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State-of-the-art summary of reliability fields due to engineering

Reliability of an object, say a technical device (in particular: a structural element, consequently: a system of elements) in its strict definition, referring to technical sciences is a probability of its effective, non-failure work in a specified time period (lifetime), regarding the time of effective work of an object a random variable of specified distribution [Solovyev, 1983].

There is a number of mathematical reliability definitions [Barlow, 1965], each one includes a time interval – reference time, called the structural lifetime.

Thus a general reliability problem is time-variant, with a stochastic process / random process qualification – functions of elementary event and time [Papoulis, 1972; Helstrom, 1984; Melchers, 1999; Śniady, 2000; Bucher, 2009]. The most widesprad approach in engineering field, oriented to practical design applications, regards the so-called basic variables – geometric and material parameters, static and non-static external actions, geometric imprfections, etc. as random variables of assumed types (probability distributions). The variable type and its governing parameters corresponding to the given basic variable are assumed on the basis of relevant statistical analysis of an existing database [Benjamin, 1977; Soong, 1981]. Specific cases of a remote random variability of a given basic variable, compared to the others, trigger its deterministic computational model.

In worldwide literature – textbooks, monographs, conference proceedings and journal articles the most wisespread background to cover uncertainty and reliability issues is probability theory and mathematical statistics (featuring estimation theory, [Deutsch, 1969]). It is a global but not unique assumption – another background sciettific field is fuzzy set theory, to be possibly linked with probability theory [Woliński, 2001; Niczyj, 2003; Biondini, 2004].

Reliability of structural elements and systems is a discipline of formal, mathematical background, to complete an engineering task – design and operation of a safe structure. Thus in civil engineering range reliability is a scientific basis of safe design, the aim implemented by engineering intuition throughout the years, while it was impossible to quantify the scatter of basic variables [Blockley, 1980]. In the 20s of the 20th century the probability theory rise due to Andrei Kolmogorov's axioms (probability in terms of measure) made it possible to regard reliability an autonomous scientific discipline. The pioneering reliability works date back in the 20s ot the 20th century, the field was further developed in post-war years. [Bolotin, 1961; Wierzbicki, 1961, Elishakoff, 1983]. The engineering approach to reliability problems, developed in further decades was based on the variation concept of basic design parameters (hence the term basic variables) thus existing a non-zero failure probability [Nowak, 2000].

Three levels of reliability assessment are distinguished in literature, due to mathematical approach to variables – structural parameters and actions (deterministic parameters or random variables of specified types) [Madsen, 1979]). The three levels are briefly characterized below:

- the 1st, semi-probabilistic level implement a deterministic design procedures, but the involved characteristic values may be fractiles of relevant probability densities. Design values involve partial safety factors calibrated on the basis of random parameter scatter. The 1st level methods form the background for engineering limit state design, in the USA known as LRFD (load and resistance factor design). Thus the procedure is deterministic only, not requiring an elaborated mathematical background in probability or statistics. The fundamentals of 1st level methods were formulated in the 40s and 50s of the 20th century [Freudenthal, 1947, 1956].

- the 2nd level methods – each basic variable is represented by two parameters only: mean value and standard deviation, in a specific problems their estimators may be sample mean and sample standard deviation referred to a real database. The 2nd level methods are distributionless. While an assumption is made of all basic variables Gaussian an algebraic limit state criterion may be formulated, the so-called limit state function *G* arises (to be also called a performance function or a safety margin), a function of basic variables of the problem. While a linear linit state function emerges it is apparently a Gaussian variable, thus reliability assessment is a Gaussian probability task. Nonlinear limit state function *G* may be linearized e.g. at the mean value point, thus a Gaussian

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variable *G* appears too. In the operations above the so-called Cornell reliability index β_C is applied [Cornell, 1969] – the ratio of mean value and standard deviation estimators of *G*. A disadvantage of Cornell's reliability index β_C formulation appears – given various G functions for the same problem different values of β_C may be obtained, hence, various faliure probabilities, so the solution is not invariant.

