Calibration of Partial Safety Factors for precast concrete products

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Summary

The objective of the study presented in this paper was to define partial safety factors adapted to precast concrete products by producing a framework for their determination taking into account the real variability encountered in fabricating precast elements under factory conditions and considering the effects of quality control.

The partial factors considered were the material factors for concrete and reinforcing steel and the partial factor for self weight of precast members. The analysis was based on concepts and values defined in EN 1990 [1].

This study was achieved within a research project funded by European Commission [2].

Keywords: precast, partial safety factor, concrete, steel, reliability, quality control.

1. Introduction

The design of structural precast concrete elements within the framework of the European standardization must be achieved in accordance with Eurocode 2 [3] and the relevant product standards. The safety of the design is based upon a probabilistic approach defined in the European Standard EN 1990 [1].

At the present time the partial factors defined for the design of in situ concrete civil engineering works have a mainly historical origin. Concerning the precast concrete products, Eurocode 2 outlines possible reasons for reducing the partial factors applicable to material strength, in particular the beneficial influence of the industrial process. Although abundant literature is available on these topics and some theoretical studies exist, no global scientific work had been undertaken in the past for precast concrete.

The present project was undertaken by a consortium including precast producers associations, technical centres, design consultants and universities; it was divided into two main work packages:

- a so called "data base" work package, which aim was to give reliable information on the real scatter of precast concrete structural elements produced in fixed industrial plants. This work package included the selection of representative structural products, the preparation and the execution of a measurement campaign in factories, the collection and the statistical treatment of the data and finally the analysis of the results in order to define a normal and high quality level and highlight the ways of achieving an accurate quality control.
- a "reliability" work package devoted to the calibration of partial safety factors. Representative structural examples have been developed, including design actions, then optimisation of the partial safety factors have been performed for the set of structural examples and considering different levels of tolerances and variability for the products. All the results have been compared with the values given by a "normal" level corresponding to the tolerances and variability allowed by the execution standards.

2. Reliability format in the design codes

2.1 Short presentation of EN 1990 Basis of Structural Design

The first European pre-standard defining the basis of the structural design [3] was published in 1994 as an experimental standard. This document served to the elaboration of the head code EN 1990 [1], the first material-independent operational code of practice which establishes the principles and requirements for the safety, serviceability and durability of structures. In addition, it describes the basis for their design and verification and gives guidance for related aspects of structural reliability.

The reliability level evaluation is based on the safety index β defined by $\Phi(-\beta) = P_f$ where P_f is the failure probability and Φ is the normal distribution function with zero mean and unit variance. For current structures, the recommended value for β is 3.8 for a 50 years reference period or 4.7 for a one year reference period. The probability of failure and its corresponding β index are only notional values that do not necessarily represent actual failure rates (which depend mainly on human errors). They are used as operational values for code calibration purposes and comparison of reliability levels of structures.

About the effects of actions to be considered, EN 1990 proposes two combinations of actions that may either be expressed as:

$$\sum_{j\geq 1} \gamma_{G,j} G_{k,j} \text{"+"} \gamma_P P \text{"+"} \gamma_{Q,1} Q_{k,1} \text{"+"} \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} \qquad (6.10)$$

or the less favourable results given by the two following expressions :

$$\begin{cases} \sum_{j\geq 1} \gamma_{G,j} G_{k,j} \text{"+"} \gamma_P P \text{"+"} \gamma_{Q,1} \psi_{0,1} Q_{k,1} \text{"+"} \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} & (6.10a) \\ \sum_{j\geq 1} \xi_j \gamma_{G,j} G_{k,j} \text{"+"} \gamma_P P \text{"+"} \gamma_{Q,1} Q_{k,1} \text{"+"} \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} & (6.10b) \end{cases}$$

Where :

"+ "	implies "to be combined with"
Σ	implies "the combined effect of"
ξ	is a reduction factor for unfavourable permanent actions *G,* to be selected in the range 0,85 – 1,00.

Note: in EN 1990, it is possible to use a modified equation 6.10 a/ including only permanent actions; this modified set is noted 6.10 a'/b in the following.

