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FROM PARTIAL FACTORS DESIGN TO FULLY PROBABILISTIC RELIABILITY ASSESSMENT OF STRUCTURES

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P. Marek and A. K. Kvedaras

1. Introduction

The improvement of computer technology affects numerous areas of human activity and initiates earlier unbelievable applications. In the area of structural design the modern PCs are unquestionably enforcing different qualitative changes, such as "re-engineering" of the reliability assessment process. The coming generation of PCs suggests introduction of an alternative design procedures based on fully probabilistic approaches and simulation techniques. One of such alternative is documented and illustrated with numerous examples in [1]. The potential of simulation based concept in design may be expressed by the following statement: not to use structural reliability assessment concepts based on simulation techniques, with powerful PC on every designer's desk, would be like using a slide rule in the slide rule era just to draw straight lines.

This paper comments on current structural reliability assessment concepts, such as the Allowable Stress Design and the Partial Factors Design, and suggests a gradual transition from current methods to qualitatively new concepts corresponding to the available powerful computer technology.

2. Design concepts and reliability assessment

2.1. Review of concepts

Every design concept developed, adopted in specifications and proved to be applicable reflects the knowledge of generations of engineers and builders devoted to their creative work. Such concepts incorporate their experience and understanding of the actual behaviour of structures and the designer's response to supporting computational tools and technology available at the time.

The main approaches to reliability assessment are reviewed in Fig 1 with three main approaches, Deterministic (Allowable Stress Design, ASD, and Plastic Design, PD), Semi-Probabilistic (Partial Factors Design, PFD) and Probabilistic Design (such as SBRA) being distinguished:

Slide Rule Era
- ⇒ **Deterministic** → *Allowable Stress Design* → **ASD (AISC etc.)**
- ⇒ **Deterministic** → *Plastic Design* → **PD**
- ⇒ **Semi-Probabilistic** → *Partial Factors Design* → **PFD** (see e.g. LRFD, EUROCODE)

Computer Era
- ⇒ **Probabilistic** → *Analytic and Numeric Methods*
- ⇒ **Probabilistic** → *Simulation* → **Moments Generated Distributions**
- ⇒ **Probabilistic** → *Simulation* ⇒ **Parameters Generated Histograms (SBRA)**

Fig 1. Review of the main reliability assessment concepts

2.2. Deterministic approach

2.2.1. ASD: The Allowable Stress Design, ASD, based on deterministic input data and Safety Factors, SF, stems from the slide rule era. Long–term application of this approach coupled with the expertise, and experience of engineers and specification writing bodies gradually improved the application of this concept to a very high level (see e.g. [2]). However, there are many limitations to this approach: difficulties in utilization of plastic reserves and regarding second-order theory problems, and the uncertainty of the actual probability of failure.

2.2.2. PD: In the sixties and seventies, attention had been given to the development of Plastic Design, PD, see [3] and [4]. The research yielded important information on the actual ultimate behaviour of steel structures; however, the corresponding reliability assessment procedure and specifications have been applied in design only in a limited number of cases.

2.3. Limit states approach

In structural reliability assessment, the concept of a limit state surface separating the multidimensional domain of random variables into **safe** and **unsafe** domains has been generally accepted. This concept can be interpreted in two different ways:

2.3.1. *Semi-probabilistic approach*. Since the Fifties, many national and international specifications for structural steel design based on semi-probabilistic Partial Factors Design, PFD (in the U.S. called Load and Resistance Factor Design, LRFD), have been developed and proposed for design. The ASD specifications have been gradually replaced by the PFD design codes (see for example [5] to [11]). PFD does not require consistent application of the computer technology, since the numerical reliability check can be conducted by calculator, slide rule or even long-hand. From designer's point of view this concept is still deterministic.