The attempt for an invariant solution with regard to limit state function transformation was proposed by Hasofer and Lind in 1974 [Hasofer, 1974], its idea lies in linearizing

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the limit state function in the so-called design point, of the lowest distance from the origin in the system of normalized basic variables. The subsequent concepts of reliability index were launched by Rackwitz and Fiessler [Rackwitz, 1978] and Ditlevsen [Ditlevsen, 1979]. The 2nd level methods operate the second moment of basic variables (first moment – mean value, second moment - variance). Distinction is made of FORM (first-order reliability methods) approximating the limit state function linearly and SORM (second-order reliability methods), of quadratic approximation [Melchers, 1999, Nowak, 2000]

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- 3rd level methods – basic variables are represented by distribution functions – PDF or CDF, estimated by normalized empirical histogram of relative frequencies or an empirical cumulative distribution, respectively. Analytical methods are not effective here, with regard to real problems of engineering. Thus the 3rd level methods are dedicated to computational methodologies, which numerically approximate the basic variable distribution functions in order to estimate the parameters of engineering importance (reliability, failure probability) or entire limit state function distributions. The relevant numerical tool to numerically analyse uncertain phenomena is Monte Carlo simulation (MCS), in fact, the method of statistical trials [Hammersley, 1946; Rubinstein, 1981]. The basic MCS algorithm referred to engineering tasks is to generate basic variables in the form of random variates, next, to conduct a simulation loop of deterministic tasks with random input, finally, collecting the results in the histogram form, estimating probability distribution of the limit state. The basic sampling techniques, called direct sampling or crude random sampling is the most accessible, easy to implement, but high-capacity tasks make it too extended due to computational time. Thus the so-called variance reduction techniques are worked out, to direct the sampling into the critical region, i.e. critical combination of basic variables, completing the task of reliability assessment only (or failure probability assessment). The developed techniques of wide application are Importance Sampling, Stratified Sampling, Directional Sampling and Latin Hypercube Sampling [Melchers, 1999; Hurtado, 1998]. A useful tool to numerically analyse uncertainty of engineering structures is the Response Surface Method - RSM [Box, 1987; Hurtado, 1998]

The first stage of every probabilistic task of reliability assessment is the definition of basic variables of the problem. Regardless of further analysis these aparameters are affected by inherent variability, implicit for the researcher. Thus the estimation task emerges here – based on statistical data the result is estimated, either sample mean (mean value estimator), sample variance (variance estimator), higher order moments or normalized histogram of relative frequencies (estimator of probability density function). The latter stores the broadest information, allows for matching a relevant variable type to the investigated parameter (quantity of interest), i.e. to match the type of PDF and CDF. The first and second moment estimation completes the level 2 approach, estimation of distribution or density functions is essential in the level 3 attempt.

Relevant distinction of basic variable types to selected engineering parameters (actions, resistances) is a subject of research, based on experimental studies, statictical data processing and accumulated engineering experience . The summary in this field is presented in [Nowak, 2000] and [Melchers, 1999]. A brief distinction is listed below:

- in the case of dead and sustained live loads the Gaussian variables are appropriate [Nowak, 2000]

- variable (live) loads – the so-called sustained part, modelled by gamma variable [Corotis, 1977; Issen, 1978], and the instantaneous part (transient live load), maximum values may be assumed the extreme type 1 (Gumbel) variable type [Gumbel, 1958; Chalk, 1980; Kotz, 2000), distinct studies are undertaken with regard to bridge structures [Nowak, 1991]

- wind load – in fact a random (stochastic) process, even a spatiotemporal random field [Simiu, 1996; Nowak, 2000] In a simplified approach wind velocity is assumed the extreme type 1 (Gumbel) variable type [Ellingwood, 1999]

- snow load – the snow load statistics adjusted to probabilistic modelling are included in [Ellingwood, 1981]. Snow load may be given the following variable types: log-normal, extreme type 1 (Gumbel) or extreme type 2 (Frechet) [Ellingwood, 1983]. A multi-author work [Ellingwood, 2017] is a reliability-based attempt to calibrate design values of snow loads

- seismic loads – random process of a long return period (approx. 50 years), simplified quasi-static analysis [Bolotin, 1961; Augusti, 1984]. Acceleration of the subsoil du to seismic excitations may be applied an extreme value type 2 random model

- geometric and material imperfections – modelled on the basis of statistical database of imperfection measurements, in the case of 2D structures random imperfection fields are applied [Biegus, 1999; Górski, 2006]

- joint wind and wave load (offshore structures) – a possible model: multivariate random processes of possible interrelation (dependence) [Wen, 1981; Simiu, 1996]

- resistance parameters (e.g. yield stress of steel) – log-normal or extreme type 3 (Weibull) variables [Weibull, 1951; Thoft-Christensen-Murotsu, 1986]. The Weibull-type variable is applicable to model fatigue resistance and in fracture mechanics problems.

