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PROBABILISTIC CALCULATION OF FATIGUE CRACK PROGRESSION USING FCPROBCALC CODE

PRAVDĚPODOBNOSTNÍ VÝPOČET ŠÍŘENÍ ÚNAVOVÉ TRHLINY S VYUŽITÍM PROGRAMU FCPROBCALC

Abstract

The paper gives examples of the probabilistic assessment of a steel cyclic loaded structure. Fatigue progression of the cracks from the edge and from the surface is used as a basis for proposing a system of inspections of details which tend to be damaged by fatigue. The newly developed method Direct Optimized Probabilistic Calculation (DOProC method) was used for solution. The method was applied in FCProbCalc software.

Keywords

Direct Optimized Probabilistic Calculation, DOProC, Safety Margin, Probability of Failure, Fatigue Crack Progression, Inspection of Structure, Random Variable.

Abstrakt

Příspěvek je zaměřen na jeden z možných způsobů posouzení spolehlivosti cyklicky namáhané ocelové konstrukce s ohledem na vznik únavových trhlin z okraje a povrchu, které vede k návrhu systému prohlídek konstrukčních detailů náchylných na únavové poškození. Pro řešení pravděpodobnostní úlohy byla použita nově vyvíjená metoda Přímého Optimalizovaného Pravděpodobnostního Výpočtu (zkráceně POPV), implementovaná do programu FCProbCalc.

Klíčová slova

Přímý Optimalizovaný Pravděpodobnostní výpočet, POPV, funkce spolehlivosti, pravděpodobnost poruchy, šíření únavové trhliny, prohlídka konstrukce, náhodná proměnná.

1 INTRODUCTION

Many calculation methods exist now for the designing and reliability assessment of load-carrying structures and elements with the specified reliability. Those methods are based on the probability theory and mathematic statistics. They have been becoming more and more popular. The methods which are referred to as probabilistic ones make it possible to analyze a reliability reserve defined by a calculation model where at least some input quantities are of a random nature. The calculation procedures contribute to a qualitatively higher level of the reliability assessment and, in turn, higher safety of those who use the buildings and facilities.

The probabilistic approach to the assessment and designing of the structures has started appearing in practice recently only. The pre-requisite is, however, a sufficient database of input quantities including the experience from practical operation because many input quantities cannot be

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based on models and laboratory measurements only (this being the case, for instance, of geotechnics, see [4]). Those computational methods are used, in particular, when designing the load-carrying systems for underground structures where degradation processes in structures can be also taken into account [8, 13]. It is possible to carry out the Performance-Based Design the result of which is structures which consider utility values such as durability, fire resistance, insulation or seismic resistance [9]. The probabilistic approach is used also in risk engineering [14].Stochastic models are being developed which describe interaction of building structures with subsoil or overlying rock in tunnels [17]. Such models are based also on sensitivity analyses of input random quantities [7].

This paper deals with the use of the Direct Optimized Probabilistic Calculation ("DOProC"), the theoretical basic of which has been described in several publications, for instance [3, 21] and which has been applied e.g. in ProbCalc [2] or Anchor [4]. DOProC is used typically for probabilistic tasks where certain input quantities are of a random nature and can be described by stochastic non-parametric (empirical) or parametric distributions. DOProC is used mainly in the probabilistic reliability assessment of load carrying structures. DOProC can be also employed in probabilistic designs of structural elements with the specified reliability. In many cases, this calculation method is very efficient and provides accurate estimates of the probabilities. Only a calculation error and an error resulting from discretizing of input and output quantities are involved there. A disadvantage is that much machine time is needed for calculation of the task because the task comprises rather many random quantities which are discretized by rather many intervals/classes. This means, optimizing techniques should be used then to reduce the machine time needed for the calculation and maintaining, at the same time, correctness of the solution [3].

DOProC has been successfully applied, among others, in the probabilistic calculation of fatigue cracks in steel structures and bridges which are subject to cyclical loads. The software used for that purpose, FCProbCalc [12], makes it possible to monitor efficiently and operatively development of fatigue damage to the structure and to specify times for service inspection. This means, the structure is compliant and well suited for operation in terms of fatigue damage. The methods and application can considerably improve estimation of maintenance costs for the structures and bridges subject to cyclical loads.

