Models of thermal actions for steel and composite bridges based on monitoring

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Abstract. The results of analysis of temperatures based on experimental bridge measurements, research reports and background documents to Eurocodes indicate that the partial factors of temperature components may be reduced to 1.2 for steel and composite bridges and to 1.3 for concrete bridges. It appears that the application of the unique value of the partial factor for most variable loads including climatic actions should be reassessed during the development of the second generation of Eurocodes.

1. Introduction

Thermal actions lead to the longitudinal movements of structures and in case that they are restrained, tensile or compressive stresses need to be considered in structural design. Guidance for determination of basic temperature components and their effects on construction works is given in the Eurocode EN 1991-1-5 [1] which is presently further developed in the framework of the second generation of Eurocodes. The main tasks include clarification of some provisions, simplification, more user-friendly applications and harmonization with other Eurocodes. Moreover, comparative analysis of inconsistencies in extremes of shade air temperature on the borders of neighboring countries could help to achieve much consistent characteristic values of shade air temperatures. Representative values of thermal actions on bridges are specified in EN 1991-1-5 [1] by the uniform temperature component and two temperature difference components in the vertical and horizontal directions.

For the determination of uniform temperature component, the national maps with isotherms of minimum and maximum shade air temperatures based on fifty years return period should be developed in the nationally implemented Eurocodes of each CEN Member State (MS). The characteristic values of the uniform temperatures can be based on the relationship between the extreme shade air temperatures and uniform bridge temperatures which is valid for the 10°C temperature range. This relationship need to be nationally verified taking into account national conditions and the specific ranges of daily temperatures given in the background document to EN 1991-1-5, Report 1999 [2].

For determination of the vertical temperature difference component, several models are given in EN 1991-1-5 [1]. Two alternative procedures based on the vertical linear difference temperature components or non-linear components are allowed for the national choice. The comparative analyses made in the Czech Republic in selected bridges made of different materials resulted in the national selection of the non-linear approach for the vertical temperature difference component as one of the Nationally determined parameter (NDP). For bridges with a shorter span, the linear difference approach could be also used.
It appears that the reduction of the linear temperature difference component by means of the reduction factor \( k_{\text{air}} \) is inconsistent with respect to the reduction of the non-linear difference temperature component given in EN 1991-1-5 [1] and should be further harmonized, see (Reports 1973, 1996).

It is expected that recent analyses of long-term experimental measurements of temperatures in some bridges in the Czech Republic and in other European countries will facilitate to refine the thermal models for national conditions.

The background document [2] to Eurocode [1] provides additional information concerning experimental measurements of temperatures which formed the basis for the development of the models of thermal actions in Eurocodes. The characteristic values of temperature components are based on the fifty years return period as other climatic actions (snow, wind velocity, icing). Presently, the Eurocodes recommend a unique value of partial factor \( \gamma_\varnothing = 1.5 \) for most variable actions \( \varnothing \) with respect to the ultimate limit states. However, the reduced factor \( \gamma_T = 1.2 \) was applied for thermal actions \( T \) in some original national standards including the Czech Republic. It appears that the partial factors of some variable actions including thermal actions should be differentiated in Eurocodes taking into account their characteristics.

The information given in the Report [2] and the recent results of experimental monitoring of selected bridges in the Czech Republic located in Prague motorway circuit, on D1 highway between Prague and Brno, and on D8 highway across the Ohre river, are considered for the analyses of temperature components and for the assessment of partial factors for thermal actions.

2. Models of temperatures

Procedures for specification of thermal models based on experimental measurements of temperatures are described in several reports including Reports [3,4] which were worked out in the KI CTU.

The extreme value distribution should be applied for modelling of extreme values of the uniform and temperature difference components. The background report [2] provides statistical characteristics of several year temperature measurements on steel, composite and concrete bridges, and also estimated characteristics based on 10-years simulations of temperatures in different heights of the concrete bridge cross-sections using simulations and software Therm. The climatic data from the Middle Germany were considered. Moreover, recent measurements provided in several Bohemian bridges were also statistically analyzed.

For the assessment of models for thermal actions and determination of their partial factors, the statistical characteristics of temperature components need to be specified for one year and 50 years reference periods. It is shown that the Weibull distribution or three parameter Lognormal distribution may be applied in all considered cases for the assessment of the characteristic and design values of temperatures.

