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IL PROGETTISTA	IL CONTRAENTE GENERALE	STRETTO DI MESSINA	STRETTO DI MESSINA
Prof. Ing. F.Braga Ordine Ingegneri Roma N° 7072 Dott. Ing. E. Pagani Ordine Ingegneri Milano n° 15408 Eurolink	Project Manager (Ing. P.P. Marcheselli)	Direttore Generale e RUP Validazione (Ing. G. Fiammenghi)	Amministratore Delegato (Dott. P. Ciucci)

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INDEX

1 Introduction

In principle, the numeric values of partial coefficients and of ψ coefficients can be determined in one of the two following ways:

a) Based on calibration with reference to a sound experience in building construction.

NOTE: For most of the partial coefficients and ψ coefficients proposed in the Eurocodes currently available this is the fundamental Principle

b) Based on the statistical interpretation of experimental data and field observations. (This should be conducted in the frame of a probabilistic theory of reliability).

When using the method b), either alone or in combination with method a), the partial coefficients for different materials and actions for the ultimate limit states should be calibrated in such a way that reliability levels for representative structures are as close as possible to the reference reliability values.

2 Description of Reliability Methods

The probabilistic calibration procedures of partial coefficients can be divided into two main classes:

- fully probabilistic methods (Level III), and
- first-order reliability methods (FORM) (Level II).

NOTA 1: The fully probabilistic methods (Level III) give, in principle, correct solutions to reliability problems as formulated. Level III methods are rarely used in the calibration of design codes because of the frequent lack of statistical data.

NOTE 2: Level II methods employ some well-defined approximations and lead to results that can be considered sufficiently accurate in most structural applications.

In both the Level II and Level III methods, reliability measurement should be identified with the probability of survival $P_s = (1 - P_f)$, where P_f is the probability of failure for the performance level (limit state) considered and within an appropriate reference period. If the probability of failure calculated is higher than a predetermined reference value P_0, then the structure should be considered unsafe as for that particular limit state.

NOTE: The "probability of failure" and its corresponding reliability index (see C5) are only reference values that do not necessarily represent the actual frequency of failures but are rather used as operational values to the purpose of calibration of codes and comparison of the levels of structure reliability.

3 Reference values of the reliability index β

The reference values of the reliability index β for different design situations, and for reference periods of 1 year and 50 years, are indicated in Table 3.1 (schedule C2). β values in schedule C2 correspond to safety levels for structural elements in reliability class RC3, RC2 and RC1, both for Ultimate Limit States and Operation ones. All the β values are obtained by rounding up.

Table 3.1 Schedule C2 – Reference values of the reliability index β for structural elements of Class RC3, RC2 and RC1, for Ultimate and Operation Limit States, and for reference life cycle V_R equal to 1 year and to 50 years. Values in bold are reported in the EC0, while the other ones are deduced.

	ULS		OLS	
V_R	1	50	1	50
RC3	**5.2**	**4.3**	3.6	2.4
RC2	**4.7**	**3.8**	**2.9**	**1.5**
RC1	**4.2**	**3.3**	2.1	-0.4

The above values can be obtained assuming a return period T_f for the ULS in class RC2 equal to 500,000 and 500 years, respectively. The values relevant to classes RC3 and RC1 are obtained multiplying and dividing by 10 said return period, respectively, as shown in the following table (Table 3.2).

Table 3.2 Schedule C2-bis – Reference values of return periods of the failure and of the relevant failure rates for structural elements of Class RC3, RC2 and RC1, for Ultimate Limit and Operation States. These values are the same for all the reference life cycles V_R

	Return Periods		Failure Rate	
	ULS	OLS	ULS	OLS
RC3	5,000,000	5,000	2E-7	2E-4
RC2	500,000	500	2E-6	2E-3
RC1	50,000	50	2E-5	2E-2

Table 3.2 (schedule C2-bis) shows that, regardless of the reference life cycle, the failure rate of the relevant limit state remains constant within the reliability class. This implies that the design carried out in this reliability framework is intended to produce structures having *constant failure rate*.

