# Time-variant reliability analysis utilizing results from non-destructive testing

**Dr. Christian Bucher**
Professor of Structural Mechanics
Vienna University of Technology, Austria
*Christian.bucher@tuwien.ac.at*

Christian Bucher, born 1956, received his civil engineering diploma (M.Sc.) and PhD degrees from the University of Innsbruck, Austria. He held faculty positions at the University of Innsbruck and Bauhaus-University Weimar (Germany) before joining Vienna University of Technology in 2007.

## Summary

Structures undergoing deterioration and damage due to corrosive actions and severe loads may eventually become unsafe. In order to prevent this, monitoring can be implemented. Since structural monitoring essentially has to be non-destructive, direct information about the current strength or resistance of the structure is not available. Hence, resistance data must be inferred from observable or measurable data such as vibration characteristics or stiffness values. This introduces uncertainty into the process, which can be modeled in terms of probability density functions. The paper presents a computational approach to combine Monte-Carlo simulation with analytical probabilistic models to assess the influence of observed stiffness values on the strength distribution model and on the prediction of expected failure rates for the future life time of the structure..

**Keywords:** Structural reliability, health monitoring, time-variant safety, conditional probability, Monte-Carlo simulation.

Life-cycle considerations play an important role in the optimal design of structures and their maintenance. In this context it is essential to take into account the statistical uncertainty of loads and resistances in the expected life time of a structure. Therefore it is useful to introduce the results of structural monitoring on a probabilistic basis. One of the major purposes of such a monitoring system is to detect significant changes of the structural behavior early so that appropriate actions such as maintenance and repair can be taken.

The entire process involves several uncertain influences. The initial vibration measurements are usually affected by measurement noise due to random influences in the transducers and the recording equipment. In the next step, the essential modal characteristics of the structure are extracted from the measurement time series. This requires the establishment of a mathematical model whose properties are derived from certain properties of the measurements. As a result, natural frequencies and mode shapes can be obtained for a model of a certain order, in which the order of the model is arbitrary to some degree. In this context, it is referred to the literature on stochastic subspace identification. Then the modal changes are related to structural stiffness changes by means of a model updating procedure. Here, typically linear behavior of the structure is assumed. As an optimization procedure is required, there may be several problems associated with the specific nature of the optimization problem such as ill-posedness when many structural parameters have to be identified. Also, random fluctuations of structural properties as described by random fields may have an important impact on the identification results. Hence the stiffness values may be significantly uncertain. Furthermore, the essential quantity, i.e. the remaining strength of the structure or parts of the structure, are not perfectly correlated to the stiffness. This, again, introduces further uncertainties. Finally, the prediction of future reliability involves assumptions on future loads, which may have statistical properties different from loads observed in the past.

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The questions which follow from that are

- How does the stiffness value obtained from measurements affect the probabilistic description of the resistance?
- How does the updated probabilistic description of the resistance affect the reliability estimate?
- What are suitable computational procedures to perform the updating of the probabilistic information?

Conceptually, the answers to these questions rely on the notion of conditional probability. It is assumed that the loads acting on a structure or structural element are characterized by annual extreme events $S_i$. These loads are compared to the actual value of the resistance $R_i$. Resistance is assumed to deteriorate on one hand due to corrosive effects characterized by a deterioration rate $\nu_i$. This rate depends mainly on environmental conditions. On the other hand, large loads just below the actual capacity can introduce additional damage, which should be compensated by proper maintenance or repair. This will result in a net change of resistance $\Delta R_i$. The temporal development of the structural resistance is analyzed using Monte-Carlo simulation of the load process. The statistics are obtained from 1,000.000 samples. Then stiffness measurements $K = K^*$ are be introduced, say at time $t = T^*$. It is assumed that the stiffness $K_i$ is log-normally distributed with a coefficient of variation of 0.10 and that it has a mean value proportional to the mean value of the strength $R_i$. Furthermore, it will be assumed that the marginal of $R$ is log-normal as well, and that the mean and standard deviation can be estimated from the simulation data on $R_i$. In order to verify this assumption, the failure rates from direct Monte-Carlo simulation are compared to those using a fitted log-normal distribution based on mean values and standard deviations of the resistance. The agreement was found to be very good.

The effect of introducing the observed values of the stiffness can be categorized as follows

- The mean value of the strength can be increased or decreased, depending on the magnitude of the observed stiffness. Values of the observed stiffness larger than its expected value will increase the updated mean of the strength, and vice versa.
- The standard deviation of the strength is reduced by the observation.
- The expected failure rates are significantly influenced by the observed stiffness values. The rates will increase if the observed stiffness is smaller than its expected value, and it will increase otherwise.

The deterioration and maintenance models are used in this paper are very simple, and should merely illustrate the basis principles of an updating procedure when the relevant quantities (strength) cannot be directly observed, but must rather be inferred from statistically correlated but different physical properties of the structure. Further studies will focus on the application to structural models involving more details regarding loading conditions, deterioration processes and failure criteria.