2.1. Shade air temperature

For specification of the uniform bridge temperature component, the characteristic values of shade air temperatures should be determined by each CEN MS in the National Annex of EN 1991-1-5 [1]. Some countries developed national maps with isotherms and they apply recommended (or calibrated) relationship between the shade air temperature and uniform (effective) temperatures considering three types of bridge superstructure (concrete, composite and steel). Some countries apply temperature ranges which are considered to be characteristic values. The Czech Republic has developed maps of minimum and maximum shade air temperatures which are based on 37 stations and 60 years of measurements, assuming the Gumbel distribution. During the new development of prEN 1991-1-5 in the framework of the second generation of Eurocodes, the consistency of the characteristic temperatures within neighboring countries should be checked. Various inconsistencies in the boarders of countries still exist, e.g. for the Czech Republic and neighboring countries, where the difference up to 12 °C in winter, and up to 6 °C in summer could be found, see Tables 1 to 4. Similar inconsistencies exists on the borders of other European countries.
Comparisons of maximum and minimum shade air temperatures in selected MS are provided in Table 1. Some countries apply directly a range of characteristic values, others have developed maps of minimum and maximum isotherms. The Eurocode EN 1991-1-5 [1] recommends assessment of the uniform temperature component from nationally determined isotherms of minimum and maximum shade air temperatures. The relationship between the uniform temperatures and shade air temperatures is given in Table 5 which is applied by several MS. The values in Table 5 are based on the daily temperature ranges of 10 °C which is assumed to be appropriate for most European countries and which could be modified for other daily ranges following recommendations of Report [2].

The characteristic values of shade air temperature in the boarders of the Czech Republic with Austria and Slovakia are shown in Tables 2-3. Polish NDPs were not available. Comparison of shade air temperatures and uniform temperature component are more significant in case of negative temperatures.

### Table 1. Comparison of temperature differences in selected CEN MS

| Country | A | BE | CZ | DNK | GE | NDL | SK |
|---------|---|----|----|-----|----|-----|----|
| $T_{\text{min}}$ | -16 | -21 | -28 | -31 | -24 | -25 | -28 |
| $T_{\text{max}}$ | 39 | 38 | 32 | 40 | 36 | 37 | 30 |

1) Austria recommends formulae where $k = 0.006$ and $h$ = height above the sea level
2) Czech Republic and Slovakia have available maps with isotherms, and apply relationship in Table 5

### Table 2. Characteristic values of shade air temperatures at Austrian - Czech boarder

| Alt. in m | CZ - $T_{\text{max}}$ | A - $T_{\text{max}}$ | $\Delta T_{\text{max}}$ | CZ - $T_{\text{min}}$ | A - $T_{\text{min}}$ | $\Delta T_{\text{min}}$ |
|-----------|----------------------|---------------------|-----------------------|----------------------|---------------------|-----------------------|
| 600-900   | 38 - 36              | 35.4 - 33.6         | 2.6 - 2.4             | -32 (-34)            | -19.6 (-21.4)       | -12.4 (-12.6)         |
| 470-500   | 40 - 38              | 36.2 - 36           | 3.8 - 2               | -30 (-32)            | -18.8 (-19)         | -11.2 (-13)           |
| 400-500   | 38 - 36              | 36.6 - 36           | 1.4 - 0               | -28 (-30)            | -18.4 (-19)         | -9.6 (-11)            |
| 200-250   | 40 - 38              | 37.8 - 37.5         | 2.2 - 0.5             | -28 (-30)            | -17.2 (-17.5)       | -10.8 (-12.5)         |

### Table 3. Characteristic values of shade air temperatures at Slovak - Czech boarder

| Region     | CZ - $T_{\text{max}}$ | SK - $T_{\text{max}}$ | $\Delta T_{\text{max}}$ | CZ - $T_{\text{min}}$ | SK - $T_{\text{min}}$ | $\Delta T_{\text{min}}$ |
|------------|----------------------|---------------------|-----------------------|----------------------|---------------------|-----------------------|
| north      | 34 - 32              | 40                  | 8 - 6                 | -34 (-36)            | -30                 | -2 (-4)               |
| central    | 36 - 34              | 40                  | 6 - 4                 | -32 (-34)            | -28                 | -4 (-6)               |
| south      | 40 - 38              | 40                  | 2 - 0                 | -30 (-32)            | -28                 | -2 (-4)               |

