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ZAKŁADANA NIEZAWODNOŚĆ NOWYCH I ISTNIEJĄCYCH HISTORYCZNYCH KONSTRUKCJI

TARGET RELIABILITY FOR NEW, EXISTING AND HISTORICAL STRUCTURES

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

Zakładany poziom bezpieczeństwa zależy głównie od dwóch czynników: konsekwencji zniszczenia i względnego kosztu. Dla obiektów historycznych należy dodatkowo uwzględnić elementy społeczne oraz polityczne. Istotnym czynnikiem jest także aktualna praktyka, jako weryfikacja procedury projektowej. Zachowanie konstrukcji wygodnie jest opisywać poprzez wskaźnik niezawodności. Porównano wskaźniki niezawodności oblicz. dla belek i słupów budynków oraz mostów projektowanych wg ACI318 i AASHTO LRFD. Zauważono, że różnice pomiędzy nowymi wymaganiami projekt. oraz kryteriami akceptacji dla istniejących mostów są b. znaczące. Planowany wskaźnik niezawodności dla konstrukcji istniejących jest niższy ze względów ekonomicznych

Słowa kluczowe: wskaźnik niezawodności, normy, stany graniczne, obiekty historyczne

A b s t r a c t

The target safety level depends mainly on two factors: consequences of failure and relative cost. For historical structures, in addition it can be affected by social and political considerations. An important reference is also a current practice as it can be considered as a verification of the design procedures. It is convenient to quantify structural performance in terms of the reliability index. The paper reviews the reliability indices calculated for beams and columns in buildings and bridges, designed according to ACI 318 and AASHTO LRFD Code. It is observed that the difference between new design requirements and acceptance criteria for evaluation of existing bridges is very significant. The target reliability index for existing structures is lower because of economic considerations.

Keywords: reliability index, design codes, limit states, historical structures

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1. Introduction

The new generation of design codes is based on the limit states. For each limit state, safety reserve is determined by a set of load and resistance factors. Limit state functions have to be formulated, representing the border between acceptable and unacceptable performance. The probability of failure is equal to the probability that limit state function takes a negative value. Structural performance can be measured in terms for the reliability index, β. The available methods for calculation of β are presented in the textbooks, e.g. Nowak and Collins (2000). The reliability analysis requires statistical models of load and resistance.

The major steps in the development of a design code include selection of representative structures, formulation of limit states, development of load and resistance models, selection of the target reliability index, and finally selection of load and resistance factors based on closeness to the target reliability (Kaszynska and Nowak 2005). The present paper deals with selection criteria for the target reliability index for new design, evaluation of existing structures and historical structures.

The reliability analysis procedures can be used for comparison of different variants of design alternatives, materials and types of structure. Optimum safety level can also be expressed in terms of the target reliability index. The development of load and resistance factor design (LRFD) codes requires the knowledge of the target reliability level. The optimum safety level depends on the consequences of failure and cost of safety. For historical structures it can also depend on social and political considerations.

Target reliability indices calculated for newly designed and existing structures are different for many reasons. One of them is a reference time period, as for example, new bridges are designed for 50-75 year life time and existing structures are checked for much shorter periods, e.g. 5 or 10 years. Load model, used to calculate reliability index depends on the reference time period. Maximum expected forces and resulting moments and shears are smaller for 5 or 10 year periods than for 50-75 year life time. However, the coefficient of variation is larger for shorter periods. Single load path components require a different treatment than multiple load path components. In new designs, single load path components can be avoided, but such components can be found in some existing structures, in particular in vey old ones. Target reliability index is higher for single load path components.

Reliability indices calculated for existing structures can be considered as the lower bounds of safety level acceptable by the society. A drastic departure from the acceptable limits should be based on an economic analysis. The target reliability index depends on costs and has different value for a newly designed structure and an existing one. In general, it is less expensive to provide an increased safety level in a newly designed structure. For bridges or buildings evaluated for 5 or 10 year periods (intervals between inspections), it is assumed that inspections help to reduce the uncertainty about the resistance and load parameters. Therefore, the reliability index can be lower for existing bridges and buildings evaluated for 5 or 10 year periods.

