PROCEEDINGS OF THE ICASP 8 CONFERENCE
SYDNEY / NEW SOUTH WALES / AUSTRALIA / 12 – 15 DECEMBER 1999

Applications of Statistics and Probability

Civil Engineering Reliability and Risk Analysis

Edited by

Robert E. Melchers & Mark G. Stewart

Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, New South Wales, Australia

OFFPRINT

A.A. BALKEMA / ROTTERDAM / BROOKFIELD / 2000

Applications of Statistics and Probability, Melchers & Stewart (eds) © 2000 Balkema, Rotterdam, ISBN 90 5809 086 8

Numerical computation of mean failure times for locally non-stationary failure models

R. Rackwitz
Technical University, Munich, Germany

K. Balaji Rao
Structural Engineering Research Center, Chennai, India

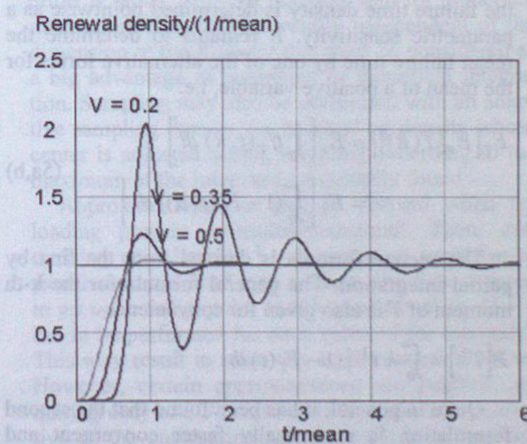
ABSTRACT: A new concept for determining optimal structures and for verifying its reliability has been proposed. Its mathematical structure is investigated in a companion paper by Hasofer/Rackwitz (1999). It makes use of renewal theory and assumes systematic rebuilding after failure. Consecutive failure times must be independent. In the paper some numerical questions concerning locally non-stationary failure models as relevant for fatigue and other deterioration are discussed and illustrated by examples.

1 INTRODUCTION

In Hasofer/Rackwitz (1999) and Rackwitz (1999) an old idea developed earlier by Rosenblueth/Mendoza (1971), Hasofer (1974) and Rosenblueth (1976) has been taken up resulting in a somehow revolutionary new basis for optimum structural reliability. It has been demonstrated that a reasonable objective function for optimal structures under time-dependent loading and/or resistance assuming systematic rebuilding after failure is as follows:

$$Z(p) = \frac{b}{\gamma} - C(p) - (C(p) + H(p))\frac{1}{\gamma\,\mu} \qquad (1)$$

where b is the (constant) benefit per unit time derived from the existence of the structure, γ the (continuous) discount rate, $C(p)$ the building cost, p the vector of design parameters, $H(p)$ the cost of failure and μ the mean time between failures (renewals) which is assumed to exist. Failure times are always positive random variables. This equation holds exactly for exponentially distributed failure times, is valid for so-called equilibrium renewal processes and is asymptotically valid if the failure times are not exponentially distributed as for ordinary and modified renewal processes. The quantity $1/(\mu\gamma)$ is nothing else than the Laplace transform of the (asymptotic) renewal density. For smaller coefficients of variation of failure times the exact renewal density has a characteristic damped oscillating behavior as shown in figure. 1. The result eq. (1) is rather general and the key to many further developments. It means that in order to evaluate equation (1) under general conditions and, possibly, maximize it with respect to the design parameter p the main computational task is to determine the mean failure time μ. Unfortunately, this is a generally difficult task in noticing that many distributions of failure times can only be determined numerically. It should, however, be emphasized that the cases considered herein form only a small proportion of the cases met in practical applications. If the failure process is locally stationary and especially if it is a Poissonian process no additional complication arises. Then, the mean time between failures is just the exponential distribution with the mean outcrossing rate as parameter.
Three cases can be distinguished when determining mean failure times



:
Figure 1: Damped oscillating behavior of exact renewal density (normal failure times)

- The failure time distribution is not exponential but known
- Failure is caused by some smooth cumulative damage process
- Failure is caused by "extreme" overloads possibly in conjunction with some smooth cumulative degradation of resistance
-

The expectation operation in general must not only be taken with respect to time but also with respect to other non-ergodic and ergodic variables here denoted by *R*-variables.

In the first case the mean failure time is known analytically. However, the parameters of this distribution may involve further *R*-variables of function of such variables. The computational task is as follows:

$$\mu = E_R[m(R)] \qquad (2)$$

where $m(R)$ is the known mean failure time.

