

# Calibration of Partial Factors for Temporary Structures

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**ABSTRACT:** The Eurocodes currently do not provide a coherent reliability-based justification for the semi-probabilistic design format of temporary structures. Besides the need for suitable target reliability levels, a coherent definition of partial factors is needed, adjusted according to the chosen target reliability level and the intended reference period considered for the design of the temporary structure. When developing such a partial factor approach, attention should be given to the coherency with current Eurocodes to avoid conceptual discrepancies between the design of long-term and temporary structures. In this contribution a full-probabilistic framework for the structural reliability quantification of temporary structures is developed, based on Latin hypercube sampling. A sensitivity study is performed to detect the most important variables to be considered for the reliability analysis. The framework is subsequently used to determine the inherent reliability levels of scaffolds associated the design guidelines and partial factors according to current standards. Furthermore, recommendations for the target reliability levels for temporary structures are proposed, considering an economic optimization procedure. Finally, adjusted partial factors for temporary structures are derived, enabling a rather simple and straightforward, but objective and coherent safety evaluation of temporary structures by practitioners. Such adjusted partial factors are obtained using two methods: (1) an optimization procedure and (2) the Adjusted Partial Factor Method, which was originally developed for adjusting partial factors for existing structures.

## 1. INTRODUCTION

Currently, the design of scaffolds follows EN 12811 and several other ‘codes of good practice’. It is, however, unclear whether these design guidelines follow a reliability-based approach similar as considered for the design of traditional long-term structures (e.g. EN 1990). Therefore, in this contribution a reliability-based evaluation and optimization of the current design guidelines for scaffolds is performed by deriving optimal sets of partial factors which can be used in a Eurocode framework.

First, a full-probabilistic framework for the determination of the inherent reliabilities of temporary structures is set up in section 2. Here, also a sensitivity study of the variables is conducted. To be able to calibrate partial factors, appropriate reliability levels need to be determined. Hence, in section 3, such target reliability levels are derived considering both human safety and economic optimization criteria. Finally, based on the results of the probabilistic calculations and the target reliability levels, two

methods are used for the derivation of appropriate partial factors, i.e. the Adjusted Partial Factor Method (APFM) and an optimization procedure based on least-square averaging, see section 4. The basic terminology related to scaffolds is introduced in Figure 1 for clarity.

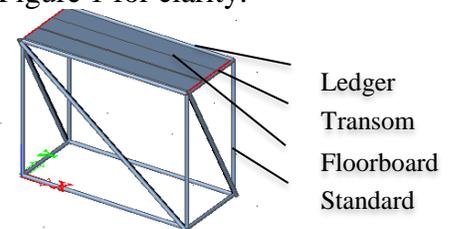


Figure 1: Example scaffold (one cell)

## 2. FULL-PROBABILISTIC ANALYSIS OF TEMPORARY STRUCTURES

### 2.1. Probabilistic framework for determination of inherent reliability levels of scaffolds

This section presents the methodology which is used to determine the reliability index of temporary structures. This methodology is based on numerical simulations and probabilistic calculations, and is performed for several possible designs of scaffolds. The structural calculations of

scaffolds are performed using the package ‘Scaffolding’ of SCIA Engineer. In order to perform probabilistic calculations, probabilistic models are assigned to different input parameters of the scaffold design. These parameters are given in Table 1 with  $\rho_{\text{tubes}}$  the density of the scaffold tubes (which have a thickness  $t$  and diameter  $D$ );  $\rho_{\text{FB}}$  the density of the floorboards; steel properties such as the Young’s modulus  $E$  and yield strength  $f_y$ ; the initial bow imperfection  $v_0$  of the elements; and the wind load (characterized by  $C_{0,w}$  and  $v_b$ ) and imposed load  $Q$ . It should be noted that LN represents a lognormal distribution, N a normal distribution and GU a Gumbel distribution.