2 USING DOPROC TO CALCULATE PROPAGATION OF FATIGUE CRACKS

Reliability of the load-carrying structure has been significantly influenced by degradation resulting, in particular, from the fatigue of the basic materials. Linear fracture mechanics is among alternative methods which can detect failures and material defects. Findings and outcomes of the linear fracture mechanics have been gradually introduced and implemented into designs of the load-carrying structures in buildings [1]. In order to describe the propagation of the crack, the linear elastic fracture mechanics [6] is typically applied. This method uses Paris-Erdogan's law [22] in order to define the limit of propagation rate of the crack $\frac{\mathrm{d}a}{\mathrm{d}N}$ and swing of the stress rate factor, ΔK, in the face of the crack:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C.\Delta K^{m} \tag{1}$$

where C, m are material constants, a is the crack size and N is the number of loading cycles. The fatigue crack will propagate in a stable way only if the initial crack a_0 exists in a construction detail which is subject to fatigue damage.

Deterministic calculation methods which are focused on rate of propagation of the crack have been supplemented by probabilistic methods which have taken into consideration uncertainties in determination in input variables. Modification of (1) and introduction of a relation between the stress swing and stress intensity factor result in the following cumulative effects of the load:

$$S = \int_{N_0}^{N} C.\Delta\sigma^m.\mathrm{d}N = C.\Delta\sigma^m.(N - N_0) \;, \tag{2}$$

where N is the total number of oscillations of stress peaks, $\Delta\sigma$, and N_0 is the number of oscillations in the time of initialization of the fatigue crack (typically, the number of oscillations is zero). R is a random variable resistance of the construction:

$$R_{(a_1)} = \int_{a_0}^{a_1} \frac{\mathrm{d}a}{\left(\sqrt{\pi.a}.F_{(a)}\right)^m} \;, \tag{3}$$

where $F_{(a)}$ is the calibration function which describes propagation of fatigue crack (e.g. from the edge or surface, [16]) and a_1 is the final length of the fatigue crack (it can be a_d = the size of the measurable fatigue crack or a_{ac} = the size of the permitted fatigue crack determined on the basis of strength criteria and size of the weakened cross-section of the load-carrying element).

If load effects, S, and resistance of the structure, R, are known, it is possible to determine the reliability function and the failure probability, P_f. A detailed description of theoretical background to the probabilistic calculation of propagation of a fatigue crack has been published in part, for instance, in [10, 20, 22, 23, 24]. This is closely related to exact definition of random phenomena which might occur in the construction in any time, "t", of the construction's service life:

- ***U***$_{(t)}$ **phenomenon:** No fatigue crack failure has not been revealed within the t–time and the fatigue crack size $a_{(t)}$ has not reached the detectable crack size, a_d . This means:

$$a_{(t)} < a_d \;, \tag{4}$$

- ***D***$_{(t)}$ **phenomenon:** A fatigue crack failure has been revealed within the t–time and the fatigue crack size $a_{(t)}$ is still below the acceptable crack size a_{ac}. This means:

$$a_d \le a_{(t)} < a_{ac} \;, \tag{5}$$

- ***F***$_{(t)}$ **phenomenon:** A failure has been revealed within the t–time and the fatigue crack size $a_{(t)}$ has reached the acceptable crack size a_{ac}. This means:

$$a_{(t)} \ge a_{ac} \;. \tag{6}$$

Once the probability of the three phenomena, U, D and T is determined, it is possible to specify the inspection times for the construction under assessment. Because it is not certain in the probabilistic calculation what the initiation crack size is and because other inaccuracies influence the calculation of the crack propagation, a special inspection is necessary to check the size of the measureable crack in a specific period of time ($a > a_d$).

