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Failure rates or time-dependent failure probabilities in structural reliability

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ABSTRACT: In 1971 Rosenblueth&Mendoza published a paper on structural optimization the concepts of which have been refined later by Hasofer in 1974 and Rosenblueth in 1976 in the context of earthquake resistant design. In essence, these authors proposed to distinguish between structures that can fail upon completion or never and structures that can fail under rare "disturbances". Furthermore they distinguished between "single mission structures" and structures which are systematically rebuilt after failure. With this concept it is rather a yearly failure rate that has to be specified and verified and not a failure probability for an arbitrary reference time. The paper reviews Rosenblueth´s and Hasofer´s developments and extends the concepts to more general failure models. Some needed computational tools are addressed.

1 INTRODUCTION

As early as 1971 Rosenblueth/Mendoza (1971) proposed to use optimization for assessing reliabilitytargets with special reference to earthquake resistant design in a fundamental paper. The concepts developed therein were later refined by Hasofer (1974) and again by Rosenblueth (1976). In particular, a distinction was made whether failure would occur upon construction or never and at "large random disturbances" only. A second distinction was made with respect to the reconstruction policy. In the extremes there are just two: no reconstruction after failure and systematic reconstruction or repair after failure, respectively. Whereas it is true that both types of failure should generally be considered depending on the type of loading on the structure the matter of reconstruction policy was apparently overlooked in the past. In fact, for almost all civil engineering structures systematic rebuilding after failure, be it caused by extreme loading, bad construction, fatigue, other deterioration, loss of serviceability, or by demolition after obsolesce, is mandatory, at least ideally because buildings serve a certain need by the users and this almost always persist to exist. Optimization for one "mission" is thinkable for certain construction operations only.

2 THEORETICAL BASIS

Assume that the objective function of a structural component is

$$Z(p) = B(p) - C(p) - D(p) \quad (1)$$

$B(p)$ is the benefit from the existence of the structure, $C(p)$ are the construction cost and $D(p)$ the expected damage cost. p generally is a design parameter vector. Without loss of generality all quantities will be measured in monetary units. A discussion on matters how and to what extent this is justified is beyond the scope of this paper. Statistical decision theory dictates that the expected values for $B(p)$, $C(p)$ and $D(p)$ have to be taken (v. Neumann/Morgenstern, 1943). $B(p)$, in general, will be unaffected or slightly decrease with each component of p but this will be neglected without substantial error so that $B = B(p)$. $C(p)$ increases with each component of p under normal circumstances. Frequently, it can be approximated by $C(p) \approx C_0 + \Sigma c_i p_i$. C_0 are those cost which do not depend on p. In general, there is $C_0 >> \Sigma c_i p_i$. $D(p)$ decreases with p in some fashion. For each involved party, i.e. the builder, the user and the society, $Z(p)$ should be positive. Otherwise one should not undertake the realization of the structure. This is illustrated in Figure 1. Benefits, cost and damages are not necessarily the same for all involved parties. Therefore, the intersection of the

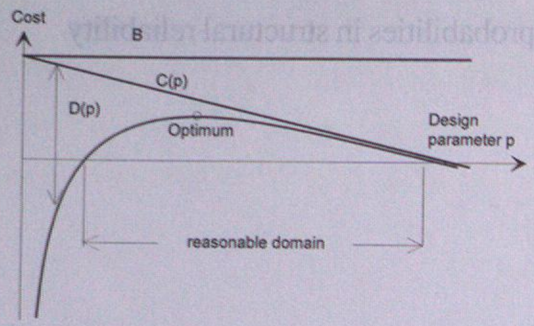

Figure. 1: Cost and benefit over design parameter p (after Rosenblueth/Esteva, 1972)

domains where $Z(p)$ is positive is the domain of p, which makes sense for all parties.
Furthermore, the decision about p has to be made at $t = 0$. This requires capitalization of all cost. In the following a continuous capitalization function is used.

$$\delta(t) = \exp(-\gamma t) \tag{2}$$

with γ the interest rate and t time in suitable time units. Usually, a yearly interest rate is defined and $\delta(t) = (1+\gamma')^{-t}$ with γ' the yearly interest rate and, therefore, $\gamma = \ln(1+\gamma')$. It will further be assumed that γ is corrected for de- and inflation and averaged over sufficiently long periods to account of fluctuations in time. Also it is assumed that the time for construction is negligible short as compared to the average lifetime of the structure.

