The Principles of Risk Assessment for Building Steel Structures with Imperfections

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***Abstract:** Modern concept of complex engineering system operation which the building structures are, assume the transition from the concept of "absolute safety" to the "acceptable risk". The new task of structural safety appears – the studying of possibility of initial design parameters' changing which could transform during the structure's service life to the hazards – the determination of risk for future structural safety.The article is dedicated to problem of assessment the safety for steel structures' services when defined and hypothetically non-defined imperfections presents. The applicability of this investigations based on the results of earlier researches. The different groups of hazards for risk identification have defined.For constructional safety the defects and deteriorations (DDs) were defined as most important hazard events. There were found two cases for risk assessment: the case A: theimperfectionshavefoundanddefinedinrelativezones, and the caseB: theimperfectionshavenot found. But, based on the design calculations (number of load cycles, for example), its presence quite possible.Taking in the consideration the results of steel structures' technical inspections and history of structure's life service, the principles of risk assessment as probability of different ratios of detected and non-detected imperfections realizations have proposed. A few possible cases with detected and non-detected imperfections with its critical parameters have examined.Proposed principles of risk assessment for future safety steel structures' service with defined and non-defined imperfections could correct the results of technical investigations for determinations of the residual life and the time range that were previously determined between these investigations. Appears the real possibility to realize the risk management system by the means of additional analysis after the renovation works and regular investigations.*

***Keywords:** destruction, imperfections,risk,steel structures, technical investigation, technical state.*

I. INTRODUCTION

Modern concept of complex engineering system operation which the building structures are, assume the transition from the concept of "absolute safety" to the "acceptable risk". This concept needs to fulfill complex risk-analysis for future development of system with possibilities of risks regulation and control for decreasing risks up to acceptable levels.

After finishing of all cumulative threatsdetermination, the level of system safety should be estimated. The new task of structural safety appears – the studying ofpossibility of initial design parameters' changing which could transform during the structure's service life to the hazards – the determination of risk for future structural safety.

II. LITERATURE REVIEW AND RELATED WORKS

Fortheaimofthisresearch, underthedefinitionsof "risk" willunderstandthefollowing notion thatisveryclosetoJCSS (Joint Committee on Structural Safety) researches[7]**:**the<u>risk</u>isaquantitativeprobabilisticcharacteristicofpossibleharms caused by unpredictableeventswhichcan lead to complete or partial structure's destruction and determine as multiplication ofprobability (relativefrequency) ofnegativeevent*i*withdefinedintensityonthevalueofpossiblelosses from this event:

$$R_i = P_i \cdot C_i; R(T) = \sum_{i=0}^{\infty} P(n(T) = i) \cdot c \cdot i \qquad (1)$$

IntheresearcharticleofJointCommitteeonStructuralSafety – JCSS [2, 3, 7], investigationsofH. KumamotoandE. J. Henley[7], T.G.Theofanous [10],T. AvenandJ. E. Vinnem[1] havedeterminedthatingeneralaspectforpartialrisk$R_i$fromallpossiblerisksarray, shoulddeterminebasedonsystem'sdevelopmentwithdifferentways – "scenarios" whichcanbe presented as:

$$R_i = (S_i, P_i, C_i), \qquad (2)$$

forequations(1) and(2):R – risk; S_i– therangeofpotential (predicted) consequences, todeterminetheriskweneedtherespectivelikelihoods;P_i – frequencyoffailures; C_i –the consequence (failure) of event; i – numberofevent (scenario); $P(n(T)=i)$ – the probability of$i$event of the considered type within the time frame T; c– the consequence associated with the occurrence of the event.

With accordance of H. Kumamoto and E. J. Henley [6], the S can be spread as direct money losses, lost time, number of fatalities and injuries, indirect losses, longevity loss.

D. D. Diamantidis, M. Holicky and M. Sykora in [5] specifiedthe parametersofriskacceptancecriteriawhich related with reliability levels of structures. They also proposed to assess the risk as differences between of assessment of existing structures reliability parameters and demands of structural design.

P. Thoft-Christensen [10]confirm, that the structures have multiple performance requirements, commonly expressed in terms of a set of serviceability an ultimate limit states, most of which are not independent, so the arising problem of risk analysis is much more complex than the specification of just a single probability.

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P. Drukis, L. Gaile and L. Pakrastins[4]proposed to use an inspection method for assessment of existing buildings, where whole essential safety aspects have been assessed in common way and in the same time and improve common guidelines for estimation of risk factors for specified essential requirements.