Table 1: Parameters and their distribution

Parameter	Distr.	$\mu$	V	Reference
$t$ [mm]	LN	3.2	0.028	(Cajot et al., 2005; CEN, 2004)
$D$ [mm]	LN	48.3	0.028	(Cajot et al., 2005; CEN, 2004)
$\rho_{\text{tubes}}$ [kg/m <sup>3</sup> ]	N	7850	0.02	(JCSS, 2001; R. Steenbergen & Meinen, 2018)
$\rho_{\text{FB}}$ [kg/m <sup>3</sup> ]	N	640.6	0.10	(JCSS, 2001; R. Steenbergen & Meinen, 2018)
$f_y$ [MPa]	LN	244	0.07	(CEN, 2004; JCSS, 2001)
$E$ [GPa]	LN	200	0.03	(CEN, 2004; JCSS, 2001)
$Q$ [kN/m <sup>2</sup> ]	GU	$0.23Q_k$	0.91	(Cajot et al., 2005)
$C_{0,w}$ [-]	LN	0.65	0.30	(fib, 2016)
$v_b$ [m/s]	GU	18	0.15	(fib, 2016)
$v_0$ [mm]	LN	$L/770$	0.6	(Zhang, Rasmussen, & Ellingwood, 2012)

For each of the variables in Table 1, 40 samples are generated using Latin Hypercube Sampling with reduced correlation (CLHS), which are subsequently used as input for the structural calculations in SCIA Engineer. From these simulations in SCIA, for each element of the scaffold 40 values of the internal forces, stresses and buckling lengths are obtained. Subsequently, distributions are fit to the latter values, representing load effects and resistances. For the stresses, a Gumbel distribution is assumed as the stresses are predominantly the result of the service

load  $Q$ . For the normal forces, bending moments and buckling coefficients a lognormal distribution is found to be appropriate.

The following limit state equations are considered for the structural reliability calculations:

$$g(\underline{X}) = f_y(\underline{X}) - \theta_\sigma \cdot \sigma(\underline{X}) \quad (1)$$

$$g(\underline{X}) = 1 - \theta_i \cdot i(\underline{X}) \quad (2)$$

$$g(\underline{X}) = \theta_b \cdot N_R(\underline{X}) - \theta_N \cdot N(\underline{X}) \quad (3)$$

These limit state equations represent failure due to yielding, interaction between normal forces and bending moments and buckling, respectively. The buckling resistance  $N_R$  and interaction between normal forces and bending moments  $i$  can be calculated using equations (4) and (5) respectively.

$$N_R = \chi \cdot A \cdot f_y \quad (4)$$

$$i = \frac{N}{N_R} + \frac{1}{1 - \frac{N}{N_{cr}}} \frac{N \cdot v_0}{M_{pl}} + \frac{M}{M_{pl}} \leq 1 \quad (5)$$

The model uncertainties  $\theta$  considered in the limit state equations (1) to (3) are the following:

- $\theta_\sigma$ : LN( $\mu=1$ ;  $\sigma=0.1$ ) (JCSS, 2001);
- $\theta_N$ : LN( $\mu=1$ ;  $\sigma=0.05$ ) (JCSS, 2001);
- $\theta_b$ : N( $\mu=1.35$ ;  $\sigma=0.10$ );
- $\theta_i$ : N( $\mu=1.31$ ;  $\sigma=0.10$ ) (Cajot et al., 2005).

Since only limited information on the model uncertainty  $\theta_b$  for buckling is available in literature, this parameter was determined based on calibration of a scaffold column which should reach a reliability of about 3.8 for loads with a 50-year reference period and this for different load ratios. Calibration was executed on the mean of the model uncertainty and the standard deviation was adopted from (Cajot et al., 2005).

## 2.2. Sensitivity study on the COV of different parameters

A sensitivity study is conducted (on a scaffold with a total length of 20.7 m (10 sections of 2.07 m), a width of 1.09 m and a height of 11 m (5 floors of 2 m + guardrail of 1 m)) in order to detect

the most important variables for the reliability analysis. The results are summarized in Table 2.

