TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
CIVIL ENGINEERING | BUDOWNICTWO

4-B/2014

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DIFFERENTIATING THE RELIABILITY OF ALUMINUM STRUCTURES[1]

RÓŻNICOWANIE NIEZAWODNOŚCI KONSTRUKCJI ALUMINIOWYCH

A b s t r a c t

The design of aluminum structures, according to the modern generation of European standards, sets new requirements regarding the reliability management of such facilities before the authors of architectural and structural designs. Reliability problems should be formulated at an early stage of the investment process – the construction design, in a clear manner, requiring the authors of detailed designs and contracting companies to provide structures exhibiting the operating parameters in agreement with the expectations of the investor. The basics of substantive and formal requirements in this respect are set out in Eurocode PN EN 1990 and the European standards dealing with the manufacturing and erection of structures. Problems of modern reliability management for aluminum structures are referred to the case of large volume buildings subject to climate actions.

Keywords: *aluminum*, *reliability*, *consequence classes*, *structural classes*, *manufacturing classes*, *supervision level*, *inspection level*

S t r e s z c z e n i e

Projektowanie konstrukcji aluminiowych wg współczesnej generacji norm europejskich stawia przed autorami projektów architektoniczno-budowlanych nowe wymagania w zakresie zarządzania niezawodnością takich obiektów. Problemy niezawodności należy sformułować już na wczesnym etapie procesu inwestycyjnego – w projekcie budowlanym, w sposób jednoznaczny, zobowiązujący autorów projektów wykonawczych, a także firmy wykonawcze do dostarczenia konstrukcji o parametrach eksploatacyjnych zgodnych z oczekiwaniami inwestora. Podstawy merytoryczne i formalne w tym zakresie są sformułowane w Eurokodzie PN-EN 1990 oraz w europejskich normach wykonania konstrukcji. Problemy współczesnego zarządzania niezawodnością konstrukcji aluminiowych odniesiono do przypadków budynków kubaturowych poddanych oddziaływaniom klimatycznym.

Słowa kluczowe: *aluminium*, *niezawodność*, *klasy konsekwencji*, *klasy konstrukcyjne*, *klasy wykonania*, *poziom nadzoru*, *poziom inspekcji*

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[1] The paper is a reprint of an article that appeared in Polish language under the title *Projektowanie konstrukcji aluminiowych. Różnicowanie niezawodności* in the journal Builder, No. 02/2014, 42-45.

1. Managing reliability in the design phase

In engineering approach to reliability problems used in the PN-EN 1990 [1] three level consequence classes have been introduced, denoted by CC1, CC2 and CC3 symbols respectively. Consequence classes are defined according to the risk to human life and health and economic consequences of structural damage or loss of fitness for purpose. CC consequence classes are associated with three corresponding structural reliability classes RC – RC1, RC2 and RC3, for which the code [1] sets the minimum required values of reliability coefficient β_u assigned to the ultimate limit states. See, among other works, [11] and [12].

Reliability diversification by the advanced mathematical method FORM [11] is based on full knowledge of the statistical parameters describing load and bearing capacity. At the present stage of the development of statistical methods, the design of building structures is permitted in three reliability classes (RC) by engineering load factors and bearing capacity method, and the FORM method allows for calibration of reliability measures in this method. For reliability class RC2 corresponding to consequence class CC2, partial coefficients are calibrated in the relevant branch Eurocodes. In particular, the basic coefficients for permanent and variable loads γ_F are specified in Annex A1 to the PN-EN 1990 [1], and bearing capacity factors γ_{Mi} for aluminum components in different parts of the Eurocodes PN EN 1999-1-1 [4] – PN EN 1999-1-5 [8].

A simple method of varying the reliability requirements for variable loads, according to [1], is an adjustment of the load factors γ_F, with K_{FI} correction factors listed in Table 1.

