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STOCHASTIC ASSESSMENT OF STRUCTURAL SYSTEMS SUBJECT TO RANDOM VECTOR OF COMBINED LOADS

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Abstract

In this paper, the reliability assessment of structural system (a pipeline) subject to a combination of loads described as random Markov processes is presented. This method assumes the ability of constructing admissible areas in the load space with respect to different limit states. The method is applied to a segment of an above ground oil pipeline with surface corrosion type defects subjected to a combination and simultaneous action of four loads: dead weight of the pipe with insulation and oil being pumped; operating pressure; wind load and exposure to a uniform wall thickness thinning. The pipeline is considered as a continuous multi-bay thin wall cylindrical beam. The pipeline design is performed according to the (conditional) limit state which is reached when the equivalent stresses in pipe wall reach the yield stress of the pipe material. The specifics of the developed approach are that it splits the task of evaluating the reliability into two independent tasks, namely, constructing admissible areas in load space, and assessment of the probability of escape of the vector load from the admissible region.

Keywords: Markovian approach; reliability assessments; random loads; structural systems; pipelines.

The problem of load combination is of great significance in structural analysis, whereby the loads are traditionally considered as constants and probably because of safety, it is taken as the maximum values, and this inputted in the design codes. The loads are rather to be considered as having a stochastic nature. For example, Figures 1 and 2 are schematic illustrations of a continuous random load process and the potential exceedance of the deteriorating structural resistance, and typical outcrossing event in structural resistance space.

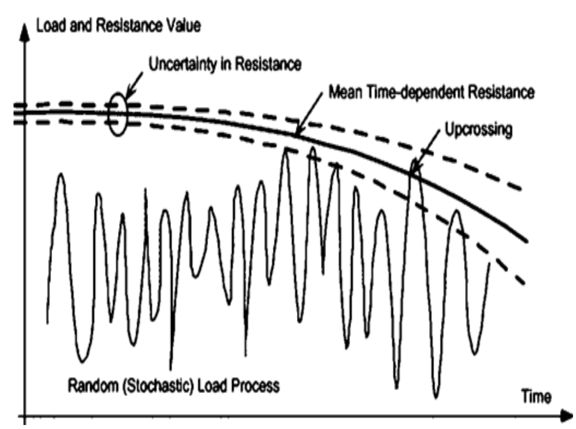

Figure 1: Realization of a continuous random load process Q(t) and the potential exceedance of the deteriorating structural resistance R(t) – Melchers, 1987, 1999 & 2005

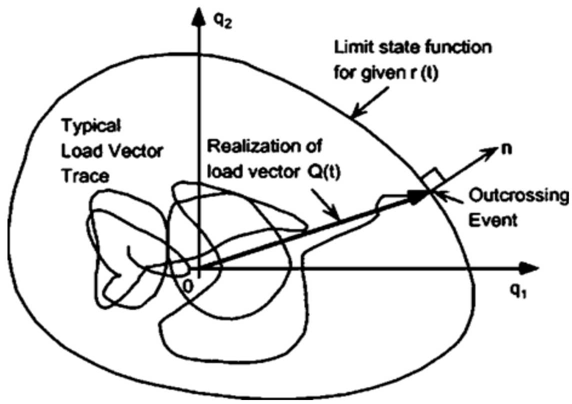

Figure 2: Typical outcrossing event in structural resistance space r(t) – Melchers, 1987, 1999 & 2005.

Reliability analysis of structural systems (such as pipeline) subject to random vector of combined loads using Markovian approach is presented in this work, where external forces are described by non-differentiable processes or when the problem requires calculations of the probabilities of processes up crossing low levels – such as when dealing with combination of random loads (Timashev, 1982; Timashev, et al., 2016; Opeyemi et al., 2015a, 2015b and 2016). An advantage of this approach is that the essence of the problem is simple to interpret and dramatic. The structural engineer will be aware of the quality criteria that are the most stringent, and the elements that do not participate in the formation of the admissible regions, even before reliability function computation.