Therefore, denoted T_f the return period, the probability of failure, in the assumption of Poisson process, is given by: $P_f = 1 - \exp(-V_R/T_f)$, which gives the corresponding value of the reliability index: $\beta = -\Phi^{-1}(P_f) = \Phi^{-1}(1-P_f)$. The dependence of β on the reference life cycle and on the return period is obtained as:

$$\beta = \Phi^{-1}\left[\exp\left(-\frac{V_R}{T_f}\right)\right]$$

This expression allows determining the reliability indexes referred to different reference life cycles. For instance, for V_R = 200 years, will give:

Table 3.3 Schedule C2-ter – Reference values of reliability index β for structural elements of Class RC3, RC2 and RC1, for Ultimate Limit and Operation States, and for reference life cycle V_R equal to 50 years and 200 years. Values in bold are reported in the EC0, while the other ones are deduced.

	ULS		OLS	
V_R	50	200	50	200
RC3	**4.3**	4.0	2.4	1.8
RC2	**3.8**	3.4	**1.5**	0.5
RC1	**3.3**	2.7	-0.4	-2.1

Failure probabilities shown in Table 3.4. correspond to these values of the reliability index.

Table 3.4 Schedule C2-quater – Reference values of the probability of failure P_f for structural elements of Class RC3, RC2 and RC1, for the Ultimate Limit and Operation States, and for per reference life cycle V_R equal to 50 years and 200 years

	ULS		OLS	
V_R	50	200	50	200
RC3	1E-5	4E-5	9.9E-3	3.9E-2
RC2	1E-4	4E-4	9.5E-2	3.3E-1
RC1	1E-3	4E-3	6.3E-1	9.8E-1

An examination of the previous table shows that if the failure rate remains constant, the probability of failure increases as the reference period increases.

4 Approach for the Calibration of Design Values

With regard to the question, the design values of the effects of E_d actions should be defined in such a way that the probability to have a worst value is:

$$P(E > E_d) = \Phi(\alpha_E \beta)$$

where α_E is the sensitivity coefficient obtained from the FORM, that can be taken equal to -0.7, provided that: $0.16 < \sigma_E / \sigma_R < 7.6$. Thus there is:

$$P(E > E_d) = \Phi(-0.7\beta)$$

When the action model contains different basic variables, the previous expression should be used only for the dominant variable. For non dominant actions, the design values can be defined by the relation:

$$P(E > E_d) = \Phi(-0.4 \cdot 0.7\beta) = \Phi(-0.28\beta)$$

NOTE. For β = 3,8, the values defined by this expression approximately correspond to the 90% fractile.

The expressions given in Table 4.1 (schedule C3) should be used to evaluate the design values of variables with assigned probability distribution.

Table 4.1 Schedule C3 – Design values for the different distribution functions

Distribution	Design values
Normal	$\mu - \alpha\beta\sigma$
Log-normal	$\mu \exp(-\alpha\beta V) \quad \text{per} \quad V = \sigma/\mu < 0.2$
Gumbel	$u - \frac{1}{a}\ln[-\ln\Phi(-\alpha\beta)]$ where : $u = \mu - \frac{0.577}{a} \qquad a = \frac{\pi}{\sigma\sqrt{6}}$ $u - \frac{1}{a}\ln[-\ln\Phi(-\alpha\beta)]$ where : $u = \mu - \frac{0.577}{a} \qquad a = \frac{\pi}{\sigma\sqrt{6}}$, so: $\mu - \frac{0.577\sigma\sqrt{6}}{\pi} - \frac{\sigma\sqrt{6}}{\pi}\ln[-\ln\Phi(-\alpha\beta)] =$ $\mu\left\{1 - \frac{V\sqrt{6}}{\pi}\{0.577 + \ln[-\ln\Phi(-\alpha\beta)]\}\right\}$

NOTE In these expressions, μ, σ and *V* are the average value, the typical deviation and the coefficient of variation of an assigned variable, respectively. For variable actions, these should be based on the same reference period of β.