The time for the first inspection of the construction, t_I, in terms of the fatigue crack in structural details in the load-carrying system which are most subject to fatigue crack (for instance, in places with the highest stress concentration) depends, in particular, on the calculated permissible dimension of the fatigue crack and determination of the failure probability, F, which will exceed, in the time of the first inspection time, the specified design probability, P_d. If no fatigue cracks are found during the inspection, the analysis of inspection results give conditional probability which can be expressed, using the law of complete probability (for details see [11]) , as follows:

$$P\left(F_{(T)} \middle| U_{(t_I)}\right) = \frac{P\left(F_{(T)}\right) - P\left(F_{(t_I)}\right) - P\left(D_{(t_I)}\right).P\left(F_{(T)} \middle| D_{(t_I)}\right)}{P\left(U_{(t_I)}\right)} \;, \tag{7}$$

where $T > t_I$. When the failure probability, P_f, this means the probability of occurring the F phenomenon, reaches the designed failure probability P_d, an inspection should be carried out in order to reveal fatigue cracks, if any, in the construction component. The inspection may result in one of the mentioned phenomena, U, D or F s, with corresponding probabilities. The entire calculation can be repeated in order to ensure well-timed inspections in the future. Theoretical background has been published in [5, 15, 18]. ProbCalc [2] has been used for several probabilistic studies, the objective being to determine the inspection system for the bridge construction [11].

ProbCalc [2] is intended, similarly, as Nessus [19], for probabilistic tasks and reliability assessments with an option to define generally a computational model. In specific probabilistic tasks, for instance, in probabilistic calculation of fatigue crack propagation, those software applications are less suitable because they are too general and less user friendly.

3 USING FCPROBCALC FOR THE PROBABILISTIC CALCULATION OF FATIGUE CRACKS

FCProbCalc has been developed using the aforementioned techniques. By means of FCProbCalc (Fatigue Crack Probability Calculation - [12], see Fig. 1), it is possible to carry out the probabilistic calculation of propagation of fatigue cracks in a user friendly environment. The cracks propagate from edges or surface and the goal of the probabilistic calculation is to determine the time for the first inspection which should reveal damage to the structure. If no fatigue cracks are found, the analysis of inspection results gives conditional probability during occurrence (7) and the time for future inspections.

In FCProbCalc, necessary input quantities can be determined deterministically or stochastically using non-parametric (empiric) and parametric probability distributions (see Fig. 1). If a period of time is specified, it is possible to determine load effects, *S,* pursuant to (2), resistance of the construction $R(a_d)$ and $R(a_{ac})$ pursuant to (3) as well as probability of elemental phenomena, *U*, *D* and *F*, pursuant to (4) through (6) which are the basis for specification of inspection times.

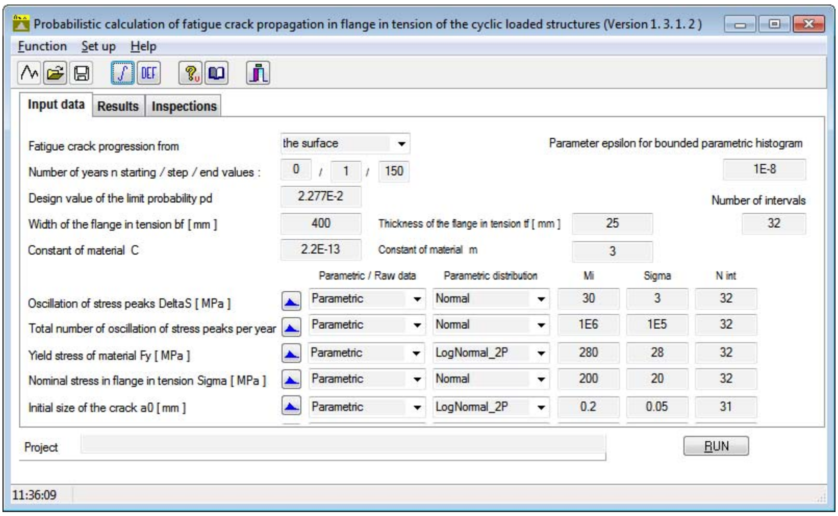

Fig. 1 FCProbCalc desktop – entry of input quantities.