Table 1

Values of K_{FI} factors for actions according to PN-EN 1990

Correction factor	Reliability class		
	RC1	RC2	RC3
(1)	(2)	(3)	(4)
K_{FI}	0.9	1.0	1.1

In reliability theory, loads are described by functions that depend on the life of the structure. Therefore, designing a building requires the determination of the design life of the structure T_d, which is the time interval in which the structure, or part thereof, is to be used as intended with anticipated maintenance, without the need for major repairs.

The PN-EN 1990 [1] introduced a systematic breakdown of the useful design life into five categories, listed in Table 2. In most cases, building structures are designed assuming a 4th category design period, which corresponds to a 50-year long designed service life of a building. The PN-EN 1990 [1] stated explicitly recommended minimum values of reliability index β only for the ultimate limit state for the reference period $T = 1$ year and $T = 50$ years. The different service life periods T_d for buildings, according to Table 2, require an interpolation formula to determine the reliability index β corresponding to the accepted category of the designed service life. One may assume that for mutually independent random load peaks, the following relationship holds between reliability indicators for the reference period $T = n$ years and $T = 1$ year, expressed in terms of Laplace functions:

$$\Phi(\beta_n) = \Phi(\beta_1)^n. \tag{1}$$

Table 2

Designed Service Life categories according to PN-EN 1990

Category of Designed Service Life	Design life of the structure T_d in years	Sample structures
(1)	(2)	(3)
1	10	Temporary structures
2	10–25	Replaceable components
3	15–30	Agricultural structures and similar
4	50	Ordinary buildings
5	100	Monumental buildings, bridges

A practical example of the reduction of characteristic variable loads Q_{kn} at time $n \neq 50$ years is the application of appropriate reliability theory models to climate loads, described by the probability distributions of maximum values. In particular, the formula given in the standard PN EN 1991-1-5 [4] applies to thermal loads:

$$T_{k,n} = T_{k,50}\left\{k_i - k_j \ln\left[-\ln\left(1-\frac{1}{n}\right)\right]\right\} = T_{k,50}\eta_d, \tag{2}$$

where:

$T_{k,50}$ – characteristic values (maximum or minimum) of air temperature in the shade, with an annual probability of exceedance equal to 0.02,

k_i, k_j – multipliers specified in PN-EN 1991-1-5 [4]: $k_i = 0.781$ and $k_j = 0.056$ for the maximum temperature T_{max} while $k_i = 0.393$ and $k_j = -0.156$ for the minimum temperature T_{min} – respectively.

For snow load, the extrapolation formula given in the standard PN EN 1991-1-3 [2] holds:

$$s_{k,n} = s_{k,50}\,\frac{1-0.78v\left\{\ln\left[-\ln\left(1-\frac{1}{n}\right)\right]+0.577\right\}}{1+2.592v} = s_{k,50}\eta_d, \tag{3}$$

where:

$s_{k,50}$ – characteristic values of ground snow load according to [2],

v – coefficient of variation specified in the standard [2]: $v = 0.7$ for buildings located at a height of $H \leq 300$ m above sea level and $v = 0.8 \exp(-0.0006H)$ when $H > 300$ m above sea level.

The reduction formula for base wind speed according to PN-EN 1991-1-4 [3] is as follows:

$$v_{b,n} = v_b\sqrt{\frac{1-0.2\ln\left[-\ln\left(1-\frac{1}{n}\right)\right]}{1-0.2\ln[-\ln(0.98)]}} = v_b\eta_d. \tag{4}$$

Table 3

Conversion coefficient values for climate loads

Return period n [years]	Conversion coefficient η_d			
	Action			
	s_k	v_b	T_{max}	T_{min}
(1)	(2)	(3)	(4)	(5)
10	0.70	0.90	0.91	0.74
15	0.77	0.93	0.93	0.81
25	0.87	0.96	0.96	0.89
30	0.90	0.97	0.97	0.92
50	1.00	1.00	1.00	1.00
100	1.13	1.04	1.04	1.11
300	1.33	1.10	1.10	1.28
500	1.42	1.12	1.13	1.36

Because of the complex structure of the formulas (2)–(4), the calculation of the characteristic climate loads for typical return periods is justified. One may present it in the form of the load conversion coefficient η_d for maximum loads having the return period of $n = 50$ years (see Table 3).