Notice that the general relation to define the design value is:

$$E_d = \gamma_{Sd} E[\gamma_{f,i} F_{rep,i}] \quad \text{dove} \quad F_{rep,V_R} = \psi F_{k,V_R} \qquad (0 \le \psi \le 1)$$

Where ψ = 1 identifies the representative value with the characteristic value, while ψ < 1 identifies the combination value.

The above equation can be simplified in many cases in:

$$E_d = E[\gamma_{F,i} F_{rep,i}]$$

A method to obtain the partial coefficient consists in dividing the design value of a variable action by its representative or characteristic value, as follows:

$$\gamma_{F,V_R} = \frac{E_{d,V_R}}{E_{rep,V_R}}$$

The reference partial coefficients γ_F are defined, for each Limit State, in reliability class RC2 and for a reference life cycle equal to 50 years (see Schedule B3 in EN1990:2002). Therefore, we have:

$$\gamma_F = \gamma_{F,RC2,50} = \frac{E_{d,RC2,50}}{E_{k,50}}$$

If you want to define partial coefficients on different reliability classes and reference periods, you can operate for instance as follows:

$$\gamma_{F,RCi,V_R} = \frac{E_{d,RCi,V_R}}{E_{d,RC2,50}} \frac{E_{k,50}}{E_{k,V_R}} \gamma_F$$

Then the K_{FI} multiplicative factor of the action partial is defined as follows:

$$K_{FI} = \frac{\gamma_{F,RCi,V_R}}{\gamma_F} = \frac{E_{d,RCi,V_R}}{E_{d,RC2,50}} \frac{E_{k,50}}{E_{k,V_R}}$$

In the assumption of normal, lognormal or Gumbel distribution of the question, this factor is determined respectively as (remember that α_E is negative):

$$K_{FI} = \frac{1-\alpha_{E,V_R}\cdot\beta_{RCi,V_R}\cdot V_{E,V_R}}{1-\alpha_{E,50}\cdot\beta_{RC2,50}\cdot V_{E,50}} \frac{1+k_{5\%}\cdot V_{E,50}}{1+k_{5\%}\cdot V_{E,V_R}}$$

$$K_{FI} = \frac{\exp(-\alpha_{E,V_R}\cdot\beta_{RCi,V_R}\cdot V_{E,V_R})}{\exp(-\alpha_{E,50}\cdot\beta_{RC2,50}\cdot V_{E,50})} \frac{\exp(k_{5\%}\cdot V_{E,50})}{\exp(k_{5\%}\cdot V_{E,V_R})}$$

$$K_{FI} = \frac{1-\frac{V_{E,V_R}\sqrt{6}}{\pi}\{0.577+\ln[-\ln\Phi(-\alpha_{E,V_R}\beta_{RCi,V_R})]\}}{1-\frac{V_{E,50}\sqrt{6}}{\pi}\{0.577+\ln[-\ln\Phi(-\alpha_{E,50}\beta_{RC2,50})]\}} \frac{1-\frac{V_{E,50}\sqrt{6}}{\pi}\{0.577+\ln[-\ln\Phi(k_{5\%})]\}}{1-\frac{V_{E,V_R}\sqrt{6}}{\pi}\{0.577+\ln[-\ln\Phi(k_{5\%})]\}}$$

From the above equations one can draw useful information about the variation of partial coefficients as the reliability class and reference period vary.

Notice for instance that, if you want to change only the class of reliability maintaining the reference period unchanged (e.g., 50 years) because the statistics of distributions remain unchanged, the previous equations are simplified as follows:

$$K_{FI} = \frac{1-\alpha_{E,50}\cdot\beta_{RCi,50}\cdot V_{E,50}}{1-\alpha_{E,50}\cdot\beta_{RC2,50}\cdot V_{E,50}}$$

$$K_{FI} = \frac{\exp(-\alpha_{E,50}\cdot\beta_{RCi,50}\cdot V_{E,50})}{\exp(-\alpha_{E,50}\cdot\beta_{RC2,50}\cdot V_{E,50})}$$

$$K_{FI} = \frac{1-\frac{V_{E,50}\sqrt{6}}{\pi}\{0.577+\ln[-\ln\Phi(-\alpha_{E,50}\beta_{RCi,50})]\}}{1-\frac{V_{E,50}\sqrt{6}}{\pi}\{0.577+\ln[-\ln\Phi(-\alpha_{E,50}\beta_{RC2,50})]\}}$$