A distinct, challenging task deals with human error quantification in reliability assessment [Nowak, 2000]

Reliability of engineering structures is a joint field of fundamental and applied sciences. Probabilistic background, relevant to the assumed random structural model leads to working out application procedures to improve design courses, computational efficiency, relevant modelling of materials, structures and actions, complemented by design economy. The scientific reliability background is included in a number of monographs [Hart, 1982; Thoft-Christensen-Baker, 1982; Augusti, 1984; Madsen, 1985; Ditlevsen, 1996; Melchers, 1999, Ang-Tang, 2007]. The Polish contribution in reliability field dates back to the works of prof. Witold Wierzbicki, the Cracow centre held by prof. Janusz Murzewski was the leading one throughout the years [Murzewski, 1972; Murzewski, 1989], there were valuable contribution in reliability of metal structures by prof. Zbigniew Mendera [Mendera, 1987]. An important contribution to probabilistic methods application was undertaken by Wrocław centre (prof. Paweł Śniady, Antoni Biegus, [Śniady, 2000; Biegus, 1999] and Kielce team, led by prof. Zbigniew Kowal [Kowal, 2003]. The leading role in national scale is held by Łódź centre, headed by prof. Marcin Kamiński [Kamiński, 2001] and the Gdańsk centre, in the past led by prof. Eugeniusz Bielewicz, at present prof. Jarosław Górski [Górski, 2006].

Wide literature references are distinguished on reliability of selected structural types, with regard to structural material, physical parameters and the assumed random model. The issues of probabilistic analysis of steel structures are addressed in [Biegus, 1999; Guedes-Soares, 2002], probabilistic analysis of timber systems is presented in [Koechler, 2007; Pieniak, 2011], reliability of concrete structures is presented in [Nowak, 2002]. There are distinguished reliability sub-disciplines related to dominant, failure-making actions: wind load [Simiu, 1996], fire [Issen, 1978], seismic events {Bołotin, 1961], joint action of waves and wind in offshore structures (time-variant problems – random process domain) [Reliability of Offshore, 1992].

Reliability in its engineering meaning is aimed at improving design procedures, making them more effective. They are essential as a background for standard rules. A widespread, established methodology is called limit state design, dealing with load and resistance partial safety factors., essential in the level 1 probabilistic methods. The present codes introduce the design rules based on probability, allowing to use advanced, proved scientific methods [PN-ISO 2394, 2000]. The Joint Commitee of Structural Safety provides a vast research on probability-based codes for partial factor calibration and advanced tools to be applied in standards [JCSS, 2001], one of the JCSS papers presents reliability assesment of existing structures [Probabilistic assessment, 2001]. The TeReCo EU project under the leadership of prof. Pavel Marek, Czech Academy of Sciences promotes the philosophy of direct probabilistic design formats, based on basic variable histograms and the crude Monte Carlo sampling [TeReCo book, 2001].

The research works on reliability, documented by literature, software, comments to standards are mostly directed to reliability assessment of structural members. A distinct problem is concerned of system reliability. Two different systems assembled from the same members may work diversely, thus showcasing various reliability measures (reliability indices, estimators of failure probability). The issue of system reliability is addressed in a number of monographs [Thoft-Christensen-Murotsu, 1986], book chapters [Ditlevsen, 1996; Melchers, 1999, Nowak, 2000] and multiple papers. Two basic connection types of the so-called structural decisive elements are distingiushed (a possible element is a real structural member or a failure mode, e.g. plastic hinge in a cross-section of a beam or a frame) [Biegus, 1999]:

- the series (weakest-link connection) – a successful system work is a simultaneous work of all elements, thus reliability of a series system made of independent elements is a product of element reliabilities. Statically determinate systems are series-connected (frames, trusses), the series model is inherent in fracture mechanics – in a random network of microcracks the weakest one starts to propagate under an ultimate load, this concept was incorporated by W. Weibull [Weibull, 1951]

- parallel connection (bundle of wires) – a reliable system work requires a single working element only, thus failure probability of a parallel system is a product of failure probabilities of components. The parallel model is relevant for selected redundant systems, here dysfunction of single desicive elements does not determine the system collapse.