Table 2: Sensitivity study on the influence of the COV of  $D$ ,  $t$ ,  $f_y$  and  $E$ -modulus on the reliability (for each set of results, the lowest value of  $\beta$  is underlined, indicating the determining limit state)

Influence COV of $t$ and $D$ on $\beta$				
COV	0.01	0.03	0.05	0.07
$\beta_{yielding}$	4.38	4.36	4.32	4.28
$\beta_{interaction}$	<u>3.49</u>	<u>3.48</u>	<u>3.43</u>	<u>3.35</u>
$\beta_{buckling}$	13.27	8.12	8.06	7.76
Influence COV of $E$ on $\beta$				
COV	0.02	0.03	0.04	0.05
$\beta_{yielding}$	4.36	4.36	4.36	4.36
$\beta_{interaction}$	<u>3.48</u>	<u>3.48</u>	<u>3.48</u>	<u>3.48</u>
$\beta_{buckling}$	8.12	8.12	8.12	8.12
Influence COV of $f_y$ on $\beta$				
COV	0.05	0.06	0.07	0.08
$\beta_{yielding}$	4.30	7.33	4.36	4.38
$\beta_{interaction}$	<u>3.43</u>	<u>3.46</u>	<u>3.48</u>	<u>3.50</u>
$\beta_{buckling}$	8.08	8.08	8.12	8.17

When changing the COV of  $t$  and  $D$ , the reliability level for limit states (1) and (2) is almost not affected. On the other hand, the reliability index for buckling is largely influenced by the COV of  $D$  and  $t$ .

Looking at  $f_y$ , changing the coefficient of variation has almost no influence on the reliability index for all three limit states. Hence, for buckling it can be concluded that the most important variable in the buckling resistance, is the cross-sectional area of the elements (dependent on  $D$  and  $t$ , for which an increased COV leads to a lower  $\beta$ ) and not the yield strength.

Finally, also the COV of the Young's modulus of the steel is varied. Again, the effect of varying the COV is negligible for all three limit states.

### 3. TARGET RELIABILITY LEVELS FOR TEMPORARY STRUCTURES

#### 3.1. Target reliability considering human safety

In literature, target reliability levels for human safety are proposed in e.g. Caspeepe, Steenbergen,

and Taerwe (2012). When considering a reference period of one year, these target reliability levels are based on following formula:

$$P_{ft,IR} \leq 10^{-5}/P_{c|f} \quad (6)$$

According to (Steenbergen & Vrouwenvelder, 2010) a value of 0.001 can be adopted for  $P_{c|f}$ , resulting in a target reliability index of 2.3. However, this value for  $P_{c|f}$  might be slightly too conservative, as it should be lower than the probability of having *at least one* casualty. Eldukair and Ayyub (1991) presented 0.005 as the probability of at least one casualty in case of failure. The latter results in a target reliability index of  $\beta_t = 2.88$ . Finally, in *fib* Bulletin 80 (fib, 2016) a slightly larger value for  $P_{c|f}$  was assumed, i.e.  $P_{c|f} = 0.01$ , which results in  $\beta_t = 3.1$ .

#### 3.2. Target reliability following from economic optimization

In order to derive a target reliability level based on an economic optimization, Rackwitz (2000) proposed the following objective function:

$$Z(x) = B(x) - C(x) - D(x) \quad (7)$$

Here,  $B$  is the benefit resulting from the structure,  $C$  is the initial cost of construction and  $D$  is the cost due to failure. The optimal reliability level is obtained through an optimum value of the decision parameter  $x$  which maximizes  $Z$  (maximum benefit and lowest costs).