Table 4.3 shows the K_{FI} multiplicative factors of the partial coefficients of the combined action, Gumbel assumed, in moving from 50 to 200 years of reference period, maintaining the reliability class unchanged. These factors are evaluated for different values of the coefficients of variation (CoV= 0.2, 0.3, 0.4, 0.5) of distributions at 50 and 200 years. The CoV values proposed in literature (see Melchers 1999) and generally employed for the statistical characterization of different load typologies are indicated in Table 4.2. It is considered the assumption that the coefficient of variation does not reduce as the reference period increases.

Table 4.2 Coefficients of variation for Different Types of Loads

Load Type	CoV	Return Period (years)	Distrib.	Reference
Own weight	0.10		Normal	Nowak (1999)
Permanent	0.10		Normal	a.a.
Max on 1 lane	0.10	75	Normal	Nowak (1999), Moses (2001)
Max on multilane	0.07	75	Normal	a.a.
Load Model	0.18		Normal	Moses and Ghosn (1985)
Wind Max	0.10	50	Gumbel	Ellingwood et al. (1980)
Wind Model	0.25		Normal	a.a.

Table 4.3 K_{FI} multiplicative factors of partial coefficients of the combined action, assumed Gumbel, in passing from 50 to 200 years of reference period. Factors are evaluated for different values of the coefficients of variation (CoV) of distributions at 50 and 200 years

		RC2,200			
	CoV	0.20	0.30	0.40	0.50
	0.20	0.94	0.98	1.02	1.05
RC2,50	0.30		0.92	0.96	0.98
	0.40			0.91	0.94
	0.50				0.90

From this table, it is clear that as the reference period varies within the same reliability class, the action partial coefficients remain essentially unchanged. This conclusion is justified by the considerations made in the previous paragraph according to which the scope of the design is to maintain a constant failure rate.

On the contrary, if we want to change the reliability class while maintaining the reference period unchanged, we obtain the results shown in Table 4.4, which reports the K_{FI}, multiplicative factors always in the Gumbel distribution assumption. These factors are evaluated for different values of the coefficients of variation (CoV= 0.2, 0.3, 0.4, 0.5) for distribution.

Table 4.4 K_{FI} multiplicative factors (in Gumbel distribution assumption) as the reliability class varies, evaluated for different values of coefficients of variation (CoV) for distribution.

	RC3,50			
CoV	0.20	0.30	0.40	0.50
RC2,50	1.11	1.13	1.15	1.16

Notice that these factors are compatible with the one, equal to K_{FI} = 1.1, defined in Table B3 of Eurocode 0 relevant to the differentiation of reliability by modifying the partial coefficients.

Table 4.5 defines the K_{FI}, multiplicative factors in moving from RC2,50 to RC3,200. These factors are evaluated for different values of the coefficients of variation (CoV= 0.2, 0.3, 0.4, 0.5) of distribution at 50 years and 200 years.

Table 4.5 K_{FI}, multiplicative factors in moving from RC2,50 to RC3,200, evaluated for different values of the coefficients of variation (CoV) of distribution at 50 years and 200 years

		RC3,200			
RC2,50	CoV	0.20	0.30	0.40	0.50
	0.20	1.04	1.12	1.19	1.24
	0.30		1.05	1.11	1.16
	0.40			1.05	1.10
	0.50				1.06

Also in this case, we notice that the increase of the reference period does not make significant changes to the amplifier factor of partial coefficients that remains essentially equal to 1.1.

Hence, we can conclude that to differentiate reliability between class RC2 and RC3 it is necessary to multiply the partial coefficients of the actions by 1.1, in line also with what reported in Table B3 of Eurocode 0. On the contrary, the increase of the reference period does not involve increases of the partial coefficients, under the design philosophy that provides a constant failure rate. Finally, it should be noted that factor 1.1 should be applied only to adverse actions.