Materials and Methods

Markovian Approach: Basic theorem

Suppose a structure is subject to a system of external loads q1(t), I = 1,…,n described as non-differentiable random processes, the reliability analysis can be estimated by using Markovian processes theory.

Consider the reliability analysis of engineering structures and systems when it is subjected to two vector-type loads, which is regarded as combination of loads. The probabilities $P_{ij}(t)$ of a process dwelling in a fixed state, when the two vector-type loads are represented as independent Markovian non-stationary homogeneous processes of Birth and Death type, can be calculated as a system of differential equations for the probability (see e.g., Gnedenko et al., 1965; Timashev, 1982) as:

$$P_{ij} = P[q_1(t) = i; q_2(t) = j] \quad (1)$$

$$\frac{d}{dt}P_{ij}(t) = -(\lambda_i + \mu_i + \lambda'_j + \mu'_j)P_{ij}(t) + \lambda_{i-1}P_{i-1,j}(t) + \mu_{i+1}P_{i+1,j}(t) + \lambda'_{j-1}P_{i,j-1}(t) + \mu'_{j+1}P_{i,j+1}(t) \quad (2)$$
$$i, j = 0.1,\ldots;\ \lambda_{-1} = \mu_0 = 0;\ \lambda'_{-1} = \mu'_0 = 0$$

The intensities of Birth λ_i and Death μ_i in this case depend only on the process $q_1(t)$, while the intensities λ'_j and μ_j depend on the process $q_2(t)$ only.

Subsequently, and without loss of generality, the initial conditions for the system in Equation (1) may be taken as:

$$P_{0.0} = 1;\ P_{ij}(0) = 0;\ i,j = 1,2,\ldots \quad (3)$$

Let's assume a region Ω with a boundary Γ is singled out in space $[q_1, q_2]$ and an auxiliary process $\bar{q}$ (t) is introduced such that $\bar{\lambda}_i=\lambda_i, \bar{\mu}_j=\mu_j, \bar{\lambda}_j=\lambda'_j$ and $\bar{\mu}_j=\mu_j$ in points $(i,j)\in\Omega$ and $\bar{\lambda}_i=\bar{\mu}_i=\bar{\lambda}_j=\bar{\mu}_j=0$ if points $(i,j)\in\Gamma$ which is the boundary that is an absorbing one, then the probability of not leaving the region Ω by the process $\bar{q}$ (t) will be equal to:

$$R(t) = \sum_{i=0}^{m-1}\sum_{j=0}^{n}\bar{P}_{i,j}(t) \quad (4)$$

The system of differential equations satisfied by $\bar{P}_{i,j}$ (t) is written thus:

$$\frac{d}{dt}\bar{P}_{ij}(t) = -\left(\bar{\lambda}_i + \bar{\mu}_i + \bar{\lambda}'_j + \bar{\mu}'_j\right)\bar{P}_{ij}(t) + \bar{\lambda}_{i-1}\bar{P}_{i-1,j}(t) + \bar{\mu}_{i+1}\bar{P}_{i+1,j}(t) + \bar{\lambda}'_{j-1}\bar{P}_{i,j-1}(t) + \bar{\mu}'_{j+1}\bar{P}_{i,j+1}(t) \quad (5)$$
$$\bar{\lambda}_{-1} = \bar{\mu}_0 = 0;\ \bar{\lambda}'_{-1} = \bar{\mu}'_0 = 0$$

The probability of the process q(t) not leaving the region Ω is equal to the probability of the process $\bar{q}$ (t) staying within the region Ω at a moment of time t, is clearly reflected in Equation (4).