FCProbCalc calculates the resistance of the building, *R*, in (3) using any of five methods based on numerical integration. Following methods are available:

- **The rectangular method** where the number of differences, *n*, can be chosen (the preset value: n = 1,000),
- **The Simpson method** where the number of differences, *n*, can be chosen (the preset value: n = 1,000),
- **The Romberg method** where *n* can be chosen (the preset value: n = 1,000),
- **The adaptive method** where the inaccuracy tolerance, tol_0, should be specified, (the preset value: $tol_0 = 1.10^{-4}$),

- **The Gauss quadrature** (in five points) where the interval a_0 (a_d through a_{ac}) is divided into three separate integrated sub-intervals in a relative range 0 through 0.01; 0.01 through 0.1 and 0.1 through 1

Other optional quantities which influence the probabilistic calculation are the number of intervals/classes, N, of each input quantity and ε which influences the method used for restriction of histograms with parametric distribution of probabilities (the preset value is ε = 1.10^{-8}: : the distribution is "truncated" then in a point where the probability equals to ε).

The reference probabilistic calculation in FCProbCalc included the probabilistic assessment of a steel/reinforced concrete bridge from [11] on the highway in a point where a longitudinal beam connects to a transversal beam. The taken input quantities were expressed both deterministically and stochastically (see Tables 1 and 2). Standard deviations of the first four random quantities in Table 1 are based on the variation coefficient equal to 10 %. In case of the initiation crack, a_0, and measurable crack, a_d, the parameters are based on [22]. The required reliability was expressed by the reliability index $\beta = 2$ which corresponded to the failure rate of $P_d = 0.02277$. The method used in the calculation was the Gauss quadrature of numerical integration with following parameters: number of intervals for the input quantities: $N = 200$, and $\varepsilon = 1.10^{-8}$. The calculation was carried out for fatigue cracks propagating from the border and surface and the goal was to determine times for inspections of the bridge construction.

Table 1: Overview of variable input quantities expressed in a histogram with parametric distribution of probabilities.

Quantity	*Parametric distribution*		
	Type	*Parameters*	
		Mean value	*Standard deviation*
Oscillation of stress peaks $\Delta\sigma$ [MPa]	Normal	30	3
Number of oscillation of stress peaks per year N [-]	Normal	10^6	10^5
Yield point f_y [MPa]	Lognormal	280	28
Nominal stress in the flange plate σ [MPa]	Normal	200	20
Initial size of the crack a_0 [mm]	Lognormal	0.2	0.05
Smallest measurable size of the crack a_d [mm]	Normal	10	0.6

Table 2: Overview of input quantities expressed in a deterministic way

Quantity	*Value*
Material constant m	3
Material constant C	$2.2.10^{-13}$
Width of the flange plate b_f [mm]	400
Thickness of the flange plate t_f [mm]	25
Designed probability of failure P_d	0.02277

Fig. 2 shows FCProbCalc desktops with icons for resulting partial quantities, the chart showing the failure probability, P_f, developing during years of operation as well as the calculated time for the first inspection.

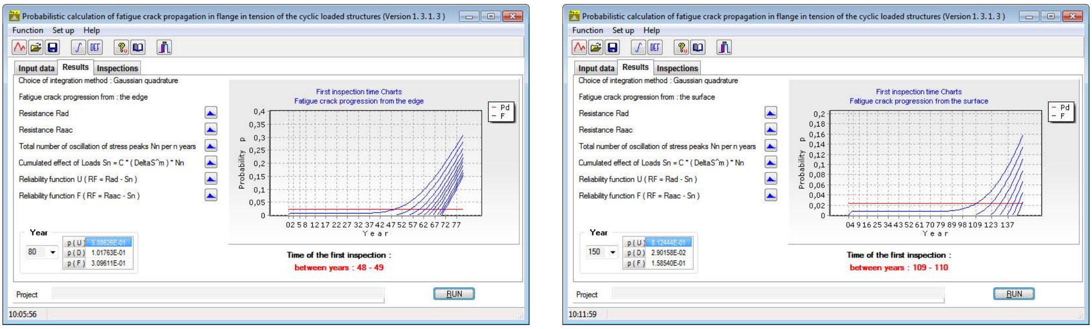

Fig. 2: FCProbCalc desktop with results of the probabilistic calculation of propagation of a fatigue crack from the edge (left) and from the surface (right), right), the Gauss quadrature with numerical integration is used, the number of intervals for the input quantities is $N = 200$.

Fig. 3, 4 and 5 show resulting histograms for load effects, S, as well as resistance of the structure during the first inspection, $R(a_d)$ and $R(a_{ac})$. The situation described there is propagation of a fatigue crack from the edge (left) or surface (right).