According to (Van Coile, 2015), the objective function can be rewritten in the following shape:

$$Z(x) \sim C_0(1 + \varepsilon(x)) \left[ 1 + \xi \frac{P_f(x)\lambda}{\gamma} \right] \quad (8)$$

To maximize  $Z$  as given in expression (7), equation (8) needs to be minimized. Here,  $\gamma$  is the continuous discount rate. The higher the discount rate, the lower the initial investment required to achieve the target reliability level. Hence, a lower discount rate is more appropriate for temporary structures. Adeli and Sarma (2006) adopt a discount rate in the range of 2% to 3% and also Holický (2012) indicates a discount rate of 0.03 in the average long run in Europe. Next,  $\varepsilon(x)$  represents the ratio of the additional costs when

changing the design parameter  $x$  to the basic costs and  $\xi$  represents the ratio of the failure cost to the initial construction cost  $C_0$ . The value of  $\xi$  is assumed to be less than 2, which is the value applied for private houses (Van Coile, 2015). Finally,  $\lambda$  indicates the renewal rate when the time between renewals is modelled by an exponential distribution. As a reference period of 1 year is used, the average time between renewals is assumed to be equal to 1 year, so  $\lambda = 1$ . This assumption implicitly states that the structure may potentially fail at every renewal, but never in between renewals, since both load and resistance have not changed since the last renewal (Van Coile, 2015). At every renewal, the probability of failure is given by  $P_f(x)$ .

In the following, the influence of the different parameters on the optimum reliability is investigated. One of the most important design parameters for scaffolds is the length of the ledgers, since this influences the load carried by each transom and thus impacts the main failure mechanism: yielding of the transoms. As an example, a scaffold of 2 m high and 30 m wide was considered, with a ledger length varying from 0.1 m to 20 m in steps of 0.1 m. The stresses in the transoms were calculated analytically. Subsequently, a FORM analysis was performed to determine the reliability index  $\beta$  for the limit state of yielding.

The influence of the discount rate on the objective function is represented in Figure 2. The minima of the objective function are situated around the same values for  $\beta$  and varying the discount rate only has an effect for low reliability levels.

Furthermore, the influence of the failure cost to the initial cost  $\xi$  was investigated (Figure 3). The objective function  $Z$  has again a flat behaviour around its minimum and towards higher values of  $\beta$ .

Similar calculations were performed for different scaffold classes and different assumptions on the initial construction cost  $C_0$  considering also the limit state of buckling, leading to analogous conclusions.

Considering these results, it can be concluded that the required level of safety only slightly depends on the assumptions of the different parameters. This behaviour is beneficial, since it is for example difficult to accurately estimate the ratio  $\xi$  of the failure cost to the initial construction cost. This can be attributed to the fact that it is not easy to determine the cost of failure of a scaffold. This cost may be very small when only a part of the scaffold fails, and some elements need to be replaced, possibly after they have been reused a significant number of times. On the other hand, possible deaths or human injuries need to be considered in the failure costs, as well as economic consequences when the scaffold collapse results in damage to other properties. Nevertheless, it can be concluded that the effect of changing this parameter is quite small and that the target reliability index could be determined more accurately considering the case-specific aspects. It should be pointed out that in any case, a target reliability index of at least 2.3 should be respected, considering human safety evaluation as explained in section 3.1.

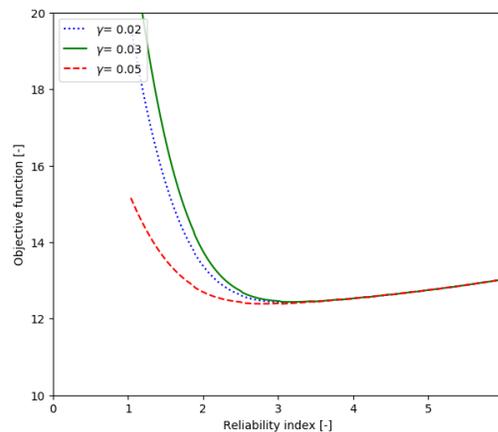


Figure 2: Objective function  $Z$  in function of the reliability index for different values of the discount rate  $\gamma$  (scaffold of class 3 with transoms of 0.73 m,  $\xi = 1$  and  $C_0 = 1$ )