The probabilities of the process $q_1(t)$ $[q_2(t)]$ at a moment of time t are in the i(j) provided the state m_j (n_i) is an absorbing one for it is denoted as:

$$P_i^{(m_j)}(t); i = 0,1,\dots,m_j; P_j^{(n_i)}(t); j = 0,1,\dots n_i \qquad (6)$$

Likewise, the corresponding systems of differential equations for estimating these probabilities are:

$$\left.\begin{aligned} & dP_i(t)/dt = -(\bar{\lambda}_i + \bar{\mu}_i)P_i(t) + \bar{\lambda}_{i-1}P_{i-1}(t) + \bar{\mu}_{i+1}P_{i+1}(t), \\ & i = 0,1,\dots,m_j; \bar{\mu}_0 = 0, \bar{\mu}_i = \mu_i, \bar{\lambda}_i = \lambda_i; \\ & i = 0,1,\dots,m_{j-1}; \bar{\lambda}_{m_i} = \bar{\mu}_{m_i} = 0; \\ & P_0(0) = 1; P_i(0) = 0; i = 1,2,\dots,m_j. \end{aligned}\right\} \qquad (7)$$

$$\left.\begin{aligned} & \frac{d}{dt}P_j(t) = -\left(\bar{\lambda}_j + \bar{\mu}_j\right)P_j(t) + \bar{\lambda}_{j-1}P_{j-1}(t) + \bar{\mu}_{j+1}P_{j+1}(t), \\ & i = 0,1,\dots,n_i; \bar{\mu}_0 = 0, \bar{\mu}_j = \mu_j; \bar{\lambda}_j = \lambda_j; \\ & j = 0,1,\dots,n_{i-1}; \bar{\lambda}_{n_i} = \bar{\mu}_{n_i} = 0; \\ & P_0(0) = 1, P_j(0) = 0, j = 1,2,\dots,n_i. \end{aligned}\right\} \qquad (8)$$

Timashev, 1982 solved the problem of deriving a system of bilateral estimates for reliability function R(t) based on solutions of simplified systems of differential equations in Equations (2), (5), (7) and (8). Comprehensive details and notes on the Markovian theories and approaches can be found in literature.

Consider the following relation $\tilde{P}_{i,j} = P_i^{(m_i)}(t).P_j^{n_i}(t)$ in the light of an intermediate theorem as a proof (Lemma). For a region Ω which is such that $m_j \geq m_{j+1}$; $n_i \geq n_{1+1}$; $i=0,1,\dots,m_0-1$; $j=0,1,\dots,n_0-1$ and any moment of time t > 0

$$H(t) = \sum_{i=0}^{m_j-1}\sum_{j=0}^{n_i-1} h_{i,j}(t) \leq 0 \qquad (9)$$

$h_{i,j}$ (t) are errors for an arbitrary point $(i,j) \in \Omega$ arising from substituting $\tilde{P}_{i,j} = P_i^{(m_i)}(t).P_j^{n_i}(t)$ into Equation (4); calculated as:

$$\begin{aligned} h_{i,j}(t) = {} & \bar{\lambda}_{i-1}P_{i-1}^{m_i}(t)\left[P_j^{n_i}(t) - P_j^{n_{i-1}}(t)\right] + \bar{\mu}_{i+1}P_{i+1}^{m_i}(t)\left[P_j^{n_i}(t) - P_j^{n_{i+1}}(t)\right] + \\ & \bar{\lambda}_{j-1}P_{j-1}^{n_i}(t)\left[P_i^{m_i}(t) - P_i^{m_{i+1}}(t)\right] + \bar{\mu}_{j+1}P_{j+1}^{n_i}(t)\left[P_i^{m_i}(t) - P_i^{m_{i+1}}(t)\right] \end{aligned} \qquad (10)$$

Based on the foregoing, the highlighted theorems below are true, and hold based on the conditions of the lemma in permission of the construction of bilateral approximates for the reliability function.

For a region Ω, there exists a time *T*, finite or infinite and that t < *T* such that $m_j \geq m_{j+1}$; $n_i \geq n_{1+1}$; $i=0,1,\dots,m_0-1$; $j=0,1,\dots,n_0-1$. The reliability function R_1 (t) estimate can be calculated from the expression:

$$R_1(t) = \sum_{i=0}^{m_j-1}\sum_{j=0}^{n_i-1} P_i^{m_i}(t)P_j^{n_i}(t) = \sum_{i=0}^{m_j-1}\sum_{j=0}^{n_i-1} P_{i,j}^{\sim}(t) \qquad (11)$$

This estimate is not larger than the true reliability function R (t) i.e., R1 (t) ≤ R (t).