2.3.2. *Probabilistic Approach*. Attention in research has been paid to the fully probabilistic reliability assessment concepts. There are two basic ways to reach this goal: (a) application of analytical and numerical methods, and (b) the simulation technique. The former is extremely difficult and may never lead to successful results due to the very complicated nature of the variables and reliability function. It is expected that the new computer literate generation of engineers will prefer the latter one. The application of the simulation techniques requires the use of a computer by the designer. Such approaches correspond to the increasing potential of personal computers in the computer era (see review in [12]).

2.4. From deterministic methods to PFD

The actual transition from the deterministic design concept to the PFD version of the limit states concept is proceeding slowly. The specifications based on PFD are already available in many countries; however, the majority of the designers still prefer the "old-fashioned" ASD concept. A slow transition from ASD to PFD can be observed in Europe as well as in the U.S., the country with many of the tallest buildings and so many other admirable steel structures reflecting the potential of engineers and the construction industry.

Hundreds of papers justifying the transition from ASD to PFD have been published all over the world explaining the limitations of the ASD concept and the advantages of the PFD method leading to the proof of reliability using statistics and probability. Each code-writing body, however, has followed its own path to reach the goal (compare, for example, [6] to [10]). Individual existing specifications based on the limit states concept differ in the definitions and analyses of loads and load combinations, in the definitions of resistance and serviceability, and in the scope of the conscious utilization of plastic reserves. Common to all is the basic format of the safety check criteria comparing the extreme load effects and minimum resistance using partial factors.

Referring to sources available to the authors of this paper, there are not yet available proofs that the PFD method leads to a consistently balanced reliability (expressed by probability of failure) of steel structural components designed according to current PFD specifications. Similarly, the claimed PFD related material savings may be dependent mainly on the calibration applied by the authors of these design codes.

3. Analysis of the reliability function

3.1. Partial factors design

Current PFD specifications for structural steel design are based on the so called "design point", reliability index β, and load and resistance factors. When considering multi-random-variable input resulting from statistical and probabilistic evaluation of data, consistent assessment of reliability based on this concept can become extremely difficult or even impossible. Designers may find the corresponding procedures to be too complicated, difficult to understand, and not efficient from their perspective. The reliability check is neither completely defined nor explained in the specifications. The calculation of the β index is excessively complex for the designer. For this reason the index of reliability β is never part of any computation required by the designer. It may be assumed that the reliability assessment scheme is hidden in a "black box", while the designer's creative work is limited to interpretation of regulations and instructions contained in the design codes.

The use of the index of reliability β as a measure of safety can be questioned, see for example, [1] and [12]. For variable resistance R and load effect S, the reliability functions RF = ln(R/S), RF = (R-S), and others allow for determining the probability of failure. However, these functions do not carry further information on safety, durability and serviceability. Therefore, they cannot serve as a consistent tool for developing the load and resistance factors leading to the uniform reliability in PFD concept.

3.2. Simulation-based concepts

With modern computer technology, the methods based on sampling and simulations are considered to be the most efficient. The reliability function can be analyzed and the probability of failure (ie the measure of reliability) expressed without extensive simplifications of the reliability assessment model (see review in [12]).

The simulation technique is a convenient and powerful tool for the analysis of load effect combinations, resistance, safety, durability and serviceability in the case of multi- as well as single-component variables. Taking into the account the potential of modern personal less serviceability limit states. In order to make the simulation procedure accessible to the

