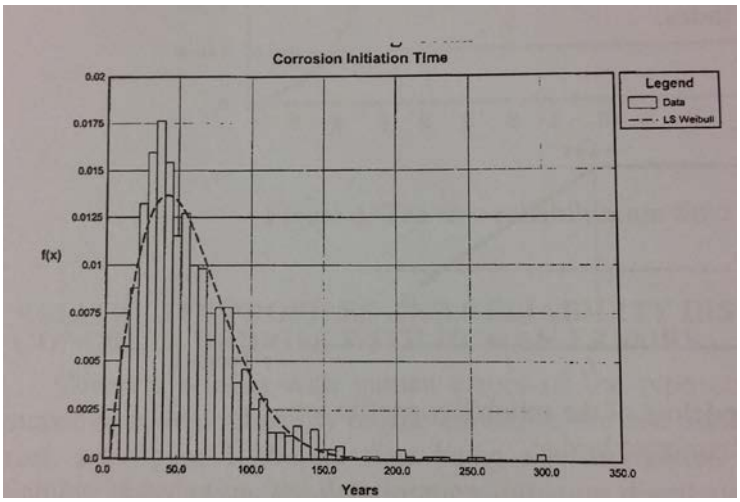

Figure 1. Density function of the corrosion initiation time.

On basis of equation (3) outcomes of the corrosion initiation time T_I has been performed on basis of the following data by simple Monte Carlo simulation (1000 simulations): Initial chloride concentration: 0%; Surface chloride conc.: Normal (0.650; 0.038); Diffusion coefficient: Normal (30; 5); Critical concentration: Normal

(0.3; 0.05); Cover: Normal (40; 8). The corresponding histogram is shown in Figure 1. The data is approximately Weibull distributed W(x; μ ,k, ε), with μ = 63.67, k=1.81 and ε =4.79.

When corrosion has started, the diameter $D(t)$ of the reinforcement bars at the time t is modeled by

$$D(t) = D_0 - c_{Corr} i_{corr} t \tag{4}$$

where D_0 is the initial diameter, c_{corr} is a corrosion coefficient, and i_{corr} is the rate of corrosion.

4. RELIABILITY DISTRIBUTIONS FOR CONCRETE BRIDGES

In this section is shown how the so-called reliability distributions for structures can be estimated, (Thoft-Christensen [10]). For a group of bridges the following reliability distributions are estimated using crude Monte Carlo simulation:

- The *initial reliability distribution* is the distribution of the reliability indices for all bridges at t = 0.
- The *deterioration initiation distribution* is the distribution of the deterioration (corrosion) initiation times for all bridges.
- The *deterioration rate distribution* is the distribution of the deterioration rates of all bridges.
- The *rehabilitation time distribution* is the distribution of the points in time by which the considered bridges reach a critical rehabilitation reliability index. If no maintenance has taken place it is called the *first rehabilitation time distribution.* If maintenance has taken place it is called the *rehabilitation time distribution after maintenance.*

The methodology is based on a simplified reliability profile for each bridge, see Figure 2. The time t = 0 is the year when the bridge in question is build. $\beta(0)$ is the reliability index at time t = 0. $\beta(t)$ is the reliability index at the time t. Deterioration is assumed to be initiated at time t_i. The deterioration rate is α . $\beta = 4.6$ is used as the critical (target) reliability index.

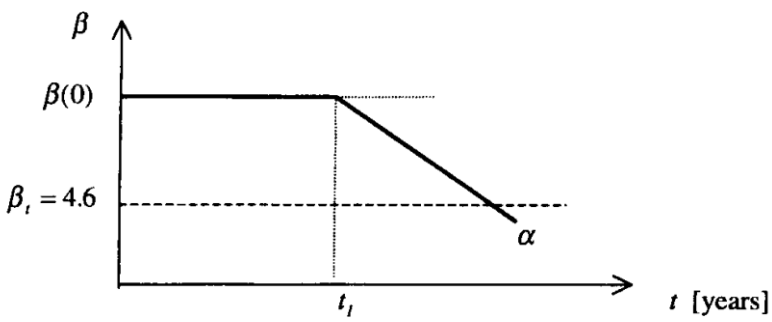

Figure 2. Modeling of the reliability profile for a reinforced concrete bridge.

The upper part of the initial reliability distribution $\beta(0)$ is based on the reliability index $\beta(0)$ for 15 “good” bridges (Thoft-Christensen & Jensen [9]). The lower part is

assumed to have only a small probability for reliability index values smaller than 4.6. Therefore, a log-normal distribution LN(2.0 ; 0.15) is used. The deterioration is limited to corrosion of the reinforcement. The deterioration reliability distribution is assumed to be a Weibull distribution with a mean value of 63.67 years and k = 1.81, (Thoft-Christensen [11]). Based on information from (Thoft-Christensen & Jensen [8]) a uniform distribution U[0.01; 0.20] is chosen for the deterioration rate distribution.