Following the conditions of the previous theorem above.

R (t) ≤ R_2 (t) holds for any t > 0. R (t) is the true reliability function, and R_2 (t) is thus estimated as:

$$R_2(t) = \sum_{i=0}^{m_j-1}\sum_{j=0}^{n_i-1} P_i^{m_0}(t)P_j^{n_0}(t) \qquad (12)$$

In the condition where R_3 (t) ≤ R_1 (t), R_1 (t) is calculated using Equation (11), and R_3 (t) is estimated as:

$$R_3(t) = \sum_{i=0}^{m_0-1} P^{n_i}(t)\left[P^{n+1}(t) - P^i(t)\right] \qquad (13)$$

Given that.

$$\left.\begin{aligned} & P^{i+1}(t) = \sum_{k=0}^{i} P_k^{i+1}(t) \\ & P^{n_i}(t) = \sum_{j=0}^{n_i-1} P_j^{n_i}(t) \end{aligned}\right\} \qquad (14)$$

The probability $R_3(t)$ is the sum of the products of the probability that within the time t the $q_1(t)$ will at least once cross the level *i* but never cross the level *i*+1 by the probability that during the time t the process $q_2(t)$ will not cross the corresponding level n_i. To obtain $R_3(t)$, it will be sufficient if the probabilities that $q_1(t)$ and $q_2(t)$ processes will not cross the arbitrary levels are known. This information (see e.g., Gnedenko et al., 1965; Barucha-Rheid, 1969) are made available through the distribution of maxima within the time t for the processes $q_1(t)$ and $q_2(t)$.

In the case of more than two vector-type loads, the results obtained from the first two theorems may be generalized. So, for an *r*-

dimensional load, the expressions for $R_1(t)$, $R_2(t)$, and $R_3(t)$ will assume the form:

$$R_1(t) = \sum_{i_1=0}^{n_1-1}\sum_{i_2=0}^{n_2-1}\cdots\sum_{i_r=0}^{n_r-1} P_{i_1}^{n_1}(t)P_{i_2}^{n_2}(t)\ldots P_{i_r}^{n_r}(t) \qquad (15)$$

$$n_i = n_1(i_2,i_3,\ldots,i_r);\, n_2(i_2,i_3,\ldots,i_r);\ldots;\, n_r = n_r(i_2,i_3,\ldots,i_r);\, r = 2,3\ldots \qquad (16)$$

The probability $P_{i,j}^{n_i}$ *characterizes the component* x_t *of the process* $\overline{Z}(t) = [x_1(t),\ldots x, r(t)]$

$$R_1(t) = \sum_{i_1=0}^{n_1-1}\sum_{i_2=0}^{n_2-1}\cdots\sum_{i_r=0}^{n_r-1} P_{i_1}^{n_1^0}(t)P_{i_2}^{n_2^0}(t)\ldots P_{i_r}^{n_r^0}(t) \qquad (17)$$

$$n_1^0 = n_1(0,0,\ldots,0);\, n_2^0 = n_2(0,0,\ldots,0);\, n_r^0 = n_r(0,0,\ldots,0) \qquad (18)$$

$$R_3(t) = \sum_{i_1=0}^{n_1-1}\left\{\left[P^{i_1+1}(t) - P^{i_1}(t)\right]\left\{\sum_{i_2=0}^{n_2-1}\left[P^{i_2+1}(t) - P^{i_2}(t)\right]x\ldots x\right.\right.$$
$$\left.\left.\sum_{i_{r-1}=0}^{n_{r-1}-1}\left\{\left[P^{i_r+1}(t) - P^{i_{r-1}}(t)\right]P^{n_r}(t)\right\}\right\}_{r-1} \{\ldots\} \qquad (19)$$

$$n_2 = n_2(i_1);\, n_3 = n_3(i_1,i_2);\ldots;\, n_r = n_r(i_1,i_2,\ldots,i_{r-1}) \qquad (20)$$