Reliability diversification of aluminum structures, an alternative to the complex calculations of probability level 2, may be done by reducing the load factors γ_F by the K_{Fi} reducing coefficients according to Table 1. The corresponding reduction factors K_{Ri} according to [1] may be used to reduce partial bearing capacity factors γ_{Mi} for sections and bars. In the current version of Eurocode PN EN 1999-1-1 [6] – PN EN 1999-1-5 [10], coefficients K_{Ri} have not been specified, because for the dominant variable loads with moderate scatter (load variation coefficients $v_F < 25\%$), the standardized values of coefficients K_{Fi} capture both the effect of reducing the loads and the strength of aluminum alloys. Climate loads, such as the snow load constitute an exception to this rule, since in Polish climate conditions, the snow load is characterized by high dispersion with variation coefficient values $v_F = 80 - 100\%$, cf [11].

A sample specification of reduction factors K_{Ri} for the strength of the AlCu4Mg2 alloy made in Poland is presented in Table 4. The values of K_{Ri} in columns (8)–(10) were calculated according to the following formula:

$$K_{Ri} = \frac{1 - 3.04 v_{\mathrm{Re}}}{1 - \beta_R v_{\mathrm{Re}}}. \tag{5}$$

Values of the partial reliability index $\beta_R = 0.8 \times 3.3 = 2.64$ for reliability class RC1, and $\beta_R = 0.8 \times 4.3 = 3.44$ for reliability class RC3 were adopted in the formula (5) according to [1]. Moreover, column (6) lists the central plastic bearing capacity factor $\overline{\gamma}_{M0}$ calculated as the ratio of average $\overline{R}_{02}$ and computational R_{ed} values (bottom quantiles calculated for the partial index β_R).

Table 4

Reliability measures $\overline{\gamma}_{M0}$ and γ_{M0}, reduction coefficients K_{Ri} specified on a statistical sample of AlCu4Mg2 alloy strength according to own research [11]

Product group	Thickness t [mm]	Yield limit R_{02} [MPa]					Reliability class RC1	RC2	RC3
		$\overline{R}_{02}$	v_{Re}	β_R	$\overline{\gamma}_{M0}$	γ_{Mo}	K_{Ri}	K_{Ri}	K_{Ri}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Plates	2–10	308	0.059	3.04	1.24	1.00	0.972	1.000	1.030
	12–25	335	0.042		1.35	1.00	0.981	1.000	1.019
	26–40	335	0.037		–	–	0.984	1.000	1.017
	41–70	328	0.044		–	–	0.980	1.000	1.020
	2–80	322	0.062		1.29	1.00	0.971	1.000	1.031
Profile bars	2–20	378	0.093	3.04	1.42	1.00	0.963	1.000	1.055
Bars	to 30	373	0.098	3.04	–	–	0.947	1.000	1.059
	> 30	383	0.087		–	–	0.955	1.000	1.049
	16–130	381	0.090		–	–	0.953	1.000	1.053

Reliability diversification of aluminum structures, in addition to the specifications given above, may also be carried out by the system safeguards. The design supervision levels classification (DSL), cited in Table 5 exhibits such a character, indeed. The DSL is defined in PN-EN 1990 [1] for the design stage are linked to the reliability classes (RC) selected according to the importance of the structure. The diversification of project supervision within the design unit may further include the classification of designers and verifiers, depending on their expertise, skills and experience.

Table 5

Design supervision levels (DSL) according to the code PN-EN 1990 [1]

Design supervision level	Supervision characteristics	Minimum recommended requirements for checking calculations, drawings and specifications
(1)	(2)	(3)
DSL3 Referring to RC3	stringent	checked by an independent design entity
DSL2 Referring to RC2	standard	checked by the verifying authority of the design unit according to own procedure
DSL1 Referring to RC1	acceptable	self control: checked by the designer

2. Reliability management during manufacturing and erection of a structure

Ensuring the required reliability of aluminum structures involves at the stage of manufacturing and installation the need to develop a specification of the execution, which in accordance with PN EN 1090-3 [5], among others includes:

a) requirements relating to manufacturing classes,
b) technical requirements taking into account work safety,
c) quality plan,
d) functionality requirements.