The assumption of random model of phenomena and basic variables in analysis and design is affected by the available real data, programming tools, the researcher's background on probability and the aim of the procedure (the latter: either a scientific research work or engineering application ot a simplified, utility form). The basic categories in random modelling are: :

- univariate random variable – a single outcome of a test, affected by elementary event only

- multivariate random variable (random vector) – a number of outcomes of a single test (e.g. yield stress, ultimate strength, Young's modulus in a static tensile test)

- univariate random process – a single test result in a direct function of elementary event and time [Augusti, 1984; Ditlevsen, 1996; Bucher, 2009]

- multivariate random process – a vector including component processes, functions of elementary event and time [Wen, 1981]

- random field – at every point of the 2D or 3D domain a random variable is defined, e.g. random shape imperfections of a cylindrical shell [Adler, 1981, Vanmarcke, 1983; Górski, 2006]

- spatiotemporal random field – at every point of a 2D or 3D domain a random process defined, a function of elementary event and time

Random process models are encountered in the cases of a significant time impact to structural response (e.g. stochastic dynamics – random vibrations) [Augusti, 1984; Bucher, 2009]

Random field models of spatial distribution are applied in the cases of system geometry to structural response (static, dynamic) [Vanmarcke, 1983,; Adler, 1981]

Reliability assessment of structural elements and systems is a vast discipline of many engineering applications, including environmental engineering [Ang & Tang, 2007]. The following related fields form a vast spectrum of reliability assessment, sometimes regarded separately as a distinct research field.

Reliability-based optimization is a developing discipline, incorporating possible random objective functions and constraints. It is illustrated nowadays by a wide array of engineering-oriented computational software [Thoft-Christensen-Murotsu, 1986; Der Kiureghian, 2003]. Cost-oriented reliability-based optimization is distinguished [Rackwitz, 2002, 2003; Augusti, 2003]. Structural probabilistic sensitivity is a branch related to optimization, here sensitivity of limit states is investigated with respect to the scatter of imput basic variables [Bjerager, 1989; Melchers, 2004]

Robust design is a keyword encountered in design domain of technical devices, structural components and systems.

The joint approach, called robust design-by-reliability, or reliability-based robust design, regarding reliability of components is addressed in [Kececioglu, 2003; Lagaros, 2007].

A vast category of reliability-based decision making is distinguished too [Benjamin, 1977; Faber, 2002]

Adler R.J. The geometry of random fields. John Wiley & Sons, 1981

Ang A. H-S., Tang W.H. Probability concepts in engineering: emphasis on applications to civil and environmental engineering. John Wiley & Sons, 2007

Augusti G., Baratta A., Casciati F. Probabilistic methods in structural engineering. Chapman and Hall, London, 1984

Augusti G. Optimal allocation of resourses in risk reduction. Workshop on Reliability-Based Design and Optimization RBO'03, eds. Jendo S., Doliński K., 15-18.09.2003, IFTR PASci + AMAS, Warsaw

Barlow R.E., Proschan F. Mathematical theory of reliability. Jonh Wiley & Sons, 1965, re-ed. SIAM, 1996

Benjamin J.R., Cornell C.A. Probability theory, mathematical statistics and decision making for engineers. WNT Warsaw 1977.