Similarly, $P^k(t)$ *specifies* $x^k(t)$

Equation (15) can be modified for a specialized case, when the last *r*-th coordinate of the *r*-dimensional process is a Poisson process for which the probability $P_{i_r}^k(t)$ is independent of the absorbing state, to the form:

$$R_1(t) = \sum_{i_r=0} P_{i_r}(t)\sum_{i_1=0}^{n_1-1}\sum_{i_2=0}^{n_2-1}\cdots\sum_{i_r=0}^{n_r-1} P_{i_1}^{n_1}(t)P_{i_2}^{n_2}(t)\ldots P_{i_{r-1}}^{n_{r-1}}(t) \qquad (21)$$

In practice when multidimensional random process is encountered in which only some components are Markovian Birth and Death processes; the reliability function R(t) can be estimated by synthesizing Equations (15) and (19).

Let $z(t)=[x_1(t),\ldots,x_r(t)]$ be an *r*-dimensional random process and K coordinates of the process z(t) be Markovian Birth and Death process. These components may be assumed to be $x_{r-k-1}(t),\ldots,x_r$, whereby the reliability function may be written as:

$$R(t) = P[z(t)\in D^r \mid 0\leq t\leq T] \qquad (22)$$

r is the dimension of the region *D.*

From Equations (15) and (19);

$$R(t) = \tilde{R}(t) = \sum_{i=0}^{n-1}\left\{\left[P^{i+1}(t) - P^{i}(t)\right]\right\} x \left\{\sum_{i=0}^{n-1}\left[P^{i+1}(t) - P^{i}(t)\right]\right\}\ldots\left\{\sum_{i_{r-k}=0}^{n_{r-k}-0}\left[P^{i_{r-k}+1}(t) - P^{i_{r-k}}(t)\right]\right\}_{r-k-1}\{\ldots\}x$$
$$P\{Z_k(t)\in D^r \mid 0\leq t\leq T\} \qquad (23)$$

A *k*-dimensional Markovian process is denoted by $Z_k(t)=[x_{r-k-1}(t),\ldots,x_r(t)]$; $D^k=D^k_{ii,\ldots iK}$ is a K-dimensional quality space region depending on the values of $i_1,\ldots, i_{r-k}$.

$$P\{Z_k(t)\in D^r \mid 0\leq t\leq T\} \qquad (24)$$

Equation (24) is the probability that the *K*-dimensional Markovian process will never extend beyond the region D^k within the time $t\in[0,T]$.

This also can be calculated using Equation (15). Estimate from the combination of Equations (15) and (19) is trivial/cumbersome compared to Equation (19). Reliability function estimates from Equation (23) is closer to the true value than the one obtained in Equation (19).

An explicit description of the numerical models used in this research work has been outlined and explained in detail. The numerical modelling which employs the theoretical and computational frameworks forms the major approaches for the solutions to the problem statement of the need for reliability and maintenance of structures under severe uncertainty as a key issue in ensuring a faultless life of engineering structures and systems despite fluctuations and changes of structural and environmental parameters and conditions. Extension to the previous works through inclusion of imprecise mean values, interval analysis, probability bounds, and Markovian description on the modelling of the deterioration phenomena and loads has been reported. Through scientific studies and understanding of the phenomena (fatigue cracks and corrosion), provision for a reliable and set guideline has been outlined by appropriating simplification of reality.

General case

In a general case, the reliability assessment of structural systems subject to random vector of combined loads can be estimated following the steps below:

Schematization of the structural (e.g.,

pipeline) system: selecting the input parameters space Q and the output parameter space U; such that introduction of system operator is inculcated as: Lu = q; $\in U, q \in Q$

The elements are singled out in the operator: in operator L, the elements x, x_o, x_s are singled out; where x, x_o are the elements of K and K_o spaces respectively of determinate properties of the system which are/are not subject to optimization; x_s is the elements of space K_S of those properties of the system which are stochastic in nature.