5 Combination of Actions through ψ_0 Coefficients

Single actions variable in time, which are essentially random processes $p(t)$, can be modelled through the distribution of the maximums within a given reference period T: $X = \max_T[p(t)]$.

For many processes, the distribution of the maximums can be approximated in an acceptable manner with a Gumbel distribution.

When two or more actions, variable in time, act at the same time, reference is made to the theory of stochastic combination of actions. A fundamental consideration is that, if these actions are independent, as is often the case, it is very unlikely that they reach the historical maximum on the same moment.

For instance, if we consider two processes variable in time, $p_1(t)$ and $p_2(t)$, simultaneously acting in a given reference period T, for which we can express their combined effect through a linear combination $p_1(t) + p_2(t)$, the random variable of interest is:

$$X = \max_T[p_1(t) + p_2(t)]$$

The correct distribution of X can be obtained only in a few cases. A possible solution to the problem is given by the Turkstra combination rule, to which many regulations refer, that considers the process:

$$X = \max_T\left\{ \max_T[p_1(t)] + p_2(t) \quad p_1(t) + \max_T[p_2(t)] \right\}$$

This combination rule considers that the maximum value of the sum of two randomly variable actions is obtained at the maximum of one of the two actions. On the contrary, this result can be generalized to any number of independent actions.

To this purpose, reference is made to the Ferry Borges-Castanheta (FBC) model, in which the process is generated by a sequence of random variables independent and identically distributed, each one acting in a given deterministic time interval. The FBC process is given by a set of rectangular pulses having variable amplitude at each successive interval t_i, called *base period*. Figure 5.1 shows the case of two actions that, in the reference period T, give rise to $N_i = T/t_i$ repetitions.

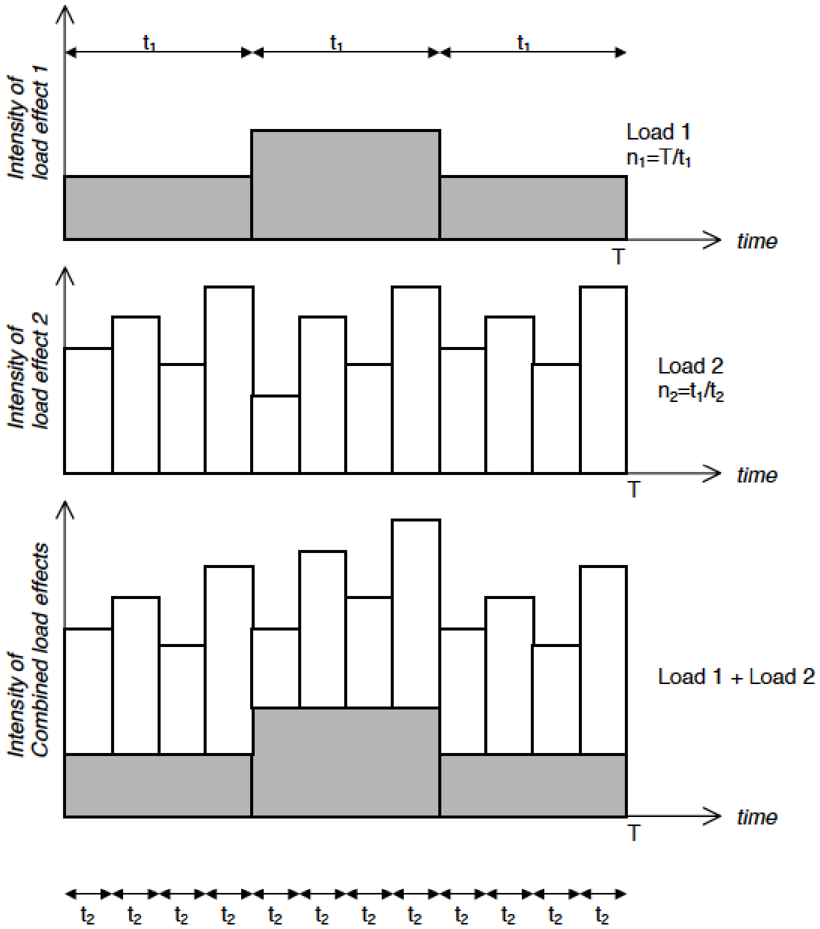

Figure 5.1 Illustration of the combination of two stresses according to the Ferry Borges-Castanheta model

Note that, as reported in notes of par. 4.1.3 of Eurocode 0, the base period for traffic actions on road bridges is assumed equal to one week.