Because of economical reasons, it is convenient to differentiate between primary and secondary components. The difference between these components depends on the consequences of failure. Target reliability index for secondary components is lower than that for primary components.

2. Load models

The considered load components include dead load and live load. The statistical parameters for load components are taken from the available literature (Ellingwood at al. 1980, Nowak 1999). The statistical parameters of load are bias factor and coefficient of variation. For each design case considered, the mean value of load is calculated as a product of the nominal (design) value and bias factor. The standard deviation is calculated as the product of the mean and coefficient of variation.

Dead load is the weight of structural and non-structural elements permanently connected to the structure. The bias factor (ratio of mean-to-nominal) value of dead load is, $\lambda = 1.05$, and coefficient of variation, $V = 0.10$ for cast-in-place concrete, and $\lambda = 1.03$, and coefficient of variation, $V = 0.08$ for structural steel and precast concrete (Nowak and Collins 2000).

Live load in buildings is the weight of people, furniture, partitions, and other items. For the maximum 50-year live load, the bias factor is $\lambda = 1.0$, and the coefficient of variation, V, varies depending on the influence area. V decreases with increasing influence area. In this study, the calculations were performed for several influence areas, but the results are presented for 40 m^2 and $V = 0.18$.

The basic load combination includes dead load and live load. The reliability analysis is performed for a full range of load ratios that are expressed as D/(D+L), varying from 0 to 1. However, the practical range of D/(D+L) is between 0.3 and 0.9.

Statistical models of load and resistance for highway bridges are described by Nowak (1993; 1995 and 1999). The statistical parameters of bridge dead load are the same as for buildings. Bridge live load includes static and dynamic components. The static live load depends on many parameters including the span length, truck weight, axle loads, axle configuration, position of the vehicle on the bridge (transverse and longitudinal), number of vehicles on the bridge (multiple presence), girder spacing, and stiffness of structural members (slab and girders). The bias factors in terms of the HS20 live load (AASHTO 2002) are between 1.65 and 2.10 (Nowak 1993). The HS20 live load is a three axle vehicle: 45 kN, 145 kN and 145 kN, with axle spacing of 4.3m. For spans longer than about 40m, HS20 consists of a uniformly distributed load of 9.3 kN/m and a concentrated force of 81 kN. The coefficient of variation is 0.11 for most spans.

The dynamic load model is a function of three major parameters: road surface roughness, bridge dynamics (frequency of vibration) and vehicle dynamics (suspension system). It was observed that dynamic deflection is almost constant and it does not depend on truck weight. Therefore, the dynamic load, as a fraction of live load, decreases for heavier trucks, and it does not exceed 0.15 of live load for a single truck and 0.10 of live load for two trucks side-by-side (Eom and Nowak 2001).

3. Resistance model

The load carrying capacity depends on resistance of its components and connections. The component resistance, R, is considered as a product of the nominal resistance, R_n and three parameters: strength of material, M, fabrication (dimensions) factor, F, and analysis (professional) factor, P,

$$R = R_n\, M\, F\, P \tag{1}$$

the mean value of R, $m_R = R_n\, m_M\, m_F\, m_P$ and coefficient of variation, $V_R = (V_M^2 + V_F^2 + V_P^2)^{1/2}$, where, m_M, m_F, and m_P are the means of M, F, and P, and V_M, V_F, and V_P are the coefficients of variation of M, F, and P, respectively.

For bridges, the statistical parameters are developed for steel girders, composite and non-composite, reinforced concrete T-beams, and prestressed concrete AASHTO-type girders (Nowak 1999). For steel girders, the parameters of R are $\lambda_R = 1.12$ and $V_R = 0.10$ for moment and $\lambda_R = 1.14$ and $V_R = 0.105$ for shear. For reinforced concrete T-beams, the parameters of R are $\lambda_R = 1.12$ and $V_R = 0.135$ for moment and $\lambda_R = 1.20$ and $V_R = 0.155$ for shear. For prestressed concrete, $\lambda_R = 1.05$ and $V_R = 0.075$ for moment and $\lambda_R = 1.15$ and $V_R = 0.14$ for shear.