3. Data on precast concrete structural members

3.1 Organisation of the measurements

The measurement campaign has been performed on precast structural elements representative of the production of several European countries. The selected products were, (reinforced or prestressed concrete):

- Beams (rectangular, I-shaped, tapered)
- Hollow core slabs (extruded or slipformed)
- Columns (rectangular or circular)
- Ribbed slabs
- Solid slabs elements

Fig. 1 Overview of different elements

21 European factories have participated to that campaign, the measurements have been targeted at a number of design parameters considered as the most important factors affecting the design strength of the products:

- placement of reinforcement and effective depth at design sections for ultimate moment and ultimate shear as relevant (see Fig. 2);
- width of compressive zone and/or webs at design sections;
- lengths and relevant section measures for the single product sufficient for calculation of the volume of the single precast element;
- weight of each element within the selected production;
- core compressive strength of specimens extracted from product zones being representative for the design sections as well as the corresponding values for separately cast specimens used for the normal routine control (see Fig. 3).

Fig. 2 Position of the protruding tendons

Fig. 3 Drilling of cores in a I beam dummy

During the measurement campaign, more than 2000 strength tests have been performed (1700 on moulded specimen and 315 on drilled cores), 6500 dimensional measurement have been made and 250 products have been weighted.

3.2 Main findings of the data base, hypothesis for the calibrations

3.2.1 Concrete strength

The information requested was the answer to the following questions:

- what can be considered as a realistic value of the coefficient of variation for concrete in precast concrete elements made under factory conditions ?
- what is the correspondence between the strength on routine control moulded specimens and the actual strength inside the products ?

Figure 4 shows the coefficient of variation of concrete versus the mean strength for all the specific productions in the visited factories. It was concluded from that figure that 6% is a realistic value of the coefficient of variation for concrete strength for precast elements.

The value is to be compared to the usually admitted value for concrete: 15 %.

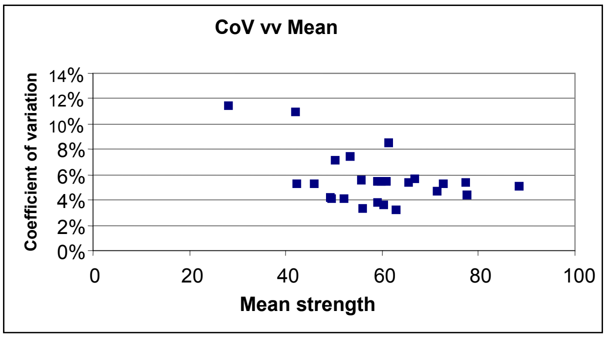

Fig. 4 Coefficient of variation / mean concrete strength

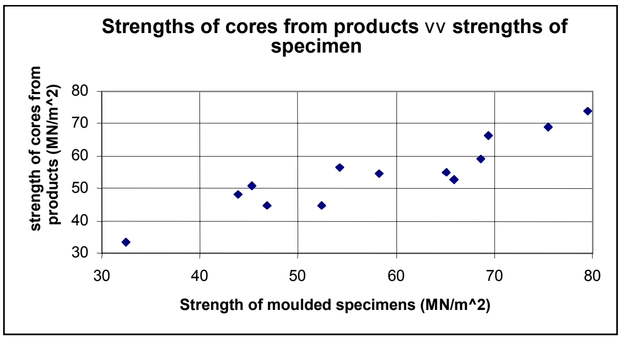

Fig. 5 Strength in dummies / strength from routine control

A comparison of the strength obtained on moulded cylinders and on drilled cores in dummies representatives of the products have shown that the average strength ratio, including shape factors, is 0,86 (see Figure 5). This value is close to the currently admitted hypothesis (η = 0,85) for the conversion factor between the strength in the structure and the strength measured on standardized moulded specimen [11], [3].