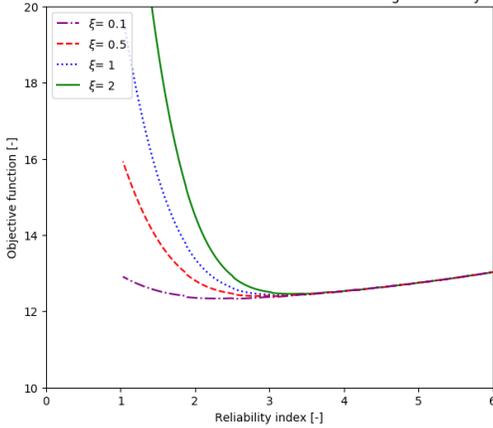


Figure 3: Objective function  $Z$  in function of the reliability index for different values of  $\xi$  (scaffold of class 3 with transoms of 0.73 m,  $\gamma = 0.02$  and  $C_0 = 1$ )

### 3.3. Conclusion on the target reliability level

For human safety, three values are proposed for the target reliability index: 2.3, 2.9 and 3.1.

When economic considerations are investigated, the minimum of the objective function varies depending on the assumed value of  $\xi$ ,  $\gamma$ , among others, where the most influencing parameter is the ratio of the failure costs to the initial costs  $\xi$ . Changing the value of  $\xi$ , the reliability index corresponding to the absolute minimum of the objective function varies between 2.5 and 3.5. Nevertheless, as shown above, in general, the objective function is quite flat around its minimum, thus slightly higher values for  $\beta$  could also lead to a feasible optimal solution from an economical point of view.

For the determination of the partial factors in the next section, three values for the target reliability level are assumed:  $\beta_t = 2.5$ ,  $\beta_t = 3.0$  and  $\beta_t = 3.5$ .

## 4. OPTIMIZATION OF PARTIAL FACTORS FOR TEMPORARY STRUCTURES

### 4.1. Optimization procedure to determine partial factors

The following formula represents the optimization procedure which can be applied to determine the optimal set of partial factors  $\gamma$ :

$$\min_{\gamma} W(\gamma) = \sum_{j=1}^L w_j (\beta_j(\gamma) - \beta_t)^2 \quad (10)$$

Here,  $L$  is the number of design situations considered. In the current study, 16 design situations are investigated, consisting of clad and unclad scaffolds, anchored and self-standing scaffolds, etc. The weight factor  $w_j$ , representing the importance of each design, is set equal to  $1/16$  for all values of  $j$ , assuming that all design situations occur equally frequent in practice. For the target reliability index  $\beta_t$ , the three values proposed in section 3.3 are considered:  $\beta_t = 2.5$ ,  $\beta_t = 3.0$  and  $\beta_t = 3.5$ .

Different sets of partial factors are assumed, considering different partial factors for the material properties ( $\gamma_M$ ), variable loads ( $\gamma_Q$ ,  $\gamma_W$ ) and permanent load ( $\gamma_G$ ). For  $\gamma_M$ , either a factor 1 or 1.1 was adopted. For the permanent loads, the factors 1, 1.35 and 1.5 were considered. For the variable loads, the partial factors varied from 0.7 to 1.6, increased by steps of 0.1. All aforementioned factors were then combined, resulting in a design space consisting of 60 different sets of partial factors. It must be noted that the partial factor for the imposed loads and for the wind loads are taken equal, as also currently in the Eurocodes only one partial factor is given for all the variable loads. It must also be pointed out that the partial factor for the permanent load is adjusted as well, even though its influence is found to be (almost) negligible.

Subsequently, the 16 design situations are elaborated, based on each specific set of partial factors, to arrive at a design which satisfies the design checks implemented in SCIA Engineer. To do so, the ledger lengths and transom lengths are adjusted, considering ledger and transom lengths used in practice. Next, the inherent reliability levels are determined for the different designs using the procedure described in section 2.1 and Equation (10) is applied, where the value of  $W$  is calculated for each set of partial factors. Finally, the optimal set of partial factors is the one which results in the minimal value of the optimization function  $W$ . These factors are summarized in Table 3. It must be noted that the influence of  $\gamma_G$  on the optimization function  $W$  is small, as for example visualized in Figure 4.