Solution of inverse problem of mechanics: the determination of the permissible subspace V in the space U, and the admissible region $\Omega_o(x_C)$ in the space Q

The system conditional reliability: estimation of the conditional reliability of the system, as:

$$R_c(t) = P[q(\Gamma) \in \Omega_c(x_C), 0 \leq \Gamma \leq t] \quad (25)$$

Finally, the total full reliability is calculated as:

$$R(t) = \int_{\chi_C} \ldots \int R_C(t) f(\chi_C) d\chi_0 \quad (26)$$

The admissible region of the reliability problem solved in the load space is constructed according to the equation.

$$V_* = H(q, X_c) \quad (27)$$

V_* is the ultimate permissible value of the quality of vector of the system, H is the inverse to operator L.

Example Applications

Consider a segment of a real above ground oil main pipeline, parameters of which are given in Table 1.

Table 1: Design parameters of an oil pipeline

Transported substance	Crude oil
Oil density	8637 kg/m^3
Pipe outlay	Above ground
Outside Diameter of Pipe	1.020m
Pipe material	Class X60: UTS = 590MPa and SM 460MPa
Steel density	7.85x10^3 kg/m^3
Pipe wall thickness	0.016m
Operating Pressure	7.5MPa
Design temperature	+20°C
Temperature at pipeline ou	– 32°C
Insulation	Epoxy anti corrosion insulation, spir coated folded pipe insulation shell thick. The insulation proper thickn 100mm
Young modulus	2.06x10^5 MPa
Linear expansion coefficien	1.2x10^{-5} 1/°C
Poisson coefficient: a) for elastic performanc metal b) for plastic performanc metal	0.3 0.5

The considered segment has six (6) spans which lengths are: L_1 = 17m, L_2 = 18m, L_3 = 16m, L_4 = 18m, L_5 = 15m, and L_6 = 18m. For simplicity's sake it is assumed that both ends of the oil pipeline segment are rigidly fixed (which creates an error in pipe strength assessment on the safe side). The oil pipeline scheme is given in Fig. 3.

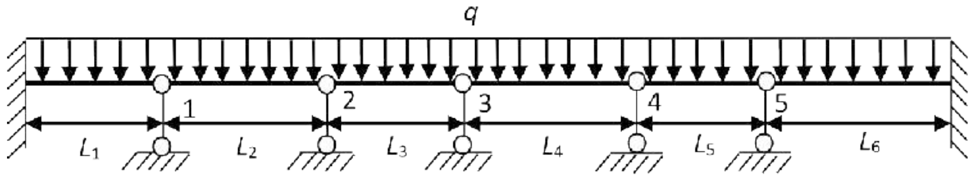

Figure 3: Design scheme of the oil pipeline segment.

from $\sigma_{c,\lim} = \max\{\sigma_{c,1}; \sigma_{c,2}\}$. These stresses are reached when the bending stresses are:

In the extension zones of the oil pipeline segment:

σ_u = 588.84MPa; and

In the compressed zones of the oil pipeline segment:

σ_u = 239.12MPa

The ultimate values of the sum of axial stresses from $\sigma_{i,\lim} = \frac{\sigma_c \pm \sqrt{4[\sigma]^2 - 3\sigma_c^2}}{2}$ are:

$\sigma^{+}_{i,\lim}$ = 529.76MPa

$\sigma^{-}_{i,\lim}$ = -298.20MPa

Thus, we have four roots of the two limit state equations, which are pairwise equal but are opposite in signs. Therefore, from two roots of one limit state (e.g., first one) we need to select the minimum value of the absolute value, i.e., the bending stress, which is created by the minimal ultimate bending moment:

From

$$\sigma_{u,\lim} = \min\left\{\left|\sigma_u^{(1)}\right|, \left|\sigma_u^{(2)}\right|\right\};$$

$$M_{\lim} = \sigma_{u,\lim} W.$$

The moments which correspond to these bending stresses are correspondingly equal to 7458923.77Nm and 3029073.30Nm. Then the ultimate bending moment is equal to the minimal moment, M_{lim} = 3029073.30Nm.

The ultimate permissible displacement of the support 3 is found to be 16.5 cm.

Several curves of moments related to the displacement of support 3 equal to Δ=0, 5, 10, 15, 16.5 cm is given in Fig. 4.