The survey of researches to risk-analysis dedicated, shown that the safety service of structures may be achieve with the assumptions, that the risk is always exists as a complex probability of unfavorable event's occurrence when the limit state is achieved with variable loads and materials properties. For real structures the uncertainty and ranges of technical parameters affected on risk, could be correctly determined only based on technical inspections' results that describe the structures' actual behavior.

III. AIMS AND SCOPES

Takinginconsiderationthe real data from the history of structure's service and technical investigations results, the specialist (researcher, investigator, enquirer) has a good basis for examination of structure's technical state. But, even having the maximum of possible information, almost all the times, exist aprobability that some imperfections were not be found during inspections. These imperfections sometimes could have dangerous level (range) of realization. Other words, always exist a possibility that structure after inspection has the imperfections which did not found and thus, did not registered for future stress-strain analysis for assessment the technical state of structure.

So, besides all compulsorystructure'sreliability calculations, all risk parameters that could exist, must be identified with each level of uncertainty and probability of its appearances.

Theeconomictasksrelatedwithdifferenttypes of lossesalsopresentindependently. It should be analyzed for each index separately. In this paper these tasks will not discuss.

IV. RISK IDENTIFICATION FOR BUILDING STEEL STRUCTURES UNDER OPERATION

Under the risk for stress-strain condition of structure will understand the probabilistic transit from one technical state to another. Normally, it is actual for transition from state 2 "need for repair" to state 3 "unfit for use (state of failure)". The relation between safety index and technical state – see[5, 12].

All discussions stated below, will relate only for steel building structures. Itcouldbeexplainedbecause of the steel do not have significant changes of its mechanical properties during the time; the propagation for each imperfection, in general, possible to evaluate by mathematical relation; the stress-strain conditions for steel structures may be sufficiently easy determined, takingthe only one material properties.

The principle for risk assessment R is a functionality F, that connect probability P of negative event and mean of expected value of losses U upon this event:

$$R = F_R\{U,P\} = \sum_i \left[F_{R_i}(U_i,P_i)\right] = \int C(U)P(U)\,dU = \int C(P)U(P)dP, \quad (3)$$

here i–the negative event, that respond to mutual risks influence.

In general case, for quantitate and qualitive analysis by the equation (3) on the basis of complex analysis of dynamic dangerous processes (defects, imperfections, damages, accidents, failures), special physical and mathematical models should be created as for local risks also for integrated type of hazard with related combinations for global risk.

Depending from the possible damage, the economic losses must be calculated:

U1– the failureisabsentorinsignificant – valueofadditionalemergencyworksforinvestigation, designingworksandrepairingworks:

U2 – thefailure issignificant – valueofadditionalemergencyworksfortechnologicalprocessre commencing, investigation, designingworksandrepairingworks;

U3 - the general – valueofexpensesfortechnicalservicedepartment(s) renewal.

For allmodels and scenariosfor hazard events' which can appearanceand develop in time t, the given, calculated and postulated hazard processes use. This approach applies a time-scale risks $R(t)$.

Thesafetyconditionswillbe specified as:

$$\{R, R_{F,t}\} \leq \{[R], [R_{F,t}]\}, \quad (4)$$

wherethe$R_{F,t}$ – riskvaluefordefinedpoint$F$fortime$t$.

$[R]$, $[R_{F,t}]$ - maximumpermittedvaluesforrisks.

Duringtechnicalinspection, two types of imperfections could be found:

- defect – the imperfection which structure got on the stages of design, transportation to the site, erection and during construction works – i.e. all works before structure start to operation;
- deterioration - the imperfection which structure got during the duration of service.

In the time following, all imperfections will define as DDs (Defects and Deteriorations).

There are exists a few reasons of failure:

1. Absence, changing (deterioration) parameters of structural safety. It includes:
   - developmentintimefoundedDDswhichcanexceedthe limits and lead to destructive;
   - realizationofhidden – non-detectedDDs, whichnot be founded during technical inspection of the structure.
2. Changing (deterioration) of organizingandtechnicalsafetyparameters – OTS. Here we shall understand all, mostly subjective or human factors, which influenced on structures' safety: lack of design papers and pre-design solutions, absence of in-time inspections and registrations systems, lack/absence of technical services, etc.
3. Deteriorated impact of the natural environment on normal structures' behavior.
4. Internaltechnologicalprocessimpactonnormalstructures' behavior.