The failure probability for the second case usually can be formulated as

$$P_f(t) = E_R[F_T(t,R)] = E_R[P(g(t,R) \le 0)] \qquad (3)$$

where $g(t,R)$ is the state function dependent on t and the *R*-vector such that the limit state is reached for $g(t,R) = 0$ and failure occurs for $g(t,R) \le 0$. It follows that the derivative with respect to t is the failure time density. Using modern FORM/SORM techniques in standard space to determine the probability in eq. (3) one finds that

$$E_R[f_T(t,R)] = \frac{\partial E_R[P(g(t,R) \le 0)]}{\partial t} = -\varphi(\beta(t))\frac{\partial \beta(t)}{\partial t} \qquad (4)$$

$\beta(t)$ is the time-dependent reliability index. Here the failure time density is determined pointwise as a parametric sensitivity. It remains to determine the mean failure time by one of the alternative forms for the mean of a positive variable, i.e.

$$E_T[E_R[T(R)]] = E_R\left[\int_0^\infty t f_T(t,R)\,dt\right] = E_R\left[\int_0^\infty (1 - F_T(t,R))\,dt\right] \qquad (5a,b)$$

The second formula is derived from the first by partial integration. The general formula for the k-th moment of *T* is also given for convenience

$$E[T^k] = \int_0^\infty k\,t^{k-1}(1 - F_T(t))\,dt$$

Quite in general, it has been found that the second formulation is numerically faster convergent and more reliable than the first. It also does not require the differentiation operation as there is $F_T(t) = E_R[P(g(R,t) \le 0)]$. A simple numerical integration scheme should suffice. Clearly, the difficulty with both formulae is primarily in the infinite upper integration limit. Use of FORM/SORM requires that the failure probabilities can be accurately determined also for probabilities around 0.5. For SORM this requires some additional considerations because its results are valid and accurate only for small (large) failure probabilities. Therefore, for probabilities around 0.5 a formula for the exact probability content of a parabolic form given by Tvedt (1990) is used. For very small (large) probabilities the usual asymptotic result is used. For moderate probabilities an interpolation between exact and asymptotic probabilities is applied.

The third case is most difficult. In general, it is only possible to determine the outcrossing rate $\nu^+(t,R)$ and from this a failure time distribution is derived. Under asymptotic conditions the failure time density, conditional on $R = r$, is then given by

$$f_T(t,r) = \nu^+(t,r)\exp\left[-\int_0^t \nu^+(\tau,r)\,d\tau\right] \qquad (6)$$

In this paper several, somewhat preliminary studies on the numerical problems in evaluating eqs. (2), (5) and (6) are presented, primarily by examples. In all cases it is out of order to attempt direct multidimensional numerical integration for dimensions larger than 3 to 5.

2 THEORETICAL CONSIDERATIONS

Without loss of generality we consider the computation of a general expectation like $E[g(R)]$ where $g(R)$ is a monotonic, complicated function of the vector *R*. In general, *R* has many dimensions and thus numerical integration is not suitable. A first approximation consists of the well-known formula

$$E[g(R)] \approx g(E[R]) + \frac{1}{2}\sum_{i=1}^{n_R}\sum_{j=1}^{n_R}\frac{\partial^2 g(E[R])}{\partial r_i \partial r_j}\sigma_{ij} \qquad (7)$$

where σ_{ij} are the elements of the covariance matrix of *R*. For non-linear functions $g(R)$ and larger variability of the *R*'s this is found to be rather inaccurate, even if the second term is included.

A second approximation is based on arguments leading to the Laplace approximation of integrals (Bleistein/Handelsman, 1975). It is convenient to first perform a probability distribution transformation $x = D(u)$ where *u* is a standard normal vector with independent components (Hohenbichler/Rackwitz, 1981). Then, given that the integrand in

$$E[g(D(u))] = \int_{R^{n_R}} g(D(u))\,\varphi(u)\,du \qquad (8)$$

has a unique maximum the expectation can be written as:

$$E[g(D(u))] = \int_{R^{n_R}} (2\pi)^{-n_R/2}\exp\left[-\frac{1}{2}k(u)\right]du \qquad (9)$$