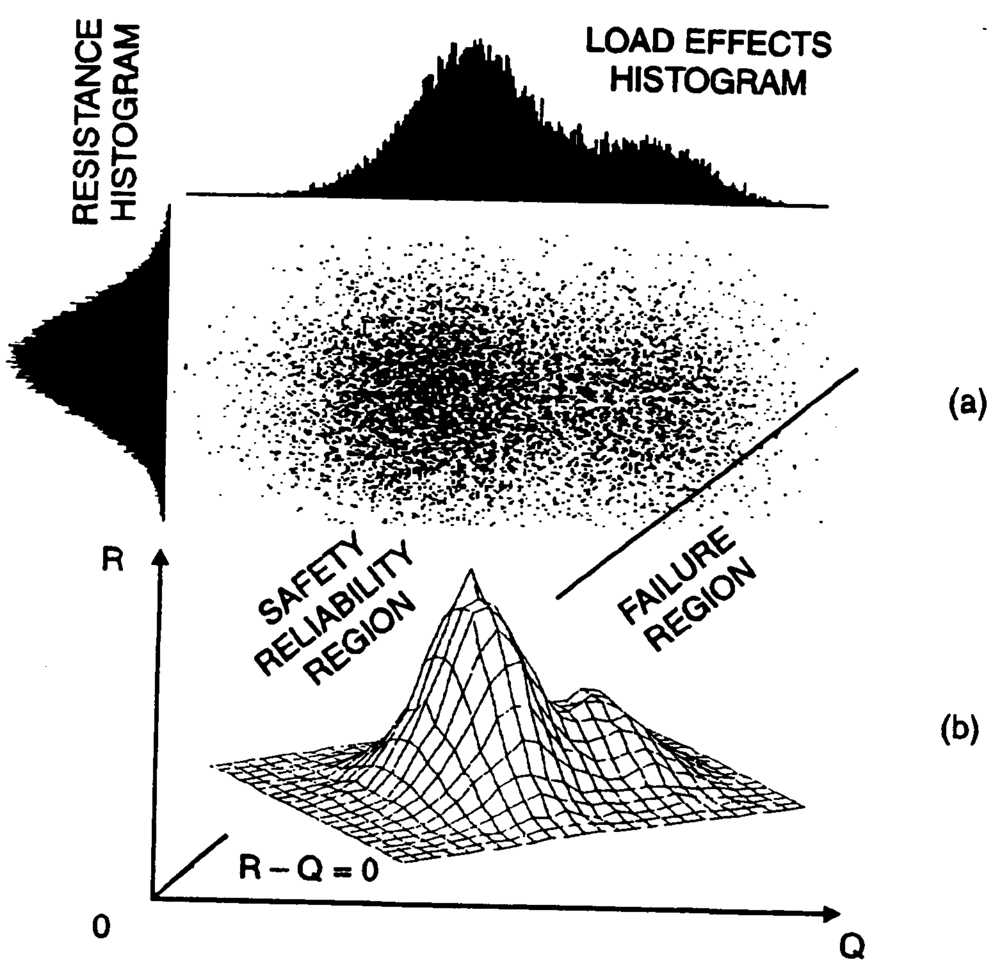

Fig 2. Simulation-based Reliability Assessment: Basic scheme (Program AntHill™ applied [13])

designer, a direct version of Monte Carlo Method is applied. Corresponding user friendly computer programs [13] demonstrate the applicability of this approach in design, teaching and research. In Fig 1 is shown the basic idea of the SBRA concept (for details see [1]).

4. Selected examples

Following examples serve only for illustration purpose of the potential of the proposed simulation based approach SBRA and for demonstration of the applicability of corresponding computer programs in design.

4.1. Short axially loaded member exposed to variable (±) force

Determine the probability of failure P_f of an axially loaded short column exposed to variable load effect (tension - compression). Let the material properties be different in tension and in compression. Buckling of the member is not considered.

Variable load effect is expressed by an axial force S. This force represents load effect combination

$$S= 8*DL+5*LL-80*SL+60*WL+5*SN+20*EQ, \quad (1)$$

where *DL, LL, SL, WL, N* and *EQ* are coefficients expressing the variability of the dead, long-lasting, short-lasting, wind, and earthquake loads (see histograms representing the load-duration curves [1]).

Resistance *R* of a short steel column is in this example defined by the onset of yielding:

* in tension $R_1 = + 938*Avar*F_{y,1}$; (2)

* in compression $R_2 = - 938*Avar*F_{y,2}$, (3)

where: A_{nom} = 938 mm² is the nominal cross-sectional area, A_{var} is a coefficient representing the variation of the cross-sectional area (for example over-rolled or under-rolled, see histograms in [1]), $F_{y,1}$ is the variable yield stress in compression, and $F_{y,2}$ $(<F_{y,1})$ is the yield stress in tension (both yield stresses represented by histograms refer to test results).