Table 3: Optimal partial factors for different  $\beta_t$

Partial factor	$\beta_t = 2.5$	$\beta_t = 3.0$	$\beta_t = 3.5$
$\gamma_G$	1.35	1.35	1.35
$\gamma_Q$	0.80	1.20	1.40
$\gamma_W$	0.80	1.20	1.40
$\gamma_M$	1.00	1.00	1.10

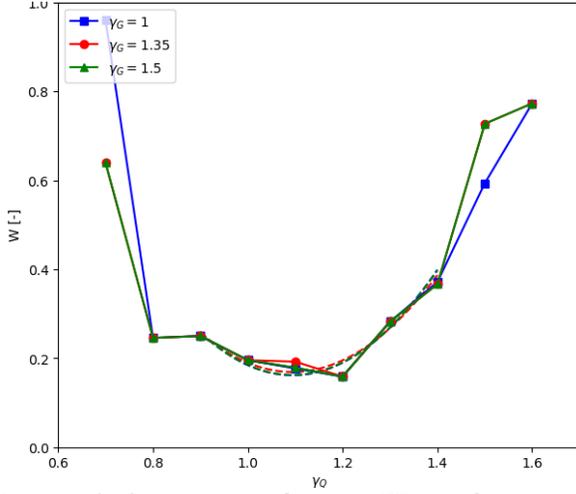


Figure 4: Optimisation function  $W$  as a function of  $\gamma_Q$  for different values of  $\gamma_G$  for  $\gamma_M = 1$  and  $\beta_t = 3$

#### 4.2. Adjusted Partial Factor Method (APFM)

In the Adjusted Partial Factor Method (APFM), adjustment factors  $\omega_\gamma$  are defined as such that  $\gamma_{x,new} = \omega_\gamma \cdot \gamma_{x,original}$ , where  $\gamma_{x,new}$  is the partial factor desired and  $\gamma_{x,original}$  is the factor as currently found in EN 12811-1. This method was originally developed for the assessment of existing structures and the formulas indicated below are adopted from *fib* Bulletin 80 (*fib*, 2016).

The adjustment factor for material properties is generally given by Equation (11), assuming a lognormal distribution for the material property.

$$\omega_{\gamma_M}(\beta_t, V_M) = \frac{\gamma_{Rd}(\beta_t)}{\gamma_{Rd}(\beta')} \exp\left(\alpha_R \beta' \delta'_M \left(\frac{\beta_t}{\beta'} \frac{V_M}{V_M} - 1\right)\right) \quad (11)$$

Here,  $\beta_t$  is the target reliability index and  $\beta'$  is the reliability index inherently found in the structure when designing according to the partial factors currently proposed by EN 12811-1. This reliability index was determined as explained in section 2.1 and is the average of the inherent reliability index found for different scaffold designs. The coefficient of variation of the material properties is indicated by  $V_M$ , where

indicates the values assumed in the original design. Since no background information related to  $V_M'$  is available, both COVs are assumed to be equal, i.e.  $V_M = V_M'$ . The sensitivity factor for the resistances  $\alpha_R$  is equal to 0.8 and  $V_{\theta Rd}$  represents to the coefficient of variation of the resistance model uncertainty. Finally, the partial factor for the material properties is calculated as follows:

$$\gamma_M = \omega_{\gamma_M} \cdot 1.1 \quad (12)$$

For the permanent actions, the adjustment factor is given by Equation (13), based on a normal distribution for the permanent actions.

$$\omega_{\gamma_G}(\beta_t, V_G) = \frac{\gamma_{Ed,G}(\beta_t)^{1-V_Q} \frac{1-\alpha_E \beta_t V_G}{\gamma_{Ed,G}(\beta')^{1-\alpha_E \beta'} V_G}}{\gamma_{Ed,G}(\beta')^{1-\alpha_E \beta'} V_G} \quad (13)$$

The sensitivity factor for the load effects is equal to -0.7. The partial factor for the permanent actions can be determined by applying an equation similar to (12), but with original partial factor 1.5.