$k(u)$ is expanded to second order

$$k(u) = \|u\|^2 - 2\ln(g(D(u))) \approx k(u^*) + \frac{1}{2}(u-u^*)^T S(u^*)\,(u-u^*) + \cdots \qquad (10)$$

with the matrix of second derivatives of $k(u)$

$$S(u^*) = \left\{\left(\delta_{ij} - \frac{1}{g(D(u^*))}\frac{\partial^2 g(D(u^*))}{\partial u_i \partial u_j} + \frac{1}{g(D(u^*))^2}\frac{\partial g(D(u^*))}{\partial u_i}\frac{\partial g(D(u^*))}{\partial u_j}\right);\ i,j = 1,\ldots,n_R\right\} \qquad (11)$$

and u^* the solution of $max\{g(D(u))\varphi(u)\}$ or of $min\{k(u)\}$. Making use of Aitken's integral

$$(2\pi)^{-n/2}\int_{R^n}\exp\left[-\frac{1}{2}x^T A x\right]dx = |\det(A)|^{-1/2}$$

with *A* a positive definite matrix the result is

$$E[g(D(u))] \approx g(D(u^*))\,(2\pi)^{n_R/2}\,\varphi(\|u^*\|)\,|\det(S(u^*))|^{-1/2} \qquad (12)$$

with usually excellent numerical accuracy. Quite frequently, $|det(S)|$ is close to unity. If it is set to unity it makes sense to speak of a first order approximation. This procedure can be recommended for eq. (2) or in cases where the expectation operation is only with respect to *R*-variables.

In eq. (6) an additional expectation operation over the failure density is required. The same formulae apply also for this case except that now $g(t,u) = t f_T(t,u)$ replaces $g(D(u))$ and (u^*,t^*) is the solution of $max\{g(t,D(u))\varphi(u)\}$ or of $min\{k(t,u)\}$. All other quantities have to be evaluated for $t = t^*$.

$$E_R[E_T[T(U)]] \approx g(t^*,u^*))\,(2\pi)^{(n_R+1)/2}\,\varphi(\|u^*\|)\,|\det(S(t^*,u^*))|^{-1/2} \qquad (13)$$

Also here, one observes surprisingly good numerical accuracy. It is noted that in this case the "first order" results are not even correct to the order of magnitude. Clearly this is a consequence of the particular function $g(t,u)$. For small coefficients of variation approaching zero one recovers the deterministic result. The same procedure could be applied to calculate higher moments of failure times, however, with increasing loss of accuracy for increasing order.

In eq. (12) and (13) no asymptotic argument can be applied except that the results become asymptotically exact for all standard deviations approaching homogeneously to zero. It is important to use eq. (10), i.e. to take $ln(g(D(u)))$ in the exponent of $k(u)$. Otherwise the critical point is $u^* = 0$, the determinant of the Hessian is unity and a trivial result corr sponding to eq. (7) is obtained.

One alternatively can use Monte Carlo simulatic with importance sampling. The difficulty in settir up a suitable scheme is that the failure density known only numerically. The inverse transfoı method usually fails due to numerical reasons (s Rubinstein, 1981). But one can estimate the integra by importance sampling. For example, if the pro lem has been formulated in standard space with r spect to the *R*-variables a simple scheme using t critical point (t^*,u^*) of eq. (13) is

$$E_R[E_T[T(U)]] \approx \frac{1}{N}\sum_{i=1}^{N}\frac{f_T(t_i|u_i)\varphi(u_i;0,1)}{\varphi(t_i;t^*,\sigma_T)\varphi(u_i;u^*,1)} \qquad (14)$$

with

$$\sigma_{\bar{T}} = \frac{\sqrt{2\pi}}{\sqrt{\left|\frac{\partial^2}{\partial t^2}\ln(t^* f_{\bar{T}}(t^*|u_R^*))\right|}} \qquad (15)$$

It is essential to adjust location parameter and spread of the sampling density to values that guarantee sampling in the important region. The spread of the sampling density is chosen proportional to the curvature of the quantity $t\ f_T(t,u)$ in (t^*,u^*). The choice of a normal sampling density appears convenient but otherwise is arbitrary. Other equally efficient sampling schemes are possible. The numerical effort is rather large but still less than for numerical integration. It is also essentially independent of the dimension of the *R*-vector that must be considered as a big advantage as compared to numerical integration. Sampling may also be performed with an adaptive sampling density, i.e. a sampling density whose center is adjusted during sampling according to the maximum of the integrand temporarily found.