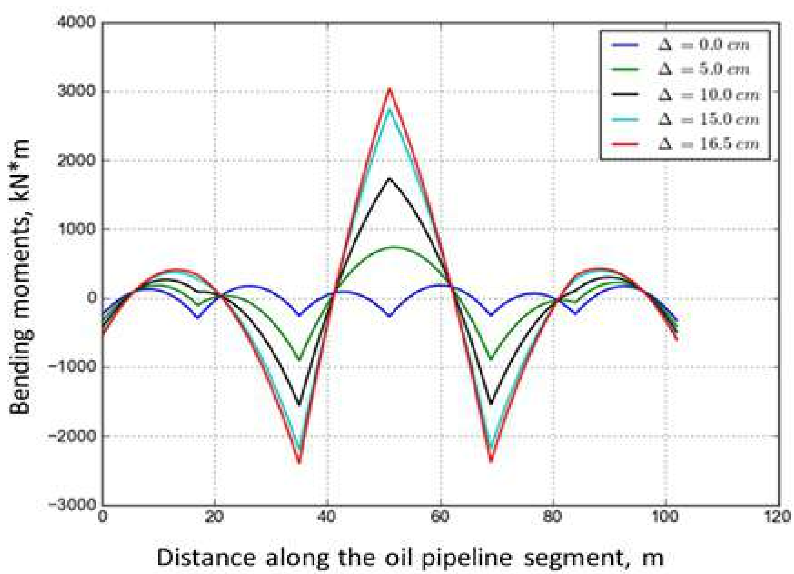

Figure 4: Bending moments for the oil pipeline segment.

For each value of support displacement, the ultimate defect depths were calculated considering their lengths (5 ultimate curves, shown in Fig. 5). According to this figure when the support displacement is equal to 15 cm and 16.5 cm the curves practically coincide, hence, in Fig. 5 they overlap.

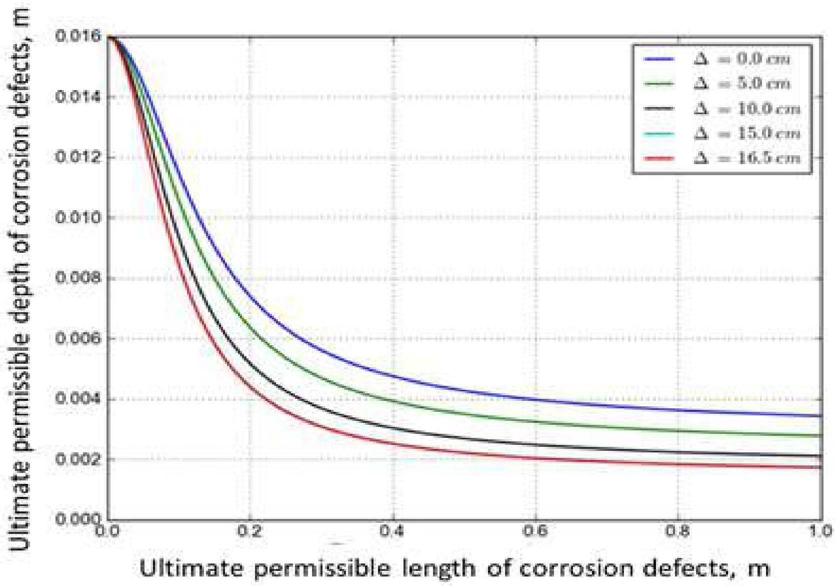

Figure 5: Ultimate permissible sizes of corrosion defects of the pipeline segment depending on the value of support displacement.

The ultimate bending moments for the wind load, depending on the displacement of support 3 are given in Fig. 6. The values of the horizontal wind load, at which ultimate value of the bending moment is reached, depending on the value of the displacement of the support 3, are shown in Fig. 7.