The imposed loads are assumed to follow a Gumbel distribution. Hence, their adjustment factor can be written as:

$$\omega_{\gamma_Q}(\beta_t, V_Q) = \frac{\gamma_{Ed,Q}(\beta_t)^{1-V_Q} [0.45 + 0.78 \ln(-\ln(\Phi(-\alpha_E \beta_t)))]}{\gamma_{Ed,Q}(\beta')^{1-V_Q} [0.45 + 0.78 \ln(-\ln(\Phi(-\alpha_E \beta')))]} \quad (14)$$

where the sensitivity factor for the load effects is again equal to -0.7. The partial factor to be applied on the imposed loads is then found by applying and equation similar to (12), with original partial factor 1.5.

The procedure to calculate the adjusted partial factors for wind loads is similar to that of the imposed loads, since the wind loads are also described by a Gumbel distribution:

$$\omega_{\gamma_W}(\beta_t, V_W) = \frac{\gamma_{Ed,W}(\beta_t)^{1-V_W} [0.45 + 0.78 \ln(-\ln(\Phi(-\alpha_E \beta_t)))]}{\gamma_{Ed,W}(\beta')^{1-V_W} [0.45 + 0.78 \ln(-\ln(\Phi(-\alpha_E \beta')))]} \quad (15)$$

The COVs used in the equations mentioned before are 0.1 for  $V_G$ , 0.91 for  $V_Q$ , 0.33 for  $V_W$ , 0.03 for  $V_M$  and 0.075 (buckling) or 0 (interaction and stresses) for  $V_{\theta R}$  (see Table 1 and section 2.1).

The results from these calculations are summarized in Table 4 and are based on an inherent reliability level of the scaffolds according to the current partial factors equal to  $\beta' = 3.59$ . This value is the average reliability level

which was obtained for all design situations considered in section 4.1.

Table 4: Adjusted partial factors based on APFM

$\beta_t$	Original partial factor		Adjustment factor		Adjusted partial factor	
2.5	$\gamma_G$	1.5	$\omega_G$	0.89	$\gamma_G$	1.34
	$\gamma_Q$	1.5	$\omega_Q$	0.66	$\gamma_Q$	0.99
	$\gamma_W$	1.5	$\omega_W$	0.72	$\gamma_W$	1.08
	$\gamma_M$	1.1	$\omega_M$	0.96	$\gamma_M$	1.05
3.0	$\gamma_G$	1.5	$\omega_G$	0.94	$\gamma_G$	1.41
	$\gamma_Q$	1.5	$\omega_Q$	0.80	$\gamma_Q$	1.20
	$\gamma_W$	1.5	$\omega_W$	0.84	$\gamma_W$	1.26
	$\gamma_M$	1.1	$\omega_M$	0.98	$\gamma_M$	1.07
3.5	$\gamma_G$	1.5	$\omega_G$	0.99	$\gamma_G$	1.49
	$\gamma_Q$	1.5	$\omega_Q$	0.97	$\gamma_Q$	1.45
	$\gamma_W$	1.5	$\omega_W$	0.97	$\gamma_W$	1.46
	$\gamma_M$	1.1	$\omega_M$	0.99	$\gamma_M$	1.10

#### 4.3. Comparison partial factors obtained using the optimization procedure and the APFM

It is important to keep in mind that both methods described in the previous sections are based on a different approach. Whereas the optimization procedure aims at finding the optimal set of partial factors to achieve an overall reliability level as close as possible to the target reliability level for different scaffold designs, the starting point of the APFM is the partial factor currently found in EN 12811-1 and the corresponding inherent reliability level, using adjustment factors to account for an adapted target reliability. Hence, this fundamental difference should be kept in mind when comparing the two sets of partial factors.