Approximations can also be derived when the loading process is multidimensional. Then, outcrossing rates have to be computed in multidimensional spaces. In order to evaluate the time integral in $g(t,u_R)$ a full β-point search conditional on $U = u$ has to be performed for each value of the integrand. This may result in relatively large numerical effort. However, certain approximations are possible, requiring only one β-point search and the time derivative of the outcrossing rate for each local iteration point (t_i,u_i). In well-behaved cases the outcrossing rate can either decay monotonically with time or is bell-shaped. The exponent term in $g(t,u)$ will produce additional decay with time. In bell-shaped cases it will shift the mode of $g(t,u)$ to the left. If, as we do repeatedly, concentrate on the maximum of the integrand and its local properties the critical point will be at the origin $t^* = 0$ for decreasing outcrossing rates and a little left of the mode of $g(t,u)$ for bell-shaped outcrossing rates. Now, a rather crude approximation of the integral using only the value of $\nu^+(t,u)$ and its time derivative will be

$$\int_0^{t_i} \nu^+(\tau,u_i)d\tau \approx \frac{\nu^+(t_i,u_i)^2}{\left|\frac{d}{dt}\nu^+(t_i,u_i)\right|} = \frac{\nu^+(t_i,u_i)}{\left|\frac{d}{dt}\ln\left(\nu^+(t_i,u_i)\right)\right|} \qquad (16)$$

with some numerical advantage for the second version.

A conservative estimate can, however, always been achieved if the upper integration limit can be taken as a parameter in a parameter study for the upper bound solution of the time-dependent failure probability

$$P_f(t) = F_T(t) \le P_f(0) + E_R\left[\int_0^t \nu^+(\tau,R)d\tau\right] \le 1 \qquad (17)$$

Subsequently, eq. (5b) can be used. The mean failure time is estimated more or less too short. Consequently, the failure rate (renewal density) is estimated too large which may be considered acceptable in view of figure 1.

3 NUMERICAL EXAMPLES

3.1 *Chloride Corrosion for Marine Structures*

This example is used to illustrate the calculation of mean failure times by eq. (5) together with eq. (3). A simplified failure criterion is

$$C_{cr} - C_s\left(1 - erf\left(\frac{c}{2\sqrt{Dt}}\right)\right) \le 0 \qquad (18)$$

where

C_{cr} = critical chloride content
C_s = surface chloride content
c = concrete cover
D = diffusion parameter
t = time

The units are chosen such that t is in years. For eq. (17) it is assumed that corrosion will be very rapid as soon as the critical value is exceeded. Thus, eq. (18) essentially is a criterion for the initiation time. The following stochastic model is assumed.

Variable	Distr.	Parameters
C_{cr}	Uniform	0.07, 0.175
C_s	Uniform	0.2, 0.4
c	Lognormal	5-6-7, 1
D	Uniform	3.15E-2, 3.15E-1

It may be typical for the conditions in the splash zone in warm marine climates. The uniform distributions are expressions for relatively large uncertainties about the actual values. The results determined by SORM and numerical integration are:

Concrete cover	Mean failure times	C.o.V. of failure time
5	221	1.51
6	312	1.37
7	416	1.24

In view of figure 1 it also is relatively easy to calculate the coefficient of variation of failure times which are also given. The magnitude of the coefficient of variation gives some indication of how close the value of 1/mean failure time to the asymptotic value is. It can be seen that the C.O.V. is a little larger that unity implying that the asymptotic value will be reached after very short time.

3.2 *Crack propagation*

A similar formulation can be given for fatigue crack propagation. Paris-Ergodan's crack propagation law is

$$\frac{da}{dn} = C\left(Y(a)\Delta S\sqrt{\pi a}\right)^m = CY(a)^m \Delta S^m \sqrt{\pi a}^m \qquad (19)$$

with material parameters m and C. ΔS is the applied random stress range. $Y(a)$ is a geometry factor usually depending on crack length a and containing $\pi^{1/2}$. For this example, $Y(a)$ is the constant $1.0\,\pi^{1/2}$ and consequently $Y^m = \pi^{m/2}$. Eq. (19) can be integrated:

$$a(t) = \{a_o^k + k\,C\,Y^m E[\Delta S^m]\,N(t)\}^{1/k},\ m\neq 2 \qquad (20a$$

$$a(t) = a_o \exp(C\,Y^2 E[\Delta S^2]\,N(t));\ m=2 \qquad (20b)$$

with $k = (1-m)/2$. a_0 is the initial crack length. For the time invariant case at hand (stationary loading) we compute the total number of cycles $N(t)$ from ν_o t (ν_o is upcrossing rate of the mean of the load process, t is time). k is negative for any m > 2. In this case care must be taken to avoid singularity of eq. (20a). If the stress variation is a narrow band Gaussian process, the stress range is Rayleigh distributed and its expected value can be computed from:

$$E\left[\Delta S^m\right] = \left(2\sqrt{2}\sigma\right)^m \Gamma\left(\frac{2+m}{m}\right) \qquad (21)$$

Failure is defined if the crack depth $a(t)$ exceeds a critical limit a_{crit}:

$$a_{crit} - a(t) \le 0 \qquad (22)$$

The stochastic model is:

Variable	Distr.	Parameter
a_0	Rayleigh	1, 0.4
$C*10^{13}$	Normal	0.02, 0.002
ΔS	Constant	50
m	Constant	3.5
a_{crit}	Constant	10
ν_0	Constant	100000

The units are chosen such that crack length is in mm and time in years (= 100000 cycles per year).