4. Reliability analysis

The available reliability methods are presented in several publications, e.g. Nowak and Collins (2000). In this study, the reliability index, β, is calculated using an iterative procedure and Monte Carlo simulations.

Reliability analysis was performed for a wide range of bridges designed according to the AASHTO Standard Specifications (2002) and the new AASHTO Code (2010). The results are summarized in Tables 1-4 for moment and shear.

Table 1

Reliability Indices for AASHTO (2002), Simple Span Moment

Span [m]	Steel Girders Spacing			R/C T-Beams Spacing			P/C AASHTO Girders Spacing		
	1.2 m	1.8 m	2.4 m	1.2 m	1.8 m	2.4 m	1.2 m	1.8 m	2.4 m
9	2.00	2.66	3.10	2.24	2.73	3.07	1.90	2.58	3.05
18	2.90	3.54	3.96	2.97	3.42	3.71	2.98	3.62	4.07
27	2.85	3.39	3.76	2.94	3.28	3.53	2.95	3.49	3.88
36	2.75	3.24	3.57	2.88	3.16	3.37	2.90	3.34	3.68
60	<u>3.19</u>	<u>3.56</u>	<u>3.82</u>				<u>3.23</u>	<u>3.65</u>	<u>3.96</u>

Table 2

Reliability Indices for AASHTO (2002), Simple Span Shear

Span [m]	Steel Girders Spacing			R/C T-Beams Spacing			P/C AASHTO Girders Spacing		
	1.2 m	1.8 m	2.4 m	1.2 m	1.8 m	2.4 m	1.2 m	1.8 m	2.4 m
9	3.36	3.90	4.36	2.89	3.25	3.60	2.93	3.35	3.72
18	2.66	3.23	3.66	2.34	2.72	3.03	2.39	2.80	3.13
27	2.04	2.53	2.92	1.91	2.22	2.47	1.94	2.26	2.53
36	1.92	2.37	2.71	1.85	2.09	2.30	1.91	2.16	2.38
60	<u>2.32</u>	<u>2.74</u>	<u>3.02</u>				<u>2.06</u>	<u>2.32</u>	<u>2.51</u>

Table 3

Reliability Indices for AASHTO LRFD (2010), Simple Span Moment

Span [m]	Steel Girders Spacing			R/C T-Beams Spacing			P/C AASHTO Girders Spacing		
	1.2 m	1.8 m	2.4 m	1.2 m	1.8 m	2.4 m	1.2 m	1.8 m	2.4 m
9	4.19	4.20	4.20	3.98	3.99	4.00	3.88	3.88	3.88
18	4.28	4.28	4.29	3.95	3.94	3.96	3.99	4.00	4.01
27	4.30	4.30	4.31	3.78	3.82	3.86	3.97	4.00	4.02
36	4.32	4.32	4.32	3.68	3.73	3.76	3.90	3.97	4.01
60	<u>4.26</u>	<u>4.27</u>	<u>4.28</u>				<u>3.82</u>	<u>3.93</u>	<u>3.99</u>

Table 4

Reliability Indices for AASHTO LRFD (2010), Simple Span Shear

Span [m]	Steel Girders Spacing			R/C T-Beams Spacing			P/C AASHTO Girders Spacing		
	1.2 m	1.8 m	2.4 m	1.2 m	1.8 m	2.4 m	1.2 m	1.8 m	2.4 m
9	4.43	4.44	4.44	3.98	3.99	4.00	4.14	4.15	4.15
18	4.49	4.49	4.49	3.94	3.93	3.95	4.04	4.05	4.06
27	4.29	4.30	4.30	3.68	3.71	3.73	3.78	3.80	3.82
36	4.46	4.45	4.46	3.69	3.72	3.74	3.77	3.81	3.83
60	<u>4.47</u>	<u>4.47</u>	<u>4.48</u>				<u>3.68</u>	<u>3.73</u>	<u>3.77</u>

For concrete buildings, the reliability indices were calculated by Szerszen and Nowak (2003), for ACI Code 318 but two different editions, i.e. 1999 and statistical parameters of resistance from 1970's and 2010 edition with statistical parameters from 2000's. The results are shown in Tables 5-9 for reinforced concrete beams (moment and shear), slabs and columns (tied and spiral).