Thegeneralmethodologyofrisk-analysisconsistson following actions:

- work planning and organization;
- hazardsidentificationandriskrecipient definition;
- risk assessment;
- calculation of losses;
- preparationofrecommendations for risk influence decreasing.

Theanalysisofhazardsallowsidentifythefollowingrisksforsteelbuildingstructures: risksthateffectonconstructivesafetyandrisks, thateffectonOTS.

Forconstructivesafety, therearefollowingriskscouldbeidentified:

K1 group –the riskofnon-detectedDDsduringtechnicalinspection. ThisDDshaveabiggerdangerousandcouldberegisteredas damaged category. For example, in Ukraine exists special state technical standard [11] (mostly for preliminary assessment) where all possible DDs are described and ranged in three categories depend on its influence on structure: C_d – normal (DDs have only small appearance), B_d– satisfactory (DDs have measured dimensions, but not crucial) and A_d– accidental (DDs have dimensions and properties which are not allowable).

K1.1– therisk of cracks in basic metal and welds existence;

K1.2– the riskofpittingcorrosionexistence;

K1.3– the riskofweldsimperfectionexistence;

K2 group – the riskofappearance of the situations, which were not taken in consideration during project preparation and did not appear during service yet. The most typical risk – the unpredictable loads increasing.

Also, the risks could be determined forOTS– therisksof stagnation, nonfulfillment or terminating the executionfor OTS measures. The possible results of its may be non-controlled changing of structural designs, connections, technological failures.

V. RISK ASSESSMENT OF NON-IDENTIFIED IMPERFECTIONS

Forpredictionofnon-detectedDDsof*K1*group, allinformationaboutdefinedDDsmustbeanalyzedandturned in account. There are two cases may be possible:

The case*A*:theimperfectionshavefoundanddefinedinrelativezones.

The case*B*:theimperfectionshavenot found. But, based on design calculations (number of load cycles, for example), its presence quite possible.

Firstly, we'll analyzethe situation of case *A*. Letassume, that:

- $K_{ti}(d_j)$ – thetotal(index "*t*")numberofDDs of*i* – nametitle, whichexistinzoned_j;
- $K_{ni}(d_j)$ –thenumberofnon-detected(index "*n*") DDsof*i* – nametitle, whichexistinzoned_j;
- $K_{di}(d_j)$– thenumberofdetected(index "*d*") DDsof*i* – nametitle, whichexistinzoned_j;

All DDs situated on thicknesses of elements, in aforesaid indexes of the zone – variable d_j is a steel thickness with subsisting DDs – the thickness of the wall, thickness of the stiffener, the steel bearing end plate of beam, the welding chord, etc.

The most common and basic is the case *A1* – when DDs exist, but the history of technical inspection is absent. Then, for risk determination – the probability of existence of non-defined DDs, the following procedure proposed.

The technical inspection must perform for all structure, which has the general dimension of all zone *j* of inspection – A_{tj}. As a rule, the detailed inspection could not be done for 100% of structure, but only on defined part A_{dj}, i.e remain the part of the structure A_{nj}, where inspections did not fulfill. On the part of $A_{вj}$, there was the $K_{вi}(d_j)$ imperfections were defined. Taking in consideration, that:

$$A_{tj} = A_{dj}+ A_{nj}, \qquad (5)$$

and

$$K_{ti}(d_j)= K_{di}(d_j)+ K_{ni}(d_j), \qquad (6)$$

Thegeneralnumberofnon-defined$K_{ni}(d_j)$ DDs3 forzone (part) A_{nj}, whereinspectionwasnotdone, couldbecalculatedas:

$$K_{ni}(d_j)= A_{tj} \cdot K_{di}(d_j)/A_{dj} – K_{di}(d_j). \qquad (7)$$

The probability of existence of *i* DDs on d_j zone can be view as ratio either zone *j*, where inspection had place to the all zone of inspection, either, that is the same, as ratio of number of defined DDs to its common number:

$$P_i(d_j)= A_{dj}/A_{tj} = K_{di}(d_j)/K_{ti}(d_j). \qquad (8)$$

The risk of future service may calculate by (3), with taking into account possible loss on structure renovation in *j* zone for *i* DDs after recovery from a damage or destruction:

$$R_j=P_i(d_j)\cdot U1_j \text{ or } R_j=P_i(d_j)\cdot U2_j. \qquad (9)$$

Realization of all number of *i*DDs on all *j* zones, where the structures situated, leads to risk:

$$R = \sum_i \cdot \sum_j P_i\,(d_j) \cdot U1_j C_j \text{ or}$$
$$R = \sum_i \cdot \sum_j P_i\,(d_j) \cdot U2_j C_j. \qquad (10)$$