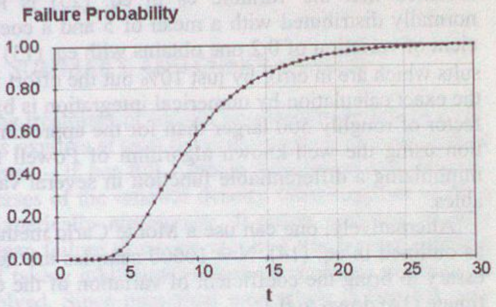


Figure 2: Failure time distribution for crack propagation example

In Figure 2 the failure time distributions shown as an example indicating that it is sufficiently well behaved. The mean failure time by simple numerical integration is calculated as 9.4 and the coefficient of variation is 0.54. Here again, the coefficient of variation is large enough to accept the quantity 1/mean as an approximation to the renewal density.

3.3 *Fatigue Failure (failure time distribution known)*

Here, the accuracy of eq. (12) will be illustrated. Assume that the mean number of cycles to failure is given by $N = \nu_0 t = C\Delta S^{-m}$. ν_0 is the cycling rate, C and m material properties and ΔS the stress range. In sufficient agreement with experiments (Rackwitz/Faber, 1991) the failure process can be assumed to be a Poisson process with exponential interarrival times having mean

$$E\left[T_{fat}\right] = \frac{C}{\nu_0 \Delta S^m} \qquad (23)$$

Thus, $1/E[T_{fat}]$ can be interpreted as the failure intensity (asymptotic renewal density) and

$$M(p) = M\,E_R\left[\frac{\nu_0(\Delta S/p)^m}{C}\right]\frac{1}{\gamma} \qquad (24)$$

is the expected discounted cost for fatigue failures with M being the loss due to fatigue failure. ν_0 and C and possibly m are non-ergodic random R-variables. For random ergodic loading one has to use a damage-equivalent constant ΔS in eq. (18) which, however, may depend on other non-ergodic variables. The parameter p has been attached to ΔS but could, of course, be used, alternatively or in addition, at other variables.

Since the ergodicity theorem is already used when assessing equivalent constant ΔS only the expectation over the R-variables has to be taken. The exponential failure time distribution may not be adequate for other types of deterioration. Then, one has to proceed using Laplace transforms.

For example, if we assume ΔS as normally distributed with $m_{\Delta S} = 200$ and standard deviation $\sigma_{\Delta S} = 100$ and C independently log-normally distributed with mean $m_C = 10^{13}$ and coefficient of variation of 1, respectively, together with $\nu_0 = 100$ and $m = 3$, we obtain from eq. (7) and exact numerical integration $E[R]/exact \approx 0.41$. From eq. (12) we obtain to first order $E[R]/exact \approx 1.14$ and to second order $E[R]/exact \approx 1.01$, respectively. The assumed large variability makes the function g(R) highly non-linear.

For other known failure time distributions one proceeds analogously.

3.4 *Outcrossing approach for fatigue (failure time distribution unknown)*

If the model eq. (6) is used the failure time distribution is not known explicitly. Assume a structural component whose resistance is decaying according to

$$b(t) = b_0 + b_1 t^m \qquad (25)$$

It is loaded by either a stationary Gaussian or a stationary rectangular wave renewal process with zero mean and unit standard deviation. Their outcrossing rates are given by

$$\nu^+(b(\tau),r) \le \lambda(1-\Phi(-b(\tau)))\,\Phi(-b(\tau)) \qquad (26)$$

for the scalar rectangular wave renewal process with jump rate λ and by

$$\nu^+(b(\tau),r) = \omega_0\varphi(b(\tau)\Psi(\dot{b}(\tau)/\omega_0) \qquad (27)$$

for the scalar Gaussian process with ω_0 the cycling rate and $\psi(x) = \varphi(x) - x\,\Phi(-x)$. The deterministic or random vector r collects, for example, the