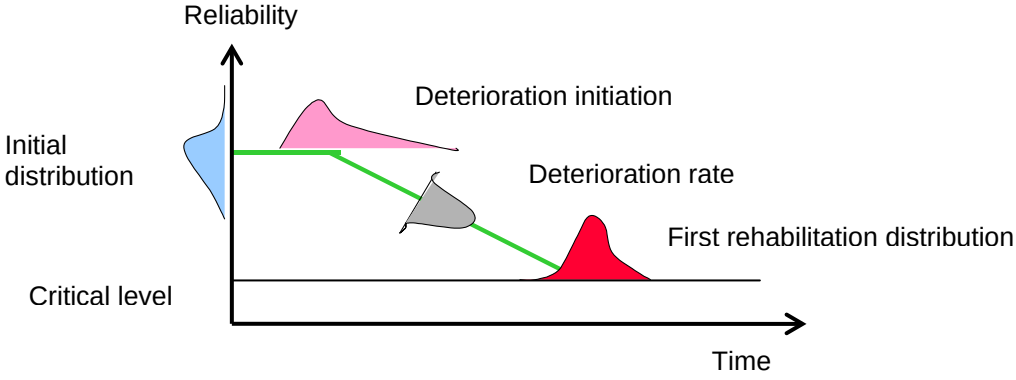

Figure 3. Illustration of the above mentioned reliability distributions.

On basis of the above-mentioned three distributions, rehabilitation time distributions can be obtained by Monte-Carlo simulation, see Figure 3. As an example the first rehabilitation time distribution for 970 reinforced concrete overbridges in UK is shown in Figure 4.

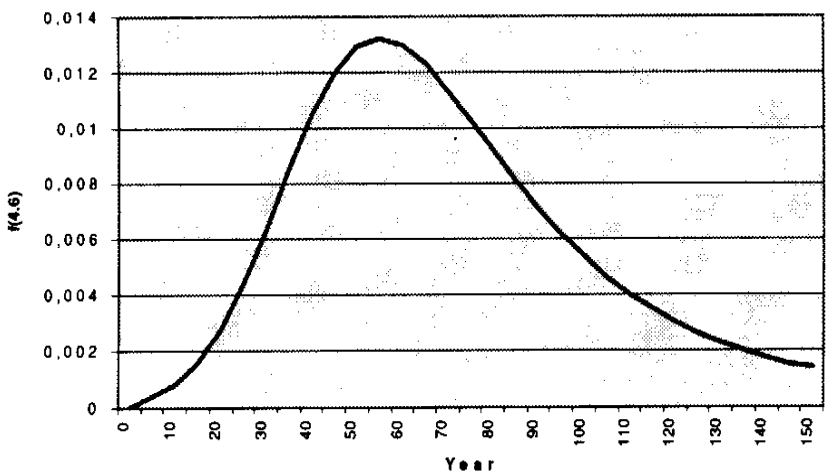

Figure 4. The first rehabilitation time distribution.

5. RELIABILITY PROFILES AND RELIABILITY DISTRIBUTIONS FOR CONCRETE BRIDGES WITH HUMAN ERRORS

Concrete bridges with human errors of the type considered in this paper are assumed to have a reliability profile similar to the one used for bridges without human errors, see figure 1. At the time being no information is available on the initial reliability distribution, the deterioration initiation distribution or the deterioration rate distribution for bridges with human errors. However, it seems reasonable to assume for bridges with human errors that:

- the initial reliability distribution has a reduced mean value and an increased standard deviation compared to bridges without human errors
- the deterioration initiation distribution has a reduced mean value and an increased standard deviation compared to bridges without human errors
- the rate distribution has higher mean value and an increased standard deviation compared to bridges without human errors.

With these assumptions the first rehabilitation time distribution for bridges with human errors has a reduced mean value and an increased standard deviation compared to bridges without human errors. As a first approximation it is assumed that the shape of the first rehabilitation time distribution for bridges with human errors has a form similar to the first rehabilitation time distribution for bridges without human errors.

6. THE FIRST REHABILITATION TIME DISTRIBUTION FOR ALL BRIDGES

From a bridge management point of view bridges without and with human errors must be treated together. Therefore a joint first rehabilitation time must be established on basis of the above-mentioned distributions for the two groups discussed above.