Table 5

Reliability Indices for ACI 318, Reinforced Concrete Beams, Moment

D/(D+L)	ACI (1999)	ACI (2010)		
	$\phi = 0.90$	$\phi = 0.85$	$\phi = 0.90$	$\phi = 0.95$
0.0	3,6	4.6	4.3	4.0
0.3	3.7	4.7	4.4	4.0
0.5	3.6	4.6	4.2	3.8
0.8	3.2	4.1	3.7	3.3
0.9	3.1	4.0	3.5	3.1
1.0	2.9	4.5	4.1	3.7

Table 6

Reliability Indices for ACI 318, Reinforced Concrete Beams, Shear

D/(D+L)	ACI (1999)	ACI (2010)		
	$\phi = 0.90$	$\phi = 0.85$	$\phi = 0.90$	$\phi = 0.95$
0.0	4.0	4.5	4.2	4.0
0.3	4.0	4.5	4.2	4.0
0.5	4.0	4.4	4.1	3.8
0.8	3.7	4.0	3.7	3.3
0.9	3.6	3.9	3.5	3.2
1.0	3.4	4.2	4.0	3.6

Table 7

Reliability Indices for ACI 318, Reinforced Concrete, Slabs

D/(D+L)	ACI (1999)	ACI (2010)		
	$\phi = 0.90$	$\phi = 0.85$	$\phi = 0.90$	$\phi = 0.95$
0.0	2.6	3.0	2.8	2.5
0.3	2.5	2.8	2.6	2.4
0.5	2.4	2.7	2.6	2.2
0.8	2.2	2.3	2.0	1.8
0.9	2.1	2.3	2.0	1.8
1.0	2.0	2.6	2.3	2.1

T a b l e 8

Reliability Indices for ACI 318, Reinforced Concrete, Tied Columns

D/(D+L)	ACI (1999)	ACI (2010)		
	$\phi = 0.90$	$\phi = 0.85$	$\phi = 0.90$	$\phi = 0.95$
0.0	4.1	5.5	5.3	5.0
0.3	4.1	5.5	5.3	5.0
0.5	4.0	5.4	5.1	5.8
0.8	3.9	5.2	4.8	4.5
0.9	3.8	5.0	4.7	4.4
1.0	3.6	5.3	5.0	4.8

T a b l e 9

Reliability Indices for ACI 318, Reinforced Concrete, Spiral Columns

D/(D+L)	ACI (1999)	ACI (2010)		
	$\phi = 0.90$	$\phi = 0.85$	$\phi = 0.90$	$\phi = 0.95$
0.0	4.5	5.9	5.5	5.2
0.3	4.5	6.0	5.5	5.3
0.5	4.4	5.8	5.5	5.2
0.8	4.1	5.5	5.2	4.8
0.9	4.0	5.3	5.0	4.6
1.0	3.9	5.6	5.3	5.1

5. Selection criteria for the target reliability index

The major selection criteria are consequences of failure and cost of increasing reliability (or benefit of decreasing β). However, in practice, it is difficult to obtain the data needed for the derivation of the optimum target reliability index. Therefore, a good reference can be established by consideration of the reliability indices corresponding to the structures designed using an existing code. If there are no reported problems for the considered class of structures, then it can be concluded that the current (existing) code is adequate, and possibly conservative. The minimum calculated value of the reliability index can be taken as the target value. Special consideration must be given to the cases of single and multiple load path components, primary and secondary components, and duration of the time period.

Reliability indices calculated for structural elements. From the system reliability point of view, a multiple path system can be considered as a parallel system. However, the elements are usually partially correlated which affects the system reliability.

A primary component is a main structural element, failure of which causes the collapse of the whole structure. In case of bridges, girders are the primary components. It is assumed that the consequences of failure of primary components are about 10 times larger than those of secondary components. Therefore, the probability of failure of secondary components can be 10 times larger than for primary components.