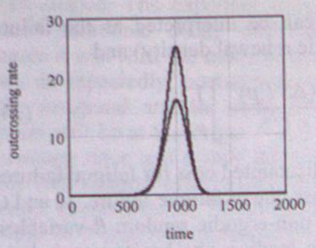


Figure 3: Outcrossing rate

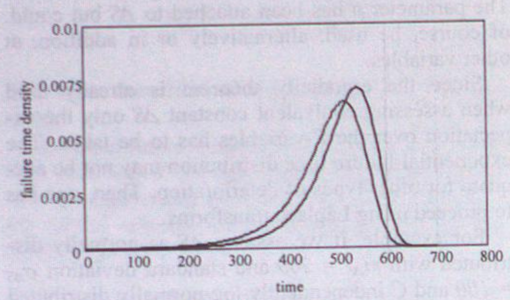


Figure 4: Failure time density

quantities b_0, b_1 and m. Let $b_0 = 5$, $b_1 = -0.000005$, $m = 2$, $\lambda = \omega_0 = 200$ be deterministic implying that the failure time density is largest for $t = 500$ time units (see figure 3). The failure density is (see figure 4)

$$f(t,r) = \nu^{+}(b(t),r)\exp\left[-\int_0^t \nu^{+}(b(\tau),r)d\tau\right] \qquad (28)$$

with maximum density $max\{f(t^{*},r\} = 5.63\ 10^{-3}$ at $t^{*} = 542$ and $max\{f(t^{*},r\} = 7.15\ 10^{-3}$ at $t^{*} = 516$, respectively. Mean and standard deviation are $E[T] = 504$ and $D[T] = 77.5$ for the rectangular wave renewal process and $E[T] = 472$ and $D[T] = 86.5$ for the Gaussian process, respectively. The failure rate or asymptotic renewal density is thus $1/E[T] \approx 0.002$, which can be compared with an admissible failure rate. Note that the coefficient of variation of the failure time distribution is only about 15 %. Note further that the time for the maximum of the failure time density is approximately one half of the maximum of the outcrossing rate, which is due to the exponent term in eq. (28). Also, due to the same reason, the densities are skewed to the left.

If the vector R has uncertain components the computational problem is substantially more complicated and numerically involved.
For example, if for the Gaussian process case it is assumed that the variable b_0 in eq. (25) is log-normally distributed with a mean of 5 and a coefficient of variation of 0.2 one obtains with eq. (13) results which are in error by just 10% but the effort for the exact calculation by numerical integration is by a factor of roughly 500 larger than for the approximation using the well-known algorithm of Powell for minimizing a differentiable function in several variables.

Alternatively, one can use a Monte Carlo method as outlined in eq. (14). $N \approx 10000$ samples are necessary to bring the coefficient of variation of the estimate (14) down to 0.1.

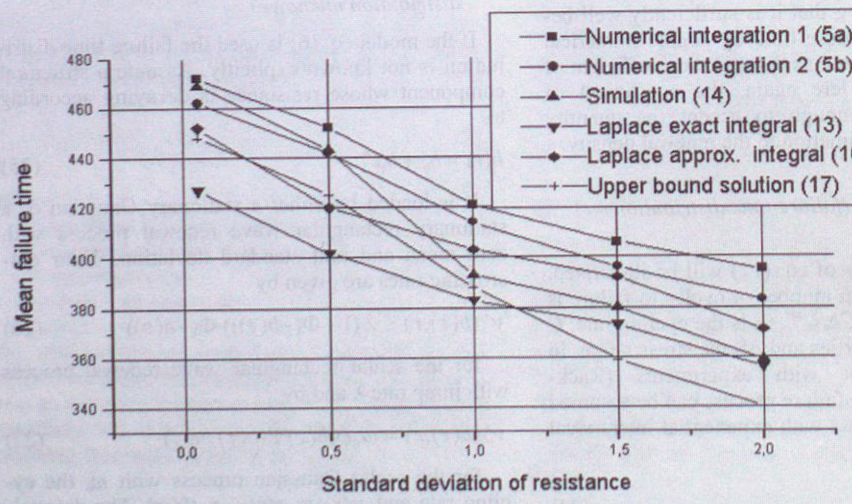


Figure 5: Comparison of different computation schemes for mean failure times of example 3.4

Finally, the upper bound solution according to eq. (17) can be used.