The safety function, *SF*, is expressed by *SF =R-S*.

All variables are considered to be statistically independent.

Using the simulation based AntHill™ computer program and procedure (see [1] and [13]), the probability of failure is p_f = *0.0015* (see Fig 3).

4.2. Column exposed to a variable axial compression

Determine the probability of failure of an axially loaded long column exposed to variable compressive force. The material properties are expressed by yield stress F_y and modulus of elasticity *E*. The 2nd order analysis of the column is considered.

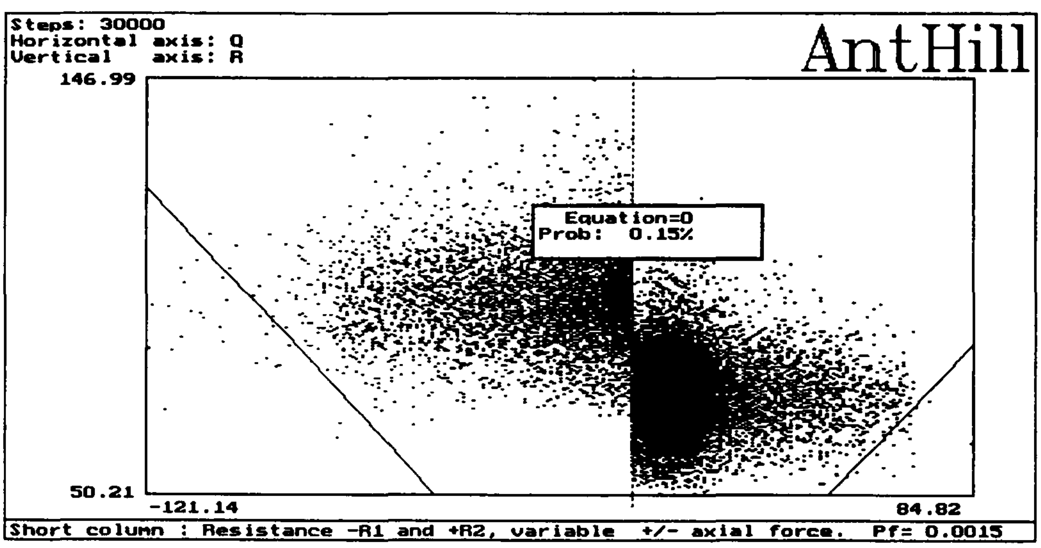

Fig 3. Probability of failure P_f = 0.0015 of a column obtained by AntHill™ program.

Variable load effect combination S is expressed by an axial force

$$S=100*DL+100*LL+130*SL, \qquad (4)$$

where DL, LL, and SL are coefficients expressing the variability of the mutually uncorrelated dead, long-lasting, and short-lasting load effects (see histograms representing the load-duration curves in [1]).

Resistance R is defined by onset of yielding (the 2nd order elastic analysis of the initially curved column is considered, see [14], [1]). The effect of residual stresses is represented by additional variable initial out-of-straightness of the column.

The resistance R is defined as

$$R = f\,(G_{nom}, Avar, F_y, EXC, ReSt), \qquad (5)$$

where the constant G_{nom} represents all nominal geometrical properties of the column, A_{var} and $ReSt$ are coefficients expressing the variability of the cross-sectional area and the effect of residual stresses, EXC is the variable initial out-of-straightness, and F_y is the variable yield stress (for more details and numerical examples see [1]).

The safety function is expressed by $SF = R - S$.

All variables are considered to be statistically independent.

Using the simulation based AntHill™ computer program the resulting probability of failure is $P_f = 0.001$ (see Fig 4).

4.3. Column exposed to variable axial ± force

Determine the probability of failure P_f of an axially loaded column exposed to variable load effect (compression - tension). The steel properties are expressed by yield stress. Buckling of the column is considered.