2.1 *Failure upon construction*

If the structure fails upon construction (or when it is put into service) or never and is abandoned after first failure eq. (1) specializes to

$$\begin{aligned} Z(p) &= B^*(1 - P_f(p)) - C(p) - H(p)P_f(p) \\ &= B^* - C(p) - (B^* + H(p))P_f(p) \end{aligned} \tag{3}$$

$1 - P_f(p)$ and $P_f(p)$ are reliability and failure probability, respectively. $H(p)$ is the direct failure cost. In most cases $H(p)$ will be constant and includes the direct physical damage and the cost of demolition and removal but also cost for human life and injury so that $H(p) = H$. B^* is the benefit derived from the existence of the structure. If the failure probability depends on an uncertain vector R an additional expectation operation is necessary and $P_f(p)$ is to be replaced by $E_R[P_f(p,R)]$. If the structure fails upon construction and is reconstructed immediately

$$\begin{aligned} Z(p) &= B^* - C(p) - (C(p)+H)\sum_{n=1}^{\infty} nP_f(p)^n(1-P_f(p)) \\ &= B^* - C(p) - (C(p)+H)\frac{P_f(p)}{1-P_f(p)} \end{aligned} \tag{4}$$

Rosenblueth/Mendoza (1971) discuss at length what is meant by reconstruction for the same reliability and independence of the failure events. Here, it is just assumed that reliability is already optimal so that there is no reason to modify the design rules after failure although, practically, the new designs themselves will almost certainly be different from the previous ones. Some ambiguity exists how to quantify the benefit B^* in eqs. (3) and (4). We have for constant b and given reference time T

$$B(T) = \int_0^T b(t)\delta(t)dt = \frac{b}{\gamma}\left[1 - \exp[-\gamma T]\right] \tag{5}$$

and for $T \to \infty$

$$B^* = \frac{b}{\gamma} \tag{6}$$

Unless the asymptotic value is taken a reference time has to be specified.

2.2 *Failure due to time-variant loads and/or resistances*

Assume that the failure process can be modeled as an ordinary renewal process. According to renewal theory (Cox, 1962) a renewal process has independent and identically distributed, positive times between failures and subsequent renewals. The density function of the failure times is $g(t)$. For structures this means, for example; that each reconstruction realizes a new structure with properties independent from the previous ones. It is useful to distinguish between *ordinary* renewal processes where all times have density $g(t)$. For a *modified* renewal process the time to first failure is $g_1(t)$ while all other failure times have density $g(t)$. For an *equilibrium* renewal process the time to first failure has the special form $g_1(t) = (1 - G(t))/\mu$ where $G(t)$ is the distribution function corresponding to $g(t)$ and $\mu = E[T]$. The modified renewal process may be important whenever the (structural) component is not "new" at $t = 0$ and the hazard function is not constant, e.g. indicates some deterioration with age or the likelihood of failure is influenced by the time which has elapsed since the last observed failure. The equilibrium renewal process should be used if it assumed that the renewal process is running already for a long time and the time origin is placed randomly between two successive renewals. For an ordinary renewal process the renewal function is defined as

$$\begin{aligned} H(t) &= E[N(t)] = \sum_{n=1}^{\infty} nP(N(t)=n) \\ &= \sum_{n=1}^{\infty} G_n(t) = \sum_{n=1}^{\infty}\int_0^t g_n(\tau)d\tau = \int_0^t h(\tau)d\tau \end{aligned} \tag{7}$$

where $N(t)$ is the number of renewals in [0,t] and

$$G_n(t) = P\left(\sum_{j=1}^{n} T_j \le t\right)$$

The renewal density as the derivative of the renewal function, also denoted as unconditional failure rate or failure intensity, is

$$h(t) = \lim_{\Delta \to 0^+} \frac{P(\textit{one or more renewals in } [t, t+\Delta])}{\Delta} = \sum_{n=1}^{\infty} g_n(t) \tag{8}$$