Figure 5 illustrates some computations of the mean failure time for various values of the standard deviation of the uncertain threshold. Numerical integration methods 1 and 2, respectively, differ by the two formulations in eq. (5). Otherwise standard integration methods are used. It is obvious from fig. 5 that some numerical noise still is present in the calculated values that needs further study. As already mentioned, numerical integration requires 100 to 1000 times more numerical effort (counted by the number of function calls) than Monte Carlo integration or the Laplace integral approximation the latter leading to conservative results. The upper bound solution obtained by numerical integration of eq. (17) according to eq. (5b) is conservative with respect to the two numerical integration results and surprisingly close to the "exact" results. However, examples can be constructed where the upper bound solution is more conservative.

4 SUMMARY AND CONCLUSIONS

The treatment of locally non-stationary failure models requires at least the determination of mean failure times – if not full Laplace transforms and their inverses of the renewal density which appears to be a numerically notoriously ill-posed problem. If only mean failure times are required the general problem of taking multidimensional expectations needs to be solved. Since numerical integration is feasible only in small dimensions certain other numerical, approximate techniques are discussed. If the distribution of failure times can be determined by simple FORM/SORM analysis running a parameter study with respect to time and subsequent numerical time integration accurate results can be achieved easily. In this case it is even possible to calculate higher moments of failure times.
Other cases require more involved methods. It is found that a Laplace integral type approximation can be used with advantage. As an alternative, Monte Carlo integration with importance sampling can be used. Such a scheme would best be based on the "critical" point to be found in the Laplace integral approximation method. Adaptive schemes may also work. A conservative estimate of the mean failure time is also presented. The different numerical schemes are illustrated by an example. All investigated methods produce more or less large errors unless unduly large numerical effort is spent. The computational aspects of the new concept for locally non-stationary failure models based on outcrossing rates, a rare but important application, cannot yet be considered as fully solved. Further work, possibly on different lines, still is necessary.

REFERENCES

Bleistein, N., Handelsman, R.A., *Asymptotic Expansions of Integrals*, Holt, Rinehart and Winston, New York, 1975

Hasofer, A.M., Design for Infrequent Overloads, *Earthquake Eng. and Struct. Dynamics*, 2, 4, 1974, pp. 387-388

Hasofer, A.M., Rackwitz, R., Time-dependent models fo optimization, submitted to ICASP 1999 for publicatio

Hohenbichler, M., Rackwitz, R., Non-Normal Dep Vectors in Structural Safety, *Journ. Eng. Mech.* ASCE, Vol. 107, No. 6, 1981, pp. 1227-1249

Rosenblueth, E., Mendoza, E., Reliability Optimiza Isostatic Structures, *Journ. Eng. Mech. Div.*, ASC EM6, 1971, pp. 1625-1642

Rosenblueth, E., Optimum Design for Infrequent Distur *Journ, Struct. Div.*, ASCE, 102, ST9, 1976, pp. 1807

Rubinstein, R.Y., *Simulation and the Monte Carlo Me* Wiley, New York, 1981

Tvedt, L., Distribution of Quadratic Forms in Normal Space-Application to Structural Reliability, *Journ. Eng. Mech.*, Vol. 116, No.6, 1990, pp. 1183-1197

Rackwitz, R., Discussion to Harbitz, A., An Efficient Sampling Method to Probability of Failure Calculation, *Strucural Safety*, 4, 1987, pp. 313-314

Rackwitz, R., Faber, M.H., Reliability of Parallel Wire Cable under Fatigue, *Proc. ICASP6, 6th Int. Conf. on Applications of Statistics and Probability in Civil Engineering*, Mexico 1991, Vol. 1, pp. 166-175

Rackwitz, R., Optimization – The Basis of Code-making and Reliability Verification, submitted to Structural Safety for publication

FROM THE SAME PUBLISHER:

Bradford, M.A., R.Q.Bridge
& S.J.Foster (eds.) 90 5809 107 4
Mechanics of structures and materials – *Proceedings of the 16th Australasian conference, Sydney, NSW, Australia, 8-10 December 1999*
1999, 21 cm, 780 pp., EUR 105.00 / $110.00 / £70
The papers represent recent findings, with a focus on Australasian work, in the broad area of structural mechanics. Topics: Keynote papers; Computational and fracture mechanics; Reinforced and prestresses concrete structures; Advances in design and construction methodologies; Steel structures; Composite structures; Building and construction products; Design codes; Environmental loadings; Composites engineering and new materials; Dynamic analyses of structures; Structural analysis and stability; Foundation engineering; Optimisation and reliability.