Variable load effect combination is expressed by an axial force S

$$S=-100*DL - 100*LL - 120*SL + 380*SN + 400*EXPL, \qquad (6)$$

where DL, LL, SL, SN and $EXPL$ are coefficients expressing the variability of the dead, long-lasting, short-lasting, snow loads and load effect due to exceptional load (eg explosion). All loads are assumed to be statistically independent. All variable coefficients are represented by histograms and by corresponding load-duration curves (see [1]).

Resistance R is defined by onset of yielding (in case of compression the 2nd order analysis of initially curved column is applied, see [14]). The effect of residual stresses is represented by a fictitious increment of the variable initial out-of-straightness of the column. The resistance is defined by a function R (see Section 5.2). For more details see [1].

The safety function is expressed by $SF = R - S$.

All variables are considered to be statistically independent. Using the simulation based AntHill™ computer program enclosed to [1], the probability of failure is $P_f = 0.0007$ (see Fig 5).

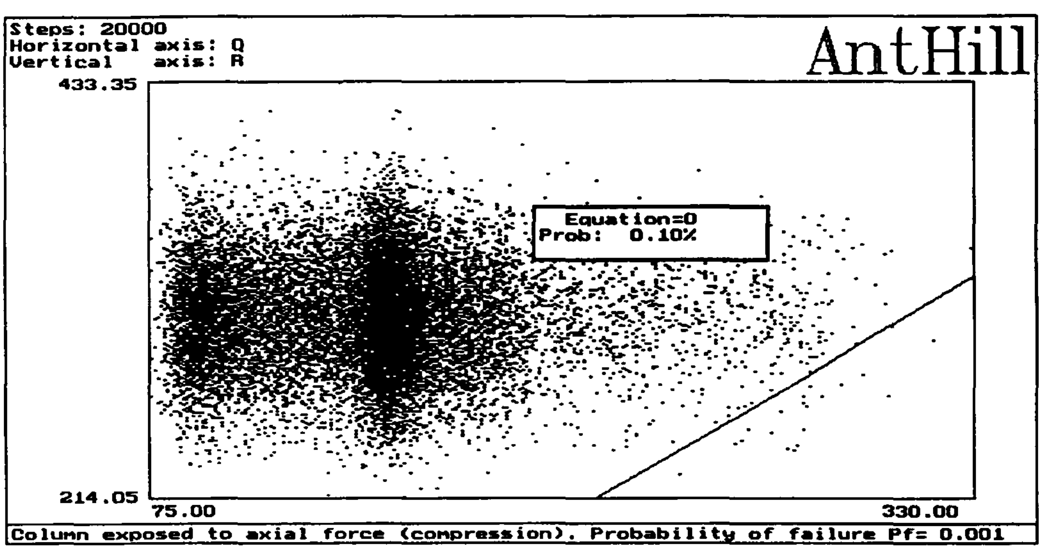

Fig 4. Probability of failure $P_f = 0.001$ of a column

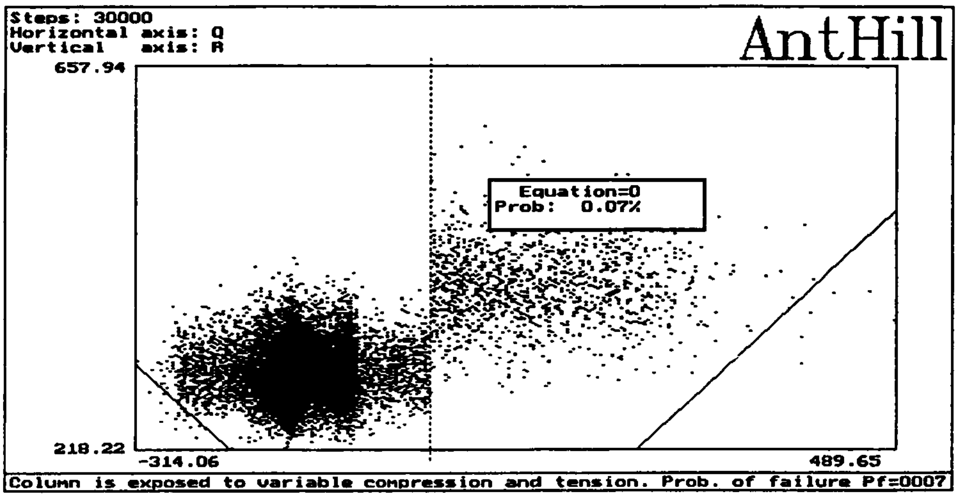

Fig 5. Probability of failure $P_f = 0.0007$ of a column exposed to variable compression and tension

5. Conclusions

5.1. Basic differences between PFD and SBRA

In order to assist in introducing the fully probabilistic analysis of the load effects, resistance and reliability to the designers, a concept and corresponding computer programs were developed [1]. Some of the main differences between the semi-probabilistic PFD and the probabilistic SBRA are:

(a) In PFD the reliability is expressed by comparing the factored load effects and factored resistance, while in SBRA the probability of failure P_f serves as a measure of reliability.

(b) The analysis of load effects and their simultaneity is not based on nominal loads, load factors and multi-step, multi-conditional approach (see e.g. [8]) but on maximum magnitudes of load effects and on load duration curves. The proposed SBRA approach allows for consistent analysis of single- as well as multi-component load effect combinations such as combined effects of biaxial bending moments, axial forces, shear forces and torque in a steel member exposed to several time-dependent loading.

(c) In the PFD, the effect of variables is considered in the analysis of the reliability index β. As already mentioned, the reliability functions such as $ln(R/S)$ (see [9]), or $(R\text{-}S)$ (see [11]) serve exclusively for determining the probability of failure and do not contain any other information on reliability. Therefore, in PFD, a calibration procedure has to be used for determining the load and resistance factors. The SBRA approach respects in the simulation based reliability analysis the actual variables and their interaction corresponding to individual situations.