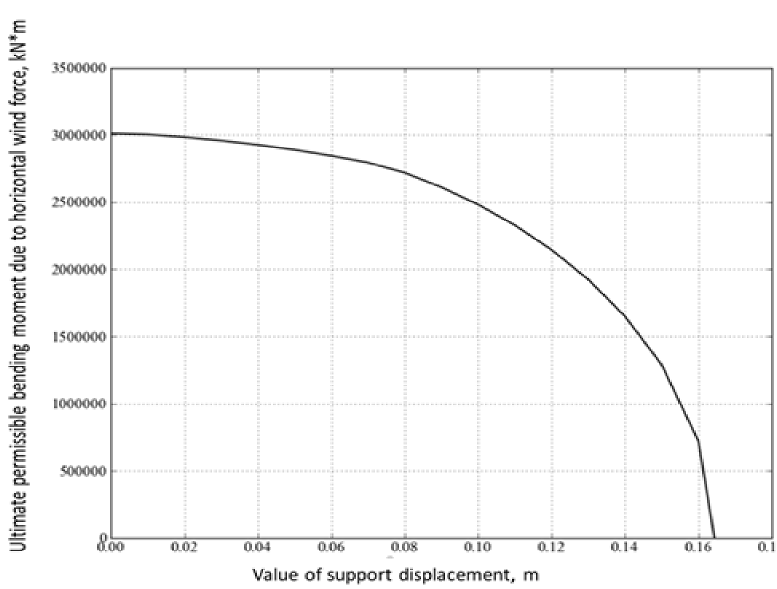

Figure 6: Ultimate permissible moment due to horizontal wind force depending on the value of support displacement.

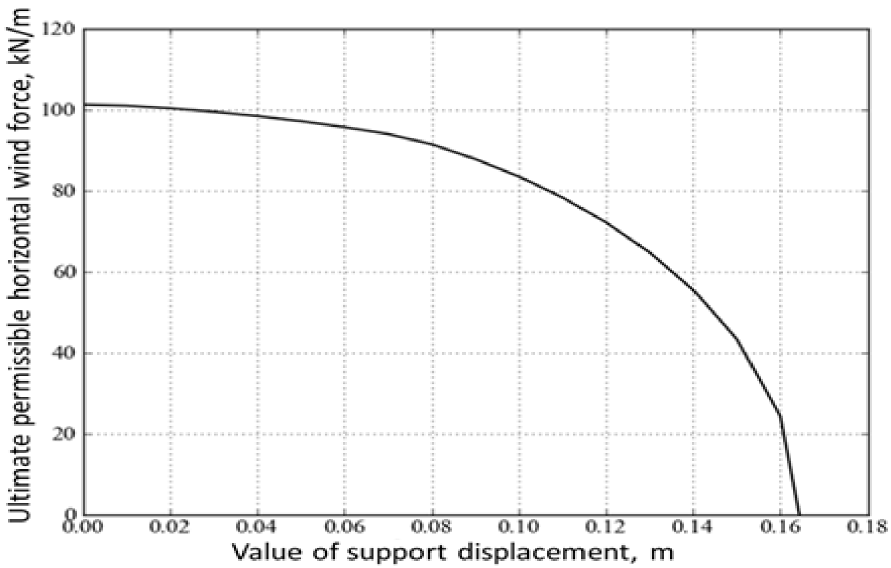

Figure 7: Ultimate sizes of defects of a pipeline segment depending on the value of support displacement.

Conclusion

The method of assessing reliability of structural systems subject to random vector of combined loads considering above-ground oil field collection and main pipelines is presented. The application of the Markovian approach for reliability analysis of above ground oil pipelines with surface corrosion defects subjected to a combination of loads has been employed. The advantage of this approach is that it will allows easy visualization and interpretation of the essence of the problem in consideration. Indeed, even before starting solving the reliability problem it will be glaring to the engineer which pipeline quality criteria are the most restrictive, and which elements of the system are not participating in constructing the admissible region in the space of loads. This will permit singling out elements with excessive reliability, and to formulate structural means for decreasing their reliability to the level which does not impede the overall reliability of the system.

The specifics of the developed approach are that it splits the task of evaluating the reliability into two independent tasks:

constructing admissible areas in load space assessment of the probability of escape of the vector load from the admissible region.

In this formulation, the dimension of the problem is not the product of the number of defects on the number of loads in combination, but just the number of loads, which allows overcoming the curse of dimensionality.

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