The target reliability indices depend on the considered time period. Theoretically, the reduced reliability indices can be obtained by reducing the load factors and/or increasing the resistance factors. However, the major difference between various time periods is in the live load model. Therefore, the live load factor is considered as the only variable. The considered adjustments are related to the live load factor rather than live load. The live load factor can be reduced by 5-10% for 5 year and 10 year evaluations (inspection intervals).

Historical structures require a special consideration. They often represent a regional or national heritage and, depending on the local regulations, any repair or rehabilitation may require permission from the government agencies. Preservation of the original design, materials and technologies are important considerations. Therefore, the extent and scope of the project can be determined by non-engineering aspects.

The load models for historical buildings and bridges are similar to other structures. However, because of age, historical structures can have a considerable accumulation of load cycles. The repairs and rehabilitation may affect the loads. Failure of a historical building or bridge can have serious consequences. Sometimes the damage can be irreparable because of availability of original materials and technologies. Repairs can be considered as a replacement, as often only outside walls are Therefore, the acceptable safety margins are can be higher compared to ordinary existing structures.

6. Recommended values of the target reliability index

The recommendations are formulated for beams in flexure and shear, slabs and columns. Based on expected consequences of failure and past practice, beams in flexure are considered as elements of a load sharing systems, as in general they have enough ductility and redundancy. Shear failure of concrete is a more brittle behavior, and therefore, the target reliability should be higher than for the moment carrying capacity. Failure of columns can be more severe than beam failure, and therefore, the target reliability index also is to be higher. Concrete slabs are designed as strips of a certain width (1 m). However, they are interconnected to form an integrated and continuous system, with a strong load sharing capability. Therefore, even though the reliability index calculated for an isolated strip can be low, the system reliability index for the slab is sufficiently high, and comparable with a system of parallel beams.

Recommended values of the target reliability indices for the time periods of 5, 10 and 50 years are listed in Table 10. The numbers are rounded off to the nearest 0.25. For shear capacity and compression capacity of columns, the recommended reliability indices are larger by 0.5 compared to values in Table 10.

Table 10

Recommended Target Reliability Indices for Different Time Periods

Time Period	Primary Components		Secondary Components
	Single Path	Multiple Path	
5 years	3.50	3.00	2.25
10 years	3.75	3.25	2.50
50 years	4.00	3.50	2.75

For existing structures, the target reliability indices can be lower for economical reasons. The recommended values of β_T are lower by 1.0 compared to values in Table 10.

For historical structures, the target reliability indices depend, in addition to engineering parameters, also on social and political considerations that are difficult to quantify. Therefore, the recommended target reliability indices are at least as those listed in Table 10, but they can be higher in case of failure meaning an irreparable damage.

For different importance levels, for new design, evaluation of existing structures, and historical structures, the recommended β_T are given in Table 11.

Table 11

Recommended Target Reliability Indices for Different Importance Levels

Importance	New Design	Existing	Historical
Low priority	3.00 - 3.50	2.00 - 2.50	3.25 - 3.50
Medium priority	3.50 - 4.00	2.50 - 3.00	3.50 - 4.50
High priority	3.75 - 4.50	2.75 - 3.50	3.75 - 4.75

7. Conclusions

Target reliability index is considered for three categories of structural components: new design, evaluation of existing structures and evaluation of historical structures. Reliability indices are calculated for beams and columns designed according to the bridge design code AASHTO (2002 and 2010) and concrete design code ACI 318 (1999 and 2010). The major parameters that effect the target reliability are consequences of failure and costs. The comparison indicates that columns have a higher reliability than beams which is justified because of differences in consequences of failure. The target reliability for existing structures can be considerably lower than that for new design because of costs. It can be very expensive to upgrade an existing structure and therefore, a lower reliability is tolerated. On the other hand, historical structures require consideration of non-technical issues as they can represent a regional or national heritage, difficult or impossible to reproduce or repair. The target reliability for historical structures varies depending on social-political considerations and it can be even higher than that of new designs.

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