### Table 4. Comparison of temperature differences at German - Czech boarder

| Type | CZ - $T_{\text{max}}$ | GE - $T_{\text{max}}$ | $\Delta T_{\text{max}}$ | CZ - $T_{\text{min}}$ | GE - $T_{\text{min}}$ | $\Delta T_{\text{min}}$ |
|------|----------------------|---------------------|-----------------------|----------------------|---------------------|-----------------------|
| Shade| 37                   | 37                  | 0                     | -36                  | -27                 | -9                    |
| 1    | 52                   | 53                  | 1                     | -36                  | -27                 | -9                    |
| 2    | 41,5                 | 41                  | 0.5                   | -28.5                | -20                 | -8.5                  |
| 3    | 39                   | 38.5                | 0.5                   | -25                  | -16                 | -9                    |

### 2.2. Uniform temperatures

The Eurocode EN 1991-1-5 [1] recommends assessment of the uniform temperature component from nationally determined isotherms of minimum and maximum shade air temperatures. The relationship between the uniform temperatures and shade air temperatures is given in Table 5 which is applied by several MS. The values in Table 5 are based on the daily temperature ranges of 10 °C which is assumed to be appropriate for most European countries and which could be modified for other daily ranges following recommendations of Report [2].

The Klokner Institute in co-operation with the Czech Hydrometeorological Institute made analyses of selected national parameters. It was decided that the daily range of 10 °C can be applied for most regions of the Czech Republic based on statistically evaluated data from 151 national meteorological stations in the period from 1961 to 2000 (daily mean temperature range is 11.2 °C). The uniform bridge temperature components $T_{\text{max}}$ and $T_{\text{min}}$ may be specified on the basis of shade air temperatures based on 50 years return period taking into account formulae in Table 5 where for the steel truss and plate girders the maximum values given for the bridge of type 1 might be reduced by 3°C.
Table 5. Relationship between extreme shade air temperature and uniform bridge temperature

| Bridge deck type | $T_{N,\text{max}}$ | $T_{N,\text{min}}$ |
|------------------|---------------------|---------------------|
| 1                | $T_{\text{max}} + 16$ | $T_{\text{min}} - 3$ |
| 2                | $T_{\text{max}} + 4$ | $T_{\text{max}} + 4$ |
| 3                | $T_{\text{max}} + 2$ | $T_{\text{max}} + 8$ |

For modeling of the uniform temperature component, the extreme value probabilistic distribution might be applied. The uniform temperature component is commonly based on the three-day maxima of shade air temperature for concrete bridges and on one-day maxima for steel and composite bridges.

It should be noted that the Report [2] provides an estimated upper bound of extreme temperatures for considered Weibull distribution. For example the upper bound of temperatures for the expansion range $\Delta T_{N,\text{exp}}$ for concrete bridges is assumed to be about 38°C and the uniform temperature $T_{N,\text{exp}}$ for steel bridges is estimated about 43°C. The upper bound is assumed to be valid for Germany and some other neighboring countries.

However, the upper bound of temperatures depends on the national climatic conditions of each country. In some European countries less or more days of temperature measurements than three months as described in [2] might be necessary to be considered for obtaining extreme temperatures, see e.g. [3,4].

The annual statistical characteristics (mean $\mu_T$, standard deviation $\sigma_T$ and skewness $\alpha_T$) of uniform temperature component (for Weibull distribution) are given in the first two rows of Table 6 for steel and composite steel concrete bridges in Germany. In the last row the results of measurements for a composite steel concrete bridge of 3 spans (slab thickness from 0.30 to 0.40 m, 5 steel girders) across the Nightingale valley situated in the Prague ring near the exit of the Lochkov tunnel are given. The composite bridge and position of sensors in concrete deck are illustrated in Figure 1.