Biegus A. Probabilistic analysis of steel structures. PWN, Warsaw-Wrocław, 1999

Biondini F., Bontempi F., Malerbaa P. Fuzzy reliability analysis of concrete structures. Computers & Structures, vol. 82, Iss. 13–14, pp. 1033-1052, 2004

Bjerager P., Krenk S. Parametric sensitivity in first-order reliability theory. Journal of Engineering Mechanics ASCE, vol. 7, 1989

Blockley D.I. The nature of structural design and safety. Ellis Horwood, 1980

Bołotin W.W. Statistical methods in structural mechanics. Arkady, Warsaw, 1961

Box G.E.P, Draper N.R. Empirical model-building and response surfaces. John Wiley & Sons, 1987

Bucher C. Computational analysis of randomness in structural mechanics. CRC Press/Balkema, Leiden, 2009

Chalk P.L, Corotis R. B. Probability models for design live loads. Journal of the Structural Division ASCE, 1980

Cornell C.A. A probability-based structural code. ACI Journal, 1969

Corotis R.B., Doshi V.A. Probability models for live load survey results. Journal of the Structural Division ASCE, 1977

Der Kiureghian A. Algorithms for reliability-based structural design. Workshop on Reliability-Based Design and Optimization RBO'03, eds. Jendo S., Doliński K., 15-18.09.2003, IFTR PASci + AMAS, Warsaw

Deutsch R. Estimation theory. PWN Warsaw, 1969

Ditlevsen O. Narrow reliability bounds for structral systems. Journal of Structural Mechanics, 1979

Ditlevsen O., Madsen H.O. Structural reliability methods. John Wiley & Sons, 1996

Elishakoff I. Probabilistic methods in the theory of structures, Wiley-Interscience, New York, 1983

Ellingwood B. Wind and snow load statistics for probabilistic design. Journal of Structural Division (ASCE), 1981

Ellingwood B., Redfield R. Ground snow loads for structural design. Journal of Structural Engineering, 1983

Ellingwood B., Tekie P.B. Wind load statistics for probability-based structural design. Journal of Structural Engineering, ASCE, 1999

Ellingwood B., DeGock D.J., Liel A.B., Harris J.R. Reliability-based design snow loads. Journal of Structural Engineering, 2017

Faber M.H. Application of decision analysis in civil engineering. Workshop on Reliability-Based Design and Optimization RBO'02, eds. Jendo S. Kleiber M., Doliński K., 23-25.09.2002, IFTR PASci + AMAS, Warsaw

Freudenthal A.M. The safety of structures. ASCE Transactions, 1947

Freudenthal A.M. Safety and the probability of structural failure. ASCE Transactions, 1956

Górski J. Non-linear models of structures with random geometric and material imperfections. Simulation-based approach. Wydawnictwo PG, 2006

Guedes-Soares C., Garbatov Y. Reliability of deteriorated steel structures. Workshop on Reliability-Based Design and Optimization RBO'02, eds. Jendo S. Kleiber M., Doliński K., 23-25.09.2002, IFTR PASci + AMAS, Warsaw

Gumbel E. Statistics of extremes. Columbia University Press, 1958

Hammersley J.M, Handscomb D.C. Monte Carlo methods. Methuen & Co. Ltd., 1964

Hart G.C. Uncertainty analysis of loads and safety in structural engineering. Prentice Hall, 1982

Hasofer A.M., Lind N. Exact and invariant fortst-order reliability format. Journal of Engineering Mechanics, 1974

Helstrom C.W. Probability and stochastic proceses for engineers. Macmillan, 1984

Hurtado J.E., Barbat A.H. Monte Carlo techniques in computational stochastic mechanics. Archives of Computational Methods in Engineering, 1998

Issen L.A. A literature review of fire and live load surveys in residences. Center for Fire Research report, Washington, 1978

JCSS Probabilistic Model Code: http://www.jcss.byg.dtu.dk/Publications/Probabilistic_Model_Code, 2001

Kamiński M. Stochastic reliability in contact problems for composites with spherical particles. Journal of Theoretical and Applied Mechanics, 2001

Kececioglu D. Robust engineering design-by-reliability with emphasis on mechanical components and structural reliability. DEStech Publications, Lancaster, 2003

Koechler J. Reliability of timber structures. ETH Zurich, 2007

Kotz S., Nadarajah S. Extreme value distributions, theory and applications. Imperial College Press, 2000

Kowal Z. Reliability of beams of deformable cross-sections, Steel Structures, 2003

Lagaros N.D, Plevris V., Papadrakakis M. Reliability-based robust design optimization of stel structures. International Journal of Simulation in Mustidisciplinary Design Optimization, vol. 1, 2007