5.2. Probability based design in structural steel design codes

Several simulation based concepts may be considered and different levels of simulation technique can be applied starting from Crude-Monte-Carlo up to special procedures such as Latin Hypercube Response Approximation. Re-engineering of the entire assessment process would be required. The loads have to be redefined in a way allowing for analysis of their combinations as well as their interaction with other variables such as material properties. The definitions of individual variables is needed and application of corresponding data bases required.

The designer is ready to apply new and advanced reliability assessment procedures if these are clear, less time and effort consuming, if they will bring non-negligible material savings, if he/she can feel that his/her creative engineering work is not limited to the interpretation of equations, and if corresponding codes would be available. In case of a positive response of designers to the proposed qualitatively different approach, the legal aspects of such codes can be discussed. In Czech Republic already exists a code letting application of the fully probabilistic concept and Monte Carlo simulation in structural steel design [15].

5.3. Conclusions

The procedures for structural reliability assessment in current design codes, based on semi-probabilistic partial factors concept, do not fully utilize the possibilities offered by available computer technology. An alternative is proposed for consideration, based on Monte Carlo simulation, that allows the analysis of load effect combinations, the determination of resistance corresponding to a specified probability of exceedance, the assessment of safety by probability of failure, and the check of the serviceability of structures (see, eg [16]).

Possible steps for further development of the simple procedures for structural reliability assessment of prior and posterior steel structures that are taking account on probabilistic long-term safety analysis including approximate dynamic models are investigated in [17-19]. Perhaps, the possibilities offered by consideration, based on Monte Carlo computer simulation, joined with those taking account on dynamic models in long-term analysis and reliability predictions, may fully then utilize the probabilistic analysis of structures with more well-founded prediction of their safety and durability.