In case of a target reliability level  $\beta_t = 2.5$ , the partial factors for the permanent loads and for the material properties found by the two different methods are comparable, so for the permanent loads, a partial factor of 1.35 can be proposed and  $\gamma_M = 1$  can be used for the material properties. For variable loads a large difference between the values proposed by the two methods is obtained. However, for standardisation purposes, partial factors less than one could be replaced by  $\gamma = 1$ . In that case, both methods lead to similar results.

For a target reliability of 3, a value of 1.2 for the partial factor for the variable loads appears to be appropriate when comparing the partial factors

found with the two procedures. Since the influence of the partial factor for the permanent actions appeared to be negligible,  $\gamma_G = 1.35$  can be adopted. At last,  $\gamma_M = 1$  results in the minimum of the objective function in the optimisation procedure, whereas a value of 1.07 is found by APFM; Hence, a value of 1.05 could be adopted for the partial factors for the material properties.

Finally, for  $\beta_t = 3.5$ , the target reliability level is almost equal to the mean of the inherent reliabilities for the different scaffold designs considered ( $\beta = 3.59$ ). Therefore, it could be suggested to use the original partial factors for  $\beta_t = 3.5$ .

The proposed partial factors are summarized in Table 5 for the different target reliability levels.

Table 5: Suggested partial factors

$\beta_t$	$\gamma_G$	$\gamma_Q$	$\gamma_W$	$\gamma_M$
2.5	1.35	1.0	1.0	1.00
3.0	1.35	1.2	1.2	1.05
3.5	1.50	1.5	1.5	1.10

## 5. CONCLUSIONS

The objective of this work was to derive partial factors for temporary structures, more specifically for façade scaffolds, based on appropriate safety levels, considering both the short life time of these structures and the possible reuse of the elements. In order to do so, a probabilistic calculation method was set up, based on Latin Hypercube Sampling, FORM analyses and structural calculations in SCIA Engineer, with different probabilistic models as input. For these probabilistic calculations, a reference period of one year was adopted and the inherent reliability index associated to failure due to yielding, the interaction of normal forces and bending moments or buckling could be calculated for different possible scaffold designs. The sensitivity of the assumed value for the COV of different input parameters was checked, in order to find the most important variables in the reliability analysis.

To be able to evaluate the structural reliability levels obtained through the probabilistic calculations, target reliability levels

for the temporary structures under consideration (which are façade scaffolds) were necessary. These target safety levels could be based on a human safety criterion or on an economic optimization. For human safety, three target reliability levels were proposed: 2.3, 2.9 and 3.1. For the economic optimization, the most influencing parameter was the ratio  $\xi$  of the failure costs to the initial costs. The value of this parameter is difficult to determine. When varying the value of  $\xi$ , the reliability index corresponding to the absolute minimum of the objective function varied between 2.5 and 3.5. Nevertheless, in general, the objective function is quite constant around its minimum. Hence, a feasible economic optimal solution could also be found for slightly higher values of  $\beta$ . If more detailed data on the parameters is available in practice, a more comprehensive investigation of the target reliability can be performed. Nevertheless, the target value of  $\beta$  should not less than 2.3, which is the limit found for human safety. For the determination of partial factors for temporary structures as executed in this contribution, three target reliabilities were considered:  $\beta_t = 2.5$ ,  $\beta_t = 3.0$  and  $\beta_t = 3.5$ .

Finally, two methods were applied to determine the partial factors: the Adjusted Partial Factor Method (APFM) and an optimization procedure based on least square averaging. The results of both methods were compared to come to a final suggestion for the partial factors for the three safety levels. Here it may also be pointed out that both methods, even though their different approach, led to quite similar results.

Before coming to final recommendations, calculations based on more detailed data might be required. Furthermore, alternative scaffold designs could be considered.

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