3.2.2 Geometry and position of reinforcement

From a statistical analysis performed on all the results collected during the campaign, two sets of values can be recommended (table 1):

- a 1st set corresponding to the average results encountered on precast products;
- a 2nd set defined as "enhanced control" corresponding approximately to 1/3 of all the "selected populations" and presenting the best results for a given parameter.

Table 1 results from statistical analysis of geometry and position measurements

Parameters	*standard deviation "precast".*	*standard deviation "precast enhanced control".*	*Distribution type*
Geometry			
Position steel	6.1 mm	3.0 mm	Normal
Effective depth	7.9 mm	3.6 mm	Normal
Depth	5.0 mm	2.0 mm	Normal
Width	5.0 mm	1.5 mm	Normal
Thickness	3.7 mm	1.6 mm	Normal

For the normal conditions hypothesis, the values have been taken from the background document of Eurocode 2, annex A [8] (table 2).

Table 2 hypothesis for normal conditions

h or *b* (mm)*	Cross section dimension s.d. (mm)	Effective depth s.d. (mm)	Position of reinforcement s.d. (mm)
≤ 150	6,1	8,6	6,1
400	9,1	12,9	9,1
≥ 2500	18,2	21,9	12,1
linear interpolation shall be applied for intermediate values			

3.2.3 Self weight

The global analysis on measured self weight versus nominal self weight of precast elements gives a coefficient of variation of 5%, this could be assumed to be the normal "precast" situation.

The analysis on measured weight versus evaluated weight gives a coefficient of variation of 2%, this value of 2% has been adopted for the "precast tightened tolerances or enhanced control" situation. In comparison, a coefficient of variation of 10 % has been adopted for dead load.

3.3 Quality and quality control

The principles for how to evaluate possible modifications of partial safety coefficients might in future be similar to those presented in [8].

Here relationships between tolerances and standard deviations for various design parameters are given for normal and tightened tolerances, each of which may be combined with either normal or strict control.

It is obvious that a reduction of partial coefficients implies the choice of reasonable tightened tolerances for influencing parameters and the rules for how the strict control shall be accomplished for said parameters. As regards dimensions it is important to note that the above document assumes that actual mean values are equal to the corresponding nominal values. Below said "nominal value" will be understood as the value used as design parameter or for calculating the design parameter.

4. Calibration of partial factors

4.1 Objective and requirements of the calibration procedure

In accordance with the Structural Eurocodes format, the calibration refers to limit states on an element level, i.e. essentially to cross-sections of the considered structural elements, and to the failure modes (limit states) connected to them (shear failure, bending moments, etc.). Therefore, the safety of a structure element is insured when the "design resistance" R_d is not smaller than the "design action effect" E_d, i.e. $R_d \geq E_d$. In turn design resistance and design load effect are obtained from "nominal" or "representative" values by appropriate "partial safety factors", that include inherent random uncertainties and model uncertainties.

4.1.1 Code format

The calibration is done with the three sets of basic combinations (6.10), (6.10 a/b), (6.10 a'/b) given by EN 1990 [1] and the corresponding load partial safety factors. Furthermore the material partial safety factors are also taken in accordance with Eurocode 2. The aim of the calibration is thus a possible reduction of the partial safety factor for precast concrete on the reinforcement (recommended value: $\gamma_S = 1.15$), the concrete ($\gamma_C = 1.5$) and the dead load for the precast element itself ($\gamma_G = 1.35$), keeping the mean safety index β.equal or higher than the recommended value.

4.1.2 Target reliability

The target safety level for the calibration of the partial safety factors for precast concrete is taken as the safety level generally accepted in the Eurocodes. Two reference values of the safety index β are considered, that is: $\beta = 4.7$ and $\beta = 3.8$ with reference to 1 year or 50 years, respectively [1]. The calibration is carried out by assuming these values as "average" target values.

4.1.3 Uncertainty Modelling

In the calibration, it is required to have models for precast concrete structural elements, with the following input parameters described: material properties and strengths (concrete, reinforcement, …), geometry, loads and model uncertainty.