Given the assumption of independence, the distribution of the maximum value in the reference period *T* is given by:

$$F_{\max_T X_i}(x_i) = [F_{X_i}(x_i)]^{N_i}$$

When different FBC processes act at the same time and the ratio of action intervals can be expressed by an integer, it is possible, in principle, to obtain the distribution of the extreme values of the combination through an iterative formula.

The *format* of the Italian and European standards (Eurocode 0) employs a different combination coefficient ψ_{0i} for each variable action. These coefficients give the ratio among fractiles of the distributions of extreme values and punctual values. They are calibrated in such a way that the probability of exceedance of the design value resulting from the combination of more actions is in the same order of the probability of exceedance of the design value resulting from one sole action. For actions variable in time these coefficients depend on the distribution parameters, sensitivity coefficients and base period t_i assumed for stationary events.

The general relation used in Eurocode 0 is as follows (the following equation also corrects an error present in the original version):

$$\frac{F_s^{-1}\left[[\Phi(-0.4\beta_1)]^{N_1}\right]}{F_s^{-1}[\Phi(-0.7\beta)]} \quad \text{Where:} \quad \beta_1 = \Phi^{-1}\left[\frac{\Phi(-0.7\beta)}{N_1}\right]$$

and in which F_s is the probability distribution function of the extreme values of the non dominant action in the reference period $T = V_R$, T_1 is the largest of the base periods for the actions to be combined, N_1 = round(T/T_1), V is the coefficient of variation of the non dominant action for the reference period. The base period of an action is the one within which the value of the action is constant.

Table 5.1 (schedule C4) gives the expressions to obtain ψ_0 coefficients in case of two variable actions, concerning the normal or Gumbel distribution cases.

Table 5.1 Schedule C4 – Expressions for the calculation of ψ0 in case of two variable actions

Distribution	$\psi_0 = F_{\text{non dominant}} / F_{\text{dominant}}$
Normal (approximation)	$\frac{1+(0.28\beta-0.7\ln N_1)V}{1+0.7\beta V}$
Gumbel (approximation)	$\frac{1-0.78V[0.58+\ln(-\ln\Phi(0.28\beta))+\ln N_1]}{1-0.78V[0.58+\ln(-\ln\Phi(0.7\beta))]}$

where T is the reference period (above denoted V_R), T_1 is the largest of the base periods for the actions to be combined, N_1 = round(T/T_1), V is the coefficient of variation of the non dominant action for the reference period.

We notice that in both the tables A2.1 and A2.3 of EN1990:2002/A1 relating to the recommended values of ψ factors for road and railway bridges, respectively, we almost always obtain that $\psi_1 = \psi_0$ (except for wind action), while ψ_2 is always null (except for thermal and construction loads).

From schedule C4 we can understand that, if we want to change the reliability class and/or the reference period, the recalibration of the combination coefficient is easily made once the action distribution type is known, whether normal or Gumbel. In the following part, similarly to what has been done above for partial coefficients, we assume a Gumbel distribution type.

Table 5.2 shows the K_{Cl} multiplicative factors of combination coefficients, Gumbel assumption, in moving from 50 to 200 years of reference period, maintaining the reliability class unchanged. These factors are evaluated for different values of the coefficients of variation (CoV= 0.05, 0.10, 0.15, 0.20) of extreme values of distributions at 50 and 200 years. It is considered that these coefficients of variation do not vary as the reference period varies. The tables are referred to base periods equal to 0.02 (one week), 0.083 (one month), 0.25 (three months), 0.5 (six months) and 1.0 (one year).