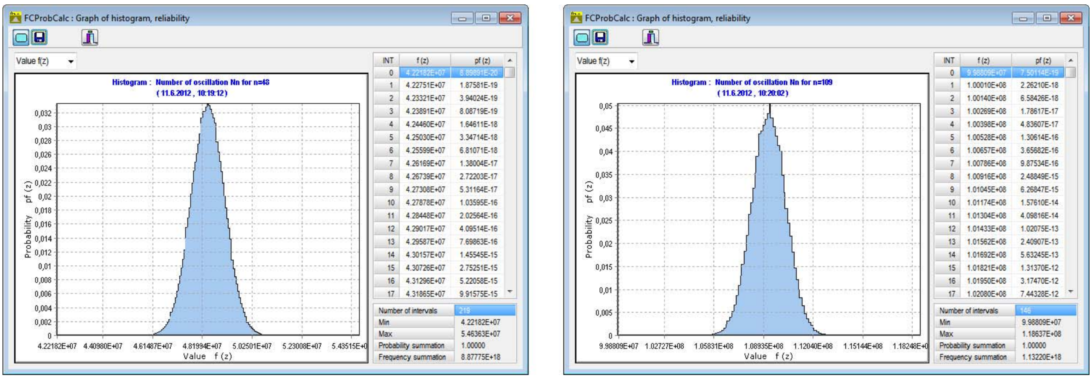

Fig. 3: Resulting histogram for the S load effects for a bridge structure after 48 years (left) and 109 year of operation (right)

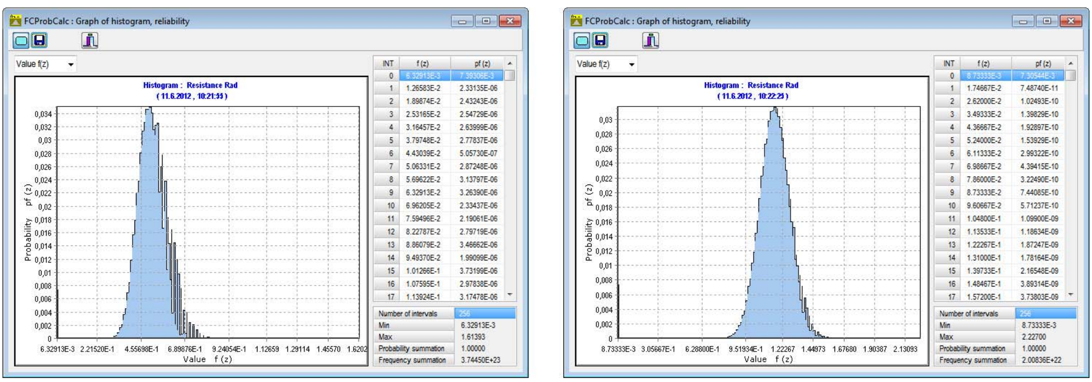

Fig. 4: Resistance histogram for the bridge structure, $R(a_d)$, subject to a fatigue crack from the edge (left) and from the surface (right), the Gauss quadrature with numerical integration is used, the number of intervals for the input quantities is $N = 200$.

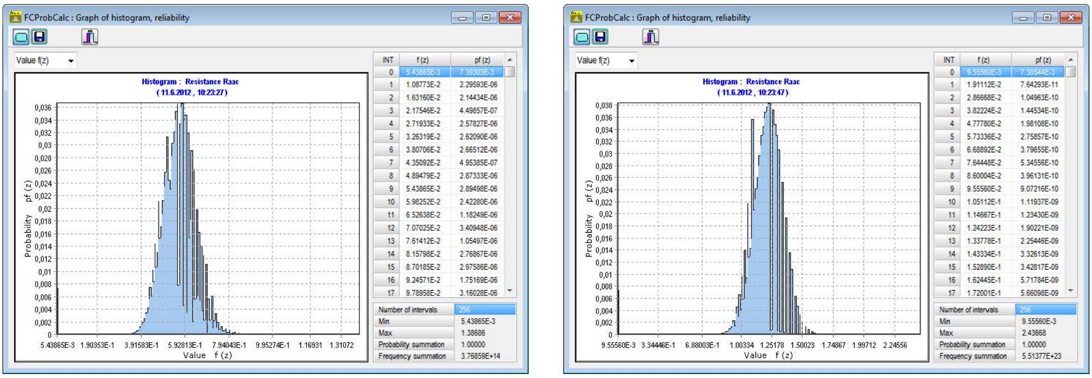

Fig. 5: Resistance histogram for the bridge structure, $R(a_{ac})$, subject to a fatigue crack from the edge (left) and from the surface (right), the Gauss quadrature with numerical integration is used, the number of intervals for the input quantities is $N = 200$.