For all structure, the maximum probability of damage for all zones d_j and all DDs:

$$P = max\,[P_i(d_j)], \qquad (11)$$

which after allowing to calculate the risk of constructive safety:

$$R_{C1} = P\cdot U1\cdot C \text{ or } R_{C2} = P\cdot U2\cdot C. \qquad (12)$$

In the practice of technical investigations also possible a case A2 – the history of investigations with defined DDs exist, that means that the results of previous investigations could be obtained. For this case propose a following order for risk determination. Suggested, that all DDs with dangerous parameters were fully renewed after the investigation.

Firstly, based on the results of previous investigation, the common number of all DDs: defined, non-defined, total, dimensions of the inspected zones, list of DDs. The calculations fulfilled with the equations (5) – (8). The time T between last (previous, first) and new (second) investigations also define.

Then, for the second investigation, that performing, based on defined DDs for all zones of inspections and types of imperfections by the (5) – (8), also all DDs' should be defined. The main step is the comparison betweenof one and the other results. For this, for one zone d_j, the number of defined DDs is calculated for the second investigation, with the same values, as for the previous investigation $K_{di,1}$:

$$K_{d,pr2} = K_{di,2P} \cdot (A_{di,1}(d_j) / A_{di,2}(d_j)), \qquad (13)$$

where $K_{di,2P}$– the number of DDs of the second investigation, which defined on total area (number of zonesd_j) $A_{di,2}(d_j)$; $A_{di,1}(d_j)$ – the total area (number of zonesd_j), where iDDs have defined during the previous investigation.

Number of $K_{di,2}$ and$K_{di,1}$ (number of iDDs of the previous investigation) compare. If, during time T with all equal parameters $K_{di,2} \geq K_{di,1}$, it shows that process of DDs is under progress. For this situation the future renovation is not economically appropriate,and structure should be substituted.

If the number of DDs $K_{di,2} \geq 0,5K_{di,1}$, it shows that the renovation works were effective, and the repairing design solutions were right.

The next important parameter is a ratio of total number of DDs (defined and non-defined) in the first (previous) $K_{ti,1}$and second (actual) $K_{ti,2}$ technical investigations. Inherently, it is a probability of existing of iDDs for zone d_j, and may characterize the probability of DDs' appearance in future:

$$P_i(d_j) = K_{ti,2} / K_{ti,1}, \qquad (14)$$

The risk of structure's safety service calculates by (9) – (12).

The other separate task is the determination of DDs' critical parameters, usually dimensions, when possible or the destruction of all structure - the global destruction, eitherits local destruction. But and it should be precisely clear, these principles may be adopted only for structures, which could be temporary exploited with the cracks. As the basic information, the critical DDs dimensions may be taken as determined parameters. For this case, for example, for development of corrosion process,the special investigations may be assumed. After the critical dimensions adopted, the global or local destruction assess as:

$$\sigma_0 \geq k \times \sigma_R, \qquad (15)$$

where σ_R – the limit bearing capacity of the structure;$k=f(R_y,t_j,z)$; z –the critical DDs parameter. Here, for example, could be DDs with parameters (dimensions) which belongs to categories $A_d$andB_d[11].

The number of detected defects, which can lead to real damages – $K_{dd}(d_j)$, determine on results of technical investigations and structure's checking calculation.

The number of non-detected defects, which can lead to damages$K_{nd}(d_j)$:

$$K_{nd}(d_j) = K_{tn}(d_j) \cdot (K_{dd}(d_j) / K_{td}(d_j)). \qquad (16)$$

where $K_{tn}(d_j)$ – the total number of all non-detected DDs and$K_{td}(d_j)$ – the total number of all detected DDs.

ThecommonnumberofDDs, with the criticalparameters fordamages of the structure:

$$K_p(d_j) = K_{вp}(d_j) + K_{нp}(d_j). \qquad (17)$$

For corrosion DDs for which on the time of investigation dimensions did not attain the critical ones, the speed of its propagation in T years after registration propose to calculate with Gaussian models:

$$\varphi(T,z) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(z-m)^2/2\sigma^2}, \qquad (18)$$

where: m – themeanofDDwithcritical$z$dimension; σ – the root-mean-square deviation.