Let

$$g_n(t) = \int_0^t g_{n-1}(t-\tau)g(\tau)d\tau; \quad n = 2,3,\ldots \tag{9}$$

be the density function of the time to the n-th renewal written as a convolution integral. The Laplace transform of $g(t)$ is

$$g^*(\theta) = \int_0^{\infty} \exp[-\theta t]g(t)dt \tag{10}$$

If $g(t)$ is a probability density we have $g^*(0) = 1$ and $0 < g^*(\theta) \le 1$ for all $\theta > 0$. For the important stationary Poisson process with intensity λ it is simply

$$g_1^*(\theta) = g^*(\theta) = \int_0^{\infty} \exp[-\theta t]\lambda\exp[-\lambda t]dt = \frac{\lambda}{\theta+\lambda} \tag{11}$$

$g_1^*(\theta) = g^*(\theta)$ just expresses the "lack of memory" of the Poisson process. For convolutions we have

$$g_n^*(\theta) = g_1^*(\theta)g_{n-1}^*(\theta) = g_1^*(\theta)\left[g^*(\theta)\right]^{n-1} \tag{12}$$

Hence, for

$$\begin{aligned} g_1^*(\theta) &= \int_0^{\infty} \exp[-\theta t]g_1(t)dt \\ g^*(\theta) &= \int_0^{\infty} \exp[-\theta t]g(t)dt \end{aligned} \tag{13}$$

we have for the modified renewal processes

$$h_1^*(\theta) = \sum_{n=1}^{\infty} g_n^*(\theta) = \sum_{n=1}^{\infty} g_1^*(\theta)\left[g^*(\theta)\right]^{n-1} = \frac{g_1^*(\theta)}{1-g^*(\theta)} \tag{14}$$

For ordinary renewal processes the result holds with $g_1^*(\theta) = g^*(\theta)$. For equilibrium renewal processes there is with the Laplace transform $g_1^*(\theta) = (1 - g^*(\theta))/(\theta\mu)$ of $g_1(t) = (1-G(t))/\mu$

$$h_{1,e}^*(\theta) = \frac{1}{\mu\theta} \tag{15}$$

For **structural facilities given up after first failure** we then have with $\gamma = \theta$ and where the failure time density can be controlled by the design parameter vector p

$$\begin{aligned} B^*(p) &= \int_0^{\infty}\int_0^t b\delta(\tau)\,d\tau\, g_1(t,p)dt \\ &= \int_0^{\infty}\left(1-\exp[-\gamma t]\right)g_1(t,p)dt = \frac{b}{\gamma}\left(1 - g_1^*(\gamma,p)\right) \end{aligned} \tag{16}$$

$$D(p) = \int_0^{\infty} g_1(t,p)\delta(t)Hdt = g_1^*(\gamma,p)H \tag{17}$$

and, therefore

$$Z(p) = \frac{b}{\gamma}\left(1 - g_1^*(\gamma,p)\right) - C(p) - Hg_1^*(\gamma,p) \tag{18}$$

The present value of the expected failure cost for **systematic reconstruction after failure** is for ordinary renewal processes

$$\begin{aligned} D(p) &= (C(p)+H)\sum_{n=1}^{\infty}\int_0^{\infty}\delta(t)g_n(t,p)dt \\ &= (C(p)+H)\frac{g^*(\gamma,p)}{1-g^*(\gamma,p)} \\ &= (C(p)+H)h^*(\gamma,p) \end{aligned} \tag{19}$$

The benefit B^* is as in eq. (6) in both cases. Therefore,

$$Z(p) = \frac{b}{\gamma} - C(p) - (C(p)+H)h^*(\gamma) \tag{20}$$

For modified renewal processes $h^*(\gamma,p)$ is replaced by $h_1^*(\gamma,p)$ and for equilibrium processes by $h_{1,e}^*(\gamma,p)$, respectively.