Let the number of bridges without human errors be N_{HE}^{-} and let the number of bridges with human errors be N_{HE}^{+} . An important (and not so easy to estimate) parameter is then

$$\alpha = \frac{N_{HE}^{-}}{N_{HE}^{-} + N_{HE}^{+}} \tag{5}$$

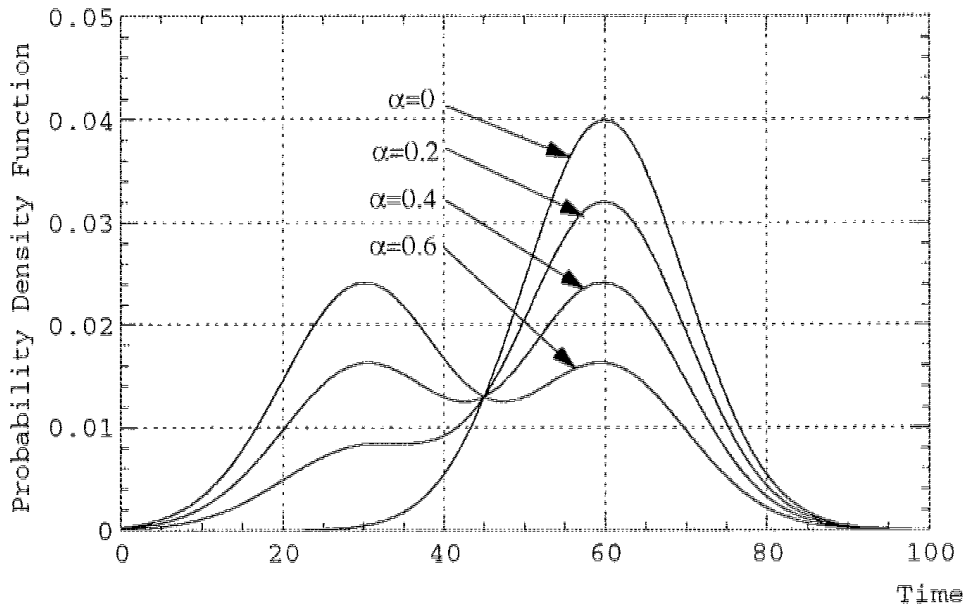

Figure 5. Joint first rehabilitation distributions.

Let the first rehabilitation time distributions for bridges without and with human errors be approximated by the distribution function $f^{-}(t)$ and $f^{+}(t)$ respectively. Then the joint first rehabilitation time distribution for all bridges is defined by

$$f(t) = (1-\alpha) \times f^{-}(t) + \alpha \times f^{+}(t) \tag{6}$$

The density function *f(t)* is illustrated in figure 5 for a number of α-values and normally distributed first rehabilitation distributions N(30;10) and N(60;10) for $f^{-}(t)$ and $f^{+}(t)$ respectively.

7. CONCLUSIONS

The structural performance can be affected by human errors. The reliability of the structure can be considered as a function of potential errors as demonstrated on the reliability profiles derived for reinforced concrete bridges.

8. REFERENCES

[1] Nowak, A.S. and Arafah, A., "Human Error in Structural Engineering", Proceedings of the Symposium on Risk Analysis, University of Michigan, Ann Arbor, MI, 1994, pp. 165-173.

[2] Nowak, A. S. and Carr, R. I., "Sensitivity Analysis for Structural Errors," The Journal of Structural Engineering, ASCE, Vol. 111, No. 8, August 1985, pp. 1734-1746.

[3] Nowak, A.S., "Structural Reliability and Human Errors", Festschrift for J. Schneider, ETH Zurich, 1994, pp. 157-162.

[4] Nowak, A.S. and Collins, K.R., "Reliability of Structures", McGraw-Hill, New York, 2000.

[5] Nowak, A.S., 1995, "Calibration of LRFD Bridge Code", ASCE Journal of Structural Engineering, Vol. 121, No. 8, pp. 1245-1251.

[6] Nowak, A. S., "Effect of Human Errors on Structural Safety," Journal of the American Concrete Institute, September 1979, pp. 959-972.

[7] Schneider, J., ed., "Quality Assurance Within the Building Process", Proceedings, Vol. 47, IABSE Workshop, Rigi, Switzerland, June 1983.

[8] Thoft-Christensen, P. , F.M. Jensen, C.R. Middleton & A. Blackmore. Assessment of the Reliability of Concrete slab Bridges. Proceedings of IFIP WG7.5 Conference, Boulder, Colorado, USA, April 1996, Pergamon, 1996, pp. 321-328.

[9] Thoft-Christensen, P. & F.M. Jensen. Revision of the Bridge Assessment Rules based on Whole Life Performance: Concrete Bridges. Final Report, Highways Agency Contract DPU 9/3/44, CSRconsult ApS, December 1996.

[10] Thoft-Christensen, P. Estimation of Bridge Reliability Distributions. Bridge Design Construction and Maintenance (eds. P.C. Das, D.M. Frangopol, A. S. Nowak), Thomas Telford, 1999, pp. 15-25.

[11] Thoft-Christensen, P. Estimation of the Service Lifetime of Concrete Bridges. Proceedings ASCE Structures Congress XV, Portland, Oregon, USA, April 13-16, 1997.