The depth of corrosion is a normal-distributed variable with parameters:

$$m = d + Tv_d; \qquad \sigma = \sqrt{\sigma'^2 + T^2\sigma_v^2}, \qquad (19)$$

where d – the measured value of critical parameter; v_d– the speed of corrosion DDs propagation; σ'– the root-mean-square deviationof initial registered dimension of DDs; σ_v– the root-mean-square deviationof speed propagation of DDs.

For determination of DDs dimensions such as cracks and welds imperfections (irreversible process of degradation), possible to use the parameters of diffuse monotonous distribution – DM distribution. The probability of acquisition of critical $z$dimension for DDs after $T_к$ years with possibility of destruction (index KP) is:

$$P_{KP,d}(T_к, z) = \int_d^z \varphi(T_к, z)\,dz. \qquad (20)$$

For independent hypothetic non-detected DDs, the specific probability of structure's destruction calculated as:

$$P_{KP,n}(T_к, z) = 1 - [(1 - (P_{KP1}(T_{к1} d_{KP1})^{m_1}) \times \ldots \times (1 - (P_{KPi}(T_{кi} d_{KPi})^{mi})], (21)$$

where$m$ – thecorrectionfactorforeachDD, whichcandetermineitsspecificsignificance, for general case $m=1$; $1 \ldots i$ – the total number of non-detected DDs.

Based on (4), the risk of possible destruction of all structure during calculated residual life for K1group (K1.1 – K1.3) defines as:

$$R_R(T_к, z) = U(Z) \times (\sum_1^i P_{KP,d}(T_к, z) + \quad + \sum_1^i P_{KP,n}(T_к, z)), \quad (22)$$

where $U(Z)$ –the losses from destruction, which calculated by economic criteria, in general aspect present as:

$$U(Z) = [U1; U2]. \quad (23)$$

Let's analyze the case B. The accidental imperfections – A_d category – did not found during investigation, but they exist as B_d and theoretically possible its existence. Then, $K_{di}(d_j)=0$ and definitions as for case *A1* and *A2* have no any mathematic sense. Based on the logic of risk, the probability of damage or accidental technical state of the structure, should consider:

- the ratio of inspected area (value, number of elements, zones) to the total area;
- the number of all DDs of $B_d$category;
- the initial design life;
- the residual life.

The following steps proposed for final adopted solution.

1. The probability ofnon-defined DDs existence is: $P_i(d_j)=A_{dj}/A_{tj}$.Suggested, that it is equal to the ratio of inspected area (value, number of elements, zones) to the total area. It is correct when the structure was in service not more that 75% of design life, has a sufficiently big residual life and where inspected area $A_{dj} \geq 0{,}8A_{tj}$.
2. For structures after its design life T_0, and with the determined residual life T_t, the probability of existence of non-defined DDs proposed as:

$$P_i(d_j) = (A_{dj}/A_{tj}) \cdot \log_{T0}(T_t), \quad (24)$$

or,what is the same,but with the defined and total numbers of DDs of B_d:

$$P_i(d_j) = (K_{dj}(d_j)/K_{tj}(d_j)) \cdot \log_{T0}(T_t). \quad (25)$$

The risk for all structure with different types of DDs and inspected zones calculates as for cases A1 and A2 by the equations (9) - (12).

Proposed principles of risk assessment for future safety steel structures' service with defined and non-defined imperfections could correct the results of technical investigations for determinations of the residual life andthe time range that were previouslydetermined between these investigations. Appears the real possibility to realize the risk management system by the means of additional analysis after the renovation works and regular investigations.

In the risk equation (3) only wage function C was not described. For steel structures, if DDs of A_d category exists, means that all of them are accidental, if exist different types of DDs of B_d category, that for residual life all of them have the same wage and then $C = 1$. But, could appear the additional parameters, which will influence for general safety level and change the probability of failure.

VI. CONCLUSIONS

1. The general relations for risk identification and calculation for safety service of steel structures are proposed.
2. Theprinciplesofriskassessmentforconstructionalsafetywith probability of existence of non-detected imperfections havedone. Thecaseswithdetectedandnon-detectedimperfectionsbasedonprevioustechnicalinspectionsandits criticalDDsparametershaveexamined.

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