For Poissonian failure processes with exponential failure times with parameter $\lambda(p,R)$ which can be controlled by p and depend on the random vector R it is for structures given up after first failure

$$Z(p) = \frac{b}{\gamma} - C(p) - \left(\frac{b}{\gamma} + H\right)E_R\left[\frac{\lambda(p,R)}{\gamma + \lambda(p,R)}\right] \tag{21}$$

$$Z(p) = \frac{b}{\gamma} - C(p) - (C(p)+H)\frac{E_R[\lambda(p,R)]}{\gamma} \tag{22}$$

as pointed out by Hasofer (1974) and already used by Rosenblueth/Mendoza (1971). If $\gamma \to 0$ and $T \to \infty$, the damage cost become finite in the first case but infinite in the second. Hence, no optimal solution to eq. (1) can be found in the latter case. Therefore, if the second strategy is taken as the only reasonable one, a discount rate $\gamma > 0$ must be assumed.

3 APPLICATIONS

3.1 *General*

The foregoing results can be used for general failure processes. Let (Schall et al., 1991):

- R be a vector of random variables which are used to model structural properties and possibly other (non-ergodic) uncertain variables like parameters of the loading variables,
- Q be a vector of stationary and ergodic random sequences which are used to model long term fluctuations in the parameters of the loading variables, for example traffic states, sea states, wind states (10 min regimes), etc.,
- S be a vector of sufficiently mixing, not necessarily stationary random processes,
- $g(r,q,s(t),t) > 0$ the safe state, $g(r,q,s(t),t)=0$ the limit state, $g(r,q,s(t),t) \leq 0$ the failure state of a technical facility and $V = \{ g(r,q,s(t),t) \leq 0 \}$ the failure domain.

The conditional outcrossing rate is

$$\nu^+(V,\tau|r,q) = \lim_{\Delta \downarrow 0} \frac{1}{\Delta} P(\{g(S(\tau),\tau) > 0 | r,q\} \cap \cap \{g(S(\tau+\Delta),\tau+\Delta) \leq 0 | r,q\}) \tag{23}$$

with $V = \{g(r,q,s(t),t) \leq 0\}$. If the process of outcrossings is a regular process (see, for example, Cramer/Leadbetter, 1967, or Cox/Isham, 1980), the mean number of outcrossing in a given time interval $[t_1,t_2]$ is

$$E[N^+(t_1,t_2)|r,q] = \int_{t_1}^{t_2} \nu^+(V,\tau|r,q)d\tau \tag{24}$$

Asymptotically for small failure probabilities the first passage time distribution then is (Cramer/Leadbetter, 1967)

$$P_f(t_1,t_2) \approx 1 - E_{R,Q}\left[\exp\left[-E\left[N^+(t_1,t_2)|R,Q\right]\right]\right] \leq 1 - E_R\left[\exp\left[-E_Q\left[E\left[N^+(t_1,t_2)|R,Q\right]\right]\right]\right] \tag{25}$$

In the stationary case eq. (25) simplifies to

$$P_f(t_1,t_2) \leq 1 - E_R\left[\exp\left[-E_Q\left[\nu^+(V)|R,Q\right](t_2-t_1)\right]\right] \tag{26}$$

It follows that the quantity $\lambda(p,R)$ in eqs. (21) and (22) can be replaced by the outcrossing rate and eq. (22) can be written as

$$Z(p) = \frac{b}{\gamma} - C(p) - (C(p)+H(p))\frac{E_{R,Q}\left[\nu^+(V,R,Q,p)\right]}{\gamma} \tag{27}$$

It is essential to recall that the failure process is a renewal process, i.e. must have independent failure times. This means that at each renewal also the non-ergodic vector R has independent realizations at each renewal.

If fatigue or other deterioration phenomena are treated by the outcrossing approach one can use the general formulation in eq. (20). The asymptotic first passage time distribution (all conditions and condition for failure at $t = 0$ dropped) is

$$G(t) = 1 - \exp\left[-\int_0^t \nu^+(\tau)d\tau\right] \tag{28}$$

with density

$$g(t) = \nu^+(t)\exp\left[-\int_0^t \nu^+(\tau)d\tau\right] \tag{29}$$

This corresponds to a non-homogeneous Poissonian failure process.