Table 6. Statistical characteristics of uniform temperature component $T_N$ (in °C) and partial factor $\gamma_T$

| Type of bridge       | $\mu_T$ | $\sigma_T$ | $\alpha_T$ | $\gamma_T$ |
|----------------------|---------|------------|------------|------------|
| Steel (GE)           | 40      | 2          | 0.6        | 1.12       |
| Composite (GE)       | 35      | 2          | 0.6        | 1.13       |
| Composite (CZ)       | 32      | 2          | 0.5        | 1.1        |

It is shown that for the uniform temperature component, the partial factor of thermal actions $\gamma_T$ could be about 1.15 for steel and composite bridges.

2.3. Difference temperatures

For the positive vertical temperature differences (heating), the statistical characteristics and partial factors are given for steel and composite bridges in Table 7.
Table 7. Statistical characteristics of the temperature difference component $\Delta T_{my,heat}$ (in °C) and the partial factor for steel and composite bridges

| Type of bridge | $\mu_T$ | $\sigma_T$ | $\alpha_T$ | $\gamma_T$ |
|---------------|---------|-----------|------------|-----------|
| Steel (GE)    | 11      | 1         | 0.65       | 1.16      |
| Composite (GE)| 15      | 1         | 0.7        | 1.17      |
| Composite (CZ)| 15      | 3         | 0.4        | 1.17      |

It is shown that for the vertical temperature difference component, the partial factor $\gamma_T$ is about 1.16 for steel bridges, about 1.17 for composite bridges.

3. Analyses of partial factors

The characteristic value of a climatic action is defined in Eurocodes as the upper fractile of the probabilistic distribution for the basic time period corresponding to the 2% probability of annual exceeding. The design value of a climatic action is considered as 0.996 fractile of the probabilistic distribution. The partial factors $\Delta T$ of a temperature component can be expressed as

$$\gamma_T = \frac{x_{p,0.98}(\Phi^{-1}(-\alpha \beta))}{x_{p,0.98}}$$  \hspace{1cm} (1)

where $\alpha$ is the coefficient of sensitivity for the leading variable action and $\beta$ is the target reliability index where $\beta = 3.8$ for bridges in common category CC2 as recommended in Eurocodes.

In case when the bridge needs to be classified to higher reliability class RC3 (considering the target reliability index $\beta = 4.3$), then the probability $p = 0.999$ should be applied in expression (5). When the bridge is to be categorised in the reliability class RC1 only ($\beta = 3.3$) as e.g. for some existing bridges with a shorter remaining life-time, then the probability $p = 0.99$ might be assumed.

The partial factor $\gamma_T$ specified for thermal actions versus the coefficient of variation $V_T$ for considered Gumbel and Weibull distributions (for two selected values 0.4 and 0.6 of skewness) is illustrated in Figure 2. It is shown that for the same coefficient of variation the value of partial factor significantly depends on the applied probabilistic distribution.

![Figure 2: The partial factor $\gamma_T$ of thermal actions versus the coefficient of variation $V_T$ for considered Gumbel and Weibull distributions](image)

The partial factor $\gamma_T$ specified for thermal actions versus the coefficient of skewness $\alpha$ for three different reliability categories RC1 to RC3 is illustrated in Figure 3. The partial factor $\gamma_T$ is increasing with increasing skewness of the probabilistic distribution of temperatures.
4. Conclusions

It appears that despite the Eurocodes recommend the application of the Gumbel distribution for modeling of climatic loads, the uniform and difference temperature components could be better represented by Weibull distribution. The skewness of the statistically evaluated data of temperature measurements is in a range from 0.3 to 0.7 what is considerably less than the skewness of the Gumbel distribution. For specification of statistical characteristics for Weibull distribution, the skewness as a third parameter should be preferable applied than taking into account rough estimation of the upper limit of the distribution only as indicated in the background document to EN 1991-1-5. It appears that a three parameter Lognormal distribution might be also applied as it has no an upper bound for positive skewness.

The results of analysis of temperatures based on the experimental bridge measurements indicate that the partial factors of the both uniform and difference temperature components may be reduced to 1.2 for steel and composite steel-concrete bridges. In case that some uncertainties in the process of further development of temperatures in the next decades should also be considered, the potential enhancement factor for consideration of climate changes, if needed, could be estimated for structures with a higher working life. Application of partial factors for thermal actions calibrated for national climatic conditions will facilitate design of bridges, bearings and thermal expansions.

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