Fig. 6 shows charts with calculated probabilities of the U, D and F resulting from (4) through (6) for both types of propagation of the fatigue crack (from the edge and surface).Those three phenomena represent the complete spectrum of phenomena that might occur in the t-time. This means:

$$P\left(U_{(t)}\right) + P\left(D_{(t)}\right) + P\left(F_{(t)}\right) = 1 \ , \tag{8}$$

which is clear from charts in Fig. 6.

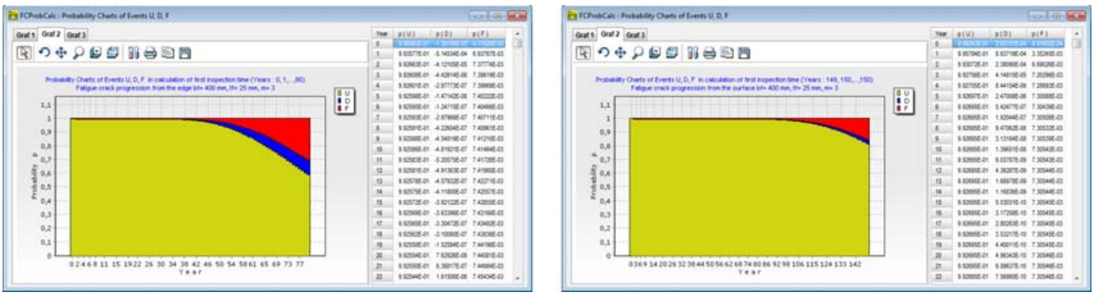

Fig. 6: Calculated probabilities of elemental phenomena, U, D and F, in a bridge construction subject to a fatigue crack from the edge (0 to 80 years, left) and from the surface (0 to 150 years, right), the Gauss quadrature with numerical integration is used, the number of intervals for the input quantities is $N = 200$.

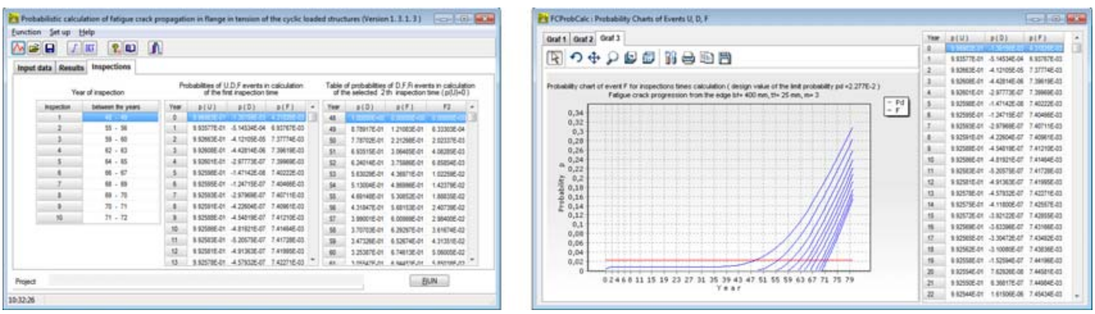

Fig. 7: Failure probability, P_f, depending on the years of operation of the bridge (0 to 80 years) in probabilistic calculation of propagation of a fatigue crack from the edge with the conditional probability being taken into account and determination of the time for the first and subsequent inspections of the bridge structure, the Gauss quadrature with numerical integration is used, the number of intervals for the input quantities is $N = 200$.