3.2 *Design for maximum admissible failure rates*

The renewal density of a Poisson process is $h(t) = \lambda$ as can easily be shown. If the failure process is conditionally a stationary Poisson process it is now easy to impose some maximum admissible failure rate, for example,

$$E_{R,Q}\left[\nu^+(V(R,Q,S,p)\right] \leq \nu_{admissible} \tag{30}$$

For non-exponential failure times this condition must be modified. The failure rate then is not necessarily constant over time. In the limit it becomes infinitely large for deterministic failure times. Unfortunately, the relation between non-exponential failure time distributions and the corresponding outcrossing rates is not yet known unless the outcrossing approach is used as in eq. (29). Even then, it is not obvious how and at which quantity to set reliability constraints. Let $G(t)$ be the non-exponential distribution function of failure times and $g(t)$ its density. In renewal theory the following important result is proven (see Cox, 1962))

$$\lim_{t\to\infty} h(t) = \frac{1}{\mu} \text{ provided that } f(t) \to 0 \text{ for } t \to \infty \tag{31}$$

with $\mu = E[T]$ the mean time between failures. It is valid for both ordinary and modified renewal processes. The condition for $f(t)$ in eq. (31) is fulfilled for all failure time models of practical interest. The limiting operation simply says that the renewal process is active already for a long time. This is in agreement with our basic assumptions, at least ideally. The unconditional failure rate or renewal density is asymptotically inversely proportional to the mean time between failures that must exist. No other detail of the particular distribution function of failure times is used. For the equilibrium renewal process the renewal density is independent of t and equals exactly $h(t) = 1/\mu$ which follows from eq. (15). Consequently, for reliability verification the mean failure time must be computed and the corresponding asymptotic renewal density must be checked against the admissible failure rate

$$\lim_{t\to\infty} h(t) = \frac{1}{E_{R,Q}\left[E\left[T(R,Q)\right]\right]} \leq \nu_{admissible} \tag{32}$$

with $E[T(R,Q)]$ the mean time to failure. The same concept should be followed if fatigue or other deterioration is investigated by the outcrossing approach. Then, for eq. (29) the limiting condition is, for example

$$\lim_{t\to\infty} h(t) = \frac{1}{E_{R,Q}\left[\int_0^\infty t\,\nu^+(t,R,Q,p)e^{-\int_0^t \nu^+(\tau,R,Q,p)d\tau}dt\right]} \leq \nu_{admissible} \tag{33}$$

This comdition is difficult to verify.

It is interesting to study the speed with which the renewal density approaches its asymptotic, stationary value. For non-exponential failure times the renewal density has a characteristic, damped oscillating graph around the asymptotic value with period approximately equal to twice the mean failure time μ for failure times with smaller coefficient of variation.. The maxima occur at μ, 2μ, 3μ....where the first maximum is largest. Damping will increase with increasing standard deviation σ. For realistically large variability of failure times, say with coefficient of variation > 0.2, the renewal density will reach its asymptotic value after a few oscillations. For example, for a gamma distribution with density and $\mu = k/\lambda$ and $\sigma = \sqrt{k}/\lambda$ one finds

$$f_n(t) = \frac{\lambda^{nk} t^{nk-1}}{\Gamma(nk)}\exp[-\lambda t]; h(t) = \sum_{n=1}^{\infty} \frac{\lambda^{nk} t^{nk-1}}{\Gamma(nk)}\exp[-\lambda t] \tag{34}$$

showing the described behavior. For the gamma distribution the infinite sum can be simplified for integer $k > 1$

$$h(t) = \frac{\lambda}{k}\sum_{j=1}^{k-1} \varepsilon(k)^j \exp\left[\lambda t(\varepsilon(k)^j - 1)\right] \tag{35}$$

with $\varepsilon(k) = \cos(2\pi/k) + i\sin(2\pi/k)$. With this model (integer k) only coefficients of variation of $V = 1/\sqrt{k}$ can be obtained. The renewal density is shown in Fig. 2 for three typical coefficients of variation. The renewal density overshoots the asymptotic value by a factor of 2 to 4 for coefficients of variation between 0.2 to 0.1, respectively, and by much less for larger coefficients of variation.