In order to use these parameters in the reliability model, it is required that they are defined in terms of probability distributions. Characteristic values to which the partial safety factors are to be applied are taken as shown in table 3. Hypothesis concerning coefficient of variation for strength, self weight and geometry are taken as define above; for model uncertainty a random parameter with a mean value equal to 1 and a coefficient of variation equal to 5 % has been used, the sensibility of the results to this parameter has been investigated.

Table 3 Uncertainty modelling, characteristic values

Parameter	*Distribution type*	*Percentile*
Loads		
Permanent Load	Normal	50% (mean value)
Permanent Load (precast)	Normal	50% (mean value)
Variable load	Gumbel	98% (1 year reference period)
Strength		
Concrete, compression	Log-Normal	5%
Reinforcement	Log-Normal	5%
Geometry	Normal	50% (mean value)
Model uncertainty (resistance)	Normal	50% (mean value)

4.1.4 Code calibration

The idea of the calibration is to find the set of partial safety factors to be used in the structural design of precast concrete elements so that the "the best approximation" to the target reliability level is obtained. As the calibration process is only a calibration on the partial safety factors related to precast concrete, and thus not a calibration on the entire code format, the effect on the scatter in reliability may be minor. However, the reliability level prescribed for precast elements can on average be set to the target reliability level.

The calibration is defined as an optimisation problem solved for obtaining the best approximation to the target reliability level [9] [10]. The optimisation problem is taken as the following:

"Average" minimum value

$$\min\ W(\gamma) = \sum_{i=1}^{L}\sum_{j=1}^{M}\left(\beta_{ij}(\gamma) - \beta_t\right)^2$$

where:

- γ is the vector of partial safety factors considered in the code calibration;
- L is the number of structural elements considered;
- M is the number of design situations considered;
- $\beta_{ij}(\gamma)$ is the reliability index for element i, design case j, based on γ;
- β_t is the target reliability index;

In order to determine $\beta_{ij}(\gamma)$ it is required to design each design situation for each structural element considered in the calibration to the limit for each set of partial safety factors considered in the calibration. This has required programming of the limit states and a design routine, which can design the structural elements to the limit given a set of partial safety factors.

4.2 Structural examples for the calibration

The elements have been chosen as representative as possible of real precast structures, in term of products and loading cases. Distributed loads are considered in terms of dead load and variable loads. Three types of loads are also considered:

- dead load G_p: dead load of the member under consideration (self weight);
- imposed dead load G_I: dead load from e.g. other members acting on the member under consideration;
- variable load Q: the variable load is taken as either imposed load or environmental load.

In the structural examples, characteristic values of the above mentioned loads are to be specified, both in terms of the external acting load and the load effect on the cross-section under consideration. Different ratios between the variable loads and dead loads in the cross section are to be considered (dominating variable load / dominating permanent load), i.e. different values of the parameters ν and μ given as :

$$\nu = \frac{Q_k}{G_k + Q_k} \quad ; \quad \mu = \frac{G_{k,p}}{G_k}$$

where $G_k = G_{k,p} + G_{k,I}$

Q_k is the characteristic variable load, G_k the characteristic dead load and G_p the dead load due to the precast elements (including the others parts of the structure). In the figure 5, the characteristic values of the above mentioned loads for the examined structural examples are reported.

The optimisation for bending was made by finding the minimum area of longitudinal reinforcement with $M_{Rd} \geq M_{Ed}$ for all the combinations of actions defined in EN 1990 [1], where M_{Rd} is the resisting bending moment according to 6.1 of EN 1992 [3], and M_{Ed} is the design bending moment.

The optimisation for shear was made by finding the minimum shear reinforcement and the minimum web width (only for I-shaped beams, hollow-core slabs and ribbed slabs) with $V_{Rd} \geq V_{Ed}$ for all the combinations of actions defined in EN 1990 [1], where V_{Rd} is the shear resistance according to 6.2 of EN 1992 [3], and V_{Ed} is the design shear force.