Table 6

Dependencies taken into account when selecting Structure Execution Classes(EXC) [6]

Consequence Classes		CC1		CC2		CC3	
Service Classes		SC1	SC2	SC1	SC2	SC1	SC2
Manufacturing Classes	PC1	EXC1	EXC1	EXC2	EXC3	EXC3[a/]	EXC3[a/]
	PC2	EXC1	EXC2	EXC2	EXC3	EXC3[a/]	EXC4

[a/] EXC4 class is applied to special structures, whose destruction would result in extreme consequences; in particular when EXC4 class is required by national codes.

Four structure execution classes: EXC1, EXC2, EXC3 and EXC4 have been defined in Eurocode EN 1999-1-1 [6], starting with the least stringent (EXC1) to the most demanding (EXC4), see Table 6. Execution classes may be applied to an entire structure, to parts of the structure, and even to its details, therefore, within a single building, several execution classes (EXC) may occur.

According to the understanding adopted by the PN-EN 1090-3 [5], if the execution class is not specified in the design documentation, EXC2 class is assumed. Selection of execution classes (EXC) depends on the manufacturing category PC (non-welded components – PC1, welded components – PC2) and category of use (see Table 7), and is associated with the consequence classes CC defined in standard [1]. Manufacturing (PC) and Service (SC) classes take into account the risks associated with the manufacturing and service of the structure. The execution class (EXC) selection procedure includes in sequence:

a) Selection of consequence class (CC), taking into account the potential consequences of a structural disaster in the form of loss of life, economic and environmental degradation.
b) Determination of the manufacturing class (PC) and the service class (SC) (see Table 7).
c) Determination of the execution class (EXC) depending on the CC, PC and SC according to Table 6 (see PN-EN 1999-1-1 [6]).

The execution class (EXC) constitutes an essential element of structural reliability because it determines the requirements for enforcement actions formulated in the PN-EN 1090-3 (Table A.3 of the code [5]). In particular, requirements for design documentation, product design, processing and merging, welding, assembly and inspection, testing and corrective action are formulated there.

Table 7

Recommended criteria for service class (SC) according to code [6]

Class (SC)	Criterion
(1)	(2)
SC1	Aluminum structures and components designed against predominately static loads
SC2	Structures subject to repeated variable loads of intensity requiring implementation of the control procedure provided for components subject to fatigue (tolerated fatigue damage method according to [8])

Table 8

Inspection levels during erection of building structures according to the code PN-EN 1990 [1]

Inspection level	Characteristics	Requirements
(1)	(2)	(3)
IL3 referring to RC3	Stringent inspection	Third party inspection
IL2 referring to RC2	Standard inspection	Inspection according to own procedures of the erecting unit
IL1 referring to RC1	Acceptable inspection	Self inspection

The execution, as well as the design phase for a structure, is subject to control, which can be provided by organizing systematic inspections at various levels. Inspection levels (IL) at all stages of execution, including the production of building materials and products are defined in code PN EN 1990 [1], see Table 8. Inspection levels are associated with a Reliability Class (RC), cf paper [12], and may be implemented by means of appropriate quality management measures.

3. Conclusions

The Eurocodes constitute a new generation of standards leading to profound systemic changes at every stage of the investment cycle. Eurocode PN EN 1990 constitutes a normalized basis for the design stage and contains the formulation of basic elements of reliability management for building structures, including structures made of aluminum alloys. In the domain of manufacturing and erecting aluminum structures, code PN EN 1090--2 constitutes the basis for quality assurance. In contemporary developments, each structural design should include: building consequence class CC; reliability class RC; the design service life category; structure execution class EXC; supervision and inspection levels DSL and IL. It is also recommended, for buildings and their components sensitive to climate action, particularly for CC3 class buildings, to make precise forecasts of loads, derived from long-term meteorological observations, as well as differentiate reliability requirements in terms of computational strength for alloys.

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