One could argue that the maximum value, i.e. $\max\{h(t)\} \approx h(\mu)$, must be used as a constraint instead of the asymptotic value $1/\mu$. For the user of a structure this requirement can make sense if and only if he/she knows its age and knows that failures do not occur totally at random. He/she then might not wish to be exposed to higher risk when the structures reaches ages of multiples of its mean failure time. If the conditions for a modified renewal process are fulfilled, possibly in regions with seismic activity where many structures will be affected by the same disturbance, the maximum renewal density may also be limited with some justification, also from a societal point of view. For society this policy would be somewhat doubtful. A steady, random stream of failures and subsequent reconstructions of many structures should be considered. But this corresponds precisely to the conditions of an equilibrium renewal process at any point in time and a constant limiting value should be used which is exactly $1/\mu$.

The determination of $max\{h(t)\}$ for failure time densities known only pointwise can involve heavy numerics. It is first necessary to take the Laplace transform numerically and then its inverse which is a notoriously difficult problem. It is mentioned that not only the Laplace integral needs to be performed but also the expectations with respect to the R- and Q-variables have to be taken. Relevant, more recent algorithms for computing the inverse Laplace transform are described in de Hoog et. al. (1982), Garbow et al. (1988) and Murli/Rizzardi (1990). All of the algorithms proposed in these references have been found to work sufficiently well and reliably but more experience is needed.

3.3 *Summary and Conclusions*

The foregoing developments are based on more than 25 years old, but apparently since then overlooked findings by Rosenblueth and Hasofer. Little is really new. It is, however, believed that far reaching comclusions should be drawn. To a certain extent they will affect the whole safety philosophy and methodology for structural facilities. They should, at least, change the philosophy for setting up reliability targets in codes and other applications and, consequently, also the principles of reliability verification.

First of all, the optimal solution for building facilities with or without a systematic rebuilding policy is based on failure intensities and not on time-dependent failure probabilities. It is neither neces sary to define arbitrary reference times of intended use nor is it necessary to undertake the complicated

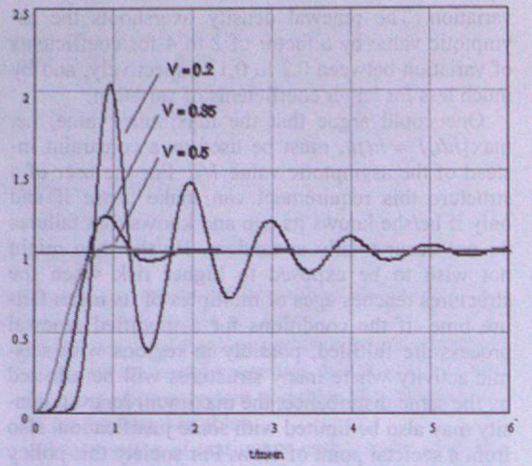

Fig. 2: Renewal density divided by asymptotic value versus time divided by mean failure time

task to compute first passage time distributions. No table of recommended reference times of usage of structures is needed. The same targets, in terms of failure rates, can be set for temporary structures and monumental buildings, given the same marginal cost for reliability and failure consequences. Nevertheless, it is necessary to define a time unit. For civil engineering facilities this is no doubt one year in consideration of the length of their life cycles. Other choices are possible provided that the failure intensities are small and much smaller than the interest rate. Also, the optimum design parameters are independent of assumed, highly variable lifetimes. This does not mean that lifetime aspects, especially in case of fatigue and other deterioration, are ignored. Here, design must be directly for mean failure times which are sufficient to derive the corresponding asymptotic renewal densities to be checked against target failure rates. It is proposed that for almost all civil engineering facilities the only reasonable reconstruction policy is systematic rebuilding or repair. A number of new, primarily computational problems evolve. A few of them are mentioned.

Structures should be optimal. A suitable objective function has been formulated. Appropriate optimization schemes are proposed in Kuschel/Rackwitz (1998). Actual optimization may not be practical in every day engineering work, however. For codes failure rates may still be assessed by optimization and, in parallel, by calibration at present practice using Lind´s postulate that present practice is already "almost" optimal (Lind, 1977). A more detailed analysis of the subject is given in Rackwitz (1999).

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