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NUO KONSTRUKCIJŲ PROJEKTAVIMO DALINIŲ KOEFICIENTŲ METODŲ Į VISIŠKAI TIKIMYBINĮ JŲ PATIKIMUMO VERTINIMĄ

P. Marekas, A. K. Kvedaras

Santrauka

Kompiuterinės ir informacinės technologijos raida leidžia tikėtis, kad bus pereita nuo deterministinės ir pusiau tikimybinės sąvokų (tokių, kaip leistinųjų įtempių ir dalinių koeficientų metodai) prie konstrukcinio patikimumo vertinimo sąvokos, pagrįstos visiškai tikimybiniu požiūriu. Naudojant Monte Karlo modeliavimo technika ir parametrais sukurtas histogramas, buvo sukurtas ir pasiūlytas modeliavimu besiremiantis požiūris.

Tokios sąvokos, kaip leistinųjų įtempių ir dalinių koeficientų metodai, kurios vartotos normose, buvo sukurtos "logaritminės liniuotės" eroje. Perėjimas nuo leistinųjų įtempių prie dalinių koeficientų metodo paskatino tolesnę metalinių konstrukcijų projektavimo raidą. Dalinių koeficientų metodo sąvoka, suvokiama kaip pusiau tikimybinė, nes naudojamasi statistika, vertinančia pradinius duomenis ir apkrovų bei atsparių koeficientus, projektuotojų nuomone, vis dėlto yra deterministinė.

Norint atkreipti dėmesį į suvokiamą kokybinę konstrukcijų patikimumo vertinimo takoskyrą, t.y. į perėjimą nuo deterministinės į visiškai tikimybinę sąvokas, straipsnis apima schematišką skaičiuojamųjų priemonių raidą ir modeliavimu pagrįstą patikimumo vertinimą. Šiuolaikinės

skaičiuojamosios priemonės susietos su tikimybine sąvoka, pagrįsta ribinių būvių filosofija, sąlygoja perėjimą į naują aukštesnę projektavimo pakopą.

Tikimybinė modeliavimu besiremianti patikimumo sąvoka yra grindžiama tokiais veiksniais: a) pradiniai duomenys, atitinkantys pavienius kintamuosius, yra išreiškiami histogramomis; b) paskiros apkrovos yra pateikiamos jų ekstremaliomis reikšmėmis ir atitinkamomis apkrovimų trukmės kreivėmis; c) patikimumo funkcijos RF (t.y. $RF = R - S$; čia R yra atsparis ir S - įrąža) yra analizuojamos taikant tiesioginę Monte Karlo modeliavimo techniką ir d) patikimumas yra išreiškiamas irimo tikimybe P_f.

Kai kurių Europos šalių projektavimo normos (pavyzdžiui, Čekijos - CSN 73 1401 - 1998) jau pripažįsta tikimybinį požiūrį ir leidžia taikyti Monte Karlo modeliavimą. Šis straipsnis apima ir modeliavimu pagrįstos patikimumo vertinimo sąvokos specialaus taikymo pavyzdžius.

Modeliavimu pagrįstam patikimumo vertinimui buvo sukurtos specialios kompiuterinės programos, leidžiančios ignoruoti "projektinį tašką", indeksą β ir dalinius patikimumo koeficientus. Naudojant AntHill™ kompiuterinę programą, dešimtys tūkstančių taškų yra sukuriami atsitiktinių skaičių generatoriumi ir Monte Karlo metodu. Ši taškų aibė atitinka "tikrąją" dvimačio dažnio aibę. Norint gauti suirimo tikimybę P_f, būtina nubrėžti tiesę $R - S = 0$, išskiriančią taškų aibę į saugų ir nesaugų ruožus. Taškų, esančių į dešinę nuo tiesės $R - S = 0$, skaičius, padalytas iš bendro taškų skaičiaus, atitinka irimo tikimybę P_f. Tikimybės įvertis yra išreiškiamas nelygybe $P_f < P_d$.

Pabrėžiamas būsimųjų inžinierių lavinimas atsižvelgiant į perėjimą nuo deterministinio į tikimybinį mąstymo būdą.

Raktažodžiai: patikimumas, tikimybė, modeliavimas, Monte Karlo, vertinimas, atsparis, įrąža, laikomoji galia, vartosena, plieno konstrukcijos.

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