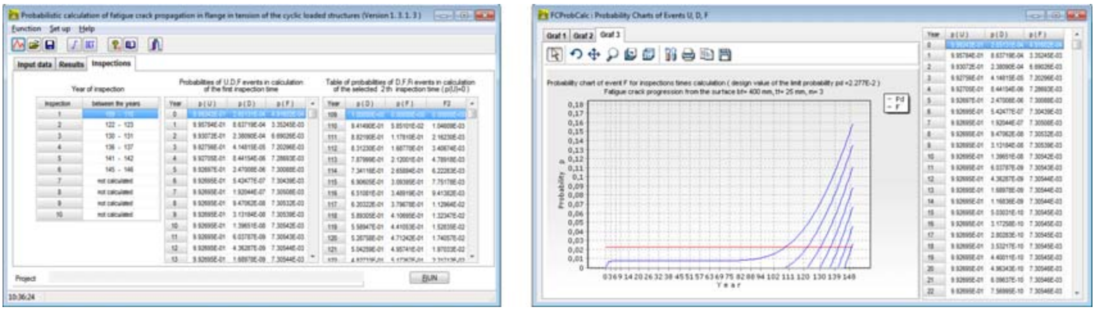

Fig. 8: Failure probability, P_f, depending on the years of operation of the bridge (0 to 150 years) in probabilistic calculation of propagation of a fatigue crack from the surface with the conditional probability being taken into account and determination of the time for the first and subsequent inspections of the bridge structure, the Gauss quadrature with numerical integration is used, the number of intervals for the input quantities is $N = 200$.

Fig. 7 (the fatigue crack from the edge) and Fig. 8 (the fatigue crack from the surface) show times for the first inspection and subsequent inspections resulting from the conditional probability (7). The both figures include a table with numerical values for the final inspection times, the probability of the *U*, *D* and *F* phenomena as well as the chart with failure probabilities, P_f, depending on years of operation.

Table 3 lists the proposed times for the inspections specified using the Gauss quadrature with numerical integration.

Table 3: Calculated times for the first and subsequent inspections of the bridge structure during propagation of fatigue cracks from the surface and edge

Inspection No.	*Time of inspection in years*	
	Failure crack from the edge	*Failure crack from the surface*
1.	**48**	**109**
2.	**55**	**122**
3.	**59**	**130**
4.	**62**	**136**
5.	**64**	**141**
6.	**66**	**145**
7.	**68**	not applicable
8.	**69**	not applicable
9.	**70**	not applicable
10.	**71**	not applicable

4 CONCLUSIONS

This paper discussed development of probabilistic methods and application of the probabilistic methods in assessment of reliabilities of structures. A particular attention was paid to the probabilistic method which is under development now: DOProC. DOProC method seems to be a good choice not only for reliability assessment tasks but also for other probabilistic calculations. For instance, theoretical information and practical guidelines are available to the probabilistic assessment of propagation of fatigue cracks from the surface and edge, a particular attention being paid to the maximum permissible dimension and proposed system of regular inspections of the structure.

The computational methods were applied in FCProbCalc which was used for the probabilistic assessment of fatigue damage to a bridge structure where cracks were propagating from both the surface and edge. Times were specified for inspections of the bridge structure, where the purpose was to monitor occurrence of certain fatigue cracks. The comparison proved that velocity of propagation of the fatigue crack from the surface is considerably slower than that from the edge.

A relatively complex algorithm in DOProC requires good theoretical knowledge and practical computing skills of the user. It is essential to know, at least, general basics of algorithms because this influences the way of defining the computational model and selection of the best optimizing procedure. This weakness is removed if the application software is customized for a specific probabilistic task, this being, for instance, the case of Anchor, see [4]. The customized software we used is FCProbCalc.

It should be pointed out that DOProC still provides many other options to be used. What is worth being investigated further is the use of statistically dependent input quantities with direct entries in the computational algorithm, assessment of reliability of structural systems and development of numerical procedures which will make the application of DOProC in matrix calculations more efficient.

If further development is made in methods used in the probabilistic calculations of fatigue damage in constructions subject to cyclical loads, another important objective would be, in particular, application of advanced numerical methods for integration of the construction resistance and optimizing of the process in order to reach the required accuracy and reduce the machine time, application of Bayes networks in the computational model describing propagation of fatigue cracks, and integration of other types of fatigue damage in steel structures subject to cyclical loads into the computational procedures.

APPENDIX

For a lite version of FCProbCalc and for other software products based on DOProC method, please, visit web pages http://www.fast.vsb.cz/popv .

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