Madsen H.O. Load models and load combinations. Technical University of Denmark, Lyngby, 1979

Madsen H.O., Krenk S, Lind N. Methods of structural safety. Prentice Hall, 1985

Melchers R. Structural reliability, analysis and prediction. John Wiley & Sons, Chichester, 1999

Melchers R., Ahamed M. A fast approximate method for parameter sensitivity estimation in Monte Carlo structural reliability. Computers & Structures, vol. 82, 2004

Mendera Z. Probability theory application in present-day standards concerning structures and loads . PWN Warsaw, 1987

Murzewski J. Safety of civil engineering structures. Arkady, Warsaw 1970

Murzewski J. Reliability of engineering structures, Arkady, Warsaw, 1989

Niczyj J. Multi-criterion reliability-based optimization and technical condition assessment of bar structures employing fuzzy set theory. Szczecin University of Technology Publishers, 2003

Nowak A.S., Hong Y.K. Bridge live load models. Journam of Structural Engineering, 1991

Nowak A.S., Collins K. Reliability of structures. McGraw Hill, 2000

Nowak A.S., Szerszen M.M. Reliability-based calibration of the design code for concrete structures. Workshop on Reliability-Based Design and Optimization RBO'02, eds. Jendo S. Kleiber M., Doliński K., 23-25.09.2002, IFTR PASci + AMAS, Warsaw

Papoulis A. Probability, random variables and random processes. WNT, Warsaw, 1972

Pieniak D., Ogrodnik P., Oszust M., Dec, L. Reliability of glu-lam pine timber at high temperatures, in the light of static flexural resistance Fire Safety and Technology, nr 3, str. 63-68, 2011

PN-ISO 2394. Reliability of civil engineering structures, general rules. Polish Standard Committee, 2000

Probabilistic assessment of existing structures ed. Diamantidis D. JCSS Report, 2001

Putresza, J., Jendo, S., Review of probabilistic methods for calculation of structural reliability. Archives of Civil Engineering, vol. 41, iss. 2, pp. 153-175, 1995.

Rackwitz R., Fiessler B. Structural reliability under combined random load sequences. Computers & Structures, 1978

Rackwitz R. Risk acceptability and optimization. Workshop on Reliability-Based Design and Optimization RBO'02, eds. Jendo S. Kleiber M., Doliński K., 23-25.09.2002, IFTR PASci + AMAS, Warsaw

Rackwitz R. Objective functions for reliability-oriented structural optimization. Workshop on Reliability-Based Design and Optimization RBO'03, eds. Jendo S., Doliński K., 15-18.09.2003, IFTR PASci + AMAS, Warsaw

Reliability of offshore operations: proceedings on an international workshop, ed. Simiu E. NIST special publication 833, 1992

Rubinstein, R.Y. Simulation and the Monte Carlo Method. John Wiley & Sons, 1981

Simiu E., Scanlan R.H. Wind effects on structures: fundamentals and applications to design. John Wiley & Sons, New York, 1996

Solovyev A.D. Analytical tehhods in reliability theory (in Polish). WNT Warsaw 1983

Soong T.T. Probabilistic modelling and analysis in science and engineering. John Wiley & Sons, 1981

Śniady P. Fundamentals of structural stochastic dynamics. Wrocław University of Technology Publishers 2000

TeReCo book. Probabilistic Assessment of Structures using Monte Carlo Simulation. Background, Exercises and Software. Marek P., Jacques Brozzetti J., Guštar M., eds. ITAM Academy of Sciences of Czech Republic, 2001

Thoft-Christensen P. Baker J. Structural reliability theory and its applications. Springer, 1982

Thoft-Christensen P., Murotsu Y. Application of structural systems reliability theory. Springer, 1986

Vanmarcke E. Random fields: analysis and synthesis. The MIT Press, 1983

Weibull W. A statistical distribution function of wide applicability. Journal of Applied Mechanics, 1951

Wen Y.K., Pearce H.T. Stochastic models for depndent load processes, 1981

Wierzbicki W. Objective reliability assessment methods of civil engineering structures. PWN Warsaw 1961

Woliński Sz., Wróbel K. Reliability of civil engineering structures. Rzeszów University of Technology Publishing House, 2001