Schuëller, G.I. & P.Kafka (eds.) 90 5809 109 0
Safety and reliability – *Proceedings of the ESREL '99 - 10th European conference, Munich-Garching, Germany, 13-17 September 1999*
1999, 25 cm, 1648 pp., 2 vols., EUR 135.00 / $140.00 / £95
226 papers cover a wide range of research and development in safety and reliability that concern aspects such as reliability modeling and assessment, structural reliability, software reliability, human factors and reliability, fault tree analysis and FMECA, Monte Carlo methods, maintenance strategies, uncertainty and sensitivity methods, expert judgement, risk analysis, quality management, inspection, optimization, cost-benefit analysis. Some of the topics included are aerospace, automotive, civil, mechanical, offshore, nuclear, chemical, electronic, software and other types of engineering. These volumes should serve as a valuable reference on recent developments in safety and reliability.

Shiraishi, N., M.Shinozuka & Y.K.Wen (eds.) 90 5410 978 5
Structural safety and reliability – *Proceedings of the 7th international conference, ICOSSAR'97, Kyoto, 24-28 November 1997*
1998, 25 cm, 2130 pp. 3 vols., EUR 179.50 / $209.00 / £126
Topics covered: Basic theory & methods; Design concepts; Design methods; Damage/maintenance; Earthquake; Geotechnical engineering; Materials; Social systems / Social science; Stochastic process; Structures; Wind; etc.

Penny, R.K. (ed.) 90 5410 977 7
Risk, economy and safety, failure minimisation and analysis Failures '98 – *Proceedings of the third international symposium, Pilanesberg, South Africa, 6-10 July 1998*
1998, 25 cm, 380 pp., EUR 77.50 / $90.00 / £55
Contributions from 13 countries report recent research and development results as well as techniques and applications involved in many industries - from power generation and petrochemical installations, to water distribution systems, power connections and vehicles. In these, metallic, nonmetallic and shape memory alloy materials are involved. It will be essential reading for owners of plant and others concerned with rational asset management.

Beynon, J.H., M.W.Brown, T.C.Lindley,
R.A.Smith & B.Tomkins (eds.) 90 5410 969 6
Engineering against fatigue – *Proceedings of an international conference, Sheffield, 17-21 March 1997*
1999, 25 cm, 740 pp., EUR 105.00 / $120.00 / £75
Topics: The mechanics and materials approach to fatigue problems in engineering; Materials aspects of fatigue; Threshold stress range for short crack growth; Fatigue strength assessment of AlSi7Mg castings; Micromechanical modelling of fatigue in nodular cast iron; Direct observation of the formation of striations; Fatigue fracture toughness of steels; A model for multiaxial small fatigue crack growth; Evaluation of fatigue life prediction under ideal circumstances; Compression fatigue damage in notched CFRP laminates; Surface roughness and crack initiation in fretting fatigue; Initiation, growth and branching of cracks in railway track; Prevention of fatigue by surface engineering; Atmospheric influence on fatigue crack propagation; etc.

Stewart, M.G. & R.E.Melchers (eds) 90 5410 958 0
Integrated risk assessment: Applications and regulations – *Proceedings of the international conference, Newcastle, Australia, 7-8 May 1998*
1998, 25 cm, 148 pp., EUR 70.50 / $82.00 / £50
The book describes methods for integrated risk assessments, and important and novel applications. Regulatory aspects provide a central theme to the book, particularly the way these are likely to develop in the foreseeable future. Engineers, scientists, regulatory authorities and other practitioners will gain valuable insights in trends in regulatory requirements, practical implementation of AS/NZS 4360-1995,, quantitative/probabilistic risk assessments and environmental risk assessments. These topics are related to the design, construction and operation of chemical and process plants, petrochemical facilities, nuclear facilities and other potentially hazardous installations.

Gorokhov, E.V. & V.P.Korolev 90 5410 731 6
Durability of steel structures under reconstruction
1999, 25 cm, 320 pp.,
EUR 70.00 / $82.00 / £49 (No rights India)
Translation of 'Dolgovechnosti stal'nikh konstrukstii v usloviyak rekonstruktsii', Moscow 1997. The book provides a fairly condensed description of extant requirements for selecting materials and protective coatings in relation to the degree of aggressiveness of the environment. Considerable attention is given to the physical and chemical aspects for corrosion damage and physical and statistical principles of computing the indexes of reliability and durability of steel structures in corrosive media. The analytical approach to prediction of corrosive damage of structural form developed and presented in this monograph was substantiated by accelerated and bench corrosion tests as well as by the voluminous data collected during studies of actual performance of structures in various countries. Contents: Requirements for protecting steel structures against corrosion; Systems analy£