Table 5.2 K_{Cl} multiplicative factors of combination coefficients (Gumbel assumption) in moving from 50 to 200 years of reference period, maintaining the reliability class unchanged

		RC2,200				
	CoV/t	0.02	0.083	0.25	0.5	1.0
	0.05	1.02	1.02	1.02	1.02	1.02
RC2,50	0.10	1.03	1.03	1.03	1.03	1.03
	0.15	1.04	1.04	1.04	1.04	1.04
	0.20	1.05	1.05	1.05	1.05	1.04

This table shows that, as the reference period within the same reliability class varies, the combination coefficients of the actions remain essentially unchanged, irrespective of the base period of the action.

If, on the contrary, the reliability class has to be modified maintaining the reference period unchanged, we obtain data shown in Table 5.3, which reports K_{Cl}, multiplicative factors always in the assumption of Gumbel distribution. These factors are evaluated for the same values of the coefficients of variation and of the base periods seen above.

Table 5.3 K_{CI}, multiplicative factors (in Gumbel distribution assumption). As the reliability class varies from RC2 to RC3

		RC3,50				
RC2,50	CoV/t	0.02	0.083	0.25	0.5	1.0
	0.05	0.97	0.97	0.97	0.97	0.97
	0.10	0.95	0.95	0.95	0.95	0.95
	0.15	0.94	0.94	0.94	0.94	0.94
	0.20	0.93	0.93	0.93	0.93	0.94

Notice that also in this case, the table shows that as the reliability class varies maintaining the reference period constant, the action combination coefficients remain essentially unchanged, regardless of the base period of the action.

Table 5.4 shows the multiplicative factors K_{CI}, in moving from RC2,50 to RC3,200. These factors are evaluated for the same values of the coefficients of variation and of base periods seen above.

Table 5.4 K_{CI} multiplicative factors in moving from RC2,50 to RC3,200

		RC3,200				
RC2,50	CoV/t	0.02	0.083	0.25	0.5	1.0
	0.05	0.99	0.99	0.99	0.99	0.99
	0.10	0.98	0.98	0.98	0.98	0.98
	0.15	0.97	0.97	0.97	0.98	0.98
	0.20	0.97	0.97	0.97	0.97	0.97

Also in this case, it is noted that the increase of the reference period does not make significant changes to the amplification factor of the combination coefficients that remains essentially equal to 1.0.

Therefore, we can conclude that the differentiation of reliability between class RC2 and RC3 does not require the modification of the action combination coefficients. Also the increase in the reference period does not involve any variation of these coefficients.

6 Conclusions

From the analyses of the values of β reliability indexes included in the Eurocode 0 it can be inferred that, regardless the reference life cycle, the failure rate associated to a limit state remains constant within a given reliability class. A design carried out with this reliability approach aims at producing structures having low constant failure.

Therefore, in compliance with the provisions of Eurocode 0, increases of the reference period do not involve any variations of the action partial coefficients. On the contrary, these variations result necessary in moving from a reliability class to another one. In line also with what indicated in Table B3 of Eurocode 0, to differentiate the reliability between class RC2 and RC3 it is necessary in particular to multiply the partial coefficients of the actions by a factor equal to 1.1. This increase of the coefficients should be applied to the sole unfavourable actions.

As far as ψ combination coefficients are concerned, these are calibrated, according to the format of the Italian and European Standards, in order that the probability of exceedance of the design value resulting from the combination of more actions is in the same order of the probability of exceedance of the design value- deriving from one sole action. For actions variable in time, these coefficients essentially depend on the distribution parameters, sensitivity coefficients and on the base period t_i assumed for stationary events.

Using the expressions given in the Eurocode 0 for the calibration of coefficients we notice that, as the reference period within a same reliability class varies, ψ coefficients remain essentially unchanged irrespective of the base period of the action. The same thing happens maintaining the reference period constant on the contrary varying the reliability class.

Therefore, we can conclude that the differentiation of the reliability between class RC2 and RC3 does not require modifying the combination coefficients of the actions. Also the increase of the reference period does not involve variations of these coefficients.

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