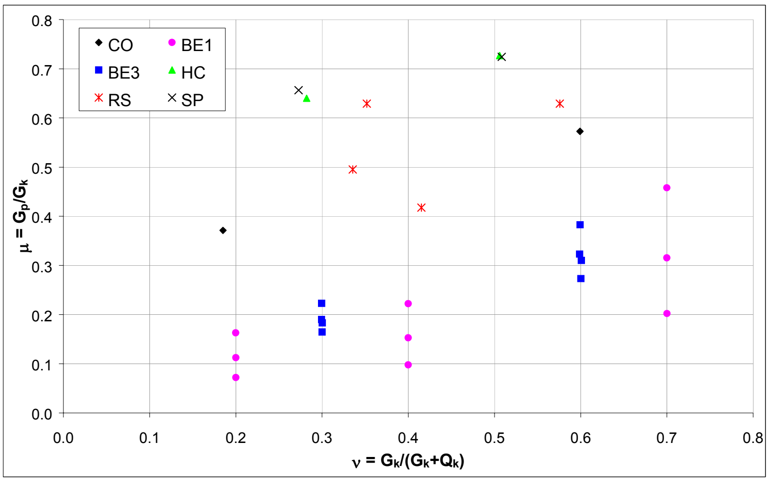

Figure 5 [ν-μ] relationship for the representative structural examples

4.3 Results of the calibration

Extensive calibrations have been achieved, including parametric studies in order to define the influence of each parameter. Although the range of the calibrated partial factors was correct, the results are expressed in terms of relative calibration compared to the results obtained with "normal situation" (normal conditions of execution), this procedure minimize the influence of poorly documented parameters such as model uncertainties.

The calibration analysis demonstrates that the partial safety factor on concrete compression and on precast dead load may be reduced for precast concrete compared to the normal situation without compromising safety. Opposite this the sensitivity analysis does not indicate that a reduction of the partial safety factor on reinforcement is possible for precast concrete compared to the normal situation for structural elements in general. The reduction factors suggested to be multiplied by the normal partial safety factors are shown in table 4.

Table 4 Reduction factors to be multiplied by the normal partial safety factors (structural elements in general)

Reduction factor	Reinforcement	Concrete compression	Precast dead load
Precast	1,0	0,95	0,95
Precast, tightened tolerances	1,0	0,95	0,90

Further calibrations carried out on structural elements sensible to geometrical scatter (e.g. slabs with height below 250 mm) have shown that the partial safety factor on reinforcement may be reduced without compromising safety. The reduction factors suggested to be multiplied by the normal partial safety factors for reinforcement are shown in table 5.

Table 5 Reduction factors to be multiplied by the normal partial safety factors for reinforcement (structural element with a high sensitivity to geometrical uncertainty)

Reduction factor	Reinforcement
Precast	0,95
Precast, tightened tolerances	0,93

5. Conclusions

Noting that the calibration gives results in the right order of magnitude, the conclusion on a possible reduction of partial safety factor without compromising safety has been estimated from a sensitivity analysis, i.e. effect of better control of geometry, dead load, etc. The sensitivity of the partial safety factor to modifications in the uncertain parameters has thus given a basis for a recommendation on a possible reduction of the partial safety factors.

In conclusion, the analysis demonstrates that the partial safety factor on concrete compression and on precast dead load may be reduced for precast concrete compared to the normal situation without compromising safety. On the contrary, the analysis indicates that a reduction of the partial safety factor on reinforcement strength cannot be recommended in general. Therefore, the recommendation of possible reductions is divided into recommendations for structural elements in general, and recommendation for structural elements with a high sensitivity to geometrical uncertainty. The suggested reduction factors are reported in 4.3 (see tables).

Attention should be paid that the present conclusion do not include judgement on the level of safety given by Eurocodes and especially Eurocode 2.

It is believed that many of the conclusions and results arrived at may be worth while to consider by the Precast Industry when laying down their rules for quality control of various products. Said conclusions may also serve as a background for the development of a Guide to Good Practice for control of precast concrete products. On the other hand, the results of the present investigation add important data, elaborated in the spirit of the “Basis of Structural Design”, and might be used by Code writers and relevant authorities to allow the indicated reductions to the values recommended in EN 1990.

6. References

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